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EFFECT OF SUPPLEMENTAL LED LIGHTING ON GROWTH AND QUALITY OF *Valerianella locusta* L. AND ECONOMIC ASPECTS OF CULTIVATION IN AUTUMN CYCLE

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Abstract. New lighting technologies that significantly reduce the energy consumption are in the centre of interest of greenhouse crop producers. In this study, the effect of several LED lights with various spectral composition and high pressure sodium lamp (HPS), as supplemental to solar radiation, on growth and yielding of lamb's lettuce 'Nordhollandse' was tested (in two autumn cultivations). At harvest time, the highest leaf length and area, fresh weight of rosettes and soluble sugars content were obtained under LED lamps that emitted 90% red and 10% blue light. The spectral composition of each kind of LED lamp increased the ascorbic acid content compared to HPS (70% red + 30% blue LED light to the highest extent). Using of LEDs with red and blue diodes reduced the consumption of electricity for *V. locusta* lighting about 36% to 55% in comparison to HPS. The highest total costs of lamb's lettuce cultivation was shown under white LEDs.

Key words: LED light, lamb's lettuce, growth, yield, energy consumption

INTRODUCTION

Light intensity and spectral properties strongly affect the growth and development of plants. The shortage of sunlight in autumn and winter at northern latitudes results in the need for artificial lighting of plants in greenhouses. Rising energy costs and concern for the environment contribute to an intensive search for alternative light sources that could replace high-pressure sodium lamps (HPS), commonly used in greenhouses. Energy inputs (heating and lighting) range from 10 to 30% of total production costs for the

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greenhouse industry [Mitchell et al. 2012]. New lighting technologies that significantly reduce consumption of electricity for crop lighting are of interest to crop growers [Klamkowski et al. 2014]. SSL LED technology (Solid State Lighting Light Emitting Diodes) is becoming a very promising light source, being gradually introduced in horticulture ‘under glass’ [Olle and Viršilė 2013, Randall and Lopez 2014]. In recent years, semiconductor light sources (light-emitting diodes, LED) have become more popular in practical lighting solutions. The main advantage of this solution over the other artificial light sources is the possibility to easily optimize the spectrum of LED modules. The use of LEDs allows for build lighting modules of any spectral characteristics, which can be adjusted to the needs of any cultivated species. Other advantages of using LEDs are: small size of a single light source, high durability and reliability, minimal heat emission [Massa et al. 2008, Mitchell et al. 2012]. The barrier that limits the widespread use of LED lamps in horticultural production is high manufacturing cost of SSL LED systems. In the literature, the possibilities of supplementary LED lighting for the plants during winter and early spring are rarely described, and they mostly concern the use of selected light colour e.g.: blue, red or far red [Heo et al. 2011, Randall and Lopez 2014].

To enhance the photosynthesis productivity of plants, the most effective proves to be the mixed red (600–700 nm) and blue (400–500 nm) light with a predominance of red [Hogewoning et al. 2010, Wang et al. 2016]. Moreover these ranges of light spectra are responsible for initiating the synthesis of many compounds beneficial for human health. Recently, numerous research have evaluated the effects of various LED light spectra on phytochemicals in vegetable, such as ascorbic acid, soluble proteins, soluble sugars, carotenoids or phenolic compounds [Bian et al. 2015, Frąszczak et al. 2015]. Despite of a large amount of such works still very little of them concern the economic aspects of the applied LED lighting. For example Fan et al. [2013] presented the energy efficiency parameter (g fresh weight of plant per 1 KW) in study with various LED light intensity in young tomato growing.

Valerianella locusta (lamb’s lettuce) chosen as a model in this research is a ready-to-eat green salad whose fresh consumption has lately increased. Owing to the high pro-healthy value (ascorbic acid, folic acid, phenolic compounds or omega-3 fatty acids) and taste qualities this plant is particularly valuable during months of limited accessibility to fresh leafy vegetables [Długosz-Grochowska et al. 2016]. The aim of our study was to produce lamb's lettuce of high yield and nutritional value for the harvest in December, as a result of lighting with red and blue LED light in various ratios, and also with two kinds of white LED light, implemented as supplemental to solar light. Our hypothesis assumed that LED lamps of proper light spectrum might replace HPS ones. Verification of this hypothesis was based on monitoring of plant growth, chemical composition of the yield and calculating the energy consumption and total costs of cultivation.

MATERIAL AND METHODS

The study was conducted in two autumn seasons in a greenhouse (50°03'N, 19°57'E) at the Agricultural University in Krakow, Poland. Lamb’s lettuce (*Valerianella locusta* L.)

cv. 'Nordhollandse' (Floraland Distribution Sp. z o.o., Nieporęt, Poland) seeds were placed in cells of 24-trays plastic vessels (three seeds per tray 7 × 8 × 8 cm) containing peat substrate (Klasmann KTS-2) on 1st October 2012 and 2013. Amounts of nutrients were as followed (mg L^{-1} , mean for two years): N 343, P 172, K 592, Ca 1417, Mg 177, S 538, B 0.57, Cu 0.21, Fe 3.78, Mn 3.23, Zn 0.70; pH was 5.56 (H_2O) and EC 0.96 mS. Plants were grown at density of 450 rosettes per m^2. After seeds germinating, supplementary lighting was implemented to prolong the length of the day to 16 hour (turning on the lamps – 18 Oct 2012 and 10 Oct 2013) and lasted until harvest time (16 Dec 2012 and 9 Dec 2013). The average growth conditions were 17.5 ±2°C, 60 ±5% RH and 358 J cm^{-2} d^{-1} of natural solar radiation (date measured and saved by computer-controlled system, Netafim Comp.). CO_2 concentration during vegetation was 360–400 ppm (additional enrichment not applied).

The modern technology of SSL LED, suitable for illuminate plants in greenhouse, allowed for fully automatic control of the lighting process. Technical details of this system and spectral characteristics of all used LED lamps were described by Grzesiak et al. [2014]. The lamps of nominal power 100 W (100 × 8 × 7 cm, included 48 OSRAM OSLON diodes 1–3 W each) were divided into 6 groups with 4 lamps each differing in the applied LED diodes and consequently the spectral properties of the emitted light. First four groups of lamps emitted red (660 nm) and blue (440 nm) light in various shares: 1) 100% red (100R); 2) 70% red and 30% blue – 70R/30B; 3) 50% red and 50% blue – 50R/50B; 4) 90% red and 10% blue – 90R/10B. The fifth group included white diodes of the colour temperature 3.500 K (WN – white neutral) and the sixth one had two sets of white diodes of the colour temperature 2.700 and 5.500 K (WD – white dynamic). The seventh light treatment was a high pressure sodium lamp (HPS, 600 W, SON-Agro, Philips) as a control. Photosynthetic photon flux density (PPFD) reaching the plants directly under the lamps was approx 200 µmol m^{-2} s^{-1} (the distance between plants and lamps was as follow: 57 cm – 100R, 66 cm – 70R/30B, 59 cm – 50R/50R, 59 cm – 90R/10B, 37 cm – WN, 45 cm – WD, 115 cm – HPS; measurements and regulation using an LI-250A Light Meter and LI-190 Quantum Sensor – LI-COR, Lincoln, Nebrasca USA) and these plants were used to the growth and chemical analyses. To the calculation of energy consumption, the plants receiving 160 ±40 µmol m^{-2} s^{-1} PPFD in each light treatment were included (in this range of PPFD there was no difference in the size of rosettes at harvest time). Each LED light treatment consisted of four diodes-lamps and the control treatment of one high pressure sodium lamp.

Growth parameters (leaf length, width and area) were measured after 30 and 60 days of supplemental lighting in ten replications each measurement. Leaf and subsoil temperature was measured using infrared thermographic camera (ThermaCAM e300; FLIR; Focal Plane Array detector; 320 × 240 pixels uncooled microbolometer; 24° × 18° the field of view) in 10 replications each measurement. Emissivity of leaves = 0.98 was adopted in accordance to Lopez [2012]. Thermograms (thermal images) of leaves have been analyzed with the use of QuickReport 1.2 and Reporter 2000 Pro software. At harvest time (about 60 days of irradiation), 10 rosettes of lamb's lettuce were randomly collected from each replication (40 rosettes per each light treatment). Results of yielding were presented as a weight of one rosette in g calculated as a mean of four replications.

Chemical analyses were conducted immediately after harvesting (60 days of lighting) and performed in four laboratory replications. Ascorbic acid (AA) content was determined in the homogenized fresh plant material according to the Polish Committee for Standardization [1988] with the use of Tillmans' method (sample of 10 g fresh weight was homogenized with 2% oxalic acid and titrated with 0.2 mg cm^{-3} w/v 2,6-dichlorophenolindoophenol sodium salt). Soluble sugars (reducing and non-reducing) were evaluated using the anthrone colorimetric method [Yemm and Wills 1954] and measured on HITACHI U2900 spectrophotometer at 625 nm. The calculation was based on the glucose standard curve. Dry matter content was estimated by drying samples at 105°C to determine the constant weight.

To the cost calculation, we took into account the following items: (1) plant material costs (seeds, peat substrate, plastic vessels, water consumption, plants protection); (2) salary costs with charges; (3) greenhouse heating costs (in analyzes were included: inside and outside temperatures, thermal transmittance, greenhouse's wall thickness, heat energy from lamps) and (4) supplementary lighting costs included real energy consumption and cost of 1 kWh (1 kWh = 3.60 PLN ≈ 0.9 EUR). The number of irradiation hours was 418 and 402 in autumn 2012 and 2013, respectively. The measurements of active power consumption by LED lamps and HPS, using the ND20 electricity meter manufactured by LUMEL Ltd were conducted.

Statistical analyses were performed using STATISTICA 9 and the differences between light treatments obtained for two year study were evaluated using Fisher's LSD test at $p \leq 0.05$. In tables and figures means for two years with the significant differences between light treatments were presented.

RESULTS

According to the Table 1, after 30 days of supplemental lighting the density of leaves in lamb's lettuce rosettes was the highest when grown under solely red LED, red and blue LED light in a ratio of 9:1 and under sodium lamp. However, at harvest, after 60 days, there were no differences in the number of leaves in rosette between plants cultivated with the use of all red + blue LEDs and HPS lamps. The slowest growth of lamb's lettuce's rosettes was observed under white LED light. Length, width and area of lamb's lettuce leaves reached high values both after 30 and 60 days of supplemental lighting under 90R/10B LEDs (tabs 1 and 2). Statistical analysis showed that at harvest time (60^{th} day) in this treatment the leaves had the highest length and area. The smallest width of the leaves was noted in case of plants grown under white neutral LEDs (WN) in the middle of plants cultivation (30^{th} day).

The temperature of leaves under sodium lamp was over one Celsius degree higher than the temperature of other leaves (tab. 2). However, the difference in the temperature of leaves after 30 days was statistically significant between plants under HPS and LED light. After 60 days, the significant differences in leaf temperature between HPS and LED lamps containing blue diodes were shown. The temperature of subsoil measured after 30 days of irradiation in HPS treatment was higher than in LEDs. Because of very large variation of subsoil temperature, there were no statistically significant differences in these temperatures at harvest time (60 days of lighting).

Table 1. Growth parameters of lamb's lettuce leaves after 30 and 60 days of supplemental lighting (means for 2012–2013). Light treatments: 100% red LED (100R); 70% red + 30% blue LED (70R/30B); 50% red + 50% blue LED (50R/50B); 90% red + 10% blue LED (90R/10B); white neutral LED (WN); white dynamic LED (WD); 7 – high pressure sodium lamp (HPS)

Light treatment	Number of leaves in rosette		Leaf length (mm)		Leaf width (mm)	
	30	60	30	60	30	60
100R	10.2 ab*	18.0 a	113.6 ab	138.2 b	26.2 ab	29.9 b-d
70R/30B	9.4 bc	17.2 ab	112.8 ab	141.3 b	27.0 ab	31.0 a-c
50R/50B	9.5 bc	16.8 ab	104.5 bc	142.3 b	27.2 ab	33.2 ab
90R/10B	10.9 a	18.0 a	117.5 a	165.2 a	28.3 a	34.6 a
WN	9.2 c	16.6 b	103.2 bc	139.9 b	19.2 c	27.2 d
WD	8.9 c	16.0 b	97.7 c	140.4 b	24.8 b	26.8 d
HPS	10.9 a	18.1 a	97.9 c	136.8 b	26.5 ab	29.3 cd

* – means within column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's test; n = 20

Table 2. Leaf area, temperature of leaf and subsoil after 30 and 60 days of supplemental lighting (means for 2012–2013). Light treatments: see Table 1

Light treatment	Area of leaf (mm^2)		Leaf temperature (°C)		Subsoil temperature (°C)	
	30	60	30	60	30	60
100R	1514.8 ab*	2051.7 cd	19.3 b	20.6 ab	18.3 b	19.3 a
70R/30B	1521.4 ab	2197.2 bc	19.5 b	20.3 b	18.2 b	18.9 a
50R/50B	1416.5 a-c	2373.9 b	18.9 b	20.4 b	18.0 b	18.9 a
90R/10B	1668.6 a	2853.0 a	19.1 b	20.0 b	18.0 b	18.5 a
WN	1007.4 d	1897.1 cd	19.4 b	21.6 ab	18.3 b	19.8 a
WD	1218.8 cd	1873.0 d	19.2 b	20.8 ab	17.9 b	18.6 a
HPS	1300.5 bc	2014.6 cd	21.3 a	22.9 a	19.3 a	20.5 a

* – means within column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's test; n = 20

As shown in Figure 1 A, supplemental lighting with 70R/30B LED light contributed to obtain the highest level of ascorbic acid (AA) content in lamb's lettuce leaves (25.3 mg AA 100 g^{-1} fresh weight). This level was about 40% higher in comparison to control rosettes (15.4 mg AA 100 g^{-1} fresh weight). It is worth noting, that irrespectively of spectrum, LED light significantly increased AA concentrations when confront the sodium light. Greater share of red in light spectrum stimulated soluble sugars accumulation (fig. 1 B), and the most effective was the mixture of 90% red with 10% blue LED light. Supplemental lighting with white (WN, WD) and 50R/50B LEDs decreased soluble sugars content compared to the control treatment. Dry matter content ranged from 6.7 to 7.4% (fig. 1 C) and was the highest as a result of lighting with white cool LED (WN), HPS as well as 9:1 and 7:1 red to blue LED light. The supplemental 100R and 50R/50B irradiation decreased accumulation of dry matter content in lamb's lettuce.

Table 3. Lamb's lettuce yield and energy consumption in various light treatments (means for 2012–2013, 410 hours of supplemental irradiation). Energy consumption was calculated for four LED lamps and one HPS. Light treatments: see Table 1

Light treatment	Fresh weight of one rosette (g)	Number of plants received 160 ± 40 µmol m^{-2} s^{-1} PPFD	Energy consumption (active power in W)	Number of kilo-watt-hours used during cultivation (kWh)	Energy consumption per one rosette (kWh)	Energy consumption per 100 g of rosettes (kWh)
100R	7.269 b*	287.0	342.8	140.5	0.489	6.727
70R/30B	8.029 a	347.5	342.8	140.5	0.404	5.032
50R/50B	6.910 b	274.3	278.4	113.8	0.415	6.006
90R/10B	8.176 a	291.5	278.4	113.8	0.390	4.770
WN	5.419 c	193.7	441.2	180.6	0.932	17.199
WD	5.218 c	221.4	441.2	180.6	0.816	15.638
HPS	7.328 b	342.3	648.0	265.3	0.775	10.576

* – means within column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's test; n = 8

Table 4. Costs calculation of lamb's lettuce cultivation per 100 g of rosettes in PLN (means for 2012–2013). Particular items used in calculating the costs are presented in Material and Methods. Light treatments: see Table 1

Light treatment	Plant material costs	Salary costs with charges	Heating costs	Lighting costs	Total costs
100R	1.77	0.29	3.23	1.91	7.20
70R/30B	1.58	0.26	2.91	1.42	6.17
50R/50B	1.95	0.32	3.51	1.79	7.57
90R/10B	1.55	0.25	2.86	1.34	5.99
WN	2.36	0.38	4.33	4.87	11.94
WD	2.61	0.43	4.69	4.71	12.44
HPS	1.96	0.32	2.14	3.36	7.78

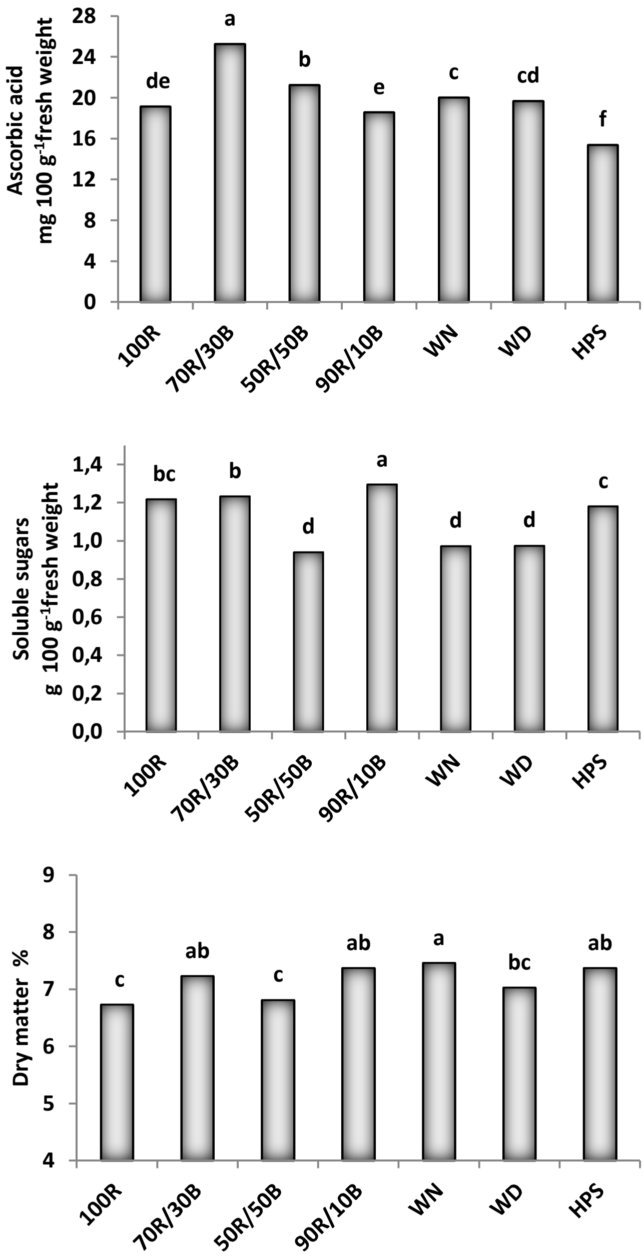

Fig. 1. Ascorbic acid (A), soluble sugars (B) and dry matter (C) content in *V. locusta* rosettes as an effect of 60 days supplemental lighting with: 100% red LED (100R), 70% red + 30% blue LED (70R/30B), 50% red + 50% blue LED (50R/50B), 90% red + 10% blue LED (90R/10B), white neutral LED (WN), white dynamic LED (WD), and high pressure sodium lamp (HPS). Means for two years, n = 8

LED light of red and blue mixture in 9:1 and 7:3 ratios had a positively effect on the yield of *V. locusta* (tab. 3). In these light treatments fresh weight of rosettes was the highest (about 11 and 9% higher compared to control plants, respectively). Values obtained under HPS, solely red LED light and red with blue in 1:1 ratio were not significantly different. The lowest yield was gained as a result of irradiation with white LEDs irrespectively of diodes' colour temperature. Moreover, under white LED lamps the smallest number of plants received the PPFD of 160 ±40 µmol m^{-2} s^{-1}. This PPFD reached the largest number of plants cultivated under 70R/30B and HPS treatments. The lowest energy consumption was measured in the case of LED lamps which emitted red and blue light in ratios 1:1 and 9:1 (278.4 W per light treatment, i.e. 69.6 W of active power per one lamp). The highest one was shown for HPS lamp (648 W). This resulted in the smallest and the greatest number of kilowatt-hours used in lamb's lettuce cultivation in these treatments: 113.8 kWh (50R/50B and 90R/10B), and 265.3 kWh for HPS, respectively. Energy consumption calculated per one rosette was the lowest under LED lamps which emitted red and blue light in ratio 9:1. The obtained value was about 50% lower compared to control and 52 or 58% in comparison to white LED, dynamic and neutral, respectively. In final calculation, energy consumption for 100 g of rosettes was evidently lower in the case of LED lamps emitted red and blue light in various ratios in comparison to HPS and white LEDs using.

The main differences in analyzed costs (plant material, salaries, heating and lighting) depend on lamb's lettuce yield (tab. 4). The highest costs were for the plants under white LEDs, and the lowest were for 90R/10B and 70R/30B (excluding heating costs). For cultivation under HPS, only the heating costs were the lowest. Lighting costs for 90R/10B and 70R/30B were about two times lower than HPS, and approx three times lower compared to white LEDs. Finally, total cultivation cost per 100 g of rosettes was the lowest in 90R/10B treatment (5.99 PLN).

DISCUSSION

The differences in the growth and chemical composition of the yield of *V. locusta* were connected with the differences in the spectral composition of light. Some authors obtained the highest fresh weight of young lettuce as an effect of red + blue (1:1) or blue LEDs lighting in comparison to the red one [Jokhan et al. 2010]. In contrary, in the case of Chinese cabbage, the most positive effects of 100% red LED light in enhancing the biomass of seedlings was shown [Li et al. 2012]. In our experiment, LED lighting was supplemental to natural radiation in the whole lamb's lettuce growing. Increasing the share of blue light up to 10% resulted in the highest leaf length and area as well as fresh weight of rosette compared to other treatments. This participation of blue light is most similar to natural sunlight (18% blue) what could be the reason of such plants' response. Interestingly, in winter cultivation of *V. locusta* we demonstrated similar results in the case of yielding [Wojciechowska et al. 2015]. Red light stimulates leaf blades development via phytochrome photoreceptors [Taiz and Zeiger 2015]. In present study this effect was evidently observed in the term of 30 days of lighting when LED lamps with red diodes were used. Taking into account the size of rosettes and sugars accumulation, our results showed indirectly that the light in the ratio of 9:1 (red to blue) effectively enhance capacity of photosynthetic apparatus of lamb's lettuce leaves. Some authors found the influence of similar light spectrum beneficial to net photosynthesis in wheat [Goins et al. 1997] or carbohydrates accumulation in radish [Samuoliene et al. 2011]. Light, influencing the photosynthesis and sugars production, affect the synthesis and accumulation of ascorbic acid. Many complex processes regulated by light, which are not fully recognized as yet, are connected with metabolism of this compound [Osashi-Kaneko et al. 2007]. Ascorbic acid content depends on the share of blue light in the spectrum that reaches the plants [Osashi-Kaneko et al. 2007]. Li et al. [2012] showed beneficial effect of blue LED light on the concentration of vitamin C in non-heading Chinese cabbage. In our study, the use of 100 and 90% red LED light resulted in the lower ascorbic acid content in *V. locusta* in comparison to other LED treatments with more blue light. Wang et al. (2016) showed that shoot dry weight of lettuce (also the leaf area and leaf number) increased with the increasing of red to blue LED light ratio. In this study such dependence did not appear. Dry matter content varied in lamb's lettuce leaves but not proportionally to the share of red or blue light used to supplemental irradiation.

The largest surface of 160 ±40 µmol m^{-2} s^{-1} PPFD was characterized by 70R/30B and HPS treatments, therefore the adequate photon density reached to more plants. However, the yield and energy consumption by lamps in particular light treatments resulted finally in energy consumption per 100 g fresh weight of rosettes. The achievement of our research was demonstrating that the plants under LEDs with red + blue diodes consumed from 36% (90R/10B) to 55% (100R) less energy than under sodium lamp. These results confirm that LEDs sources may reduce the consumption of electricity for crop lighting [Klamkowski et al. 2014]. However, these effects depend on spectral composition and the proper construction of LED lamps. Some of results revealed that heat costs (lightening and heating) in horticulture production under covers account for nearly 60% of all production costs [Rutkowski 2004]. Our results showed that in experimental conditions this costs exceed even 70%. The highest share of heat cost in the total value was calculated for white LED light treatment. The cost of production was determined mostly by heating cost. In the cost analysis it is important also to include the investment cost of light treatment. There are comparative economic analyzes of traditional vs. LED lighting, that show reduction of the production cost of vegetables in the long-run (several years) introducing of LEDs [Singh at al. 2015]. It is related to the LEDs high energy efficiency, low maintenance cost and longevity. However, prices of LED lighting systems are still high to achieve cost effectiveness and economic viability of greenhouse crop production.

CONCLUSIONS

Based on monitoring of *V. locusta* growth and chemical composition of the yield and on calculating the energy consumption, the best results were achieved under LED lamps that emitted 90% red + 10% blue and 70% red + 30% blue light. Only white LEDs, irrespectively of colour temperature, resulted in worse effects compared to HPS.

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WPŁYW DOŚWIETLANIA UZUPEŁNIAJĄCEGO LAMPAMI LED NA PAMETRY WZROSTOWE I JAKOŚCIOWE *Valerianella locusta* L. ORAZ ASPEKTY EKONOMICZNE UPRAWY W CYKLU JESIENNYM

Streszczenie. W centrum zainteresowania producentów szklarniowych upraw ogrodniczych są nowe technologie doświetlania roślin, które zmniejszyłyby koszty zużycia energii. W prezentowanym doświadczeniu badano wpływ doświetlania (uzupełniającego światło naturalne) lampami LED o różnym składzie spektralnym oraz wysokoprężną lampą sodową (HPS) na wzrost i plonowanie roszponki warzywnej 'Nordhollandse' w dwóch sezonach jesiennych. W terminie zbioru, największą długość i powierzchnię liści, świeżą masę rozet oraz zawartość cukrów rozpuszczalnych w liściach uzyskano pod lampami LED emitującymi światło czerwone i niebieskie w udziale 90 i 10%. Skład spektralny każdego rodzaju lampy LED wpływał na zwiększenie zawartości kwasu askorbinowego w porównaniu z HPS (w największym stopniu 70% światła czerwonego + 30% niebieskiego). Wykorzystanie lamp LED z diodami czerwonymi i niebieskimi zmniejszyło koszty zużycia energii od 36 do 55% w porównaniu z HPS. Największe koszty całkowite uprawy roszponki wykazano pod lampami LED emitującymi światło białe.

Słowa kluczowe: światło LED, roszponka warzywna, wzrost, plon, zużycie energii

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