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Effect of supplementary lighting on selected physiological parameters and yielding of tomato plants

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ABSTRACT

Light is one of the basic factors needed by plants for their development. The aim of this study was to measure the effect of supplementary lighting of tomato plants with HPS and LED lamps on the chosen physiological parameters and yielding of autumn-winter cultivation crops. Two tomato cultivars ('Komeett' F_1 and 'Starbuck' F_1 by De Ruiter Seeds) were used in this experiment. After the plants were planted, LED and HPS lamps of 100 µmol m^{-2} s^{-1} light intensity were installed. The results show that the introduction of a supplementary light source to tomato cultivation caused an increase in the intensity of photosynthesis, transpiration, stomatal conductance and chlorophyll by 57.7%, 17.1%, 39.3% and 24.4% on average, respectively. Higher values of those parameters were obtained with HPS lamps than with LED lamps. The amount of marketable crops, number of fruits and mean fruit weight were higher in both combinations in which supplementary lighting was applied, and the values of these traits were higher when the cultivation was supplementary lighted with HPS lamps than with LED lamps. Due to the overhead light configuration and continued low light output, there was no increase of efficiency when using LED lamps compared to HPS lamps despite better focusing and spectral distribution.

Key words: chlorophyll, gas exchange, HPS, LED, *Solanum lycopersicon*

INTRODUCTION

Light is one of the most important factors affecting many physiological processes such as the intensity of photosynthesis, resulting in the proper growth and development of plants, as well as their yield and crop quality (Blom and Ingratta 1984, Blain et al. 1987, Hendriks 1992, Kopsell and Kopsell 2008, Perez-Balibrea et al. 2008).

Supplemental lighting with HPS (High Pressure Sodium) lamps is applied mainly in the production of vegetable and ornamental plant seedlings as well as pot and cut flowers (Massson et al. 1991, Hendriks 1992, McCall 1992, Fierro et al. 1994). Adverse economical conditions (extreme costs of energy carriers) do not allow the common usage of these lamps in plant cultivation, despite positive research results (Blom and Ingratta 1984).

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VERSITA

Supplemental lighting increases leaf photosynthesis rates, plant growth and development, and fruit yield and quality of greenhouse crops (Hovi et al. 2004, 2006, Gunnlaugsson and Adalsteinsson 2006, Hovi-Pekkanen and Tahvonen 2008, Pettersen et al. 2010 a). Despite a number of investigations on supplemental lighting of plants with lamps that have various light effectiveness, there is still little information showing how the quality of light affects the growth and development of plants and how particular light spectra may cause various changes in a plant. Hernandez et al. (2012) states that changes between 0% and 16% of blue light in red-blue LED lamps in greenhouse conditions did not make any difference in the development and physiology of tomato seedlings. Xiaoying L. (2012) shows that plants grown in only artificial light had significant differences in photomorphogenesis in different spectra. Blue and red-blue light grown plants had significantly higher dry and fresh weights, and were also shorter than plants treated only with red light. Joining red and blue light together in a proper ratio may significantly modify the content of such parameters as chlorophyll, net photosynthesis or the total nitrogen content (Matsuda et al. 2004). Thus, intensive research has been performed on LED (Light-Emitting Diode) lamps, whose spectrum can be composed of the point spectra of particular diodes and readjusted to particular plant species and cultivars needing different light spectra at particular times of their development (Wang et al. 2009).

The present research aimed at revealing the effect of supplementary lighting of tomato plants with HPS and LED lamps on the chosen physiological parameters (photosynthesis, transpiration, stomatal conductance) and yielding of the autumn-winter cultivation crops.

MATERIAL AND METHODS

The study was performed in the greenhouse of the Department of Vegetable and Medicinal Plants at the Warsaw University of Life Sciences – SGGW (longitude 21ºE, latitude 51º15'N) in 2010 and 2011. It was performed on two greenhouse tomato cultivars ('Komeett' F_1 and 'Starbuck' F_1 by De Ruiter Seeds Company) cultivated in the autumn-winter productive cycle. The seeds were sown on 12 August 2009 and 10 August 2010. Seedlings were produced in mineral wool blocks under optimal conditions (temperature, soil and air humidity, fertilisation, light intensity). The tomato plants were planted in mineral wool slabs in three chambers of 60 m^2 each, with plants grown in each chamber in three 9-metre long rows, on 23 September 2009 and 17 September 2010. Immediately after planting, LED lamps of 100 μmol m^{-2} s^{-1} light intensity were installed in one chamber and HPS lamps of 100 μmol m^{-2} s^{-1} light intensity in the other. Expected light intensity was obtained at a 1m distance from LED lamps and was uniform for the entire length of the row at a width of 0.6 m, while HPS lamp light intensity was variable all across the row but the average level was maintained at the same level for the same area (0.6 m per 9 m). The experiment was concluded on 30 March 2010 and 31 March 2011.

The spectral distribution of light was determined following guidelines from prior experiments (Kim et al. 2004, Matsuda et al. 2004) and was selected to obtain maximum photosynthesis. The blue to red ratio reflected relative photosynthetic plant response. LED lamps were made in a custom design by the Electrotechnical Institute, with each lamp consisting of two units containing 16 pieces of 640 nm diodes, eight pieces of 660 nm diodes and eight pieces of 450 nm diodes. Diodes were supplied with 350 mA current resulting 1W power. LUXEON REBEL diodes were used. HPS lamps were provided by Gavita and the light sources used were GE Lucalox 400W lamps with a 220V power supply. There were 15 LED lamps (30 units) per room and six HPS lamps per room. This configuration resulted in double the power consumption of HPS lamps as compared to the LED.

In the third chamber, plants were cultivated under a natural light source (control combination). Lamps were installed 1 m over the plants and were lifted as the plants grew. The lamps were automatically switched on when the natural light intensity was below 175 W m^{-2} (approximately 700 μmol m^{-2} s^{-1}) and switched off when the natural light intensity was above 225 W m^{-2} (approximately 900 μmol m^{-2} s^{-1}). The lighting period for lamps was 16 h. The plants were trained on a single stem held by a string using a high wire system for the entire growing cycle with a mean density of 2.7 plants m^{-2}. Tomatoes were fertigated by a computer controlled drip-irrigation system and fertilised with similar rates of macro- and micronutrients, according to the levels recommended for tomato. The amount of the nutrient supply ranged from 70 to 200 cm^3 per plant and was adjusted in accordance to the standard recommendations for a tomato developmental state. Nutrient concentration in the solution, EC and pH were continuously controlled and kept at the same levels for all experimental objects. The concentration of nutrients (in mg dm^{-3}) was as follows: $N\text{-}NO_3$ – 210, P – 60, K – 340, Mg – 50, Ca – 200, Fe – 2, Mn – 0.6, B – 0.3, Cu – 0.15, Zn – 0.3, Mo – 0.05. The experiment was established in a randomised block design, in six replicates, with 12 plants in each. The temperature, RH and CO_2 levels were kept equal in all of the chambers by a Synopta climate computer. The temperature was 22-23ºC/18-19ºC during the day/night, respectively. CO_2 was supplied up to 800 ppm and the supply was disabled during physiological measurements. RH was approximately 70%.

The following physiological parameters were determined with the CIRAS-2 (PP Systems) apparatus:

- photosynthesis (μmol CO_2 m^{-2} s^{-1})
- transpiration (mmol H_2O m^{-2} s^{-1})
- stomatal conductance (mmol H_2O m^{-2} s^{-1})
- photosynthetic photon flux (area) density (PPFD) at measurement point (μmol m^{-2} s^{-1})

The chlorophyll content was determined in SPAD units.

Both chlorophyll content and physiological parameters were measured twice a month starting on 21 October 2009 until 24 February 2010 and 18 October 2010 until 20 February 2011. There were six measurements per chamber, or three per combination, taken from various plants on the 6^{th} leaf from the apex of the plant. A distance greater than 1m from the light source was always maintained, the measurement apparatus light source was removed, and measurements were always conducted between 9am-12am under both natural and artificial light. The average light intensity at the measurement point was as follows: 70 μmol m^{-2} s^{-1} in natural light, 100 μmol m^{-2} s^{-1} in the LED and 150 μmol m^{-2} s^{-1} in the HPS. A reduced increase of PPFD in the LED was a result of both the higher shading of lamps and a higher attenuation of the parallel downward flux of light.

Plant yielding was assessed. The marketable yield (kg m^{-2}) was calculated as well as the number of fruits per 1 m^2 and the fruit weight (g).

A statistical analysis was performed using the one-way analysis of variance (ANOVA). A detailed comparison of means was performed using the Tukey test at a significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Adverse light conditions from November to mid-March in the countries located in the north of Europe are the reason for the very poor assimilative processes taking place in plants. Vegetables cultivated under covers at that time need some supplemental lighting (Piszczek and Głowacka 2005, Petersen et al. 2010a). The obtained results of the study show that the intensity of photosynthesis in tomato plants, even with supplemental lighting in the form of sodium discharge lamps and LED lamps, was at a low level. However, there were some significant differences in the intensity of photosynthesis in plants supplementary lighted with an additional light source. Photosynthesis intensity was significantly higher in plants lighted with sodium discharge lamps than in both LED and natural light. Plants supplementary lighted with LED lamps were characterised by higher photosynthesis as compared to the control combination but significantly lower when compared to the combination with HPS lamps (Tab. 1). A similar tendency can be noted while observing stomatal conductance. The highest stomatal conductance was obtained in plants supplementary lighted with sodium discharge lamps, which was 62.1% higher than the stomatal conductance obtained for plants supplementary lighted with LED lamps and 16.6% higher than in plants from the control combination (Tab. 2). An important parameter in proper plant growth and development is the intensity of transpiration. According to Ravin and Blom (2001), the transpiration process is a key factor for both the general life of the plant, regulating its temperature and allowing the transfer of ions and organic molecules into and inside the plant, and for the photosynthesis process. The obtained

Table 1. Effect of supplementary lighting and tomato cultivar on photosynthesis

Photosynthesis (μmol CO_2 m^{-1} s^{-1})				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	2.1	4.0	2.4	2.8 A
Komeett	1.9	4.2	2.0	2.7 A
Mean for combination	2.0 B	4.1 A	2.2 B	

Means separation at 5% level; capital letters between mean values, lowercase letters between combination and cultivar values

Table 2. Effect of supplementary lighting and tomato cultivar on stomatal conductance

Stomatal conductance (mmol H_2O m^{-2} s^{-1})				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	392.43	718.87	519.93	543.74 A
Komeett	408.70	576.43	412.33	465.82 A
Mean for combination	400.57 B	647.65 A	466.13 B	

Explanations: see Table 1

Table 3. Effect of supplementary lighting and tomato cultivar on transpiration

Transpiration (mmol H_2O m^{-2} s^{-1})				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	4.07	5.03	3.80	4.30 A
Komeett	3.47	4.60	4.13	4.07 A
Mean for combination	3.77 B	4.82 A	3.97 AB	

Explanations: see Table 1

results of the study show that higher transpiration was characteristic for plants supplementary lighted with sodium discharge lamps and LED lamps as compared to plants from the control combination (Tab. 3). Similar results were obtained in studies by Kim et al. (2004), Blom and Zheng (2009), Li and Kubota (2009), Pettersen et al. (2010a) and Johkan et al. (2012).

Many researchers (Pettai et al. 2005, Ralph and Gademann, 2005, Pettersen et al. 2010b, Trouwborst et al. 2011) have found that supplementary lighting of plants significantly affects their chlorophyll content. The research performed shows that introducing an additional light source within cultivation significantly increased the content of chlorophyll in tomato leaves. This content in the combination with sodium discharging lamps and LED lamps was 24.4% higher on average than in the control combination (Tab. 4).

Supplementary lighting of plants under covers during the autumn-winter period guarantees high and good quality yields (Vezina et al. 1991, Dorias et al. 1991). Numerous studies show that introducing a supplementary light source to cucumber cultivation (Hovi et al. 2004), as well as in other species (Karami and Weaver 1972, Tibbitts et al. 1993), significantly affected the quantity and quality of their crops. The obtained results show that introducing a supplementary light source to tomato cultivation increased the tomato fruit yield by 150.9% on average as compared to the control combination. The highest marketable yield of fruit was obtained when plants were supplementary lighted with HPS lamps and the lowest in the control combination (without supplementary lighting). The yield of tomato fruit obtained from supplementary lighting with LED lamps was 76.3% higher than the yield obtained in the control combination but 54.1% lower than that obtained in the combination with HPS lamps (Tab. 5). Supplementary lighting applied to tomato plants also significantly affected the mean weight of the fruit; this was higher for the HPS lamps than in the other two light sources. The largest number of fruit was produced by tomato

Table 4. Effect of supplementary lighting and tomato cultivar on chlorophyll

Chlorophyll (SPAD)				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	35.43	46.87	44.43	42.24 A
Komeett	35.90	43.27	42.93	40.70 A
Mean for combination	35.67 B	45.07 A	43.68 A	

Explanations: see Table 1

Table 5. Effect of supplementary lighting and tomato cultivar on marketable yield

Marketable yield (kg m^{-2})				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	4.05	14.11	7.34	8.50 A
Komeett	4.94	15.14	8.50	9.53 A
Mean for combination	4.49 C	14.62 A	7.92 B	

Explanations: see Table 1

Table 6. Effect of supplementary lighting and tomato cultivar on numbers of fruits

Number of fruits m^{-2}				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	32.35 d	89.05 bc	52.10 cd	57.83 B
Komeett	65.93 c	183.62 a	112.43 b	120.66 A
Mean for combination	49.14 C	136.34 A	82.26 B	

Explanations: see Table 1

Table 7. Effect of supplementary lighting and tomato cultivar on average weight of fruit

Average weight of fruits (g)				
Cultivar	Combination			Mean for cultivar
	Control	HPS Lamps	LED Lamps	
Starbuck	125.16	159.11	141.71	141.99 A
Komeett	74.75	82.32	75.67	77.58 B
Mean for combination	99.96 B	120.71 A	108.69 AB	

Explanations: see Table 1

plants supplementary lighted with HPS lamps, and was significantly lower in LED combinations and then even more significantly lower in plants from the control combination. There were also significant differences in the number of fruit between cultivars. The 'Komeett' F_1 cultivar had a higher number of fruit compared to the 'Starbuck' F_1 cultivar, which was most probably caused by the classification of those cultivars on account of fruit size ('Komeett' F_1 produces medium-sized fruit and 'Starbuck' F_1 produces large-sized fruit) rather than the introduction of a supplementary light source (Tab. 6). A higher mean fruit weight was obtained in plants supplementary lighted with HPS lamps and LED lamps as compared to plants from the control combination (without supplementary lighting). There were also significant differences in the fruit weight between cultivars. The 'Starbuck' F_1 cultivar was characterised by a higher fruit weight than the 'Komeett' F_1 cultivar, which similarly as in the case of the number of fruit rather resulted from the classification of those cultivars on account of fruit size than the use of a supplementary light source (Tab. 7).

In real-life applications, such as the growth of higher plants in a typical greenhouse, light distribution greatly affects the growth of both plants and fruit, and light sources cannot be matched only by PPFD measured on the surface at the top of the plants because dissipated light greatly contributes to both photosynthesis and yielding. Lamps contribute in both the lighting and shading of the plants; while under HPS shading is low, due to the typical low light output of a single fixture it cannot be neglected in LED lamps.

LED lamps should only be considered as an HPS alternative at higher light levels than 100 µmol focused at the plant top because light flux focusing reduces the light level in the middle of the canopy. Both light intensity and the light distribution angle should be increased. The experiment revealed that in an overhead lamp configuration, LED lamps cannot compete with HPS lamps at current LED efficiency even though energy consumption was halved.

CONCLUSIONS

1. The introduction of an HPS light source to tomato cultivation caused a significant increase of the intensity of photosynthesis, transpiration and stomatal conductance, while the introduction of an LED light source increased these parameters only by a non-significant amount.
2. Chlorophyll content in tomato leaves was higher in both HPS and LED lamp cultivation compared to natural light.
3. Marketable yield and the number of fruit were higher in HPS cultivation than with LED lamps and the lowest numbers were obtained for natural light cultivation.
4. Mean fruit weight was higher in both combinations in which supplementary lighting was applied. However, the values of those traits were higher when the plants were supplementary lighted with HPS lamps than with LED lamps.

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WPŁYW DOŚWIETLANIA NA FOTOSYNTEZĘ, TRANSPIRACJĘ ORAZ PLONOWANIE ROŚLIN POMIDORA

Streszczenie: Światło jest jednym z podstawowych czynników niezbędnych roślinie do rozwoju. Celem niniejszego doświadczenia było wykazanie wpływu doświetlania roślin pomidora z zastosowaniem wysokoprężnych lamp sodowych (WLS) oraz lamp diodowych (LED) na wybrane parametry fizjologiczne i plon w uprawie jesienno-zimowej. Wykorzystano dwie odmiany pomidora (Komeett F_1 i Starbuck F_1 - De Ruiter Seeds Company). Po posadzeniu uruchomiono doświetlanie o intensywności 100 µmol m^{-2} s^{-1} złożone z lamp WLS lub LED. Wprowadzenie doświetlania do uprawy pomidora spowodowało wzrost fotosyntezy o 57,7%, transpiracji o 17,1%, przewodności szparkowej o 39,3%, jak również zawartości chlorofilu o 24%. Większy wzrost uzyskano dla lamp WLS niż dla lamp LED. Plon handlowy, liczba owoców oraz średnia waga owocu były wyższe w obu doświetlanych kombinacjach, przyrost tych parametrów był również wyższy dla lamp WLS niż diodowych. Ze względu na stosowanie oświetlenia górnego oraz wciąż niską wydajność lamp , pomimo lepszego ogniskowania i składu widmowego nie wykazano wzrostu przydatności lamp diodowych w porównaniu do lamp WLS.

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