한국환경생태학회지 30(5) : 821~828, 2016
Korean J. Environ. Ecol. 30(5): 821-828, October 2016

pISSN 1229-3857 eISSN 2288-131X
http://dx.doi.org/10.13047/KJEE.2016.30.5.821

Effects of the Light Source of LEDs on the Physiological and Flowering Response of Endangered Plant *Silene capitata* Kom.[1a]

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LED광질에 따른 분홍장구채(*Silene capitata* Kom.)의 생리 및 개화 반응[1a]

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ABSTRACT

We examed physiological and flowering response of *S. capitata,* the endangered plant in Korea, under LED light conditions in plant factory to cultivate artificially for conservation. We cultivated *S. capitata* and measured its physiological responses and the number of flowers under red, blue, white, red+far-red mixed, red+blue mixed, and red+blue+white mixed light. The results showed that its photosynthetic rate and chlorophyll content were recorded relatively high in red+blue+white and red+blue mixed light respectively. Transpiration rate and stomatal conductance appeared relatively high in the white single light while water use efficiency was no difference. Photochemical efficiency of photochemical photosystem II by minimum and maximum chlorophyll fluorescence was the highest in the red+blue+white mixed light condition than other ones. The number of flowers of *S. capitata* was at its peak under the red light or red+far-red mixed light. Therefore, we conclude that the most efficient way to grow for flowering of *S. capitata* is to provide red light or red+far-red mixed light in the plant factory.

KEY WORDS: ARTIFICIAL LIGHT CONDITION, PLANT FACTORY, REPRODUCTIVE RESPONSES

요 약

본 연구에서는 한국 멸종위기식물인 분홍장구채의 보전 및 인공재배를 위해 식물공장 내 인공적인 광 조건에서 일어나는 생리와 개화반응 특성을 알아보았다. 이를 위해 분홍장구채를 식물공장의 각 챔버에 적색광, 청색광, 백색광, 적색+원적색 혼합광, 적색+청색 혼합광 그리고 적색+청색+백색 혼합광 하에서 재배하여 광합성률, 증산률, 기공전도도, 수분이용효율, 엽록소함량, 최소엽록소형광, 최대엽록소형광, 광계II의 광화학적 효율 그리고 잎과 꽃 수를 측정하였다. 그 결과 적색 단일광과 적색+원적색 혼합광에서 분홍장구채는 가장 많이 개화하였으며, 이 광조건에서는 광합성률, 증산률 그리고 기공전도도는 상대적으로 다른 조건보다 높았으나 수분이용효율은 차이가 없었으며, 엽록소함량은 적었다. 특히 최소 및 최대 엽록소형광과 광계II의 광화학적 효율은 적색 단일광 조건에서 다른 광 조건보다 낮았다. 이러한 결과는 분홍장구채의 꽃의 생산을 위해서는 적색 단일광이나 적색+원적색의 인공광 조건에서 재배하는 것이 효율적이

1 접수 2016년 6월 21일, 수정(1차: 2016년 10월 26일), 게재확정 2016년 10월 27일
Received 21 June 2016; Revised (1st: 26 October 2016); Accepted 27 October 2016
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a 이 논문은 2016년도 정부(교육부)의 재원으로 한국과학창의재단(2016년도 학부생 연구프로그램)의 지원을 받아 수행된 연구임.
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라는 것을 의미한다.

주요어: 인공 광 조건, 식물공장, 생식기관 반응

INTRODUCTION

Extreme weather conditions such as local torrential rainfall, drought, and heavy snowfall caused by climate changes have long-been a global issue and these environmental changes are having their impact on the growth of plants (Kim *et al*., 2011).

The plant factory that allows cultivation of crops under controlled settings with a maximized use of space is being popularized as the current climate changes can cause a serious environmental impact on the growth and propagation of plants grown in the openness (Kim *et al*., 2011). A plant factory is a system integrated with a computer that allows the cultivation of plants irrespective of the weather and spatial conditions with its ability to artificially set its own environmental factors like light, temperature, humidity, concentration of CO_2 and culture medium (Yoon, 2012).

LED refers to a semiconductor device that glows when applied with a forward current (Yoon, 2012) and has many benefits in the plant cultivation within the plant factory settings. With the usage LED light source, which has monochromatic diodes, one is able to choose the wavelength that is effective in photosynthesis and the photomorphogenesis for optimization of plant cultivation unlike the natural light which consists of various colors of mixed lights (Yoon, 2012). Also in comparison to the high pressure sodium and metal halide lamp, which are a type of discharge lamp, LEDs produce less heat which results to less plant damages during cultivation (Lee, 2010). LEDs are environmental-friendly as their production does not require mercury, their maintenance cost is low with their long lifespan of 10,000 to 50,000 hours and a high power saving efficiency (Hwang *et al*., 2004; Yoon, 2012). Thus the LED light sources are often used in the field of photobiology (Robin et al., 1994; Tripathy and Brown, 1995). Studies on the growth characteristics of plants grown under LEDs in plant factory are being actively done locally with culinary vegetables like red and green lettuces, horseradish, and bokchoy (Kim et al., 2014; Kim and You, 2013; Lee *et al*., 2012).

The LEDs of red, blue, white, far-red, red+blue, red+blue+white, red+far-red using this study were often used to research on the plant factory or plant physiology (Kim *et al*., 2014; Kim and You, 2013).

The *S. capitata* is Korean endangered plant established by Ministry of environment (Ministry of environment, 2015). It is herbaceous perennial belong to Caryophyllaceae. This plant's peduncles fall in the ground because they grow too long. Its flower blooms between October and September. Pink-colored small flowers are gathered at the end of peduncle. The height of *S. capitata* is relatively small with an average of 30cm. It can be cultivated in limited space like a plant factory due to its capacity to grow under low light conditions (Lee, 2003).

Specially, confirming the number of flowers *S. capitata* was needed for its artificial proliferation because of forming a number of seeds per flower. For this reason, we studied physiological characteristics and the number of flowers of *S. capitata*. Until today, the physiological response and reproduction on a variety of plants have studied (Goins *et al*., 1997; Zhou Y *et al*., 2002; Choi, 2003; Govert *et al*., 2010; Choi *et al*., 2013; Bernier *et al*., 1993; Corbesier and Coupland, 2005) except them of *S. capitata*.

Thus this study was done to confirm *S. capitata* can be stable cultivated and multiplied in the plant factory even if climate change continued and to find optimal light source for their optimal physiological response and flowering.

MATERIALS AND METHODS

1. Cultivation and Maintenance

S. capitata was disseminated in a seed bed (width 60 ㎝, length 30 ㎝, and height 3.5 ㎝) filled with bed soil (horticultural bed soil with mineral supplements, Han Areum Co.) on March 20, 2013.

Water was supplied every 2 to 3 days from dissemination until germination. Germinated seedling was transplanted into a round container (diameter 12cm, and height 15 ㎝) filled with bed soil. Each light condition of the plant factory was allotted with 3 plants and 6 different light conditions were looked at while cultivation took place for 10 months from June 2013 to March 2014.

The fertilizer (GoldSoil, KGChemical Co.) which consists of 70% organics, 4.3% nitrogen, 1.7% phosphoric acid, 1% potassium, was diluted in water by 3% and supplied every 7 days as a soil nutrient.

The average photosynthetic photon flux density (PPFD) was measured during the cultivation period, and the average PPFD of each plant factory chamber was 150.59±27.29 μ $molm^{-2}s^{-1}$ (Table 1). Temperature was set at 19.42±5.10℃ on average and adjusted using a cold and hot-air circulator (SS-2000, Zero engineering Co, Korea). Humidity was kept at an average of 71.81±9.22% using a humidifier (Fox-1H, Parus Co, Korea). The CO_2 concentration within the plant factory was at 401.59±86.87 ppm during cultivation. Above-mentioned data were collected in computer and were measured every 10 minutes using LCSEMS (PARUS Co., Korea). Photoperiod was set at 16 hours out of 24 hours.

2. Light Conditions within the Plant Factory

Red, blue, white, red+blue mixed, red+blue+white mixed, red+far-red mixed (R; B; W; R+B; R+B+W; R+fR respectively hereafter) were used as the light sources within the plant factory (Table 1), using 'the LED grow light' system (Parus Co. 2010). Each of light qualities was selected by ones mainly used in plant factory. Red and blue light are commonly used photosynthesis in plants and white light similar to daylight. Infrared light relate to photomorphogenesis.

The power consumption of each light source is 200watt and the dimensions of the chamber installed in the plant factory were 120㎝ in width, 52㎝ in length and 50㎝ in height.

The optimal spectrum of each light source reached its peak when the wavelengths of the light were measured at 660nm with R, 450nm with B and 780nm with fR. White LED light was used that its wavelength is 450-540nm.

3. Measurements of the Physiological Response

Physiological response measured in October, 2013 when growth activity is vigorous. To investigate the physiological response of *S. capitata*, photosynthetic rate ($umolCO_2g^{-2}s^{-1}$), transpiration rate ($mmolg^{-2}s^{-1}$), stomatal conductance ($mmolH_2Om^{-2}s^{-1}$), water use efficiency ($umolCO_2mmolH_2O^{-1}$), chlorophyll content (CCI), minimum and maximum chlorophyll fluorescence (Fo, Fm) and the photochemical efficiency of photosystem II (Fv/Fm) were measured.

Photosynthetic rate, transpiration rate and stomatal conductance were measured by Photosynthesis measuring apparatus (Lci Ultra compact Photosynthesis System, ADC Co.) between 10:00AM to 12:00PM when the solar radiation was higher than the light saturation point. When measured, leaves were inserted that's chamber and wait 5 min for stabilizing. Water use efficiency was calculated from dividing the photosynthetic rate by the transpiration rate (Lee *et al*., 2012).

Chlorophyll contents was measured using the Chlorophyll contents Measuring Apparatus (CCM-200, Chlorophyll Content Meter, ADC Co.). CCI(chlorophyll content index), its unit, is quantified value in a non-destructive manner as comparing two lights absorption when irradiating the lights of 940nm and 660nm in the leaves.

Fo, Fm and Fv/Fm were measured using a Chlorophyll Fluorometer (OS30p, Continuous source Chlorophyll Fluorometer, ADC Co.) between 02:00PM to 04:00PM. When measuring, leaves were done dark adaptation for 20 min then irradiated the light of 660nm in a moment.

3. Measurements of Growth and Flowering Response

S. capitata is the plant that form rosette has rosette leaves and also its flower stalk has leaves (Lee, 2003). In this study, we counted total leaves per plant.

Multiples of tiny flowers grow on the tip of the flower stalk or the axil of the *S. capitata* (Lee, 2003). In this experiment, the number of inflorescence which flowered on each plant under different light conditions was counted. On each plant, total number of inflorescences per plant was counted. Then, 15 inflorescences per plant were selected and the number of flowers on each of the selected inflorescence was counted on November 2013. Based on this, we calculate total number of flowers per plant.

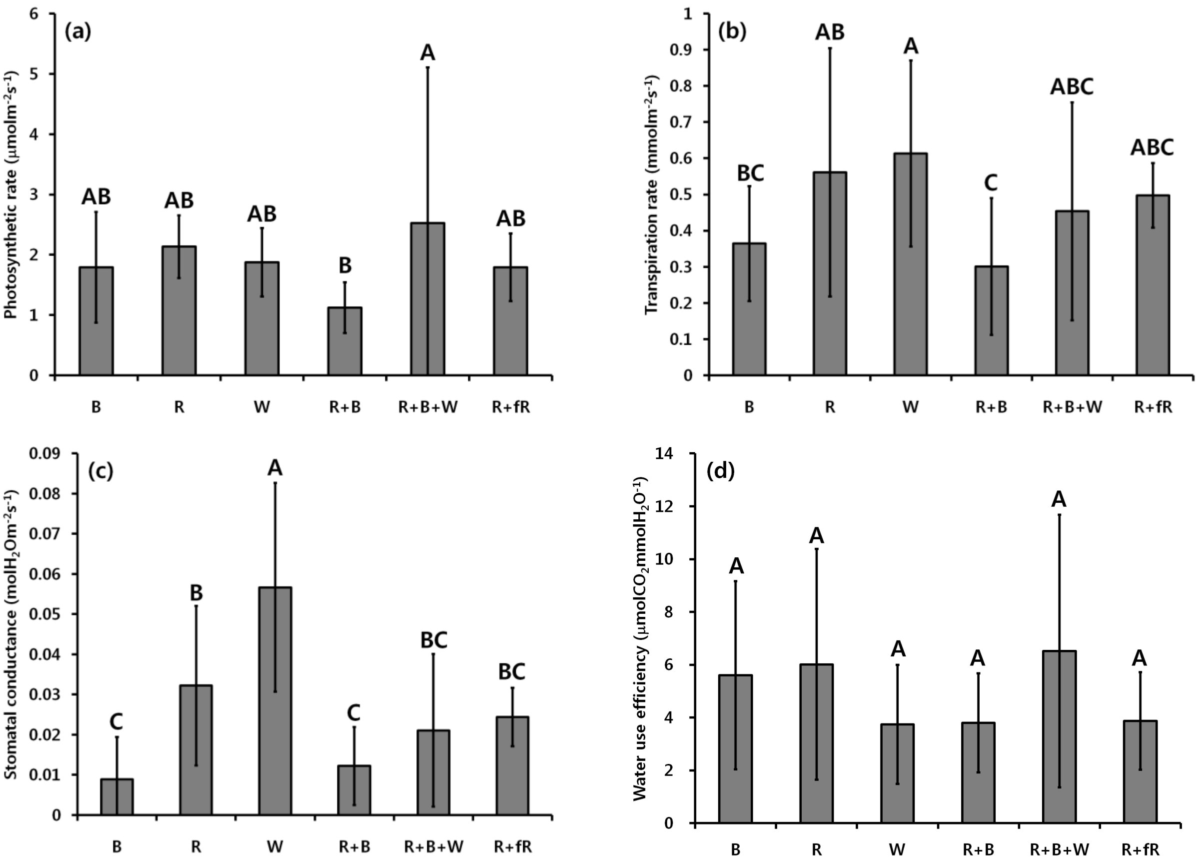
3. Statistical Analysis

The effects of different LED irradiation patterns on the physiological and flowering responses of *S. capitata* were tested using one-way ANOVA. The statistical differences between the treatment groups were evaluated via Fisher's least significant difference test as post-hocs, with significance at P=0.05. The data processing was conducted using STATISTICA 8 (Statsoft Inc. 2006, Tulsa, USA).

RESULTS AND DISCUSSION

1. Physiological response

In the increasing orders, the photosynthetic rates ranged from R+B+W ≥ B, R, W, R+fR ≥ R+B (Figure 1A). Similarly, the photosynthetic rate of rice (*Oryza sativa* L.) is higher in the R+B than R (Matsuda *et al*., 2004), that of Cocklebur (*Xanthium strumarium* L.) is higher in the R than B (Sharkey and Raschke, 1981).



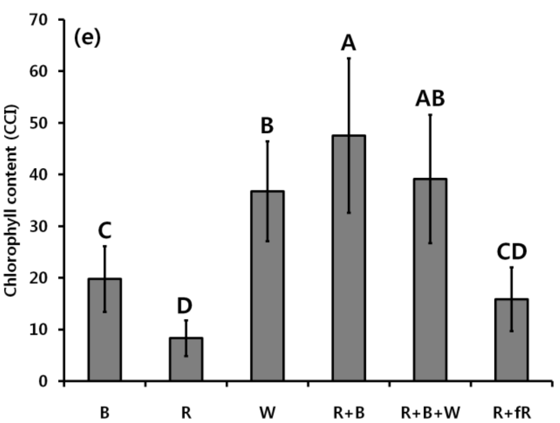


Figure 1. The photosynthetic rate (a), transpiration rate (b), stomatal conductance (c), water use efficiency (d) and chlorophyll content (e) of *S. capitata*. Alphabets on the bars represent the significant differences among the LED light treatments in the plant factory (Fisher's least significant difference, p>0.05).

Specially, photosynthetic rate under R+B+W was higher than R+B because the wavelength of W including the wavelength of green and yellow as well as red and blue compensates the defect of R and B. Its cause is considered by the pigments absorbing green and yellow wavelength in the plants (Hopkins and Huner, 2004; Robert, 2010).

The transpiration rate for *S. capitata* ranged from W≥R ≥R+B+W, R+fR≥B≥R+B (Figure 1B) while water use efficiency was no difference (Figure 1D) because the increasing patterns of photosynthetic rate and transpiration rate are too similar.

The stomatal conductance ranged in the following increasing order, W>R≥R+B+W, R+fR≥B, R+B (Figure 1C). This increasing pattern is similar to transpiration rate than photosynthetic rate. It seems like that photosynthetic rate has dissimilar pattern by the difference of carbon assimilation ability (Ball *et al*., 1987) while stomatal conductance affects on the transpiration rate.

The chlorophyll concentrations ranged in the following increasing order, R+B≥R+B+W≥W>B≥R+fR≥R (Figure 1E). In a similar experiment, the chlorophyll contents of *P. ginseng* is higher in W than B (Park *et al*., 1989) and red lettuce is higher in B than R (Johkanm *et al*., 2010). Also, *Fragaria x ananassa* cv. akihime, the cultivar of strawberry, is higher in R+B than R and B. In the case of plants, which are adapted to low light conditions, it is known that the most of the energy is spent on the manufacture and maintenance of the light-harvesting machinery (Chavan *et al*., 2011). In the case of *S. capitata*, the photosynthetic rate was the lowest under R+B. Hence it can be deduced that the most of its acquired energy was invested on the maintenance of chlorophyll content for efficient photosynthesis.

In the increasing orders, the minimum chlorophyll fluorescence (Fo) ranged from B≥R+B, R+fR≥W≥ R+B+W≥R (Figure 2A), the maximum chlorophyll fluorescence (Fm) ranged from B, W, R+B, R+B+W>R+fR>R (Figure 2B) and photochemical efficiency of photosystem II (Fv/Fm) ranged from R+B+W≥W≥B, R+B, R+fR>R (Figure 2C). Wang *et al*. (2009) reported that the Fv/Fm of *Cucumis sativa* is increased in the order of W≥B>R.

In this experiment, R+B+W which is the most close in 0.83, is the light condition that *S. capitata* feels low stress but R is the most stressful light condition because of low value of Fv/Fm. Under R+B+W, photosynthetic rate is the highest because photoinhibition did not happen nearly. W includes the wavelengths of green and yellow lights, which are absorbed by anthocyanin, carotin, and xanthophylls (Hopkins and Huner, 2004; Robert, 2010). These pigments have functions protected leaves from photoinhibition (Hopkins and Huner, 2004; Robert, 2010).

2. Growth response

The number of leaves per plant of *S. capitata* has no difference (Figure 3). This result means that it's the number of leaves was not affected by physiological responses on the different light qualities.

3. Flowering response

The number of flowers per plant ranged in the following

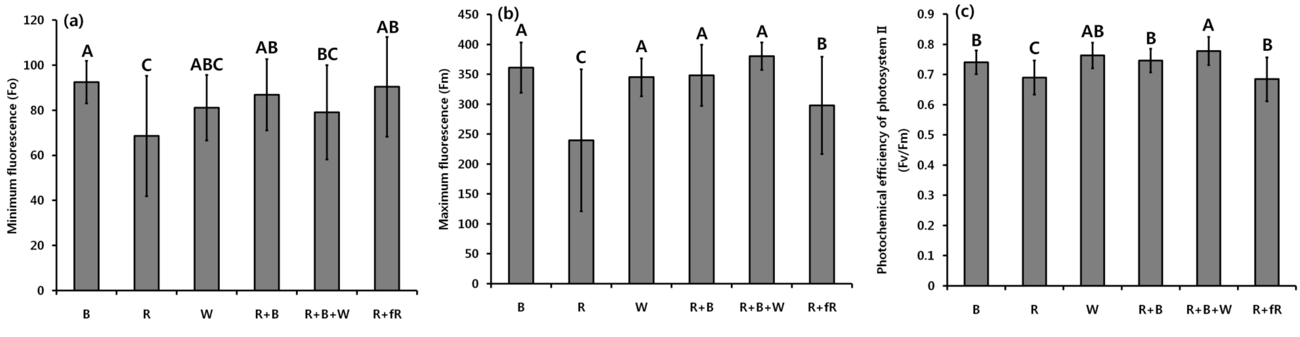


Figure 2. The minimum chlorophyll fluorescence (a), maximum chlorophyll fluorescence (b) and photochemical efficiency of photosystem II (c) of *S. capitata*. Alphabets on the bars represent the significant difference among the LED light treatments in the plant factory (Fisher's least significant difference, $p>0.05$)

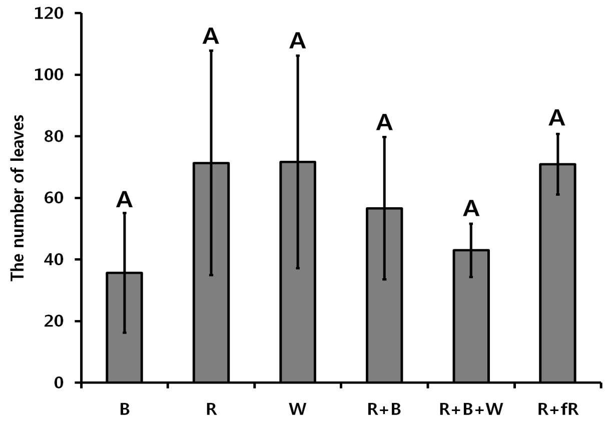


Figure 3. The number of leaves of *S. capitata*. Each group was analyzed by One-way ANOVA (Fisher's least significant difference, p>0.05). Alphabets on the bars represent the significant difference among the LED light treatments in the plant factory

increasing order, R, R+fR>R+B>B, W, R+B+W (Figure 4). In a similar experiment with *Cyclamen persicum* Mill. Cv. 'Dixie White', the number of flowers is more in R than B (Jeong *et al*., 2003). The number of flowers of cranberry (*Vaccinium macrocarpon* Ait) is more in R than W. Generally, phytochrome affected dominantly by red or far-red light induce flower bud. In this our study red light enhanced the flowering rate (Figure 4). But this result is opposed to flowering phenomenon of Arabidopsis suppressed by red light (Hopkins and Huner, 2004). These results

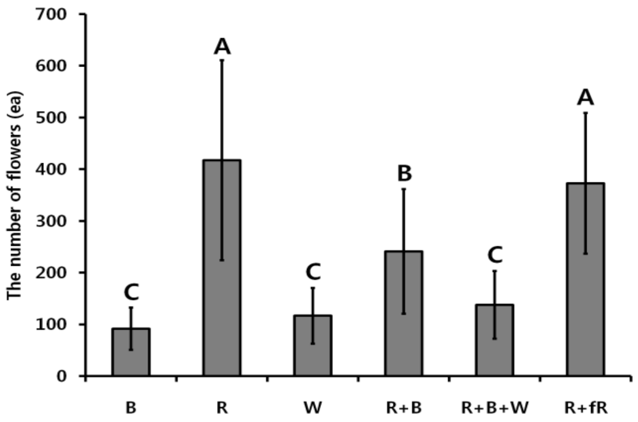


Figure 4. The number of flowers of *S. capitata*. Alphabets on the bars represent the significant difference among the LED light treatments in the plant factory (Fisher's least significant difference, p>0.05)

show that the change of physiological response on the light quality affects on the number of flowers except the number of leaves of *S. capitata*. Specially, R and R+fR seem that it's light stress and the number of flowers increased than the others. In terms of climate change, these results mean if global warming increased, stable artificial cultivation and proliferation of *S. capitata* will be possible using plant factory.

ACKNOWLEDGEMENT

This work was supported by the Korea Foundation for the Advancement of Science & Creativity(KOFAC) grant funded by Ministry of Education(MOE).

REFERENCES

Boardman N.K.(1977) Comparative photosynthesis of sun and shade plants. Ann. Rev. Plant Physiol. 28:355-377.

Bernier G., A. Havelange, C. Houssa, A. Petitjean and P. Lejeune(1993) Physiological signals that induce flowering. The Plant Cell. 5:1147-1155.

Ball J.T., I.E. Woodrow and J.A. Berry(1987) A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. Prog. in Photosyn. Res. 4:221-224.

Bjorkman O. and B. Demmig(1987) Photon yield of O_2 evolution and chlorophyll fluorescence characteristics at 77K among vascular plants of diverse origins. Planta. 170: 489-504.

Choi Y.W.(2003) Effect of Red, Blue, and Far-red LEDs for Night Break on Growth, Flowering, and Photosynthetic Rate in *Perilla ocymoides*. J. Kor. Soc. Hort. Sci. 44(4):442-446. (in Korean with English abstract)

Choi H.W.(2014) Study of luminous characteristics of white LEDs depending on phosphors. Master's Thesis, Univ. of Hallym, Chuncheon. 24pp. (in Korean with English abstract)

Corbesier L. and G. Coupland(2005) Photoperiodic flowering of Arabidopsis : integrating genetic and physiological approaches to characterization of the floral stimulus. Plant, Cell and Environment. 28:54-66.

Chavan B.L., N.S. Sonwane and I.R. Ustad(2011) Effect of tree canopy shade on Photosynthetic pigment in Mangifera indica. Deccan Current Sci. 4(1):249-252.

Choi H.G., J.K. Kwon, B.Y. Moon, N.J. Kang, K.S. Park, M.W. Cho and Y.C. Kim(2013) Effect of different light emitting diode (LED) lights on the growth characteristics and the phytochemical production of strawberry fruits during cultivation. Kor. J.

Hort. Sci. Technol. 31(1):56-64. (in Korean with English abstract)

Epron D., E. Dreyer and N. Breda(1992) Photosynthesis of oak trees(*Quercus petraea* (Matt) Liebl.) during drought stress under field conditions: diurnal course of net CO_2 assimilation and photochemical efficiency of photosystem . Planta, Cell and Environ. 15(7): 809-820.

Franklin K.A. and G.C. Whitelam(2005) Phytochromes and shade-avoidance responses in plants. Ann. of Bot. 96: 169–175.

Goins GD, N.C. Yorio, M.M. Sanwo and C.S. Brown(1997) Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. Journal of Experimental Botany 48(312):1407-1413.

Gamon J.A. and R.W. Pearcy(1989) Leaf movement, stress avoidance and photosynthesis in Vitis californica. Oecologia 79:475-481.

Groom Q.J. and N.R. Baker(1992) Analysis of light-induced depressions of photosynthesis in leaves of a wheat crop during the winter. Plant Physiol. 100:1217-1223.

Hwang M.K., C.S. Huh and Y.J. Seo(2004) Optic characteristics comparison and analysis of SMD type Y/G/W HB LED. J. of the Kor. Institute of Illuminating and Electrical Installation Eng. 18(4):15-21. (in Korean with English abstract)

Heo J.W., Y.B. Lee, D.E. Kim, Y.S. Chang, and C.C. Hun(2010) Effects of supplementary LED lighting on growth and biochemical parameters in *Dieffenbachia amoena* ‘Camella’ and Ficus elastica ‘Melany’. Kor. J. Hort. Sci. Technol. 28(1):51-58. (in Korean with English abstract)

Hopkins W.G. and N.P.A. Huner(2004) Introduction to plant physiology. 3rd ed. Jhon Wiley & Sons Inc. Hoboken. N.J. 367-388pp.

Hopkins W.G. and N.P.A. Huner(2008) Introduction to plant physiology. 4th ed. Jhon Wiley & Sons Inc. Hoboken. N.J. 223-480pp.

Im J.U., Y.C. Yoon, K.W. Seo, K.H. Kim, A.K. Moon and H.T. Kim(2013) Effect of LED light wavelength on Chrysanthemum growth. Protected Hort. and Plant Factory. 22(1):49-54. (in Korean with English abstract)

Jeong W.H., W.L. Chun, H.N. Murthy and K.Y. Paek(2003) Influence of light quality and photoperiod on flowering of *Cyclamen persicum* Mill. cv. ‘Dixie White’. Plant Growth Regulation 40:7-10. (in Korean with English abstract)

Jahns P. and A.R. Holzwarth(2012) The role of the xanthophyll cycle and of lutein in photoprotection of photosystem II. Biochimica et Biophysica Acta (BBA) – Bioenergetics. 1817(1):182-193.

Johkan M., K. Shoji, F. Goto, S. Hashida and T. Yoshihara(2010) Blue light-emitting diode light irradiation of seedlings improves seedling quality and growth after transplanting in red leaf lettuce. Hortscience. 45(12):1809-1814.

Kim Y.H., D.E. Kim, G.L. Lee, D.H. Kang and H.J. Lee(2011) Current status and development direction of the domestic and overseas for the artificial plant factory. Kor. J. Hort. Sci. Technol. 29(S2):37. (in Korean with English abstract)

Kim Y.H. and C.H. Lee(1998) Light intensity and spectral characteristics of fluorescent lamps as artificial light source for close illumination in transplant production factory. Kor. Soc. for Agr. Machinery. 23(6):591-598. (in Korean with English abstract)

Kim S.B., K.M. Lee, H.R. Kim and Y.H. You(2014) Effects of light sources, light quality on the growth response of leafy vegetables in closed-type plant factory system. Kor. J. of Ecol. and Environ. 47(1): 32-40. (in Korean with English abstract)

Kim H.R. and Y.H. You(2013) Effects of red, blue, white, and far-red LED source on growth responses of *Wasabia japonica* seedlings in plant factory. Kor. J. Hort. Sci. Technol. 31(4):415-422. (in Korean with English abstract)

Kinoshita T., M. Doi, N. Suetsugu, T. Kagawa, M. Wada and K. Shimazaki(2001) phot1 and phot2 mediate blue light regulation of stomatal opening. Nature. 414:656-660.

Lee S.W.(2010) Plant cultivation used plant factory and LED artificial light. Optical Sci. and Technol. 14(3):12-19. (in Korean with English abstract)

Lee T.B.(2003) Coloured flora of Korea. Hyangmoon Publisher, Seoul. 325pp. (in Korean)

Lee S.G., C.S. Choi, J.G. Lee, Y.A. Jang, C.W. Nam, K.H. Yeo, H.J. Lee and Y.C. Um(2012) Effects of different EC in nutrient solution on growth and quality of red mustard and Pak-Choi in plant factory. J. of Bio-Environ. Control. 21(4):322-326. (in Korean with English abstract)

Lee K.M., H.R. Kim, H. Lim and Y.H. You(2012) Effect of elevated CO_2 concentration and temperature on the growth and ecophysiological responses of Ginseng(*Panax Ginseng* C. A. Meyer). Kor. J. Crop Sci. 57(2):106-112. (in Korean with English abstract)

Ministry of Environment(2015) 2015 White paper of environment. Ministry of Environment. Seoul. Korea. 59-84pp. (in Korean)

Merzlyak M.N., O.B. Chivkunova, A.E. Solovchenko and K.R. Naqvi(2008) Light absorption by anthocyanins in juvenile, stressed, and senescing leaves. J. of Expt. Bot. 59(14):3903–3911.

Maxwell K. and G.N. Johnson(2000) Chlorophyll fluorescence-a practical guide. J. of Expt. Bot. 51(345):659-668.

Matsuda R., K. Ohashi-kaneko, K. Fujiwara, E. Goto and K. Kurata(2004) Photosynthetic characteristics of rice leaves grown under red light with or without supplemental blue light. Plant Cell Physiol. 45(12):1870-1874.

No H.J. and H.J. Jeong(2002) Well-defined statistical analysis according to statistica. Hyeongseok Publisher, Seoul. 628pp. (in Korean)

Nhut D.T., T. Takamura, H. Watanabe, K. Okamoto and M. Tanaka(2003) Responses of strawberry plantlets cultured in vitro under superbright red and blue light-emitting diodes (LEDs). Plant Cell, Tissue and Organ Cult. 73(1):43-52.

Okuya A. and T. Okuya(1988) The transpiration of greenhouse tomato plants in rockwool culture and its relationship to climatic factors. Acta Hort.(ISHS) 230:307-312.

Ogren E. and M. Sjostrom(1990) Estimation of the effect of photoinhibition on the carbon gain in leaves of a willow canopy. Planta 181(4):560-567.

Park H., M.K. Lee and S.D. Ahn(1989) Effect of light quality on the growth of Panax ginseng in a phytotron with natural light. Kor. J. Ginseng Sci. 13(2):165-168. (in Korean with English abstract)

Robert E.R.(2010) The economy of nature. sixth ed. W.H. Freeman and company. N.Y. 35-40pp.

Richardson A.D., S.P. Duigan and G.P. Berlyn(2002) An evaluation of noninvasive methods to estimate foliar chlorophyll content. New Phytol. 153(1): 185-194.

Robin C., M.J.M. Hay, P.C.D. Newton and D.H. Greer(1994). Effect of light quality(red:far-red ratio) at the apical bud of the main stolon an morphogensis of Trifolium repens L. Ann. Bot. 74(2):119-123.

Sharkey S.D. and K. Raschke(1981) Effect of light quality on stomatal opening in leaves of *Xanthium strumarium* L. Plant Physiol. 68:1170-1174.

Tripathy B.C. and C.S. Brown(1995) Root-shoot interaction in the greening of wheat seedlings grown under red light. Plant Physiol. 107(2):407-411.

Taiz L. and E. Zeiger(2008). Plant physiology 4th ed. Sinauer Associates Inc. Sunderland, M.A. 65-197pp.

Trouwborst G., J. Oosterkamp, S.W. Hogewoning, J. Harbinson and W.V. Leperen(2010) The responses of light interception, photosynthesis and fruit yield of cucumber to LED-lighting within the canopy. Physiologia Plantarum 138: 289–300.

Wang H., M. Gu, J. Cui, K. Shi, Y. Zhou and J. Yu(2009) Effects of light quality on CO_2 assimilation, chlorophyll-fluorescence quenching, expression of Calvin cycle genes and carbohydrate accumulation in *Cucumis sativus*. J. of Photochemical and Photobiology B: Biology. 96(1):30-37.

Yoon C.G.(2012) A study on the LED illumination lamp development and application for plant factory. PhD Diss., Hongik Univ., Seoul. 45pp. (in Korean with English abstract)

Zhou Y. and B.R. Singh(2002) Red light stimulates flowering and anthocyanin biosynthesis in American cranberry. Plant Growth Regulation 38:165-171.