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Utilization Efficiencies of Electric Energy and Photosynthetically Active Radiation of Lettuce Grown under Red LED, Blue LED and Fluorescent Lamps with Different Photoperiods

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Abstract

Purpose: This study was conducted to analyze the utilization efficiencies of electric energy and photosynthetically active radiation of lettuce grown under red LED, blue LED and fluorescent lamps with different photoperiods. **Methods:** Red LED with peak wavelength of 660 nm and blue LED with peak wavelength of 450 nm were used to analyze the effect of three levels of photoperiod (12/12 h, 16/8 h, 20/4 h) of LED illumination on light utilization efficiency of lettuce grown hydroponically in a closed plant production system (CPPS). Cool-white fluorescent lamps (FL) were used as the control. Photosynthetic photon flux, air temperature and relative humidity in CPPS were maintained at 230 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 22/18°C (light/darkness), and 70%, respectively. Electric conductivity and pH were controlled at 1.5-1.8 $dS \cdot m^{-1}$ and 5.5-6.0, respectively. The light utilization efficiency based on the chemical energy converted by photosynthesis, the accumulated electric energy consumed by artificial lighting sources, and the accumulated photosynthetically active radiation illuminated from artificial lighting sources were calculated. **Results:** As compared to the control, we found that the accumulated electric energy consumption decreased by 75.6% for red LED and by 70.7% for blue LED. The accumulated photosynthetically active radiation illuminated from red LED and blue LED decreased by 43.8% and 33.5%, respectively, compared with the control. The electric energy utilization efficiency (EEUE) of lettuce at growth stage 2 was 1.29-2.06% for red LED, 0.76-1.53% for blue LED, and 0.25-0.41% for FL. The photosynthetically active radiation utilization efficiency (PARUE) of lettuce was 6.25-9.95% for red LED, 3.75-7.49% for blue LED, and 2.77-4.62% for FL. EEUE and PARUE significantly increased with the increasing light period. **Conclusions:** From these results, illumination time of 16-20 h in a day was proposed to improve the light utilization efficiency of lettuce grown in a plant factory.

Keywords: Artificial lighting source, Electric energy consumption, LED, Light utilization efficiency, Photosynthesis, Photosynthetically active radiation

Introduction

Protected horticulture is the art of growing vegetables, fruits, flowers, or ornamental plants in greenhouses even though outside environment is not appropriate for the cultivation of horticultural crops. Greenhouse is a structure in which temperature and humidity can be controlled for the cultivation or protection of plants. However, it has been changed as an energy-intensive facility because electric energy was largely consumed for year-round production of horticultural crops grown in greenhouses. Moreover, resources (CO_2, water, minerals, and pesticides) as well as natural light are required for producing abundant and high-quality products in greenhouses (Stanghellini et al., 2003).

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Light is one of the most important environmental factors that act on plants as one source of energy. Light environment covers the light intensity, light quality, photoperiod and illumination direction. Growth of horticultural crops is accomplished by their photosynthesis that is a photochemical process for the conversion of light energy from the sun light or artificial lighting sources into chemical energy stored in organic matter.

Light-emitting diodes (LED) have been recently used as a new artificial lighting source to promote photosynthesis (Hoenecke et al., 1992; Goins et al., 1997; Tennessen et al., 1995), to control photomorphogenic responses (Brown et al., 1995; Stutte, 2009), and to enhance phytochemicals (Wu et al., 2007; Li and Kubota, 2009, Xu et al., 2012) due to their small mass and volume, low electric consumption, long lifetime, specific wavelength, and easy pulse drive (Barta et al., 1992; Bula et al., 1991). Some studies on the application of LED lamps for improving the seedling quality (Kim and Park, 2003; Kim and Lee, 2004) and growth after transplanting of some vegetables (Lee et al., 2012) were reported. LED lamps generate heat which should be removed to ensure maximum performance and lifetime. Park et al. (2011) demonstrated that photosynthetic photon flux (PPF) illuminated from LED lamps increased with water cooling system. A measurement system to determine PPF and illumination efficiency of artificial lighting sources including LED lamp was developed by Lee and Kim (2012).

Light utilization efficiency is an important factor to evaluate the performance of the lighting systems installed in a plant factory or greenhouse (Charles-Edwards, 1982). However, little published information is available on the light utilization efficiency of some vegetables grown under controlled environment. The objective of this study was to investigate the utilization efficiencies of electric energy and photosynthetically active radiation of lettuce grown under red LED, blue LED and fluorescent lamps with different photoperiods.

Materials and Methods

Lettuce (*Lactuca sativa* L., cv. 'Jeokchima') seedlings, having 4 true leaves, were transplanted in growing beds with a deep flow hydroponic system in a closed plant production system (CPPS). The inner size of CPPS was 3,300(W) x 2,700(D) x 2,500(H). Steel plate filled with polyurethane (100 mm thick) as insulating material was used as the wall of CPPS. Two shelves (1,000(W) x 640(D) x 1,800(H)) for hydroponic culture beds were installed inside CPPS. Two circulation pumps (P70913, Grundfos, Italy) were used to supply nutrient solution from a nutrient solution tank to growing beds.

Red LED (KLRR1203-1, KODENSHI AUK, Korea) with peak wavelength of 660 nm and blue LED (KLBB1203-1, KODENSHI AUK, Korea) with peak wavelength of 450 nm were used to analyze the effect of three levels of photoperiod (12/12, 16/8, 20/4 h) of LED illumination on light utilization efficiency of lettuce grown hydroponically (Table 1). Cool-white fluorescent lamps (DULUX L55 W/840, OSRAM, GERMANY) were used as the control. Five red or blue LED bars were installed to obtain the PPF of 230 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on the surface of growing beds. And, ten cool-white fluorescent lamps were used to give the same PPF. The vertical distance from the artificial lighting sources to growing bed was 30 cm. A spectro-radiometer (LI-1800, LI-COR, USA) was used to analyze the spectral characteristics of LED and fluorescent lamps used as artificial lighting sources in this study (Figure 1).

Table 1. Artificial lighting sources and photoperiods treated in this study

Artificial lighting source	Photoperiod (h) (light/darkness)	Treatment code
Red LED	12/12	R_1
	16/8	R_2
	20/4	R_3
Blue LED	12/12	B_1
	16/8	B_2
	20/4	B_3
Fluorescent lamps (Control)	12/12	FL_1
	16/8	FL_2
	20/4	FL_3

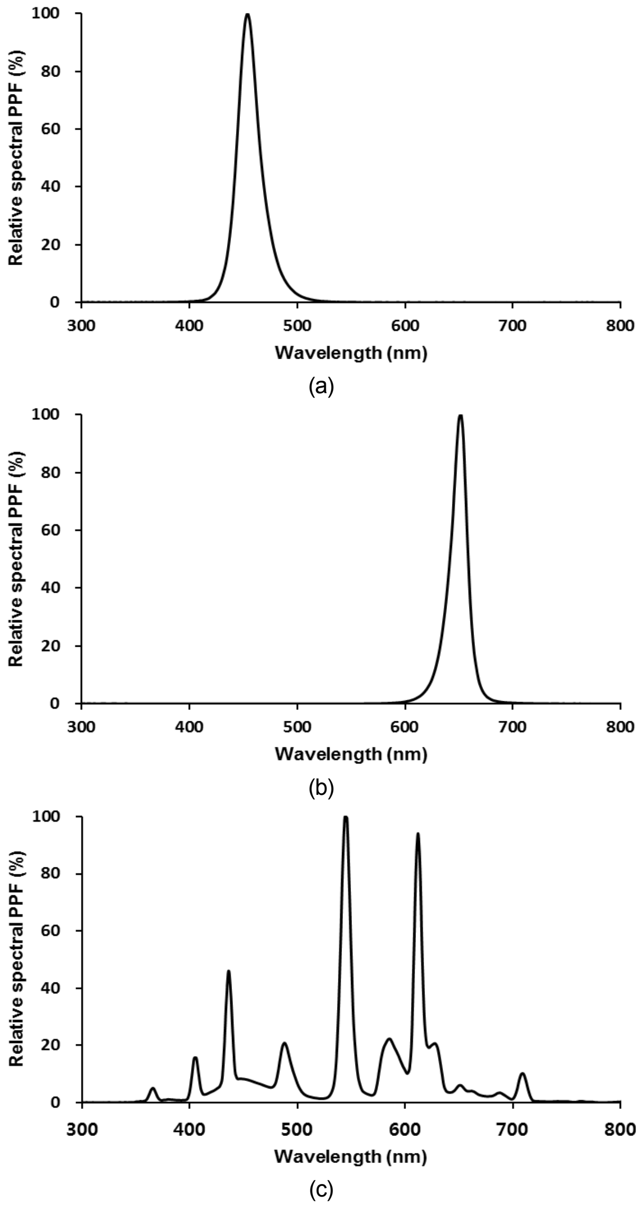

Figure 1. Spectral characteristics of (a) blue LED; (b) red LED; (c) fluorescent lamps used in this study.

Air temperature and relative humidity in CPPS were maintained at 22/18°C (light/darkness) and 70%, respectively. Electric conductivity and pH were controlled at 1.5-1.8 $dS{\cdot}m^{-1}$ and 5.5-6.0, respectively. Leaf fresh weight and dry weight (DW) of lettuce were measured using an electronic balance (AB204-S, METTLER TOLEDO, SWITZERLAND) at 14 days and 28 days after transplanting. A quantum sensor (SKP215, Skye Instruments, UK) was used to measure the PPF illuminated from artificial lighting sources.

Light utilization efficiency defined as the fraction of light energy converted into chemical energy during photosynthesis is as follows.

$$\eta_E = \frac{\triangle H}{\Sigma E} \times 100 \quad (1)$$

$$\eta_{PAR} = \frac{\triangle H}{\Sigma PAR} \times 100 \quad (2)$$

In the equation (1), η_E denotes the electric energy utilization efficiency that is calculated as the ratio of chemical energy converted to the accumulated electric energy (ΣE, $kcal{\cdot}m^{-2}$) consumed by artificial lighting sources, where $\triangle H$ ($kcal{\cdot}m^{-2}$) means the chemical energy converted from the change of dry weight of lettuce for a growing period of 14 days. And η_{PAR} in the equation (2) shows the photosynthetically active radiation (PAR) utilization efficiency that is computed as the ratio of chemical energy converted to the accumulated PAR (ΣPAR, $kcal{\cdot}m^{-2}$) incident on the surface of growing bed. PAR was measured by a PAR sensor (SKP510, Skye Instruments, UK). The chemical energy converted was calculated from the increase in dry weight of lettuce. Planting density and calorific value of carbohydrate needed for calculating light utilization efficiency were assumed to be 49 plants/m^2 and 4.1 $kcal{\cdot}g^{-1}$DW, respectively. A digital multimeter (179, FLUKE, USA) was used to measure the current and voltage applied to power controller of LED lamps.

SAS (V9.2, SAS Institute INC., USA) was used to perform the least significant difference test on fresh and dry weight of lettuce at a significance level of P = 0.05.

Results and Discussion

In this study, light utilization efficiency of lettuce based on electric energy consumption and photosynthetically active radiation was calculated by two growth stages. One is the light utilization efficiency of lettuce grown during 14 days after transplanting (growth stage 1), and the other is the light utilization efficiency for the second growth stage of lettuce grown during 14 days followed by the first growth stage. Initial dry weight of lettuce right after transplanting was 0.05 g/palnt for 12/12 h, 0.1 g/plant for 16/8 h, and 0.02 g/plant for 20/4 h, respectively.

Statistical analysis on leaf fresh and dry weights of lettuce grown under red LED, blue LED, and fluorescent lamps (FL) were shown in Table 2. Fresh weight and

Table 2. Statistical analysis on fresh and dry weights of lettuce measured at 14 and 28 days after transplanting

Treatment code	At 14 days		At 28 days	
	Fresh weight (g/plant)	Dry weight (g/plant)	Fresh weight (g/plant)	Dry weight (g/plant)
R_1	14.30cd[z]	0.77de	58.53c	2.56de
R_2	24.72b	1.10bc	113.52b	4.83bc
R_3	39.95a	1.59a	173.34a	6.34a
B_1	8.00de	0.53ef	34.95d	1.80e
B_2	17.15c	0.93cd	57.74cd	2.84d
B_3	26.31b	1.23b	106.45b	5.46b
FL_1	6.66e	0.43f	41.70cd	1.84e
FL_2	26.15b	1.26b	113.02b	4.11c
FL_3	26.06b	1.25b	128.65b	5.17b
$LSD_{.05}$	6.76	0.29	23.46	0.81

[z] Means with the same letter are not significantly different.

Table 3. Chemical energy of dry lettuce, electric energy consumption and photosynthetically active radiation (PAR) calculated during 14 days after transplanting

Treatment code	△H1 (kcal·m^{-2})	△H2 (kcal·m^{-2})	ΣE (kcal·m^{-2})	ΣPAR (kcal·m^{-2})
R_1	144.9	360.3	27,864.1	5,763.7
R_2	201.3	750.9	37,152.2	7,685.0
R_3	316.1	956.2	46,440.2	9,606.2
B_1	96.6	255.7	33,437.0	6,818.2
B_2	167.1	384.5	44,582.6	9,091.0
B_3	243.6	851.5	55,728.3	11,363.7
FL_1	76.5	283.9	114,243.0	10,256.2
FL_2	233.5	573.7	152,324.0	13,675.0
FL_3	247.6	789.1	190,405.0	17,093.7

△H1: the chemical energy converted from the change of dry weight of lettuce at growth stage 1 (kcal·m^{-2})
△H2: the chemical energy converted from the change of dry weight of lettuce at growth stage 2 (kcal·m^{-2})
ΣE: the accumulated electric energy consumed by artificial lighting sources for a growing period of 14 days after transplanting (kcal·m^{-2})
ΣPAR: the accumulated photosynthetically active radiation incident on the growing bed for a growing period of 14 days after transplanting (kcal·m^{-2})

dry weight of lettuce increased significantly with increasing photoperiod. At 28 days after transplanting, R_3 treatment showed the greatest fresh weight and dry weight. Fresh weight of lettuce grown under red LED increased by 0.4-40.4% as compared to the control. On the contrary, fresh weight of lettuce grown under blue LED decreased by 16.2-48.9%, compared to the control. Dry weight of lettuce grown under red LED increased by 17.5-39.1% as compared to the control. However, dry weight of lettuce grown under blue LED decreased by 2.2-30.9%, compared to the control. Red LED promoted leaf expansion and increase in shoot weight and dry weight of leaf lettuce (Yorio et al., 2001; Johkan et al., 2010).

Table 3 shows the chemical energy converted from the change of dry weight of lettuce, the accumulated electric energy consumed by artificial lighting sources, and the accumulated PAR incident on the growing bed. The chemical energy converted was calcuted from the increase in dry weight of lettuce measured at 14 days and 28 days after transplanting. In this study, chemical energy converted was determined based on two growth stages. One (△H1, kcal·m^{-2}) is the chemical energy converted for growing stage 1 (from 1 day to 14 days after transplanting) and the other (△H2, kcal·m^{-2}) is the chemical energy converted for growing stage 2 (from 15 days to 28 days after transplanting). The accumulated electric energy (ΣE, kcal·m^{-2}) consumed by artificial lighting sources was calculated from the daily electric energy consumption of artificial lighting sources for a growing period of 14 days. And, the accumulated PAR (ΣPAR, kcal·m^{-2}) was determined by the PAR, photoperiod and the growing period of 14 days. As compared to the control the accumulated electric energy consumption decreased by 75.6% for red LED

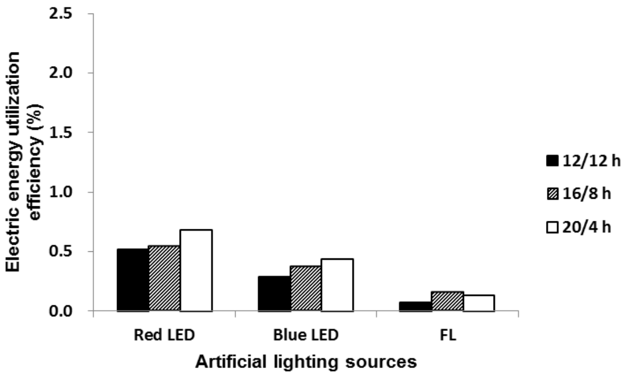

Figure 2. Electric energy utilization efficiency of lettuce grown under different artificial lighting sources and photoperiods at growth stage 1.

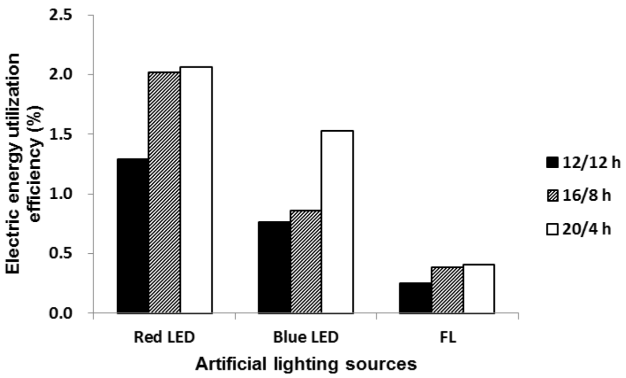

Figure 3. Electric energy utilization efficiency of lettuce grown under different artificial lighting sources and photoperiods at growth stage 2.

and by 70.7% for blue LED. In addition, the accumulated PAR illuminated from red LED and blue LED decreased by 43.8% and 33.5%, respectively. These results implied that the electric energy consumed by fluorescent lamps was higher than electric energy consumed by red LED or blue LED.

The electric energy utilization efficiency (EEUE) of lettuce grown under different artificial lighting sources and their photoperiods at growth stage 1 was shown in Figure 2. EEUE of lettuce was 0.52-0.68% for red LED, 0.29-0.44% for blue LED, and 0.07-0.13% for FL at growth stage 1. At growth stage 2, EEUE of lettuce was 1.29-2.06% for red LED, 0.76-1.53% for blue LED, and 0.25-0.41% for FL. As compared to the control, EEUE for red LED increased by 4.0-4.3 times (Figure 3), even though dry weight of lettuce grown under red LED at growth stage 2 increased by 17.5-39.1%. EEUE for blue LED at growth stage 2 increased by 1.3-2.7 times, but dry weight of lettuce grown under blue LED except photoperiod of 20/4 h decreased by 2.2-30.9%. These results were ascribed to low EEUE of fluorescent lamps with high electric energy consumption.

As lighting-up time of red LED at growth stage 2 increased from 12/12 h to 16/8 h, EEUE for red LED increased by 56.6%. However, as lighting-up time of blue LED at growth stage 2 increased from 16/8 h to 20/4 h, EEUE for blue LED increased by 77.9%. From

Table 4. Analysis of variance for the electric energy utilization efficiency of lettuce grown under different artificial lighting sources (ALS) and photoperiods (PHOTO) at growth stage 2

Source	DF	Sum of squares	Mean square	F value	Pr > F
Model	8	19.3483	2.4185	40.65	<.0001
ALS	2	2.4190	1.2095	20.33	<.0001
PHOTO	2	15.6680	7.8340	131.66	<.0001
ALS*PHOTO	4	1.2614	0.3154	5.30	0.0018
Error	36	2.1421	0.0595		
Total, corrected	44	21.4904			

Table 5. Test of least significant difference for the electric energy utilization efficiency of lettuce grown under different artificial lighting sources (ALS) and photoperiods (PHOTO) at growth stage 2

Grouping, ALS	Mean	Grouping, PHOTO	Mean
Blue LED	1.0508b[z]	12/12 h	0.7683c
Red LED	1.7920a	16/8 h	1.0866b
FL	0.3468c	20/4 h	1.3347a
$LSD_{.05}$	0.1806	$LSD_{.05}$	0.1806

[z] Means with the same letter are not significantly different.

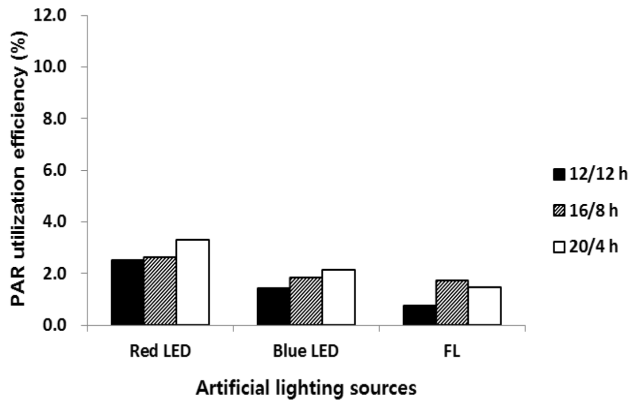

Figure 4. PAR utilization efficiency of lettuce grown under different artificial lighting sources and photoperiods at growth stage 1.

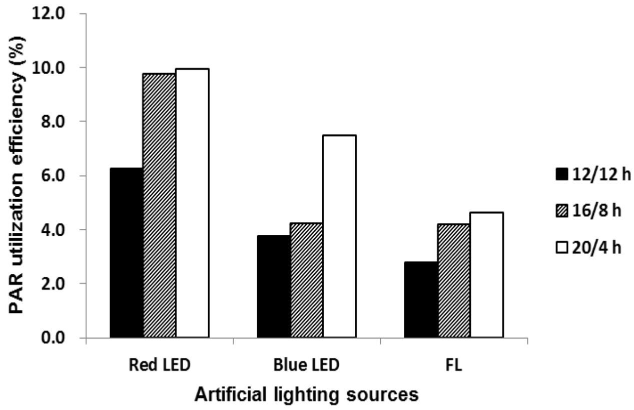

Figure 5. PAR utilization efficiency of lettuce grown under different artificial lighting sources and photoperiods at growth stage 2.

the analysis of variance (ANOVA) for EEUE of lettuce grown under different artificial lighting sources and photoperiods at growth stage 2, we found that EEUE was highly significant according to artificial lighting sources and photoperiods (Table 4). EEUE significantly increased with the increasing light period (Table 5).

PAR utilization efficiency (PARUE) of lettuce grown under different artificial lighting sources and their photoperiod at growth stage 1 was shown in Figure 4. PARUE of lettuce was 2.51-3.29% for red LED, 1.42-2.14% for blue LED, and 0.75-1.71% for FL at growth stage 1. At growth stage 2, PARUE of lettuce was 6.25-9.95% for red LED, 3.75-7.49% for blue LED, and 2.77-4.62% for FL. PARUE for red LED and blue LED increased by 115.4-132.6% and 0.1-62.1%, respectively, as compared to the control (Figure 5).

Similarly, as lighting-up time of red LED at growth stage 2 increased from 12/12 h to 16/8 h, PARUE for red LED increased by 56.3%. However, as lighting-up time of blue LED at growth stage 2 increased from 16/8 h to 20/4 h, PARUE for blue LED increased by 77.1%. From the ANOVA for PARUE of lettuce grown under different artificial lighting sources and photoperiods at growth stage 2, we found that PARUE was highly significant according to artificial lighting sources and photoperiods (Table 6). PARUE significantly increased with the increasing light period (Table 7).

Table 6. Analysis of variance for the PAR utilization efficiency of lettuce grown under different artificial lighting sources (ALS) and photoperiods (PHOTO) at growth stage 2

Source	DF	Sum of squares	Mean square	F value	Pr > F
Model	8	279.9226	34.9903	21.07	<.0001
ALS	2	72.9035	36.4517	21.95	<.0001
PHOTO	2	185.1428	92.5714	55.73	<.0001
ALS*PHOTO	4	21.8763	5.4691	3.29	0.0213
Error	36	59.7973	1.6610		
Total, corrected	44	339.7199			

Table 7. Test of least significant difference for the PAR efficiency of lettuce grown under different artificial lighting sources (ALS) and photoperiods (PHOTO) at growth stage 2

Grouping, ALS	Mean	Grouping, PHOTO	Mean
Blue LED	5.1532b[z]	12/12 h	4.2551c
Red LED	8.6633a	16/8 h	6.0657b
FL	3.8629c	20/4 h	7.3585a
$LSD_{.05}$	0.9544	$LSD_{.05}$	0.9544

[z] Means with the same letter are not significantly different.

It is a common misconception that LED does not create any heat (Bourget, 2008). It is estimated that 15-25% of electric energy consumed by LED lamps was approximately converted into visible light, and the remaining 75-85% was released into heat. Visible light illuminated from LED was absorbed by plants, and then carbohydrates were synthesized by photosynthesis. Light utilization efficiency of lettuce grown under red LED, blue LED and fluorescent lamps with different photoperiods was analyzed in this study. Maximum light utilization efficiency of lettuce grown under artificial lighting sources was 2.06% for EEUE and 9.95% for PARUE. The photosynthetic efficiency was 1.8% when expressed on the basis of incident global energy and 3.9% when expressed by absorbed net radiation (Hanan, 1998). The potential efficiency of the photosynthetic process from light capture to carbohydrate synthesis was examined by Zhu et al. (2008). They reported that maximum conversion efficiency of solar energy to biomass was 4.6% for C3 photosynthesis, but 6% for C4 photosynthesis.

Conclusions

Light utilization efficiency of lettuce grown under red LED, blue LED and fluorescent lamps with different photoperiods was investigated in this study. As compared to the fluorescent lamps, the accumulated electric energy consumed by red LED and blue LED decreased by 75.6% and 70.7%, respectively. The accumulated PAR consumed by red LED and blue LED decreased by 43.8% and 33.5%, respectively. Thus, EEUE of lettuce at growth stage 2 was 1.29-2.06% for red LED, 0.76-1.53% for blue LED, and 0.25-0.41% for FL. And PARUE of lettuce was 6.25-9.95% for red LED, 3.75-7.49% for blue LED, and 2.77-4.62% for FL. EEUE and PARUE increased with increasing light period. From these results, illumination time of 16-20 h in a day was proposed to improve the light utilization efficiency of lettuce grown in a plant factory.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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References

Barta, D.J., T.W. Tibbitts, R.J. Bula and R.C. Morrow. 1992. Evaluation of light emitting diode characteristics for space-based plant irradiation source. Advances in Space Research 12(5):141-149.

Bourget, C.M. 2008. An introduction to light-emitting diodes. HortScience 43(7):1944-1946.

Brown, C.S., A.C. Schuerger and J.C. Sager. 1995. Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. Journal of the American Society for Horticultural Science 120:808-813.

Bula, R.J., R.C. Morrow, T.W. Tibbitts, D.J. Barta, R.W. Ignatius and T.S. Martin. 1991. Light-emitting diodes as a radiation source for plants. HortScience 26(2): 203-205.

Charles-Edwards, D.A. 1982. Physiological determinants of crop growth. Academic Press, Sydney. P. 161.

Goins, G.D., 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 48:1407-1413.

Hanan, J.J. 1998. Greenhouse: advanced technology for protected horticulture. CRC Press LLC. pp. 116-122.

Hoenecke, M.E., R.J. Bula and T.W. Tibbitts. 1992. Importance of blue photon levels for lettuce seedlings grown red-light-emitting diodes. HortScience 27(5): 427-430.

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. and M.G. Lee. 2004. Tuber production and growth of potato transplants grown under different light quality. Acta Horticulturae 659:267-272.

Kim, Y.H. and H.S. Park. 2003. Graft-taking characteristics of watermelon grafted seedlings as affected by blue, red, and far-red light-emitting diodes. Journal of the Korean Society for Agricultural Machinery 28(2): 151-156 (In Korean).

Lee, J.S., H.I. Lee and Y.H. Kim. 2012. Seedling quality and early yield after transplanting of paprika nursed under light-emitting diodes, fluorescent lamps and natural light. Journal of Bio-Environment Control 21(3): 220-227 (In Korean).

Lee, J.S. and Y.H. Kim. 2012. Measurement system of photosynthetic photon flux distribution and illumination efficiency of LED lamps for plant growth. Journal of Biosystems Eng. 37(5):314-318 (in Korean).

Li, Q. and C. Kubota. 2009. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environmental and Experimental Botany 67(1):59-64.

Park, C.H., J.S. Lee, D.E. Kim and Y.H. Kim. 2011. Analysis of optimum water cooling conditions and heat exchange of LED lamps for plant growth. Journal of Biosystems Eng. 36(5):334-341 (In Korean).

Stanghellini, C., F.L.K. Kempkes and P. Knies. 2003. Enhancing environmental quality in agricultural system. Acta Horticulturae 609:277-283.

Stutte, G.W. 2009. Light-emitting diodes for manipulating the phytochrome apparatus. HortScience 44(2):231-234.

Tennessen, D.J., R.J. Bula and T.D. Sharkey. 1995. Efficiency of photosynthesis in continuous and pulsed light emitting diode irradiation. Photosynthesis Research 44:261-269.

Wu, M.C., C.Y. Hou, C.M. Jiang, Y.T. Wang, C.Y. Wang, H.H. Chen and H.M. Chang. 2007. A novel approach of LED light radiation improves the antioxidant activity of pea seedlings. Food Chemistry 101:1753-1758.

Xu, H., Q. Xu, F. Li, Y. Feng, F. Qin and W. Fang. 2012. Applications of xerophytophysioloy in plant production - LED blue light as a stimulus improved the tomato crop. Scientia Horticulturae 148(4):190-196.

Yorio, N.C., G.D. Goins, H.R. Kagie, R.M. Wheeler, and J.C. Sager. 2001. Improving spinach, radish, and lettuce growth under red light emitting diodes (LEDs) with blue light supplementation. HortScience 36(2):380-383.

Zhu, X, S.P. Long, and D.R. Ort. 2008. What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? Current Opinion in Biotechnology 19:153-159.