A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Analyses of Photosynthesis and Productivity of Paprika (*Capsicum annuum* L. 'Cupra') using Sulfur Plasma and High-Pressure Sodium Lamps as Supplemental Light Sources

황 플라즈마 및 고압나트륨 램프를 이용한 보광에 따른 파프리카의 광합성 및 생산성 분석

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JANUARY, 2017

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UNDER THE DIRECTION OF DR. JUNG EEK SON
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY

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FEBRUARY, 2017

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ABSTRACT

Supplemental lighting with artificial light sources is a practical method that enables normal growth and enhances the yield and quality of products. The objective of this study was to investigate the effect of sulfur plasma (SP) and high-pressure sodium (HPS) lamps as supplemental lighting sources on the growth and yield of paprika in greenhouses. For the SP and HPS lamps, the effects of primary lighting on plant growth was compared in walk chamber and that of supplemental lighting also compared in greenhouse. In the growth chamber; plant height, leaf area, stem diameter, number of leaves, fresh weight, and dry weight were measured every week at the SP and HPS lamps from 2 weeks after transplanting. In the greenhouse, no supplemental lighting (only sun light) was considered as the control. The supplemental lights were turned on when outside radiation became below 100 W m^{-2} from 07:00 to 21:00. From 3 weeks after supplemental lighting, the growth was measured every week while the number and weight of paprika fruits measured every two weeks. In the growth chamber, the growth of paprika was better at the SP lamps than the HPS lamps due to higher photosynthetic rate at the SP lamps than at the HPS lamps. In the greenhouse, the yield was higher at the supplemental lightings of the HPS and SP lamps than at the control, while the proportion of marketable yield was lower at the supplemental lightings than at the control. No significant differences were observed in the plant height, number of node, leaf length and fresh and dry weights between the SP and HPS treatments. However, at harvest, the number of fruits rather than the weight of fruits was higher at the SP lamps. It was suggested that new cultivation methods including fertigation strategy are needed to reflect the effect of supplementary lighting on plant growth.

Keywords: high-pressure sodium lamp, paprika, photosynthesis, productivity, sulfur plasma lamp, supplemental lighting.

Student Number: 2012-21088

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March 23 to April 27, 2016; and (d) weight of fruits from March 23 to April 27, 2016.

INTRODUCTION

Light is an essential energy source that acts as a signal for survival and reproduction for plants. Since 89% of greenhouses area relies only on the sunlight, the yields and quality of products change according to drastic fluctuations in light intensity and day length with season (Oh, 2011). Although the light environment in the greenhouse can be changed depending on the type of cover materials and structural materials of greenhouse, light intensity of radiation is commonly lowered by 30~40% as compared to the outside by cover and structural materials. Light intensity and day length that transmit through a greenhouse act as critical limitation factors for plant growth and yield of production, so assimilates can be decreased in the environment of small daylight hours and low light intensity, as in the winter season of high latitude regions; this can lead to early falling flowers and fruits or irregular fruit settings (Heuvelink and Komer, 2001). Consequently, the yield and quality of products decrease in winter season of middle-latitude regions, such as South Korea, or high-latitude regions, such as the Netherlands.

The prevalent cropping season of paprika starts from the end of August to harvesting in July of the next year. Therefore, in the period of low light (from October to February), harvest days after fruit setting can get longer; furthermore, fruit setting rate can get lower and the incidence of malformed fruit can increase with many cloudy days. More specifically, since the fruit setting rate of paprika is susceptible to change due to the amount of light when light intensity widely fluctuates, as in South Korea, periodical changes in yield became greater, leading to a decrease in the productivity (Jeong et al., 2009). In the Netherlands, to overcome the low light intensity in winter season, growers use high-pressure sodium lamps to compensate the lack of light and to increase the yield in fruit vegetables (Dorais, 2003; Hao and Paadopoulos, 1999).

For protected cultivation, numerous studies have focused on the enhancement effects of supplemental lighting on the productivity and quality of fruits in the low-light season. However, due to operation costs, high-pressure sodium lamps have been mostly used as supplementary lights. Recently the use of sulfur plasma lamp for plant production have received much attentions because it has a similar spectrum with sunlight. However a few studies have focused on using these lamps for crop growth and development; Kwon et al. (2016) reported that supplemental lighting with sulfur plasma lamps improved the qualities like sugar contents. The objectives of this study was to figure out the enhancement effect of supplemental lighting with sulfur plasma lamps on paprika growth and productivity, as compared to the use of high-pressure sodium lamps.

LITERATURE REVIEW

Plant responses to supplemental lighting

The optimum environments in crop cultivation varies with the kind of crops or the stage of growth and development; this environment factor includes both the aerial factors such as light, air temperature, and carbon dioxide level, and the root-zone factors such as soil water, nutrients, and temperature. Alone or together, these environmental factors can affect the plant morphological change and physiological activity (Kim et al., 2005).

Light environment is a most critical limiting factor among the aboveground environment parameters in greenhouse cultivation. In order to improve light intensity, it is needed a supplemental lighting with an artificial light source to maximize the influx of sunlight. With regard to supplemental lighting, previous research has reported that supplemental lighting by artificial lighting sources increases dry weight of shoot and root in celery, tomatoes, broccoli, and lettuce (Demers et al., 1991; Fierro et al., 1994; Masson et al., 1991). Another study has demonstrated that the yield of paprika increases due to the use of supplemental lighting in winter season (Kim et al., 2011).

Although supplemental lighting with an artificial light source has been proved to be an effective way to enhance the quality and yield of products in greenhouse cultivation in winter season, it is used just at seedling nursery and plant factory due to its excessive cost in terms of initial installation and operation. However, in northern Europe and Canada, supplemental lighting has recently been commercialized in greenhouses that cultivate leaf vegetables, like lettuce and celery, and fruit vegetable, like cucumbers, tomatoes, and paprika (Dorais et al., 2002).

Plant responses to various lighting sources

In the cultivation experiment on strawberry using supplemental lighting with fluorescent lamp and LED, the high photosynthetic photon flux density of LED has been shown to lead to the increased photosynthesis rate and improved crop growth, resulting in an increase of fruit weight, number, and marketable yield (Hidaka et al., 2013).

Even though HPS has a small portion of blue light, it is widely used for supplemental lighting in winter season in high-latitude regions like northern Europe. Consequently, HPS complemented with blue LED was used in a cultivation experiment with paprika; in this study, the wavelength of 470, 505nm LED complementation showed significant improvements of photosynthesis rate, transpiration rate, and stomatal conductivity (Aiste et al., 2015).

Therefore, apart from photomorphogenesis, a crop's photosynthesis is affected by wide wavelengths of light, as well as by the quantity of PPFD; thus, the spectral characteristics can reasonably be expected to be an important factor for choosing the light source of supplemental lighting. Most light sources used as supplemental lighting emit a spectrum that of substantially different from that of natural sunlight. There is an interesting study conducted with a developed artificial light source, the so-called artificial sunlight. Compared to HPS and fluorescent lamps, this new light source releases the spectrum that is almost identical to that of natural sunlight.

The weight of cucumbers cultivated in growth chambers equipped with the artificial solar was 1.6 and 2.3 times higher than the weight of cucumbers cultivated in the HPS and fluorescent lamps conditions each. Especially as concerns plant height, cucumbers grown in the artificial sunlight showed 4~5-fold differences as compared to HPS and fluorescent lamps treatment each (Hogewoning, 2010). These results imply that a spectrum similar to that of the natural sun light have a positive effect on the growth and development of crops and could be helpful to increase the yield.

Although light-emitting plasma (LEP) lamps are magnified with the spectrum nearest to that of natural sunlight in the field of agroindustry in Europe, relevant studies of these lamps' application in agriculture are scarce. With regard to paprika, significant differences have been reported in the photosynthetic rate, dry weight of fruits, and the number of harvested fruits grown in the LEP lamp as compared to the HPS lamp (Lee et al., 2014).

MATERIALS & METHODS

This experiment was conducted in venlo-type greenhouses at National Institute of Horticultural and Herbal Science of Rural Development Administration (RDA) located at Haman, Korea. Two venlo-type greenhouses (L 45 m x W 9.6 m x H 4.0 m) were divided to 3 plots for comparative experiments with two supplemental lighting treatments of high-pressure sodium lamps (HPS; E-papillon 1000 W, Light Interaction, Eindhoven, Netherland) and sulfur plasma lamps (SP; SPLS-1000, LG Electronics, Seoul, Korea); no supplementary lighting was used as the control.

Supplemental lighting started on March 2, 2016 and the growth and yield of paprika were investigated. From 07:00 to 21:00, the supplemental lights installed at the height of 4 m from the ground turned on when outside solar radiation was below 104.2 $W \cdot m^{-2}$ (in average of 10 min). Eighteen SP lamps were installed at the interval of 3 m x 3 m (horizontal x vertical) and 15 HPS lamps were installed at the interval of 3 m x 4 m. The average photosynthetic photon flux density (PPFD) at the ground surface were 112.8 and 140.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at the SP and HPS lamps, respectively. The schematic diagram of the installation is shown in Fig. 1. Seeds of paprika (*Capsicum annuum* L. ‘Cupra’) were sown on September 25, 2015 and transplanted on December 8, 2015. Nutrient solutions was maintained at an electrical conductivity (EC) of 2.5~3.0 $mS \cdot m^{-1}$, a pH of 5.8~6.0, and air temperatures of 25℃/18℃ (day/night).

To identify the effect of light sources on paprika growth and development, cultivation was conducted in growth chambers set at 14 h/10 h (day/night). Air temperature and relative humidity for day were maintained at 25℃ and 50%, while maintained at 18℃ and 50% for night. Paprika seeds were sown on March 27, 2016 and transplanted on April 21, 2016. After 3 weeks of growing in the greenhouses, the plants were placed in the chambers (on May 18, 2016).

In the chambers, the spectrum of each light source was measured by using a radio spectrometer (Li-1800, Li-COR, Lincoln, USA). Maximum leaf length, plant height, number of nodes, diameter of stem, and leaf area were measured every week; in addition, fresh and dry weights were measured every two weeks. At 1 week and 8 weeks after transplanting in the chamber, photosynthetic rates were measured with a photosynthesis measuring apparatus (Li-6400, Li-COR, Lincoln, USA); a thermos-graphic camera (Ti-105, Fluke, Washington, USA) was used to measure leaf temperature.

To figure out the difference in light environment in the greenhouses, the light spectrum was measured at no supplemental lighting, supplemental lightings of the HPS and SP lamps in the greenhouses on a clear day and a cloudy day by using the radio spectrometer. The maximum leaf length, plant height, number of nodes, diameter of stem, and leaf area were measured every two weeks after three weeks of supplementary lighting; furthermore, the number and weight of fruits were measured every week. Photosynthetic rates and leaf temperatures were measured by using the photosynthesis measuring apparatus and the thermos-graphic camera, respectively.

RESULTS

The spectrum and spectral characteristics measured in growth chambers are shown in Table 1 and Fig. 2. The SP lamp has a similar light spectrum to sunlight than the HPS lamp, with higher PPFD and UV ratio and lower NIR and R/FR ratio than the HPS lamp. Light spectrum in greenhouses were measured before sunrise, after sunset, on a cloudy day, and at night on March 2, 2016 (Fig. 3). Although there was solar radiation before sunrise, after sunset, and on cloudy days, the light intensity was very low, resulting in similar tendencies to the results observed in the chambers. From 07:00 to 21:00 in a day, supplemental lights turned on for about 3 hours a day (1 hour in the morning and 2 hours in the evening).

The plant height cultivated at the SP lamps in the chambers was significantly higher than that at the HPS lamps. The number of leaves was higher and consequently leaf area was bigger at the SP lamps, while the number of nodes was not significantly different (Table 2). Especially, the differences in plant height between the SP and the HPS lamps were getting bigger with time (Fig. 4). Han (2012) reported that leaf length, leaf width, and plant height increased more at red LED lamps than at blue LED lamps. Therefore, it was concluded that the spectral characteristics of the SP lamps influenced this results due to specifically more red wavelengths and smaller R/RF ratio.

The fresh and dry weights of leaves and stems were significantly higher in the SP lamps than the HPS lamps (Table 2). This results may be related with higher photosynthetic rates at the SP lamps than the HPS lamps (Fig. 5). The leaf length, width, shape index, and chlorophyll contents did not show significant differences between the two treatments.

In contrast to these results, photosynthetic rates in greenhouses were higher at the HPS lamps than at the SP lamps, except for the bottom leaves of the plants, indicating faster leaf aging at the SP lamps than at the HPS lamps (Fig. 6). Although no significant differences in plant height were observed, stem diameters and number of nodes were somehwat higher at the SP lamps (Table 3).

The average number and weight of fruits were not significantly different. However, compared to the overall yield at no supplemental lighting, supplenetal lightings of HPS and SP lamps increased the number by 160% and 153% and the weight of fruits by 163% and 125%, respectively (Table 4, Figs. 7a and 7b). In particular, because it may be effective to set a limit in March and April due to the short day and lack of light intensity, the average yield was greater and the effects of supplementary lighting were remarkable in accumulative yield: 278% and 365% increase in the number and 281% and 288% increase in the weight of fruits were observed at the HPS and SP lamps, respectively. Between the supplemental lights, the SP lamps were more effective than the HPS lamps (Table 4, Figs. 7c and 7d).

To verify the relationship of the increase of yield with the growth in greenhouses, the ratio of scattering light was measured at different four points; vertical downwards of lamps at the height of 120 and 50 cm, the middle of two lamps at the height of 120 and 50 cm (Table 5). Regardless of the distance from light sources or locations, the SP lamps showed higher PPFD than the HPS lamps. This result agrees well with those in the chambers where the PPFD of the SP lamp was higher than the HPS lamp.

Considering that our experiments started from March to May, 2016, the cultivation conditions rapidly improved with the increase of solar radiation and air temperature. Because the supplementary lighting promoted the physiological activities of the plants, adequate fertigation might be adjusted to meet the increased requirements. Application of conventional cultivation method might cause the occurrence of unmarketable products, such as blossom-end rot, cracking of fruit, at supplemental lighting. Further studies need to investigate the fertigating system control adapted to supplementary lighting.

It was reported that the yield of tomato increased with the increase in the amount of light received from anthesis to harvest (McAvoy et al., 1989). When the light level on the top of the canopy or within the canopy was low, application of supplemental lighting at the top of the canopy or within the canopy enhanced the yield of tomato and other species (Rodriguez and Lambeth, 1975; Grimstad, 1987; McAvoy and Janes, 1989; Hovi et al.,2004; Pettersen et al., 2010). In the present study, the results were in agreement with the findings of these researchers. With supplemental lightings, the growth and yield were enhanced than those without supplemental lighting (Table 4, Fig. 7). Considering the difference in amount of fruits, the yield of tomato per energy was higher in the SP lamps than the HPS lamps.

CONCLUSION

The effect of sulfur plasma (SP) and high-pressure sodium (HPS) lamps on the growth and yield of paprika were investigated as supplemental lighting sources. In the growth chamber, the growth of paprika was higher at the SP lamps than the HPS lamps. In the greenhouse, the yield was higher at the supplemental lightings than at the control. In detail, there were no significant differences in the plant height, number of node, leaf length and fresh and dry weights between the SP lamp (having higher PAR and lower R/FR ratio) and the HPS lamp, but in harvest, the number of fruits than weight of fruits was higher at the SP lamps. In addition, it was suggested that new cultivation methods including fertigation strategy are needed to reflect the effect of supplementary lighting on plant growth.

Table 1. Specifications of high pressure sodium (HPS) and sulfur plasma (SP) lamps.

Unit	HPS	SP
Input power (W)	1000	1030
Luminous flux (Lm)	146,000	92,000
Luminous efficiency ($lm \cdot W^{-1}$)	146	89.3
PPF ($\mu mol \cdot s^{-1}$)	1850	1444
PPF/W ($\mu mol \cdot s^{-1} \cdot W^{-1}$)	1.850	1.402
UV (300-400 nm)	0.03	0.14
PAR (400-700 nm)	23.40	30.65
NIR (700-1100 nm)	56.05	3.29
R/FR	4.35	2.76

Table 2. Plant growth indexes and chlorophyll contents of paprika grown at high pressure sodium (HPS) and sulfur plasma (SP) lamps in growth chamber.

Light source	Plant height (cm)	Stem diameter (cm)	No. of leaves (ea)	Leaf area (cm^2)	Chlorophyll Content (SPAD)	Fresh weight (g)			Dry weight (g)		
						Leaf	Stem	Total	Leaf	Stem	Total
HPS	44.5	9.9	30.4	2802.6	60.7	106.5	43.9	150.5	12.1	6.3	18.4
SP	49.9	9.7	31.9	3082.9	58.1	112.3	48.0	160.4	12.7	6.4	19.1

Table 3. Plant growth indexes of paprika grown at no supplemental lighting (Control), supplemental lightings of high pressure sodium (HPS) and sulfur plasma (SP) lamps in greenhouse.

Light source	Plant height (cm)	Stem diameter (cm)	No. of nodes (ea)	Leaf area (cm^2)
Control	186.4a	17.5b	50.8a	6235.2a
HPS	173.4a	18.5a	47.3a	5891.2a
SP	182.4a	18.2ab	52.5a	5867.5a

Table 4. Fruit yield of paprika grown at no supplemental lighting (Control), supplemental lightings of high pressure sodium (HPS) and sulfur plasma (SP) lamps in greenhouse from March 16 to May 23, 2016 and from March 23 to April 27, 2016.

Light source	No. of fruits		Fruit weight (kg)	
	March 23 ~ May 16	March 23 ~ April 27	March 23 ~ May 16	March 23 ~ April 27
Control	252	65	36.5	9.4
HPS	405	181	59.7	26.3
SP	385	237	45.7	27.0

Table 5. Total and scattered light ratios and distributions of supplemental lighting sources in greenhouses: High pressure sodium (HPS) and sulfur plasma (SP) lamps.

Light source (measurement position)	Height (cm)					
	50			120		
	Total (μmol·m^{-2}·s^{-1})	Diffuse (μmol·m^{-2}·s^{-1})	Ratio	Total (μmol·m^{-2}·s^{-1})	Diffuse (μmol·m^{-2}·s^{-1})	Ratio
HPS (center)	75.0	45.1	0.60	80.0	25.5	0.32
SP (center)	100.0	69.3	0.69	116.1	62.5	0.54
HPS (middle)	76.6	54.0	0.70	84.9	62.6	0.74
SP (middle)	102.4	78.1	0.76	118.2	79.6	0.67

Table 6. The ratio of marketable yield in number of fruits and in weight of fruits at no supplemental lighting (Control), supplemental lightings of high pressure sodium (HPS) and sulfur plasma (SP) lamps in greenhouse.

Light source	No. of fruits (A, ea)		Weight of fruit (C, kg)		B / A	D / C
	Marketable (B)	Non-marketable	Marketable (D)	Non-marketable		
Control	134	47	21.1	5.5	0.74	0.79
HPS	163	141	31.6	14.5	0.54	0.69
SP	129	205	17.9	19.9	0.39	0.47

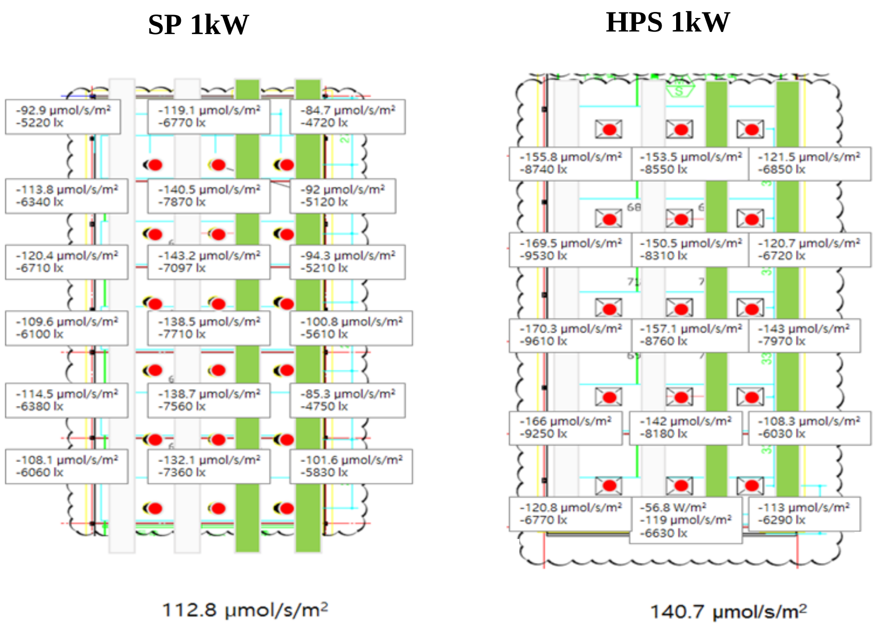

Fig. 1. Locations of installed sulfur plasma (SP) and high pressure sodium (HPS) lamps and light distributions in greenhouses.

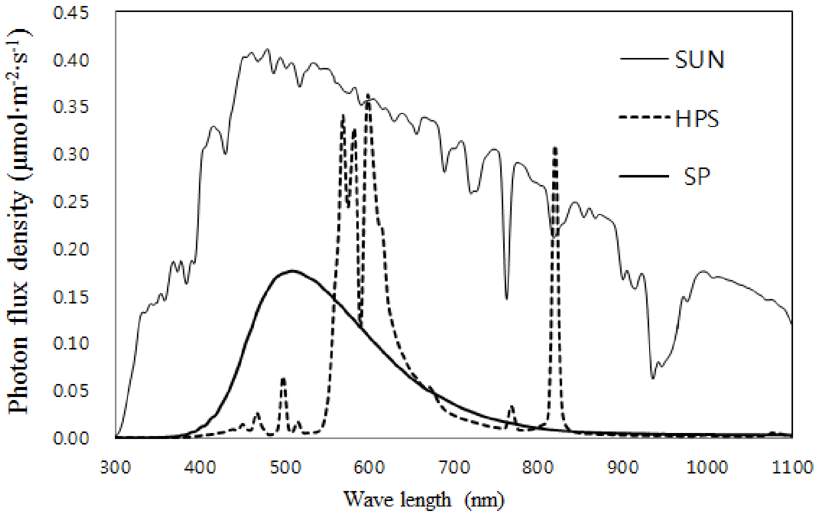

Fig. 2. Spectral distributions of sun light (SUN), high pressure sodium (HPS) and sulfur plasma (SP) lamps.

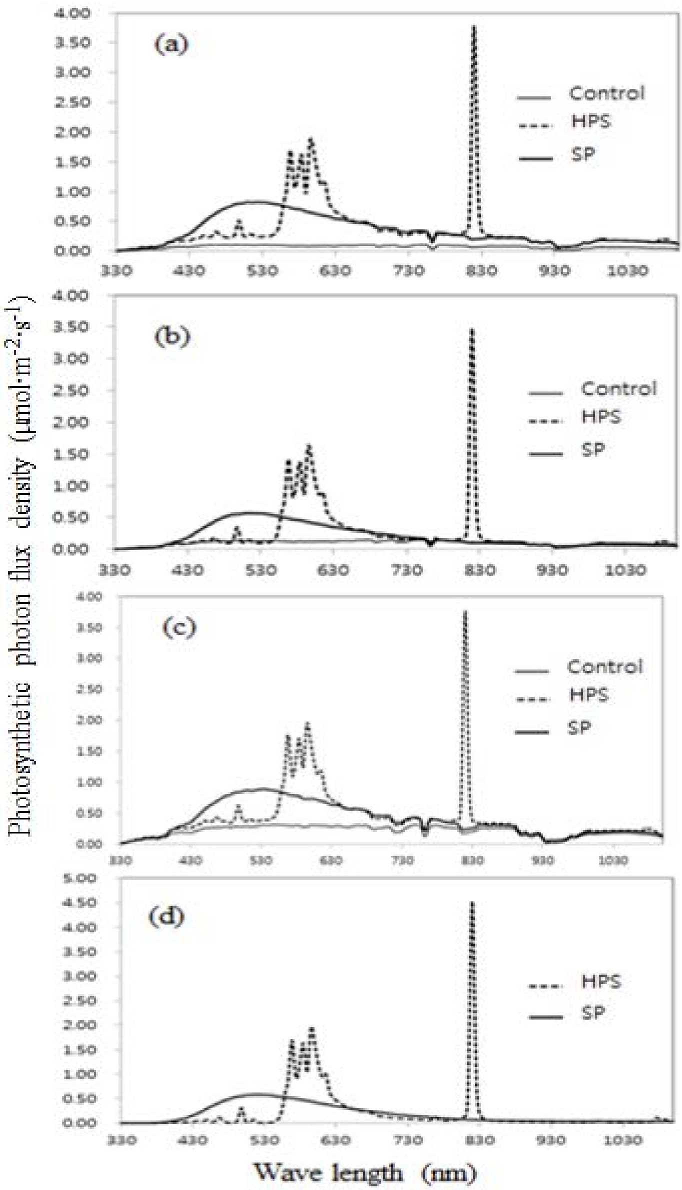

Fig. 3. Spectral distributions with time at no supplemental lighting (Control), supplemental lightings of high pressure sodium (HPS) and sulfur plasma (SP) lamps in greenhouses: (a) before sunrise, (b) after sunset, (c) cloudy day, and (d) midnight.

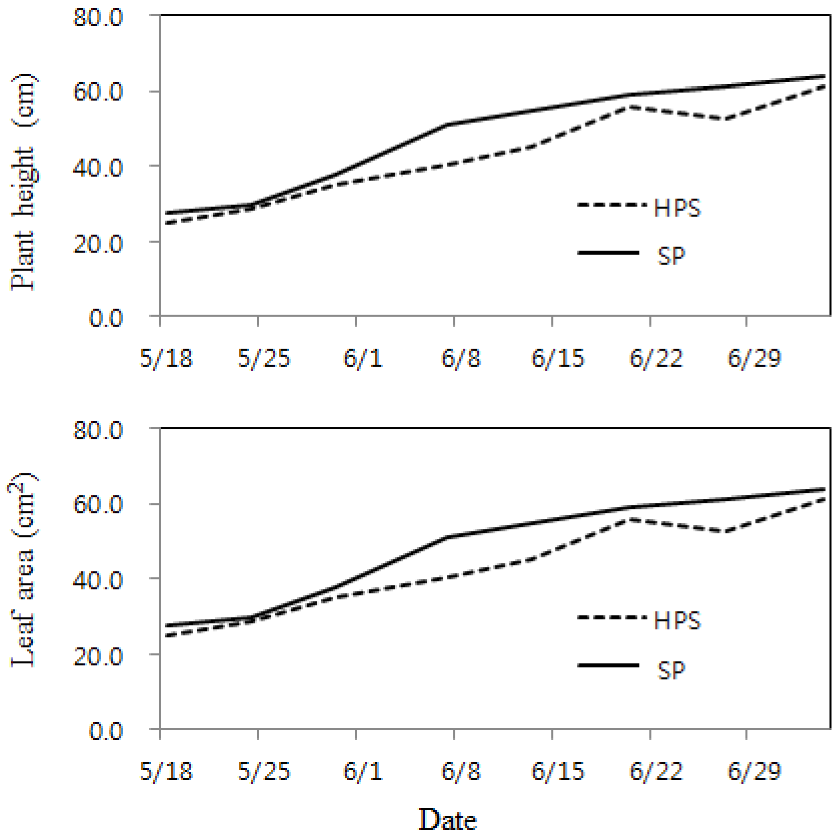

Fig. 4. Plant height and leaf area of paprika grown at high pressure sodium (HPS) and sulfur plasma (SP) lamps in growth chamber (from May 18 to July 5, 2016).

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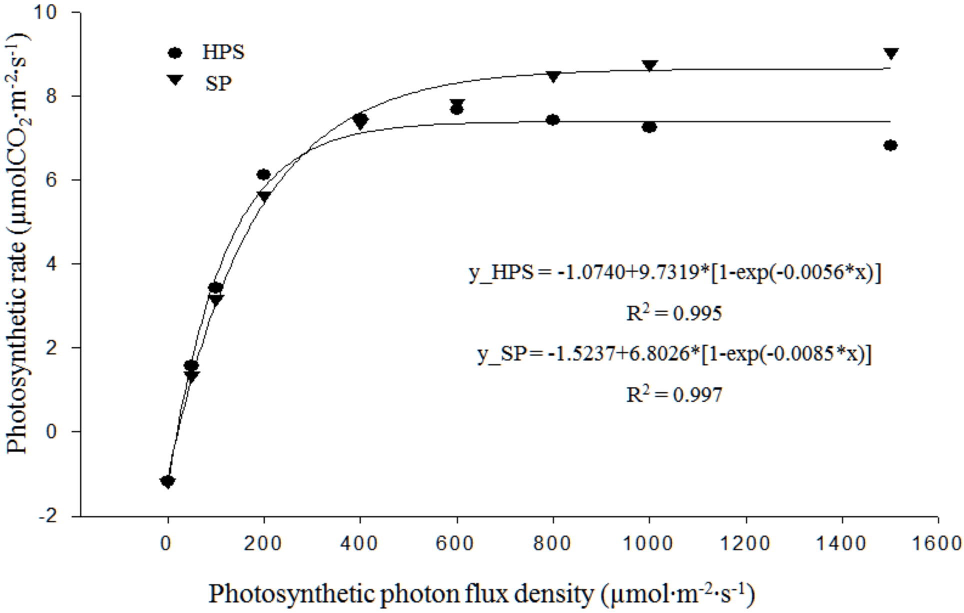

Fig. 5. Photosynthetic rates of paprika grown at high pressure sodium (HPS) and sulfur plasma (SP) lamps in growth chamber.

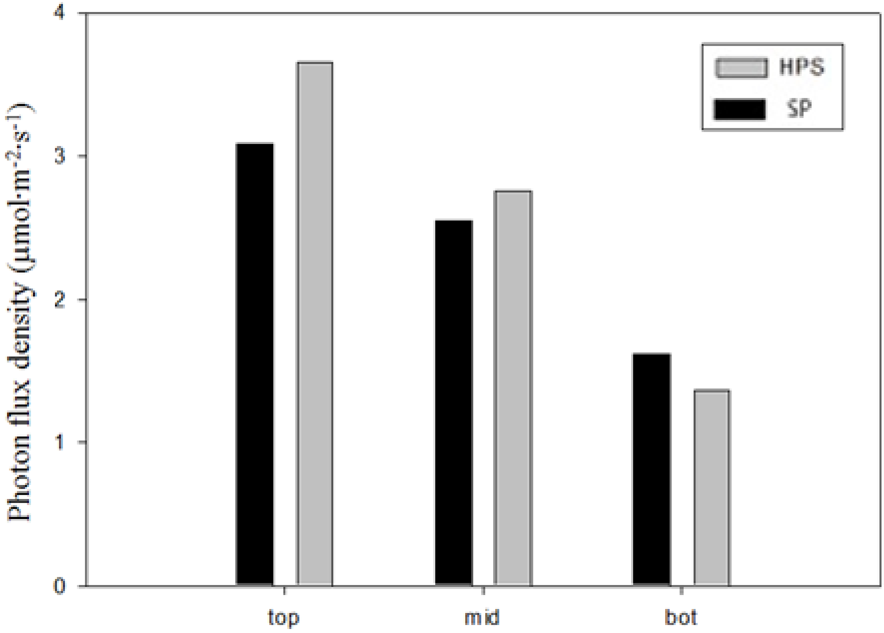

Fig. 6. Photosynthetic rates of paprika grown at supplemental lightings of high pressure sodium (HPS) and sulfur plasma (SP) lamps in greenhouses.

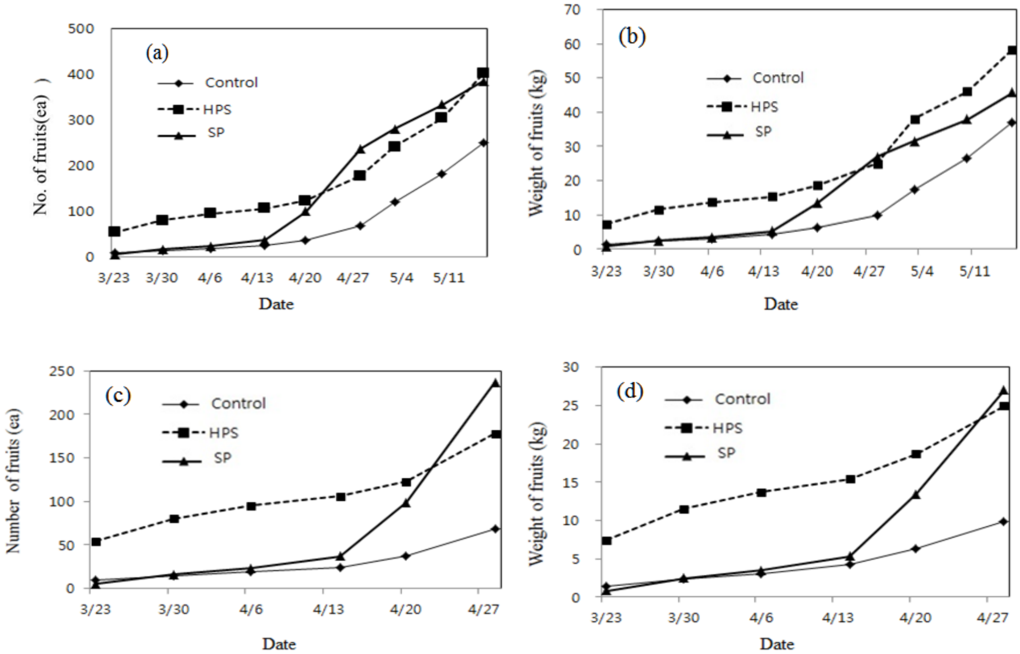

Fig. 7. Yields of paprika fruits grown at no supplemental lighting (Control), supplemental lightings of high pressure sodium (HPS) and sulfur plasma (SP) lamps in greenhouses: (a) number of fruits from March 23 to May 16, 2016; (b) weight of fruits from March 23 to May 16, 2016; (c) number of fruits from March 23 to April 27, 2016; and (d) weight of fruits from March 23 to April 27, 2016.

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ABSTRACT IN KOREAN

약광기 파프리카 재배시 보광원 종류가 파프리카의 생육과 수량에 미치는 효과를 분석하기 위하여 수행하였다. 인공광을 이용한 보광은 광이 부족하기 쉬운 시설재배에서 작물의 정상적인 생육과 수확량을 보전하고 수확물의 품질을 증진시키기 위해 보편적으로 사용되는 방법이다. 이 연구에서는 광원 자체의 종류에 따른 효과를 분석하기 위하여 생장상을 이용한 작물반응을 관찰하였고 온실재배를 통하여 보광효과를 분석하였다. 생장상에서는 황 플라즈마(SP)와 고압나트륨(HPS) 광원을 각각 사용하였고 정식 후 2 주부터 초장, 엽면적, 줄기직경, 엽수, 엽면적, 생체중, 건물중을 매주 측정하였다. 벤로 타입의 온실재배에서는 SP 와 HPS 광원을 보광원으로 사용하였고 무보광을 대조구로 하였다. 보광처리는 오전 7 시부터 오후 9 시까지 외부일사 100W 미만일 때 처리되도록 하였다. 보광처리 후 3 주부터 13 주까지 생육량을 2 주간격으로 측정하였고 매주 수확하여 과실수와 과실무게를 측정하였다. 생장상에서는 HPS 보다 SP 광원에서 생육량이 유의적으로 높았다. 온실에서는 보광처리가 대조구보다 수확량이 유의적으로 높았다. 초장, 마디수, 엽장, 생체중, 건물중은 SP 광원과 HPS 광원간의 유의적인 차이는 없었다. 그러나 수확 시

과실수는 SP 광원에서 많았다. 추후 식물생육에 대한 보광 효과를 반영하여 관비 전략을 포함한 새로운 재배 방법의 개발이 필요하다.

주요어: 광합성, 고압나트륨램프, 보광, 생산성, 파프리카, 황 플라즈마램프

학 번: 2012-21088