Effect of short-term exposure to red and blue light on dill plants growth

B. Frąszczak

Department of Vegetable Crops, Faculty of Horticulture and Landscape Architecture, Poznań University of Life Sciences, Poznań, Poland

Frąszczak B., 2013. **Effect of short-term exposure to red and blue light on dill plants growth**. Hort. Sci. (Prague), *40*: 177–185.

Effect of the end-of-day and the end-of-night red and blue light in dill growth was investigated. Ambrozja dill (*Anethum graveolens* L.) cvs were grown in vegetation chambers in completely controlled conditions exposed to white diode light. Red and blue light was employed for 30 min before the initiation or after the end of the lighting period. The values of plant fresh mass, area and height parameters were the highest for plants treated with red light at the end of night. The application of red light at the end of day exerted a similar effect on plants as the exposure of plants to blue light at the end of night. Plants treated with blue light at the end of the lighting period were characterised by the poorest growth rate. Plants additionally lighted with blue light were found to have both distinctly smaller mass as well as area in comparison with plants exposed to red light. Both methods are useful to control the plants growth depending on the phase of plant development and growers' requirements.

Keywords: *Anethum graveolens* L.; EOD; EON; LEDs; photomorphogenesis

Light plays a key role in plant life, determining their photomorphogenesis and photosynthesis rates (Avercheva et al. 2009). Light spectral composition reaching plants affects their growth and development via the participation of plant photoreceptor cells (Folta et al. 2005). Cryptochromes and phototropins are specifically blue light-sensitive, whereas phytochromes are more sensitive to red than to blue light (Rajapakse, Shahak 2007).

Red light is important for the development of the photosynthetic apparatus of plants and may increase starch accumulation in several plant species by inhibiting the translocation of photosynthates out of leaves (Paradiso et al. 2011). In contrast, blue light is important in the formation of chlorophyll, chloroplast development, stomatal opening, enzyme synthesis, activation of the circadian rhythm of photosynthesis, and photomorphogenesis (Christie 2007; Kang et al. 2008; Demarsy, Frankhauser 2009; Goh 2009). Physiological responses to spectral changes can vary among different plant species (Hirai et al. 2006).

The grow lights available for supplemental lighting for closed system are fluorescent lamps (Wheeler 2008). These lamps vary in spectral quality (Bourget 2008), which can result in differences in plant growth, development or phytochemical response. A controlled light quality with an appropriate ratio of blue, red or far-red light quality provided as supplemental light may improve phytochemical content and biomass of plants grown under white light (Li, Kubota 2009).

End of day (EOD) light quality treatment was studied as an effective method to control stem and hypocotyl elongation (Bloom 1995; Hatt Grahamm, Decoteau 1997; Haidar, Orr 1999; Chia, Kubota 2010). Due to the low light intensity requirement and recently increasing availability of lighting emitting diodes (LED), EOD light quality treatment may be an economically feasible, non-

chemical means to control plant morphology in which EOD-red (R, 600–700 nm wavelength) and far-red (FR, 700–800 nm) light treatments can reduce and enhance the stem/hypocotyl elongation rate, respectively (Yang et al. 2012).

The solid-state lighting technology using LEDs with particular spectral components (Morrow 2008) makes it possible to satisfy the requirements needed for healthy plant growth.

With the development of the LED, the potential to actively implement dynamic lighting strategies to control plant growth and development and nutritional quality holds great promise in the future. LED is an ideal tool to study light quality requirements of every horticultural crop. Their small size, durability, long operating lifetime, wavelength specificity, relatively cool emitting surfaces, and linear photon output with electrical input current make these solid-state light sources ideal for use in plant lighting designs (Massa et al. 2008; Liu 2012).

The objective of this research project was to investigate the impact of short-term exposure of plants to blue and red light on growth and morphology of dill plants.

MATERIAL AND METHODS

Pot experiments were carried out in 2011 in the Marcelin experimental station of the Poznań University of Life Sciences, Poland.

Plant material and growth conditions. Dill (*Anethum graveolens* L.) cv. Ambrozja was grown in growing rooms only under artificial white light. The red, blue and white light source was high-power solid-state lighting module (LED, type SMD; Seoul Semiconductor, Ansan, South Korea). The spectra of the light sources used are presented in Fig. 1 and Table 1. Photosynthetic photon flux density (PPFD), from the top of plants, amounted to about 166 μmol/m^2·s (±14 SD) for white light and 60 μmol/m^2·s (±8 SD) for blue and red light. PPFD was measured using a quantum sensor (PAR-10; Sanopan, Białystok, Poland). Spectral distribution of light treatments was measured with a spectroradiometer BLACK-Comet CXR, 280–900 nm (UV-VIS by StellarNet Inc., Tampa, USA). Measurements were made 15 cm under the lamps, more or less at the height of the tops of the plants. The phytochrome photostationary state (Φ) was calculated based on the method developed by Sager et al. (1988). A 16-h photoperiod and the day/night temperature of 23/18°C were maintained. The relative air humidity was 65–70%.

Dill was seeded in a white peat bedding substrate (Klassmann-Deilman, Geeste, Germany). The number of plants grown in a single pot was identical and amounted to 40 (±5 plants). They were grown in pots of 280 cm^3 and 49 cm^2 cultivation area. Plants were watered on capillary mats every other day.

Treatment of light. In one of the growing rooms plants were exposed to no supplemental light (control) during the dark period. In other two growing rooms, plants were exposed for a brief period of time, that is 30 min, to supplemental light during the dark period. Plants were treated with blue or red light during the following two different times: at the end of the dark period – end of night (EON) or after the light period – end of day (EOD).

Plant measurements and experimental design. The plants were evaluated every 7 days during the vegetation period, the first time – seven days after emergence and later on the 14th, 21st and 28th day after germination. Harvesting involved hand-cutting of plants close to the surface of the substrate. After harvest, the weight of the fresh matter of plants from a given pot was determined. In addition, measurements of plant height, hypocotyl length and leaf area were taken (10 plants in every pot). A scanner (Mustek 1200 UB; Mustek System Inc., Hsinchu, Taiwan) and the Skwer program (IksmodaR, Poznań, Poland) were used to calculate the surface of leaves. Dry mass was determined by drying the material to constant weight at 105°C for 24 h (PN-90/A-75101/03 1990).

Table 1. Characteristics of white light source

Light colour	Wavelength (nm)	PFD (μmol/m^2·s)	PDF share (%)
UV	320–380	0.5	0.3
Violet	380–450	15.4	15.5
Blue	450–495	30.3	16.3
Green	495–570	53.5	28.7
Yellow	570–590	18.7	10.1
Orange	590–620	21.8	11.8
Red	620–700	26.4	14.2
Far Red	700–780	5.6	3.1
Sum	320–780	172.2	100
R:FR	–	4.6	–

PFD – photon flux density

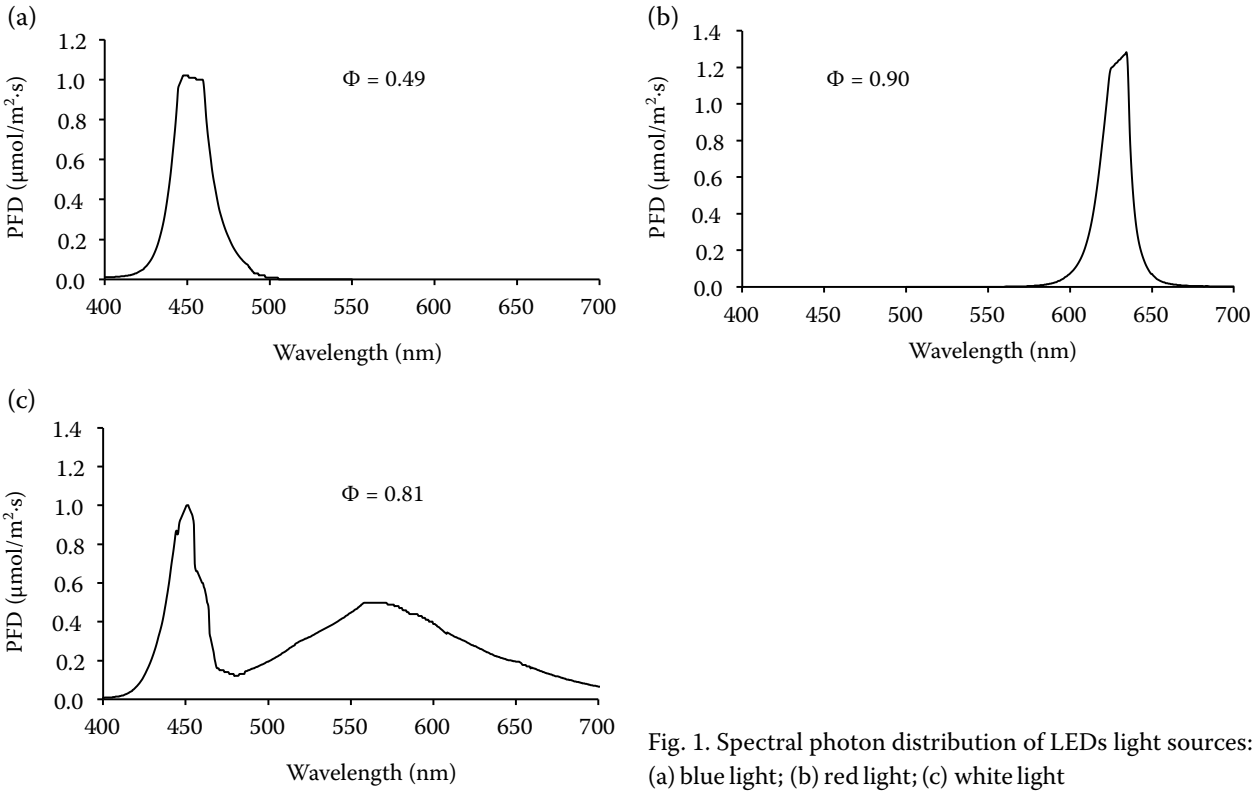

Fig. 1. Spectral photon distribution of LEDs light sources: (a) blue light; (b) red light; (c) white light

The research was conducted as a two-factorial experiment in six repetitions as an independent design. Three pots were treated as one repetition. The investigations were conducted in two series (replications, after each other). The presented results are means of two replications. The significance of the impact of the light source on plant height, hypocotyl length, yields and leaf area as well as physiological indices was determined employing the ANOVA. Differences between means were estimated using the Newman-Keuls test at the level of significance $\alpha = 0.05$. All statistical analyses were carried out applying the Statistica program (StatSoft Polska, Kraków, Poland).

Physiological indices. Dry mass and leaf area data were used to determine the following physiological indices of growth: relative growth rate, leaf area index, net assimilation rate and specific leaf area. Values of indices refer to individual pots and were calculated as described by Hunt (1982).

The index of the relative growth rate (RGR) was calculated on the basis of the following formula:

$$RGR = (\ln W_2 - \ln W_1)(t_2 - t_1)$$

where:
W_2, W_1 – plant dry mass (g)
t_2, t_1 – time of days (day)

The leaf area index (LAI) refers to the area of the leaf surface in relation to the floor area taken up by all plants. It was calculated on the basis of the following formula:

$$LAI = A/P$$

where:
A – plant assimilation area (dm^2)
P – floor area (dm^2)

The net assimilation rate (NAR) is the increment of biomass per unit of time and per unit of any measure of magnitude of the assimilation organs:

$$NAR = dW/(A \times dt)$$

where:
A – area of assimilation organs (dm^2)
W – dry mass (g)
t – time of cultivation (day)

Specific leaf area (SLA) is defined as the ratio of leaf area to the dry mass of leaves:

$$SLA = L_A/L_W$$

where:
L_A – leaf area (dm^2)
L_W – dry mass of leaves (g)

RESULTS

When we look at the results concerning the cooperation of supplemental lighting and the time of its application, it is quite evident that the values of plant fresh mass, area and height were the highest for plants exposed to red light at the end of night (EON-R; Table 2). The exposure of plants to red light at the end of day (EOD-R) exerted a similar influence on them, as the application of blue light at the end of night (EON-B). Experimental plants exhibited the smallest growth rate, when they were treated with blue light at the end of the day (EOD-B). After four weeks of cultivation plants exposed to red light on both times of its application were characterised by higher quantities of fresh mass in comparison with the control and blue light. The highest length of plants was observed for EON-R, while the highest mass – for EON-R and EOD-R. Plant supplementation with blue light on both times of their exposure produced 28-days-old plants characterised by considerably smaller areas as well as mass in comparison with the control and red light. One of the parameters important for seasoning plants cultivated in containers is the length of their hypocotyl. It is quite evident from the results of our experiments that the use of red light at the end of the night inhibited significantly the growth of hy-

Table 2. Effects of supplemental lighting on dill morphological parameters

Treatment	Hypocotyl length (cm)	Height (cm)	Fresh mass (g/pot)	Plants area (dm^2/pot)
7th day				
EOD-R	3.86^{b}	6.74^{b*}	1.02^{b}	0.14^{a}
EON-R	3.53^{c}	7.54^{a*}	1.43^{a*}	0.15^{a}
EOD-B	4.57^{a*}	6.18^{c}	0.86^{c}	0.10^{b*}
EON-B	4.05^{b*}	6.81^{b*}	1.09^{b*}	0.11^{b*}
Control	3.73	6.26	0.93	0.16
14th day				
EOD-R	4.06^{b*}	10.03^{b*}	2.76^{b}	0.29^{b}
EON-R	3.83^{c}	10.69^{a*}	3.54^{a*}	0.42^{a*}
EOD-B	4.65^{a*}	9.35^{c*}	2.17^{c*}	0.18^{c*}
EON-B	4.14^{b*}	9.98^{b*}	2.66^{b}	0.31^{b}
Control	3.81	11.22	2.52	0.28
21st day				
EOD-R	3.93^{c}	11.07^{b*}	4.43^{b*}	0.61^{b}
EON-R	4.10^{c}	12.25^{a}	4.80^{a*}	0.71^{a*}
EOD-B	4.77^{a*}	11.05^{b*}	3.35^{c}	0.55^{c}
EON-B	4.42^{b*}	11.16^{b*}	4.40^{b*}	0.64^{b}
Control	3.90	11.58	3.80	0.59
28th day				
EOD-R	4.57^{b}	13.18^{b}	10.75^{a*}	1.27^{b}
EON-R	4.22^{c}	13.75^{a*}	11.05^{a*}	1.46^{a}
EOD-B	5.73^{a}	12.05^{c}	4.44^{c*}	0.63^{c*}
EON-B	4.86^{b*}	12.83^{b}	5.84^{b*}	0.72^{c*}
Control	4.43	12.30	10.00	1.37

values followed by the same letters for individual dates do not differ significantly at $\alpha = 0.05$; *values differ significantly from the control at $\alpha = 0.05$; EOD – end of day; EON – end of night; R – red light; B – blue light

Table 3. Impact of individual light colours and time of their application on morphological features of dill plants

Examined feature	Light colour			Time of treatment	
	red	blue	white	EOD	EON
7th day					
Hypocotyl (cm)	3.70[b]	4.31[a]	3.73[b]	4.21[a]	3.79[b]
Height (cm)	7.14[a]	6.49[b]	6.26[b]	6.46[b]	7.17[a]
Fresh mass (g/pot)	1.23[a]	0.98[b]	0.93[b]	0.94[b]	1.26[a]
Area (dm^2/pot)	0.15[a]	0.10[b]	0.16[a]	0.12[a]	0.13[a]
14th day					
Hypocotyl (cm)	3.94[b]	4.40[a]	3.81[c]	4.35[a]	3.98[b]
Height (cm)	10.33[b]	9.66[b]	11.22[a]	9.69[b]	10.33[a]
Fresh mass (g/pot)	3.15[a]	2.42[b]	2.52[b]	2.46[b]	3.10[a]
Area (dm^2/pot)	0.60[a]	0.25[b]	0.28[b]	0.24[b]	0.37[a]
21st day					
Hypocotyl (cm)	4.02[b]	4.60[a]	3.90[b]	4.35[a]	4.26[a]
Height (cm)	11.66[a]	11.11[a]	11.58[a]	11.06[b]	11.70[a]
Fresh mass (g/pot)	4.62[a]	3.87[b]	3.80[b]	3.89[b]	4.60[a]
Area (dm^2/pot)	0.66[a]	0.60[b]	0.60[b]	0.58[b]	0.68[a]
28th day					
Hypocotyl (cm)	4.39[b]	5.30[a]	4.43[b]	5.15[a]	4.51[b]
Height (cm)	13.46[a]	12.44[b]	12.30[b]	12.62[b]	13.29[a]
Fresh mass (g/pot)	10.90[a]	5.14[c]	10.00[b]	7.60[b]	8.45[a]
Area (dm^2/pot)	1.36[a]	0.68[b]	1.40[a]	0.95[b]	1.10[a]

values followed by the same letters do not differ significantly at $\alpha = 0.05$; EOD – end of day; EON – end of night

pocotyls, although the recorded differences were not significant in relation to the control. On the other hand, exposure to blue light at the end of day caused elongation of the hypocotyl in comparison with the other combinations.

When we compare the effect of individual light colours (Table 3) on the experimental parameters, it is quite evident that red light exerted a more stimulatory influence on plant growth, while blue light had an inhibitory impact on plant growth (but without elongation of hypocotyl). It is worth emphasising that despite greater growth rate, plants exposed to red light were characterised by significantly shorter hypocotyls in comparison with plants cultivated with supplementation of blue light. Particularly strong differences between red and white light and blue light were observed for 28-days-old plants with respect to the area and fresh mass of plants. Plants supplemented with blue light were characterised both by considerably smaller mass as well as area. Results collated in Table 3 show that the exposure time at the EON was more favourable for plants. Plants exposed to supplemental lighting at this time were characterised by greater height, fresh mass and area and smaller hypocotyls (without 21st day of measurement) in comparison with plants exposed to supplemental lighting at EOD.

Relative growth rate values varied throughout the entire period of cultivation (Fig. 2). After the second week of growth the value of this index was found highest in plants growing exposed to white light supplemented with red light at the end of night. At day 21 of cultivation, RGR was highest also in plants supplemented with red light but at the end of day. At the end of the cultivation period treatment EOD-B was characterised by a high value of this index. Similar results were observed for net assimilation rate.

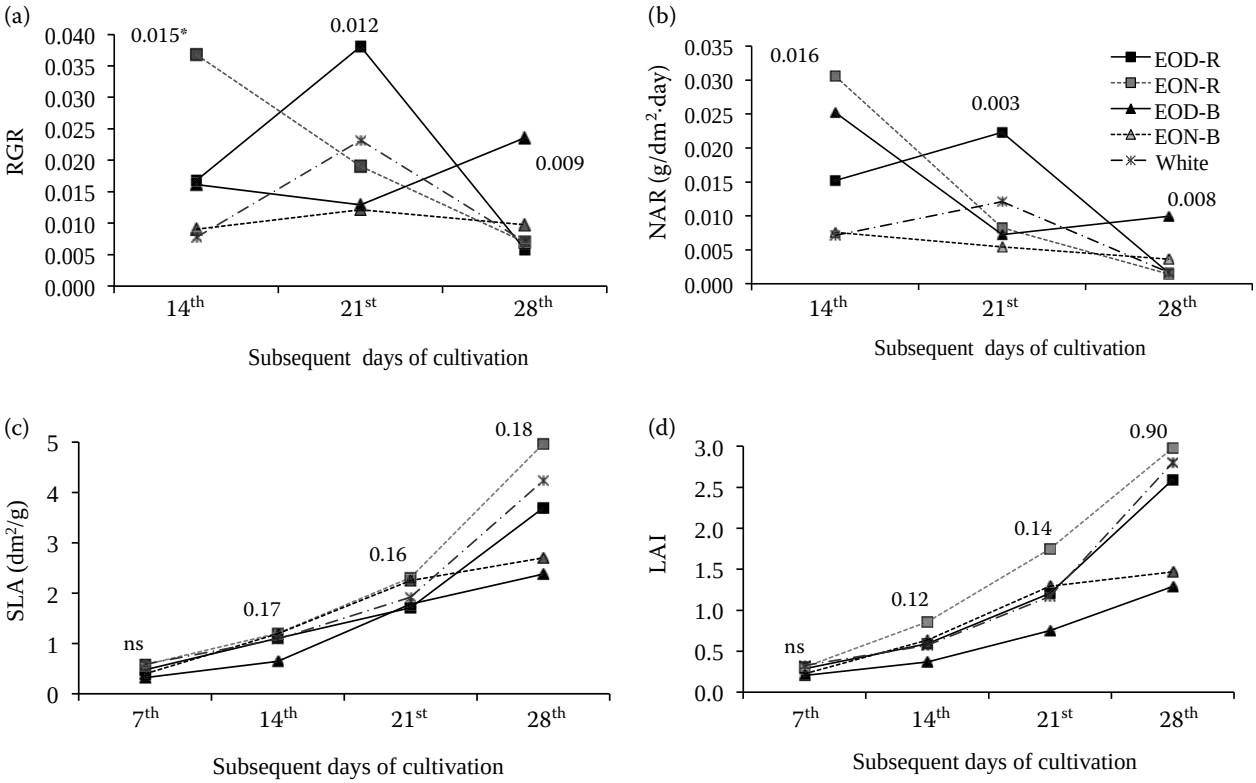

Fig. 2. Effect of different light treatment of (a) RGR – relative growth rate index; (b) NAR – net assimilation rate; (c) SLA – specific leaf area; (d) LAI – leaf area index
EOD – end of day; EON – end of night; R – red light, B – blue light; *LSD – least significant differences; ns – not significant at $P < 0.05$

During the initial period of plant growth no significant differences between individual experimental combinations were recorded in the value of specific leaf area and the leaf area index. However towards the end of growth plants growing exposed to only white light white and light supplemented with red light were characterised by considerably higher value of these index in comparison with the combinations where plants were supplemented with blue light. Similar results were observed for net assimilation rate.

DISCUSSION

The obtained research results indicate that red light as well as supplemental lighting at the end of night stimulated plant growth, whereas additional light at the end of day inhibited it. That is why plants exposed to red light during EOD were significantly smaller in comparison with the plants treated with red light before the end of night. A similar plant response was observed for blue light. This can be explained by the fact that elongation is not constant during a 24 h cycle and that elongation rate in many plant species is higher during the dark period than the light period (Myster 1999). On the basis of the performed experiments, it is possible to assume that treatment of plants at the end of day exerted a stronger influence on the inhibition of their growth than additional lighting at the end of night. Xiong et al. (2002), in their experiments on cucumbers also observed a significant inhibition of their growth when light was applied at the EOD. It is also worth stressing that similar results were obtained for red light applied at the end of day as well as for blue light used at the end of night. According to Sung and Takano (1997), stomatal conductance and photosynthetic rate of cucumber seedlings grown under natural light with high irradiance were increased by the exposure to blue-enriched light in morning twilight. From this study, an increase in photosynthetic rate due to further opening of stomata is probably one of the major reasons why a brief exposure to blue light at the end of the dark period causes the acceleration of growth.

It is known that blue light inhibits extension growth, including stem elongation and leaf area (Appelgren 2003; Folta et al. 2003; Dougher, Bugbee 2004). Runkle and Heins (2001) reported that environments deficient in blue light promoted internode elongation in several long-day plants compared to unfiltered sunlight with a similar daily light integral. Laskowski and Briggs (1988) grew pea seedlings under red light and characterized the effects of a 30-s pulse of blue light (80 μmol/m^2·s) on epicotyl elongation. Elongation was rapidly inhibited by blue light and recovery began about 30 min after the irradiation with blue light. An inhibitory effect on elongation occurred not only during the irradiation with blue light, but also during a period of time following the blue light exposure. These results are consistent with the results reported with chrysanthemum (Shimizu et al. 2006). In our own experiments, blue light exerted a stronger impact on the inhibition of plant leaf area than on their height. This agrees with Britz and Sager (1990), who found that leaf area was lower in soybean plants grown under daylight fluorescent lamps, which are rich in blue light compared to low-pressure sodium lamps, which have low but measurable amounts of blue light. The threshold response for induction of phytochrome response is subject to some controversy, but a general guide is that $\Phi > 0.6$ is active (Stutte 2009). Light blue was characterized by a low value of the phytochrome photostationary state ($\Phi = 0.49$). This could cause low effect of blue light on hypocotyl elongation. Additionally, plant supplementation with blue light at such a low level of active phytochrome could have a negative impact on the mass and plants area.

On the other hand, a brief exposure to red light causes inhibition of stem extension (Kasperbauer 1971). Under natural radiation environment, R:FR of daylight decreases at the end of daily light period and plants probably perceive the diurnal changes in R:FR as the end of day through decreases in phytochrome photoequilibrium (P_{fr}/P), the fraction of total phytochrome in the active state (Smith 1982). Therefore, a brief end-of-day exposure to red light (with 90% of active phytochrome in own study) can cause increases in P_{fr} present at the beginning of the dark period and, consequently, inhibition of stem extension and dry matter partitioning to root are thought to increase (Kasperbauer et al. 1984). On the basis of the described experiments, it can be presumed that this could have been the main cause of the observed smaller height of plants treated with red light after the end of day in comparison with the plants exposed to this light at the end of night. Similar correlations were reported by Hanyu and Shoji (2002) in spinach cultivation.

Such parameter as SLA, which depends on the growth environment, can describe morphological adaptation to this environment and NAR physiological adaptation (De Groot et al. 2001). In the performed studies, the control exhibited a high value of this indicator which appears to suggest that white light exerted the least influence on plant morphological changes. Also in experiments conducted by Brazaitytė et al. (2010), SLA for tomato seedlings exhibited the highest values for plants exposed to sodium-vapour lamps when compared with plants cultivated under diode lamps of red and blue colour. In Hanyu and Shoji (2002) experiments, the value of SLA as well as of other parameters depended on the application timing of the specific light colour. Higher SLA values and height of spinach plants were recorded for EON-B and EOD-R. In our own experiments, in the final stage of plant growth, the smallest NAR value was observed for blue light suggesting that this colour exerted the strongest influence on plant physiological processes. This may further be corroborated by low RGR and LAI values obtained for blue light during the terminal phase of the experimental cultivation.

CONCLUSIONS

Supplemental treatment of plants at the end of day exerted a significantly stronger effect on the inhibition of their growth than additional lighting at the end of night. Also, blue light was found to inhibit plant growth, especially leaf area, more strongly than red light. That is why the greatest length was obtained for EON-R and the smallest – for EOD-B. EOD-R and EON-B treatments produced similar results with respect to the morphological parameters of experimental plants.

References

Appelgren M., 2003. Effects of light quality on stem elongation of *Pelargonium in vitro*. Scientia Horticulturae, *45*: 345–351.

Avercheva O.V., Berkovich Y.A., Erokhin A.N., Zhigalova T.V., Pogosyan S.I., Smolyanina S.O., 2009. Growth and photosynthesis of Chinese cabbage plants

grown under light-emitting diode-based light source. Russian Journal of Plant Physiology, *56*: 14–21.

Bloom T.J., Tsujita M.J., Robert G.I., 1995. Far-red at end of day and reduced irradiance affect plant height of easter and asiatic hybrid lilies. HortScience, *30*: 1009–1012.

Bourget C.M., 2008. An introduction to light-emitting diodes. HortScience, *43*: 1944–1946.

Brazaitytė A., Duchovskis P., Urbonavičiūtė A., Samuolienė G., Jankauskienė J., Sakalauskaitė J., Šabajevienė G., Sirtautas R., Novičkovas A., 2010. The effect of light-emitting diodes lighting on the growth of tomato transplants. Zemdirbyste – Agriculture, *97*: 89–98.

Britz S.J., Sager J.C., 1990. Photomorphogenesis and photoassimilation in soybean and sorghum grown under broad spectrum or blue-deficient light sources. Plant Physiology, *94*: 448–454.

Chia P.L., Kubota C., 2010. End-of-day far-red light quality and dose requirements for tomato rootstock hypocotyl elongation. HortScience, *45*: 1501–1506.

Christie J.M., 2007. Phototropin blue-light receptors. Annual Review of Plant Biology, *58*: 21–45.

De Groot C.C., Marcelis L.F.M., Van den Boogaard R., Lambers H., 2001. Growth and dry-mass partitioning in tomato as affected by phosphorus nutrition and light. Plant Cell & Environment, *24*: 1309–1317.

Demarsy E., Frankhauser C., 2009. Higher plants use LOV to perceive blue light. Current Opinion in Plant Biology, *12*: 69–74.

Dougher T.A.O., Bugbee B., 2004. Long-term blue light effects on the histology of lettuce and soybean leaves and stems. Journal of the American Society for Horticultural Science, *129*: 467–472.

Folta K.M., Lieg E.J., Durham T., Spalding E.P., 2003. Primary inhibition of hypocotyl growth and phototropism depend differently on phototropin-mediated increases in cytoplasmic calcium induced by blue light. Plant Physiology, *133*: 1464–1470.

Folta K.M., Lawrence L.K., MacMorrow R., Hyeon-Hye K., Kenitz J.D., Wheeler R., Sager J.C., 2005. Design and fabrication of adjustable red-green-blue LED light arrays for plant research. Plant Biology, *5*: 17.

Goh C.H., 2009. Phototropins and chloroplast activity in plant blue light signaling. Plant Signaling and Behavior, *4*: 693–695.

Haidar M.A., Orr G.L., 1999. The response of *Cuscuta planiflora* seedlings to red and far-red, blue light and end-of-day irradiations. Annals of Applied Biology, *134*: 117–120.

Hanyu H., Shoji K., 2002. Acceleration of growth in spinach by short-term exposure to red and blue light at the beginning and at the end of the daily dark period. Acta Horticulturae (ISHS), 580: 145–150.

Hatt Graham H.A., Decoteau D.R., 1997. Young watermelon plant growth responses to end-of-day red and far-red light are affected by direction of exposure and plant part exposed. Scientia Horticulturae, *69*: 41–49.

Hirai T., Amaki W., Watanabe H., 2006. Action of blue or red monochromatic light on stem intermodal growth depends on plant species. Acta Horticulturae (ISHS), 711: 345–349.

Hunt R., 1982. Plant Growth Curves, the Functional Approach to Plant Growth Analysis. London, Edward Arnold: 248.

Kang B., Grancher N., Koyffman V., Lardemer D., Burney S., Ahmad M., 2008. Multiple interactions between cryptochrome and phototropin blue-light signaling pathways in *Arabidopsis thaliana*. Planta, *227*: 1091–1099.

Kasperbauer M.J., 1971. Spectral distribution of light in tabaco canopy and effects of end-of-day light quality on growth and development. Plant Physiology, *47*: 775–778.

Kasperbauer M.J., Hunt P.G., Shojika R.E., 1984. Photosynthate partitioning and nodule formation in soybean plants that received red or far-red light at the end of the photosynthetic period. Plant Physiology, *61*: 549–554.

Laskowski M.J., Briggs W.R., 1988. Regulation of pea epicotyl elongation by blue light. Plant Physiology, *89*: 293–298.

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

Liu W., 2012. Light environmental management for artificial protected horticulture. Agrotechnology, *1*: 101.

Massa G.D., Kim H.H., Wheeler R.M., Mitchell C.A., 2008. Plant productivity in response to LED lighting. HortScience, *43*: 1951–1956.

Morrow R.C., 2008. LED lighting in horticulture. HortScience, *43*: 1947–1950.

Myster J., 1999. The effects of temperature alternations, irradiance level, photoperiod, and day extension light quality on morphogenesis, growth, and flowering of *Begonia* × *hiemalis* Fotsch. Gartenbauwissenschaft, *64*: 206–213.

Paradiso R., Meinen E., Snel J.F.H., Marcelis L.F.M., van Ieperen W., Hogewoning S.W., 2011. Light use efficiency at different wavelengths in rose plant. Acta Horticulturae (ISHS), 893: 849–855.

PN-90/A-75101/03, 1990. Przetwory owocowe i warzywne. Przygotowanie próbek i metody badań fizykochemicznych. Oznaczanie zawartości suchej masy metodą wagową. [Fruit products and vegetable. The preparation of samples and method of physicochemist investigations. Marking the content of dry mass with weight method.] Warsaw, PKN.

Rajapakse N.C., Shahak Y., 2007. Light-quality manipulation by horticulture industry. In: Whitelam G.C., Halliday K. J. (eds), Light and Plant Development. Oxford, Blackwell Publishing: 290–312.

Runkle E.S., Heins R.D., 2001. Specific functions of red, far red, and blue light in flowering and stem extension of long-day plants. Journal of the American Society for Horticultural Science, *126*: 275–282.

Sager J.C., Smith W.O., Edwards J.L., Cyr K.L., 1988. Photosynthetic efficiency and phytochrome photoequilibria determination using special data. American Society of Agricultural Engineers, *31*: 1882–1889.

Shimizu H., Ma Z., Tazawa S., Douzono M., Runkle E.S., Heins R.D., 2006. Blue light inhibits stem elongation of chrysanthemum. Acta Horticulturae (ISHS), 711: 363–367.

Smith H., 1982. Light quality, photoperception and plant strategy. Annual Review of Plant Physiology, *33*: 481–518.

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

Sung I.K., Takano T., 1997. Effects of supplemental blue- and red-lights in the morning twilight on the growth and physiological responses of cucumber seedlings. Environmental Control in Biology, *35*: 261–265.

Wheeler R.M., 2008. A historical background of plant lighting: An introduction to the workshop. HortScience, *43*: 1942–1943.

Xiong J., Patil G.G., Moe R., 2002. Effect of DIF and end-of-day light quality on stem elongation in *Cucumis sativus*. Scientia Horticulturae, *91*: 219–229.

Yang Z.C., Kubota C., Chia P.L., Kacira M., 2012. Effect of end-of-day far-red light from a movable LED fixture on squash rootstock hypocotyl elongation. Scientia Horticulturae, *136*: 81–86.

Received for publication July 11, 2013
Accepted after corrections October 3, 2013

Corresponding author:

Dr. Eng. Barbara Frąszczak, Poznań University of Life Sciences, Faculty of Horticulture and Landscape Architecture, Department of Vegetable Crops, ul. Dąbrowskiego 159, 60 594 Poznań, Poland
phone: + 48 618 466 320, fax: + 48 61 848 7966, e-mail: barbaraf@up.poznan.pl