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LED lighting affected the growth and metabolism of eggplant and tomato transplants in a greenhouse

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Abstract: Light-emitting diodes (LEDs) were used for the spring greenhouse cultivation of eggplant (*Solanum melongena* L.) 'Milar F1' and tomato (*S. lycopersicon* L.) 'Benito F1' transplants. Seedlings were grown under natural light conditions with the supplemental LED light. A 16-h photoperiod provided plants with a DLI of 12.6 (eggplant) and 9.6 (tomato) mol m^2/day. Four supplemental light spectra were tested: L1 (90% red + 10% blue); L2 (80% red + 20% blue); L3 (43% red + 42% blue+15% green) and L4 (56% red + 26% blue + 15% green + 3% UV-A). The PPFD in each LED light treatment was 150 ± 20 μmol/m^2·s. Compared to the control plants (without LED lighting), the eggplant transplants had about a 25% larger leaf area and a higher level of total phenol content as well as a higher antiradical scavenging activity under the L1 spectrum. The favourable spectrum for the tomato transplants consisted of red to blue in a ratio of 1 : 1 mixed with a green light (L3) – the leaves were characterised by a higher content of dry matter, soluble sugars, photosynthetic pigments and total phenols; also the radical scavenging activity increased in comparison to the control group. It was shown that the supplemental irradiation of transplants was economically acceptable.

Keywords: antioxidant properties; growth parameters; photosynthetic pigments; sugars

Many producers of horticulture crops are, recently, more and more interested in new technologies of plant lighting, which could be more energetically efficient and versatile. New-generation luminaries based on light-emitting diodes (LEDs) have appeared as very promising sources of artificial light for plants (Mitchell 2015; Dutta Gupta, Agarwal 2017). LED lighting systems are proving to be useful in controlled-environment agriculture (CEA) and its applications are constantly expanding: from fully controlled closed growing systems (*in vitro* cultures, growth chambers) to multilayer vertical farming, greenhouse production or postharvest treatments. The wide range of LED applications in plant cultivation result from its unique technical advantages in comparison with other light sources used in agriculture (Morrow 2008; Dutta Gupta, Agarwal 2017).

During the last years, efforts have been put into the study on the impact of various LED light spectra and its intensity on the growth and development, physiological processes, primary and secondary metabolism of many horticultural species (Singh et al. 2015; Viršilė et al. 2017; Bantis et al. 2018). Most of the studies have shown a positive effect of blue LEDs combined with red because the absorbance maxima of the photosynthetic pigments are concentrated

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at these wavelength ranges (chlorophyll *a* – 430 and 660 nm, chlorophyll *b* – 450 and 640 nm, carotenoids – 450 and 480 nm). However, the question of what ratio of red to blue light will give the best results is still open. The observed effects seem to be species-specific and may vary depending on growth factors (Ouzounis et al. 2015; Wojciechowska et al. 2015).

Knowledge about photobiological reactions of plants is dynamically expanding and provides a theoretical basis for practical applications (Folta, Carvalho 2015). Responses to light are connected with the activation of specific photoreceptors sensitive to particular wavelengths. It was found that plants can absorb ultraviolet B (280–315 nm) by UVB-RESISTANCE8; ultraviolet A (315–400 nm) and violet-blue light (400–490 nm) by cryptochromes, phototropins or the recently identified large group of ZTL/FKF1/LPK2 photoreceptors; red (600–700 nm) and far-red (700–750 nm) light are detected by the family of phytochromes (Galvão, Fankhauser 2015; Kong, Okajima 2016). Each photoreceptor acts as an individual sensor which initiates a light signal transduction pathway leading to the specific reaction. According to this knowledge, researchers or growers can modulate the intensity of the photosynthesis, photomorphogenesis or chemical composition of the plants. For example, blue light, which regulates the chloroplast and stomatal movements or suppresses a stem elongation, may also enhance the synthesis of the photosynthetic pigments and increase some secondary metabolites like the concentration of the phenolic compounds (Kopsell et al. 2015; Długosz-Grochowska et al. 2017).

The *Solanum lycopersicon* and *S. melongena*, used in the present study are among the most economically important vegetables in the world. In 2017, the global tomato and eggplant production was about 182 and 52 million tonnes, respectively (Statista 2019). Tomatoes are widely consumed either raw or after processing and can provide a significant proportion of the total antioxidants required in the diet. They are a rich source of lycopene, flavonoids and hydroxycinnamic acid derivatives (Martínez-Valverde et al. 2002). Eggplants have been found to contain a high level of phenolic compounds with a high antioxidant activity and necessary amounts of some minerals also, like P, K, Ca or Mg (Raigón et al. 2008). In northern latitudes, the commercial cultivation of both species in open fields is possible only with the use of transplants. Due to the climatic conditions, transplants must be produced in the greenhouse and can be planted outdoor around mid-May when the danger of ground frost has passed. The proper environmental conditions during the growth of seedlings must be maintained to grow the highest quality transplants (Dursun et al. 2002) and one of them is with light. Vegetable seedlings, including eggplant and tomato are usually not grown with supplemental light during spring production in the greenhouse.

Will it be possible to improve the transplant quality with the use of additional LED lighting when the natural day's length gradually increases (March to May)? If so, will it be economically justified? A question arises: Is it enough to use the red and blue radiation for the supplemental lightning or to optimise the transplants' growth with a broader spectrum similar to sunlight? It is a current issue because the effect of LEDs with different proportions of blue, red and green light with a UV (or far red) addition on the plant growth and development has been tested in a great deal of horticultural research recently (Bantis et al. 2018; Peixe et al. 2018).

The purpose of the present research was to evaluate the growth, and some biochemical parameters of eggplant and tomato transplants grown in a greenhouse with supplemental LED lighting. Four LED lighting spectra were tested: two with red and blue light in various ratios and two with a broader spectrum including red, blue and green. Additionally, in the fourth spectrum, a UV-A wavelength was introduced. The control plants were cultivated with natural solar radiation only.

MATERIAL AND METHODS

Plant material and growth conditions. The experiment was conducted in 2016 and 2017 in a high-tech greenhouse (50°03′N, 19°57′E) of the Faculty of Biotechnology and Horticulture at the University of Agriculture in Krakow. The plants used in the study were the eggplant (*Solanum melongena* L.), the very early cultivar 'Milar F_1' (Fito Semillas) and the tomato (*Solanum lycopersicon* L.), the mid-late cultivar 'Benito F_1' (Bejo Zaden). The seeds were sown individually into 96-cell multi-pots (60 × 40 cm) with a volume of 0.23 dm^3 each (400 plants per m^2) and germinated in the peat substrate Florabalt Seed (Floragard Product) (pH 5.6; N 140, P_2O_5 80 and K_2O 190 mg/L^3). After the formation of the second pair of true leaves, the seedlings were transplanted into 40-cell multi-pots (56 × 36 cm) with a volume of 0.53 dm^3

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Table 1. Important cultivation parameters and approximate lighting cost

Experiment schedule, lighting costs and climate conditions	Eggplant 'Milar F_1'	Tomato 'Benito F_1'
Sowing	4 March, 2016	10 March, 2017
Lighting implementation[1]	21 March, 2016	17 March, 2017
Transplantation	6 April, 2016	7 April, 2017
End of experiment[2]	16 May, 2016	28 April, 2017
DLI[3] for control treatment	11.6 mol/m^2·day	8.2 mol/m^2·day
DLI for LED light treatments	12.6 mol/m^2·day	9.6 mol/m^2·day
Sum of artificial lighting per cultivation period	107.5 h	114 h
Energy consumption per 100 plants[4]	19.35 kWh	12.8 kWh
Approx. total lighting cost per 100 plants[5]	2.47 EUR	1.61 EUR
Ambient temperature	22.9 ± 2 °C (day) 17.6 ± 2 °C (night)	20.4 ± 2 °C (day) 18.3 ± 2 °C (night)
Relative humidity	50.8%	52.0%

[1]just after seeds' germination; [2]the term, when growth and chemical analyses were conducted; [3]daily light integral; [4]included the energy consumption of eight LED lamps used in the experiment (0.720 kW), the sum of hours with artificial lighting in the whole experiment and the number of plants additionally irradiated (400 eggplants and 640 tomato transplants); [5]cost of 1kWh was 0.128 Euro in 2016 and 0.126 in 2017

each containing the peat substrate Klassmann KTS-2 (on average, pH 5.8; EC 1.2 mS/cm; N 410, P_2O_5 160, K_2O 620, Ca 1325, Mg 146 and S 305 mg/L, and other microelements). The seedlings were fertilised twice with a water solution of Kristalon Green 18 + 18 + 18 Yara (N-18%, P-18%, K-18%, Mg-3%, S-5%, B-0.025%, Cu-0.01 %, Fe-0.07%, Mn-0.04%, Mo-0.004%, Zn 0.025%) fertiliser at a concentration of 0.1%.

The terms and conditions of both cultivations are presented in Table 1. Approx. 500 eggplant and 800 tomato transplants were grown in all the experiments.

Light treatments. Plants were grown in photoperiod of 16/8 h day/night. Artificial lighting was implemented only to extend the day's length (not to increase the daylight intensity). An astronomical clock built into the system controller allowed one to turn on the lamps with the sunset and switch off the lamps 8 h before the sunrise. The LED lighting duration decreased with the lengthening of the natural day: in 2016, from 3 h 43 min on March 21 (after the eggplant seeds germination) to 12 min on May 16 (end of the experiment) and, in 2017, from 4 h 4 min on March 17 (after the tomato seeds germination) to 1 h 16 min on April 28 (end of the experiment). The supplemental light treatments included four LED light spectra (in brackets: the percentage share in the spectrum, colour and wavelength, respectively) were as follows: L1 (90% red 660 nm + 10% blue 450 nm); L2 (80% red 660 nm + 20% blue 450 nm); L3 (29% red 660 nm + 14% red 630 nm + 42% blue 450 nm + 15% green 520 nm); L4 (38% red 660 nm + 18% red 630 nm + 26% blue 450 nm + 15% green 520 nm + 3% UV-A 330 nm). The photosynthetic photon flux density (PPFD) reaching the plants under all the lamps was 150 ± 20 μmol/m^2·s. The active power of each lamp was 90 W. Each light treatment consisted of two identical lamps (approx. 50 eggplant and 80 tomato plants were grown under each lamp). The control plants were grown in daylight only (without any supplemental lighting). The DLI (daily light integral) values are presented in Table 1.

Growth analyses. Twenty randomly chosen plants of each species and treatment were harvested to perform the following measurements: stem length (from the substrate surface to the apical meristem, using a ruler), stem diameter (using an electronic calliper), leaf number and leaf area, measured with a system for leaf surface analysis (WinDIAS, Geomor-Technic).

Chemical analyses. Twenty randomly selected leaves (the fully developed second or third leaf from the apex) of each species and treatment were harvested for the chemical analyses. All the chemical analyses were performed in four laboratory replications for each light treatment.

The dry matter content (%) of the leaves was estimated by drying 1 g of the shredded fresh material at 105 °C. The samples were dried to determine the constant weight (about three hours).

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The soluble sugar content was evaluated using the anthrone colorimetric method described by YEMM and WILLS (1954). The optical density of the ethanol extracts after reaction with the anthrone reagent was measured at 625 nm on a Helios Beta spectrophotometer (Thermo Fisher Scientific Inc., USA). The content of the soluble sugars was calculated according to the calibration curve of the glucose as a standard.

The photosynthetic pigments were extracted in 80% (v : v) aqueous acetone, and the absorbance reading was carried out at 470, 646 and 663 nm. The procedure and calculations were performed as described by Lichtenthaler and Wellburn (1983).

The content of the phenolic compounds in the eggplant leaves was measured using methanol extracts according to the spectrophotometric method described by Fukumoto and Mazza (2000). The absorbance was detected at a wavelength of 280 nm using a Hitachi U2900 (Japan) UV-VIS spectrophotometer. The content of the total phenols was calculated using the calibration curves for chlorogenic acid.

The total phenolic content in the tomato leaves was determined in the 80% methanol extracts using a Folin-Ciocalteu reagent (Cicco et al. 2009), and the absorbance was detected at 740 nm. A calibration curve was calculated using gallic acid as the standard.

The radical scavenging activity (RSA) was performed spectrophotometrically (516 nm wavelength, Hitachi U2900) using a 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical (Pekkarinen et al. 1999). The RSA of the methanol extracts, at 30 min for the eggplant and 15 min for the tomato, was expressed as the percentage of the DPPH neutralisation.

Statistical analysis. The data were analysed by a one-way analysis of variance (ANOVA) (Statistica, version 12) followed by Fisher's LSD post-hoc test. For the establishment of the significant differences between the mean values of the analysed parameters, homogenous groups were determined at a probability of $P < 0.05$.

RESULTS AND DISCUSSION

Successful vegetable production is determined by high-quality transplants: thick stems, a short internode length or well-developed leaves and roots. The biochemical parameters, the contents of photosynthetic pigments or sugars indicate the condition of the plants. A high level of phenolic compounds is usually correlated with the high ability to scavenge free radicals which are necessary to reduce the adverse effects of many stresses (Samuolienė et al. 2017).

In this study, the more intense growth of the eggplant stem under 80% red with 20% blue correlated with the reduction of the dry matter in the leaves, compared to the control group (Table 2). The tomato seedlings did not exhibit such dependence (Table 3). Most studies indicate an increase in the leaf biomass as a consequence of using a high proportion of red to blue light (Olle, Viršilė 2013; Bantis et al. 2018). In a closed cultivation system, 88% red+12% blue LED light increased the leaf dry matter and plant biomass of nine tomato genotypes (Ouzounis et al. 2015). In greenhouse cultivation, supplemental lighting with 80% red+20% blue or 95% red+5% blue LED light increased the growth (including the leaf expansion) of six cultivars of tomato seedlings (Gomez, Mitchell 2015). In the present experiment, the leaf surface of both tested species was improved when treated with the highest share of red light (90% red + 10% blue); higher by about 25% in the eggplant and 48% in the tomato compared to control group (Tables 2 and 3). The red radiation might stimulate the leaf expansion thorough the phytochrome-mediated pathway, altering the gene expression (Kong, Okajima 2016). Additionally, the increase in the egg-

Table 2. Growth parameters and the leaf dry matter concentration of the eggplant transplants

Treatment	Stem length (cm)	Stem diameter (mm)	Leaf number	Leaf area (cm^2)	Leaf dry matter (%)
Control	13.50^{a}	3.43^{a}	6.35	57.34^{a}	14.16^{b}
L1	14.50^{ab}	3.88^{b}	6.45	72.01^{c}	13.85^{ab}
L2	15.88^{b}	3.90^{b}	6.75	60.95^{ab}	11.74^{a}
L3	14.58^{ab}	3.63^{ab}	6.40	68.07^{bc}	13.45^{ab}
L4	13.30^{ab}	3.63^{ab}	6.65	67.75^{bc}	13.52^{bc}

Mean separations within the columns by Fisher's LSD test at $P < 0.05$, $n = 20$; the ratio of red to blue light with modifications: L1 (9 : 1), L2 (4 : 1), L3 (1 : 1 + Green) and L4 (2 : 1 + Green + UV); details in Material and Methods

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Table 3. Growth parameters and the leaf dry matter concentration of the tomato transplants

Treatment	Stem length (cm)	Stem diameter (mm)	Leaf number	Leaf area (cm^2)	Leaf dry matter (%)
Control	22.52	5.76	5.2	47.54^{a}	8.04^{b}
L1	23.08	5.47	5.0	70.56^{c}	7.45^{a}
L2	21.93	5.43	5.0	53.84^{ab}	8.06^{b}
L3	22.01	5.67	5.2	55.77^{ab}	8.98^{c}
L4	20.53	5.22	5.1	60.03^{b}	8.70^{c}

Mean separations within the columns by Fisher's LSD test at $P < 0.05$, $n = 20$; the ratio of red to blue light with modifications: L1 (9 : 1), L2 (4 : 1), L3 (1 : 1 + Green) and L4 (2 : 1 + Green + UV); details in Material and Methods

plant leaf area was also found under a green with a blue and red light in the spectrum (Table 2). This observation could be explained by the fact that green light has proven to be effective in the so-called shade avoidance symptoms. In *Arabidopsis* seedlings, Zhang et al. (2011) observed that the addition of the green to red and blue light spectrum increased the petiole length and total leaf length. Green light can inhibit a blue-light response (Wang, Folta 2013; Folta, Carvalho 2015). Hence, the effect of a higher blue light share that usually suppresses leaf expansion might be less effective in our experiment because of the addition of the green light.

Except for the red and blue light, which is the most photosynthetic active radiation, also the green one (490–550 nm) was found to be effectively used in the photosynthesis due to its absorption by the chlorophylls that was observed *in vivo* in the leaves (Terashima et al. 2009). Samuolienė et al. (2012) showed that the supplementation of high-pressure sodium (HPS) lamps` lighting with a green (505 nm) LED light resulted in an increased fresh and dry weight, leaf area or photosynthetic pigment concentration in the transplants of tomato, sweet pepper and cucumber. In this study, under lamps enriched in green diodes (L3, L4), the dry matter content significantly increased in the tomato leaves, compared to the other treatments (Table 3). Moreover, in comparison to the control tomato, a green light (15%) mixed with a red (43%) and blue (42%) light in the L3 spectrum, significantly enhanced the accumulation of the chlorophylls, carotenoids and soluble sugar content, which was not observed in the eggplant leaves (Tables 4 and 5). In cherry tomato seedlings (Xiaoying et al. 2012), the addition of green light to the red + blue spectrum significantly enhanced the soluble sugar accumulation in the leaves compared to white light, but not to the red + blue treatment. According to Kang et al. (2016), the addition of 10% green to red and blue light did not have a positive effect on the photosynthetic rate and the growth of lettuce. Various results presented in such studies are mostly related to the different plant species or cultivation and the difference in the light treatments (Viršilė et al. 2017).

The present study showed that the reaction of *S. melongena* with the addition of 3% UV-A (330 nm) in the L4 spectrum was stronger than that of S. *Lycopersicon* (Tables 4 and 5). The eggplant revealed the decrease of the assimilation pigment content with the simultaneous mobilisation of defensive mechanisms against free radicals; the content of the total phenols increased, and the radical scavenging activity was the highest in this treatment. Short

Table 4. Content of the soluble sugars (% in fresh weight), photosynthetic pigments (mg/g fresh weight), total phenols (mg/100 g fresh weight) and radical scavenging activity (RSA, %) in the leaves of the eggplant transplants

Treatment	Soluble sugar	Chlorophyll *a*	Chlorophyll *b*	Carotenoids	Total phenols	RSA
Control	0.69^{ab}	1.90^{b}	0.56	0.38^{b}	116.4^{a}	18.6^{a}
L1	0.71^{ab}	1.80^{b}	0.54	0.36^{b}	137.3^{b}	24.3^{b}
L2	0.67^{a}	1.87^{b}	0.55	0.37^{b}	113.3^{a}	17.4^{a}
L3	0.75^{b}	1.89^{b}	0.57	0.40^{b}	110.0^{a}	17.4^{a}
L4	0.73^{ab}	1.50^{a}	0.47	0.29^{a}	163.0^{c}	34.7^{c}

Mean separations within the columns by Fisher's LSD test at P < 0.05, n = 4; the ratio of red to blue light with modifications: L1 (9 : 1), L2 (4 : 1), L3 (1 : 1 + Green) and L4 (2 : 1 + Green + UV); details in Material and Methods; RSA – radical scavenging activity

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Table 5. Content of the soluble sugars (%), photosynthetic pigments (mg/ g fresh weight), total phenols (mg/100 g fresh weight) and radical scavenging activity (RSA, %) in the leaves of the tomato transplants

Treatment	Soluble sugars	Chlorophyll *a*	Chlorophyll *b*	Carotenoids	Total phenols	RSA
Control	0.24^{b}	1.63^{a}	0.49^{a}	0.30^{a}	37.2^{b}	2.83^{a}
L1	0.21^{a}	1.78^{ab}	0.54^{ab}	0.32^{ab}	33.1^{a}	3.75^{ab}
L2	0.21^{a}	1.87^{ab}	0.57^{ab}	0.33^{ab}	37.0^{b}	3.86^{ab}
L3	0.28^{c}	2.02^{b}	0.62^{b}	0.34^{b}	42.1^{c}	5.48^{c}
L4	0.25^{b}	1.74^{a}	0.53^{a}	0.29^{a}	42.2^{c}	5.13^{bc}

Mean separations within the columns by Fisher's LSD test at $P < 0.05$, $n = 4$; the ratio of red to blue light with modifications: L1 (9 : 1), L2 (4 : 1), L3 (1 : 1 + Green) and L4 (2 : 1 + Green + UV); details in Material and Methods

wavelength radiation in the range of ultraviolet light (280–400 nm, UV) may cause oxidative stress, but its effect depends on, among others, the plant species, the intensity of the UV radiation and the different light spectra accompanying the UV (Mosadegh et al. 2018). In research with tomatoes in a growth chamber (Khoshimkhujaev et al. 2014), a monochromatic UV-A with an intensity of 6.8 W/m^2 improved the growth and development of the seedlings compared to 3.4 W/m^2 (UV-A was added to the red light). In our study, the specific effects of the UV-A on growth or biochemical parameters of the tomato seedlings was not observed (Table 5). The total phenol content and radical scavenging activity in the L3 and L4 treatments were similar. Kim et al. (2014) showed that a monochromatic blue light stimulates the biosynthesis of the total phenolics and antioxidant capacity of cherry tomato seedlings. The green light demonstrated about a two-fold lower effect on these parameters. The effects of blue and green radiation in various light combinations on the antioxidant activity of many plant species have been widely reported in the review of Samuolienė et al. (2017).

Summarising, greenhouse supplemental LED lighting could be effectively used for tomato and eggplant transplant production in the spring. However, this effect is related to the appropriate spectrum. The study also showed that the additional irradiation was acceptable from an economic point of view. The total lighting cost calculated for 100 transplants was around 2.5 and 1.6 EUR in the case of eggplant and tomato, respectively. The base of the calculation was presented in the Material and Methods section (see Table 1 with footnote). Further studies concerning the impact of supplemental lighting applied at the juvenile stage of the eggplant and tomato on the quantity and quality of the yield of the mature plant are needed.

CONCLUSION

A combination of red and blue light in a ratio of 9:1, used as supplemental radiation for increasing the day's length, allowed one to improve the eggplant 'Milar F_1' transplants' quality. In the case of the tomato 'Benito F_1', high-quality transplants were obtained under a broader spectrum enriched in green light. The presence of green light resulted in the highest accumulation of total phenols and radical scavenging activity in the tomato leaves. In the eggplant leaves, such results were obtained under a spectrum enriched in a green light mixed with a UV light (however, in this light treatment, a decrease in chlorophyll a and carotenoids was recorded). Green light in combination with a red and blue light in the LED lamps' spectrum significantly increased the soluble sugar content in the tomato leaves. The presented results indicate, for the first time, that the quality of eggplant and tomato transplants in spring greenhouse cultivation (usually not additional illuminated) can be improved by inexpensive supplemental LED irradiation, used for increasing the daylength, with an adequately selected spectrum.

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