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THE EFFECTS OF LIGHT QUALITY ON PHOTOSYNTHETIC PARAMETERS AND YIELD OF LETTUCE PLANTS

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Abstract. The influence of light emitted by light-emitting diodes (LEDs) of different spectral composition towards white fluorescent light FL (W) on the photosynthetic activity of leaves and yield of lettuce was evaluated in pot experiments conducted in controlled conditions at PPFD of 200 µmol m^{-2} s^{-1}. The LEDs emitting white (12W), red (12R) and red-blue (R/B) radiation from lamps of different ratio of red diodes (R) towards the blue ones (B) (9R+3B; 10R+2B; 11R+1B) was used. The results showed that the lowest yield was found in plants grown under LED (12W), and the highest one under FL (W) light. The mass and leaf area of plants illuminated by FL (W) and LED (12R) were similar. The increase of radiation R and decrease of B caused an increase in biomass, leaf area (LA), and specific leaf area (SLA) decrease of chlorophyll concentrations in leaves. Leaves of plants cultivated under LED (R/B) had the higher stomatal conductance, photosynthesis and transpiration parameters than under other treatments. The lowest value of chlorophyll fluorescence parameters (*Fo*, *Fm*, *Fv*/*Fm*) were noted under the LED (12R) lighting. However, taking into account the energy consumption by the using light sources, the plant yielding, and other determined parameters, the most beneficial for lettuce production seems to be LED (11R + 1B) light. Taking into account the energy consumption of light sources, the plant yielding, and other determined in the study parameters, LED (11R + 1B) light appears the most beneficial for lettuce production.

Key words: LEDs, fluorescent lighting, photosynthetic pigments, gas exchange, chlorophyll fluorescence

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INTRODUCTION

Light emitting diodes (LEDs) have a huge potential as a supplemental or main source of light for plants. Their small size, durability, longevity, capability of spectral composition control, high level of radiation at low thermal radiation, small energy consumption and low costs of installation are big advantages towards traditional lighting sources [Massa et al. 2008]. However, the LEDs emit a narrow spectrum of light, so that there is an urgent necessity to adapt spectral composition for specific plant species. Hanyu and Shoji [2000] state that it is possible to control light quantity and quality.

It is commonly known that plant pigments absorb red and blue light the most effectively. The most experiments conducted up to date have studied the influence of these two light wavelengths on plants. Such research was done on lettuce by: Yangi et al. [1996], Okamoto et al. [1997], Yorio et al. [2001], Johkan et al. [2010], Lin et al. [2013], Borowski et al. [2014], as well as on other plant species, such as: *Lilium* [Lian et al. 2002], *Chrysanthemum* sp. [Kim et al. 2004a], *Withania somnifera* [Lee et al. 2007], *Doritaenopsis* [Shin et al. 2008], *Brassica rapa* subsp. *chinensis* [Li et al. 2012], *Valerianella locusta* [Wojciechowska et al. 2013]. The red LED light, as manifested during a research conducted on lettuce and spinach [Barta et al. 1992, Matsuda et al. 2008, Johkan et al. 2010], stimulated elongation of leave petioles and blades, but at the same time caused that they were thin and characterized with lower contents of chlorophyll and carotenoids.

In the light of previous studies, the blue light affects plants in a different way. Blue LEDs inhibited the number of lettuce leaves, stem and leaf length but increased carotenoids content in comparison to other wavelengths [Yangi et al. 1996, Li and Kubota 2009], and applied for only 30 minutes in order to extend the day, decreased weight and area of a dill leaves [Frąszczak 2013]. Ohashi-Kaneko et al. [2007] stated that blue fluorescent lamps (BF) were completely useless in cultivation of spinach as they extremely decreased the dry weight of leaves, simultaneously increasing the contents of carotenoids.

The authors of all the articles mentioned above that relate to lettuce and other species of plants, unanimously emphasize an advantageous effect of red-blue LED lighting. However, the question of what should be the ratio between the red and blue lights in cultivation of lettuce and other plants of similar form is still to be answered. Bula et al. [1991] report, that 10% share of a blue fluorescent light is necessary for lettuce cultivated under a red LED lighting. On the other hand, Yorio et al. [2001] in similar studies conducted on lettuce, radish and spinach noted, that even 10% of blue fluorescent light was insufficient for optimal growth of these species. Hogewoning et al. [2010] in studies on cucumber plants growing under the LED lamps noted that 7% share of a blue light prevented dysfunction of photosynthesis, and intensity of photosynthesis increased to the 50/50% ratio. Nhut et al. [2003] in similar studies concerning growth of strawberry young plants in '*in vitro*' cultures found that the most favourable ratio of a red/blue LED lighting was 70/30%.

In the research that had been conducted on lettuce the red LED lighting was supplemented with the blue fluorescent light [Bula et al. 1991, Yorio et al. 2001]. Fluorescent lamps characterize with wider spectrum than LEDs. That is why it is difficult to prove if the proportion between the blue and red lights proposed by the authors is optimal for lettuce. Some authors studied effect of the ratio between red and blue LED light on growth of lettuce but the experiments were carry out in early stage of lettuce and gave different results [Yangi et al. 1996, Okamoto et al. 1997, Johkan et al. 2010]. Therefore, in this study we compared the yielding of plants, concentration of photosynthetic pigments, gas exchange and chlorophyll fluorescence parameters in lettuce plants grown under LED lamps assembled from red and blue diodes in different proportions. The control plants were cultivated under white fluorescent and white LED lighting.

MATERIALS AND METHODS

Plant material and growth conditions. Seeds of lettuce (*Lactuca sativa* L.) cv. 'Królowa Majowych' were sown into substrate for vegetables cultivation (Kronen, Poland). Germination and seedling emergence were conducted under laboratory conditions in the temperature of 20–23°C under white fluorescent light. Ten days after sowing, 48 the best-developed seedlings of uniform size were selected and planted individually to plastic pots of 18 cm diameter, filled with the same substrate (1.2 kg). Pots were placed in a vegetation room, where the temperature was set to 22/18°C (day/night), with 12 hours photoperiod and 80 ±10% relative air humidity. After 7 days plants were fertilized with full-strength Hoagland's N°1 nutrient solution. During the vegetation plants were watered, keeping the moisture level at 70% of maximum field capacity. All measurements were conducted after 35 day growth of plants under different light.

Light treatments. Each of 8 pots with lettuce (treatment repetitions; experimental unit) were treated with light of different spectral composition emitted by the following lamps: 1) white fluorescent FL (W), 2) LED composed of 12 white diodes – LED (12W), 3) LED composed of 9 red + 3 blue diodes – LED (9R + 3B), 4) LED composed of 10 red and 2 blue diodes – LED (10R + 2B), 5) LED composed of 11 red and 1 blue diodes – LED (11R + 1B), 6) LED composed of 12 red diodes – LED (12R). The lighting used in the experiment were Philips 58W fluorescent lamps and Epiled 1W LED diodes.

The movable FL lamps were placed 20 cm and the LED ones 55 cm over the upper leaves. In this way the photosynthetic photon flux density (PPFD) measured on the level of leaves' tips with the use of an radiation sensor (LCA-4, ADC BioScientific Ltd., UK) was equalized to around 200 µmol m^{-2} s^{-1}. Because of the narrow spectrum of LED lighting 40 lamps were used in this research and each plant was illuminated with 1 lamp. The spectral composition of the lamps determined with a diode array spectrometer (USB 4000, Ocean Optics, USA) is showed in Figure 1. The percentage ratio between the red and blue radiation in the lighting used in this experiment was determined by the measurement of the peak area at the range of 638–663 nm for the red light and 428–453 nm for the blue light for each lamp type individually (fig. 1). The area of peaks was estimated with the use of a laser scanner. Measurements for all the lamp types mentioned in this subsection had the following share of the blue light: FL (W) – 59%, LED (12W) – 36 %, LED (9R + 3B) – 21%, LED (10R + 2B) – 17%, LED (11R + 1B) –12%, and LED (12R) – 0%. *The daily energy consumption by FL (W) and*

LEDs lamp systems was assessed on the basis of laps wattage, their total number, and number of light hours per day.

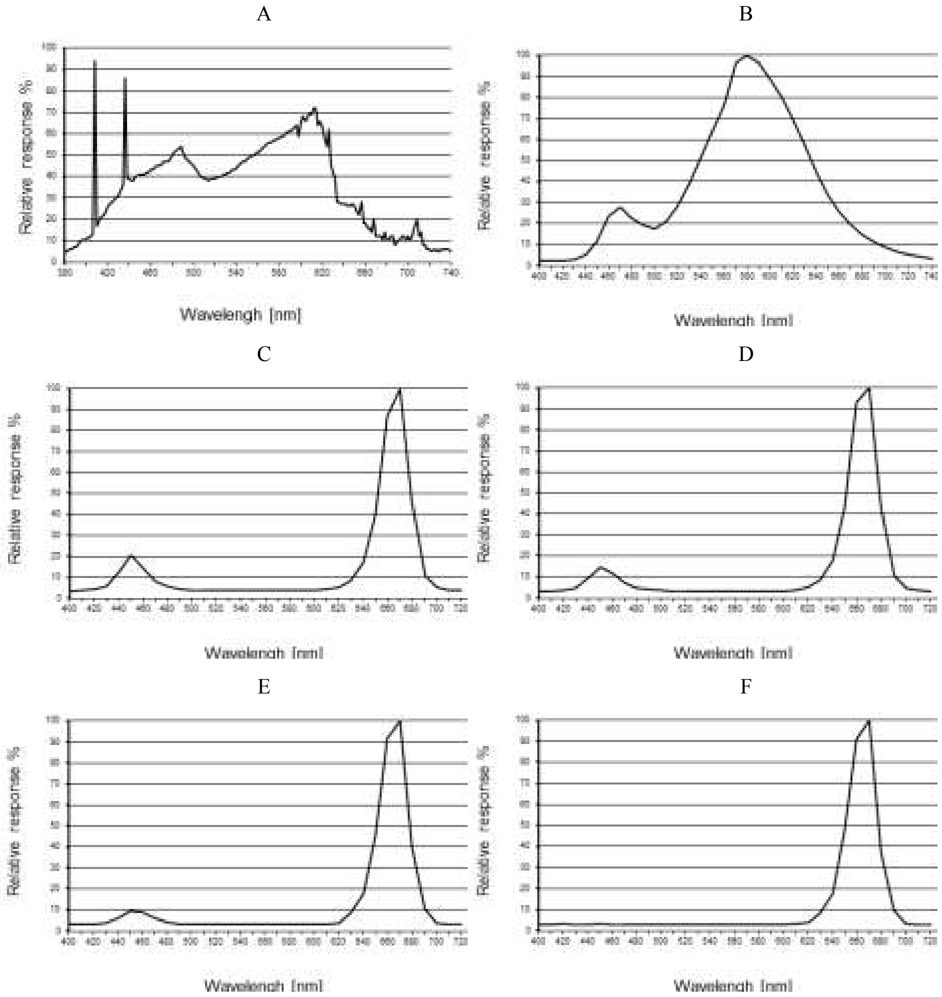

Fig. 1. The spectral composition of light lamps used in the experiment: A – fluorescent lamps – FL (W), B – 12 white warm diodes – LED (12W), C – 9 red + 3 blue diodes LED (9R + 3B), D – 10 red + 2 blue diodes – LED (10R + 2B), E – 11 red + 1 blue diodes – LED (11R + 1B), F – 12 red diodes – LED (12R)

Plant growth measurements. A fresh weight (FW) of shoots, the leaves area (LA) and specific leaves area (SLA) were measured in this experiment. The LA of every plants was measured by a laser scanner (CI-202, CID Bio-Science, USA). But SLA was calculated as quotient from leaf area (cm^2) and shoot dry weight (g).

Photosynthetic pigments concentration. The chlorophyll *a* and *b* as well as total carotenoid (xanthophyll + carotene) concentrations were determined spectrophotometrically following the procedures of Lichtenthaler and Wellburn [1983]. The leaf samples were collected from middle leaves of 4 randomly selected plants. The pigments were extracted by grinding the tissue with 80% (*v*/*v*) acetone. The obtained homogenate was transferred quantitatively on a filter linked with a vacuum pump, and then bathed with small portions of a solvent. The obtained extracts were placed in measuring flasks and diluted to the volume of 25 cm^3. The extinction of the solution was marked at the wavelength of 663, 645 and 470 nm. The concentration of each pigment was calculated using of the formulas given by Lichtenthaler and Wellburn [1983].

Gas exchange parameters. The values of a leaf stomatal conductance (gs), a transpiration rate (T) and a net photosynthesis rate (Pn) were measured by a gasometric apparatus used to control microclimate of leaf (LCA-4, ADC BioScientific Ltd., UK) in the middle of a day. Gas exchange was determined at a CO_2 concentration of 360 μmol mol^{-1}, 80% relative humidity and 200 μmol m^{-2} s^{-1} PPFD. Measurements were done on the middle leaf and were repeated eight times on each plant in light treatment.

Chlorophyll fluorescence parameters. The analysis of minimal (*Fo*), maximal (*Fm*) level of chlorophyll fluorescence and maximal photochemical efficiency of photosystem II (PS II; *Fv*/*Fm*) [Schreiber et al. 1994] were measured using a fluorimeter (Hansated Instruments Ltd) on the same leaves that were used to measure gas exchange parameters. Lettuce leaves were adapted to darkness for 15 min before the measurements by attaching light-exclusion clips. Fluorescence parameters was determined by a 0.8 s saturating pulse of light at 650 nm wavelength at intensity 1500 μE · m^{-2} s^{-1}.

Statistical analysis. All measurements were evaluated for significance by one-way analysis of variance (ANOVA). Significance of differences was assessed using the Tukey's multiple range test at the confidence level of $p < 0.05$. The presented results represent mean values obtained from two independent experiments.

RESULTS

Plant growth and morphology. The results of the measurements concerning the effect of FL and LED lights of a different spectral composition on shoot FW, LA and SLA of lettuce plants are presented in Table 1. The highest shoot FW was noted in plants treated with FL (W) light and the lowest one, in those treated with LED (12W). An increased share of red radiation at the cost of the blue one under LED lighting increased the shoot FW, and the highest yield was produced by plants under the LED (12R) light. The lights used had a similar influence on LA, however in this case significantly higher value of LA had plants grown under the LED (12R) than LED (11R + 1B) light, but there was no significant difference under lights LED (12R) and FL(W). The types of light used in our experiments have not exactly similar effect on SLA, because the lower value of SLA was noted under LED (9R + 3B) and LED (10R + 2B) light, significantly higher under LED (11R + 1B), LED (12W) and FL(W), and the highest one was under LED (12R) (tab. 1).

Table 1. The effect of fluorescent and LED lighting of different spectral composition on shoot fresh weight (shoot FW), leaf area (LA) and specific leaf area (SLA) of lettuce plants

Light treatments	Shoot FW (g plant^{-1})	LA (dm^{-2} plant^{-1})	SLA (cm^2 g^{-1})
FL (W)	206.1 d	93.5 c	935 b
LED (12W)	103.0 a	45.7 a	896 b
LED (9R + 3B)	122.5 b	45.5 a	712 a
LED (10R + 2B)	136.6 b	53.4 a	752 a
LED (11R + 1B)	178.4 c	78.1 b	845 b
LED (12R)	180.9 c	97.6 c	1047 c

The mean values marked with the same letter within columns do not differ significantly at $p < 0.05$

The morphology of lettuce grown under different light conditions used in this research is presented in Figure 2. The widest rosettes received from lettuce cultivated under lamps FL (W) and LED (12R). However, the shape of plants was differentiated. Under the FL (W) light leaves were more rounded, dark green, directed upwards, while under the LED lighting they were elongated, light green and directed downwards. Moreover, plants grown under LED (12W) had loose rosettes. The diameter of rosettes increased with the increase of red radiation in the LED lighting.

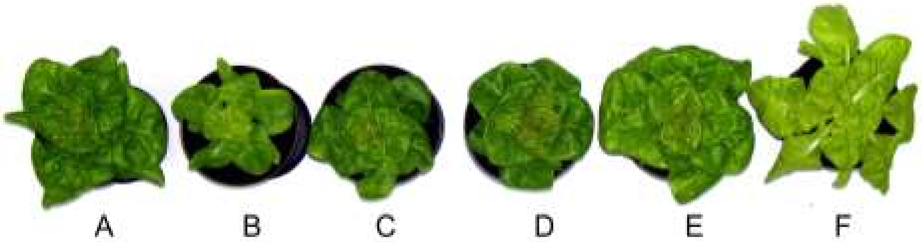

Fig. 2. A morphology of 4-week old lettuce plants grown under different light quality: A – fluorescent lamps – FL (W), B – 12 white warm diodes – LED (12W), C – 9 red + 3 blue diodes LED (9R + 3B), D – 10 red + 2 blue diodes – LED (10R + 2B), E – 11 red + 1 blue diodes – LED (11R + 1B), F – 12 red diodes – LED (12R)

Photosynthetic pigments concentration. The concentrations of chlorophyll *a* in lettuce leaves were about 5 times higher than chlorophyll *b*, regardless of the light source. The lowest chlorophyll levels contained plants treated with LED (12R). The increased share of blue radiation and decrease of the red one in LED lamps caused a significant increase of chlorophyll *a* and *b* contents. The middle chlorophyll content obtained from plants treated with LED (12W). The highest concentration of photosynthetic pigments contained plants grown under LED (9R + 3B) lamps. Control plants grown under FL(W) light had the same contents of chlorophyll as those cultivated under the LED (11R + 1B) lighting. The influence of the treatments was less pronounced in the case of carotenoids. Lettuce cultivated under LED (12R) and LED (12W) lighting contained low amounts of these pigments, significantly higher under FL(W) light and the remaining types of LED lighting (tab. 2).

Table 2. The effect of fluorescent and LED lighting of different spectral composition on concentrations of chlorophyll *a* (chl *a*), chlorophyll *b* (chl *b*) and carotenoids (car) in lettuce leaves

Light treatments	Photosynthetic pigment concentrations (mg dm^{-2})		
	Chl *a*	Chl *b*	Car
FL (W)	2.20 c	0.45 c	0.51 b
LED (12W)	1.67 b	0.37 b	0.38 a
LED (9R + 3B)	2.59 d	0.54 d	0.58 b
LED (10R + 2B)	2.31 cd	0.48 cd	0.55 b
LED (11R + 1B)	2.20 c	0.47 c	0.51 b
LED (12R)	1.29 a	0.28 a	0.31 a

The mean values marked with the same letter within columns do not differ significantly at $p < 0.05$

Gas exchange and fluorescence parameters. The results of the measurements presented in Table 3 show, that the lighting used in our experiment had a similar influence on gs, T and Pn. Low gs and Pn characterized lettuce cultivated under LED (12R), LED (12W) and FL (W) lights, and significantly higher value of these parameters was noted under red-blue LED (9R + 3B; 10R + 2B; 11R + 1B) lighting. The influence of lighting on plants transpiration (T) varied more widely among treatments. The lowest transpiration rate was found in plants under LED (12R) light, significantly higher under LED (12W) and FL (W), and the highest under red-blue LED lighting (tab. 3).

Table 3. The effect of fluorescent and LED lighting of different spectral composition on stomatal conductance (gs), transpiration (T) and net photosynthesis (Pn) of lettuce plants

Light treatments	gs (mmol m^{-2} s^{-1})	T (mmol m^{-2} s^{-1})	Pn (μmol m^{-2} s^{-1})
FL (W)	65.00 a	0.88 b	7.38 a
LED (12W)	68.00 a	0.87 b	7.36 a
LED (9R + 3B)	97.00 b	1.07 c	10.33 b
LED (10R + 2B)	88.00 b	1.00 c	10.06 b
LED (11R + 1B)	83.00 b	1.01 c	10.31 b
LED (12R)	52.00 a	0.60 a	6.99 a

The mean values marked with the same letter within columns do not differ significantly at $p < 0.05$

Table 4. The effect of fluorescent and LED lighting of different spectral composition on minimal fluorescence (*Fo*), maximal fluorescence (*Fm*) and maximal quantum efficiency of PS II (*Fv/Fm*) in leaves of lettuce plants

Light treatments	*Fo*	*Fm*	*Fv/Fm*
FL (W)	274.2 b	1777.8 c	0.846 b
LED (12W)	279.8 b	1755.8 c	0.840 b
LED (9R + 3B)	264.5 ab	1577.0 ab	0.832 ab
LED (10R + 2B)	269.0 b	1703.7 bc	0.842 b
LED (11R + 1B)	276.8 b	1728.8 bc	0.840 b
LED (12R)	235.0 a	1477.3 a	0.815 a

The mean values marked with the same letter within columns do not differ significantly at $p < 0.05$

The analysis of chlorophyll fluorescence parameters (tab. 4) show, that low values of *Fo* and *Fv*/*Fm* characterized plants grown under LED (12R) and LED (9R + 3B) lighting. Significantly more advantageous effect on *Fo* and *Fv*/*Fm* had light emitted by other LED lamps and FL (W) lamps. Also *Fm* was the lowest in lettuce leaves under LED (12R) lighting, significantly higher under red-blue LED and the highest under white LED and FL lighting.

DISCUSSION

Lettuce is one of the most common vegetables in the world and its cultivation in the autumn-winter and winter periods usually needs supplemental lighting. Lamps used for supplemental illumination emit light of different spectral composition, so that the research concerning this issue seems important. The basic importance for plants have photons of red and blue wavelength as they are not only the most photosynthetically active [Yorio et al. 2001], but also, *via* phytochrome and cryptochrome systems, they regulate the photomorphogenesis processes [Okamoto et a. 1997]. The results presented in this work show, that the higher share of the red light (R) in LED lamps, the higher was the shoot FW, LA and SLA. The increased share of the blue light (B) had a reverse effect on plants, decreasing shoot FW, LA and SLA (tab. 1, fig. 2). These results confirm the research on lettuce conducted by Bart et al. [1992], Yanagi et al. [1996] and Johkan et al. [2010] as well as on dill [Frąszczak, 2013]. Matsuda et al. [2008] conducting experiments on spinach noted that the radiation with the share of B light increased the production of biomass, and with addition of R light – elongation of plants. The opposite opinion was given by Ohashi-Kaneko et al. [2007], who stated that blue fluorescent lamps (BF) were completely useless in cultivation of this species.

Looking for the proper lamps for supplemental illumination of lettuce, not only the highest yield should be taken into consideration but also its good quality. Therefore, there is a question what should be the rate of R/B in proposed light sources. The new instrument which gives the possibility to answer this are LED lamps, in which, through montage of the proper diodes (narrow spectrum) it is possible to create the spectral composition of light in any way. It was not possible earlier, and the researchers tried to solve the problem by adding to the LED-W (white) or LED-WR (white/red) light, the B photons coming from BF lamps (of wider spectrum). As a result of such experiments, Bula et al. [1991] stated that the 10% share of BF is necessary for lettuce cultivated under LED-R lighting, while Yorio et al. [2001] presented that 10% addition of BF light was insufficient for the proper growth of lettuce, radish or spinach.

The results obtained in our research imply, that in a studied light range, the LED (11R + 1B) lamps, in which the share of B light was 12%, were the best for the growth of lettuce. In this conditions the leaves had a high photosynthetic activity and the biomass of shoots was relatively high, as well as the leaves had a high quality (determined on the SLA and photosynthetic pigments level basis) (tab. 1–4, fig. 2). Also Okamoto et al. [1997] studied effect four different ratios of LEDs red : blue light on weight of the lettuce seedlings confirmed that the most advantageous was the ratio 90 : 10%. Another requirement with regard of light has strawberry. Nhu et al [2003] stated that the best for the growth was the ratio 70 : 30 of R/B in LED lighting.

The lowest shoot FW characterized lettuce grown under LED (12W) lamps, what probably was caused by the high share of B radiation in relation to R (36%). It is definitely more difficult to explain the significantly more advantageous influence of FL (W) lamps on yield of lettuce in this situation, because the share of the B radiation in relation to R was even higher (59%). It might be only assumed that it was related to more proportional share of all light wavelengths in FL (W) lamp than in the LED (12W) one, and especially with much higher share of the green radiation (G) which, as suggested by Klein [1992], better penetrates the inside of the leaves tissue than R/B radiation. Therefore, it increases photosynthetic activity and delays senescence of lower leaves, what seems to have a special significance in case of lettuce and other species of similar shape. Hyeon-Hye et al. [2004] state that addition of 24% of green fluorescent light to LED R/B light had an advantageous effect on lettuce yielding. The similar influence was also observed by Kim et al. [2004b]. Our results measuring of Pn (tab. 3) related to individual good illuminated leaves, in order explain this problem is necessity measurement of Pn whole plants. Thus plants illuminated by fluorescence lamps-FL(W) produced the highest shoot fresh weight despite significantly lower Pn from unit area than in other plants, therefore that showed the highest LA value and presumably high share in photosynthetical productivity of whole plants, lower leaves (tab. 1, 3).

The results of our experiments show that LED (9R + 3B) light had a more positive effect on the contents of chlorophyll and carotenoids than LED (12R) and LED (12W) lighting. Also Li and Kubota [2009], Johkan et al. [2010], Wojciechowska et al. [2013] and Borowski et al. [2014] confirmed the advantageous effect of LED R/B lighting on the contents of chlorophyll and carotenoids in leaves of lettuce and *Valerianella locusta*, respectively.

LED R/B light, as presented in the Table 3, more favourably affected gs than the other light treatments, what in combination with high contents of chlorophyll and carotenoids in these plants might have been the reason for the significantly higher Pn as well as T than in case of other light types. However, it was not probably connected with the primary photosynthetic reactions defined with *Fo*, *Fm*, *Fv*/*Fm*, as their values were not significantly different, except the LED (12R) lighting. However, the lowest values of the analysed chlorophyll fluorescence parameters in the plants lighted with LED (12R) result from extremely low content of chlorophyll a in leaves. Also Kim et al. [2004a] in the research on chrysanthemums and Wojciechowska et al. [2013] on lamb's lettuce, stated that Pn under LED R/B lighting was higher than under FL (W) light. However, according to Lee et al. [2007] in case of *Withania somnifera*, there were no differences in the values of gs, T and Pn under FL (W) and LED R/B lighting (1/1). According to Wang et al. [2009], especially adverse effects on Pn and *Fv*/*Fm* in cucumber plants had the monochromatic light. The values of these parameters were lower under R than W light, what was also confirmed in the presented work.

CONCLUSIONS

Light, apart from temperature and water, is the main environmental factor that influences quantity and quality of plants yield. During the periods of sunlight deficiency, the plants cultivated in greenhouses are illuminated with artificial light. The LED lighting have been used more and more often for the last 15–20 years. Their superiority over the traditionally lamps is such that with the selection of proper diodes it is possible to compose it's quality. The main aim of this work was to estimate the optimal share of the blue radiation in relation to the red one in LEDs for cultivation of lettuce plants. The criteria of the evaluation of the light emitted by 5 types of LED lamps and white fluorescent lamps (control) was the photosynthetic activity of leaves and yield of plants. The results of our research imply that the most beneficial influence on lettuce plants had LED lighting with 12% share of the blue radiation – LED (11R + 1B). Although the yield of lettuce obtained in such conditions was 14% lower than under fluorescent lamps (FL), but the energy consumption of LEDs in comparison to FL was about 40% lower.

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WPŁYW JAKOŚCI ŚWIATŁA NA PARAMETRY FOTOSYNTETYCZNE LIŚCI SAŁATY I ICH PLON

Streszczenie. W doświadczeniach wazonowych prowadzonych w kontrolowanych warunkach przy PPFD 200 µmol m^{-2} s^{-1} na roślinach sałaty badano wpływ światła LED o zróżnicowanym składzie spektralnym wobec białego światła fluorescencyjnego (FL-W) na aktywność fotosyntetyczną liści i plon biomasy. W badaniach zastosowano lampy LED emitujące światło białe (12W), czerwone (12R) i czerwono-niebieskie (R/B) z lamp o różnym stosunku w lampie diod czerwonych (R) do niebieskich (B) [9R + 3B; 10R + 2B; 11R + 1B]. Wyniki badań wykazały, że najniższe plony wydały rośliny przy LED (12W), a najwyższe FL(W). Zbliżone pod względem masy i powierzchni liści efekty w stosunku do FL(W) miały rośliny przy LED(12R). Wzrost promieniowania R a spadek B powodował wzrost biomasy, powierzchni liści i SLA oraz spadek zawartości chlorofilu w liściach. Liście roślin przy świetle LED R/B wykazywały wyższą przewodność szparkową, fotosyntezę i transpirację niż przy pozostałych rodzajach światła. Najniższą wartość wskaźników fluorescencji chlorofilu (Fo, Fm, Fv/Fm) stwierdzono przy świetle LED (12R). Biorąc pod uwagę zużycie energii przez zastosowane źródła światła, plonowanie roślin i inne określone w pracy parametry, najbardziej korzystne dla produkcji sałaty wydaje się światło LED(11R + 1B).

Słowa kluczowe: LED-s, światło fluorescencyjne, barwniki fotosyntetyczne, wymiana gazowa, fluorescencja chlorofilu

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