ACTA Acta Sci. Pol., Hortorum Cultus 13(5) 2014, 211-224

THE RESPONSE OF LETTUCE TO FLUORESCENT LIGHT AND LED LIGHT RELATIVE TO DIFFERENT NITROGEN NUTRITION OF PLANTS

Edward Borowski, Barbara Hawrylak-Nowak, Sławomir Michałek
University of Life Sciences in Lublin

Abstract. In two successive pot experiments with lettuce cv. 'Królowa Majowych', conducted in a phytotron, this study investigated the effect of cool white fluorescent light (FRS) at a PPFD 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and red-blue LED light at a PPFD of 200 and 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on photosynthesis, yield, leaf area, SLA, and the content of photosynthetic pigments, total N and nitrates. Experimental plants were grown in sphagnum peat supplemented with full-strength Hoagland's solution at the beginning of the experiment. 10 days after plants were pricked out, 4 experimental series were made which differed in the form of N supplied to the growing medium at a rate of 420 mg (2N): 1) Hoagland's solution (control); 2) Hoagl + 2N-NO_3; 3) Hoagl + 2N-NH_4; 4) Hoagl + 2N-NH_4/NO_3. The obtained results showed that the lettuce leaf yield under FRS light was distinctly higher than under LED light at a PPFD of 200, and in particular at 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Besides, the leaves grown under FRS light showed a significantly thinner leaf blade (SLA) and a lower content of photosynthetic pigments, total N and nitrates. The photosynthetic rate was higher under LED light relative to FRS light. Different nutrition of plants with N-NO_3, N-NH_4 and N-NH_4/NO_3 had a similar effect on the yield and analysed traits of lettuce leaves, regardless of the type of light and the level of irradiation with LED light. LED lamps seem to be a very promising light source for plants, but they require further research on how to adapt the spectral distribution of light to their requirements.

Key words: spectral composition, *Lactuca sativa,* yield, leaf area, SLA, photosynthetic pigments, N-total, nitrates, photosynthesis

INTRODUCTION

Light is the only source of energy for the process of photosynthesis, but it is also an important impulse for the growth and development of plants. It has been long known that plants respond not only to the intensity of light, but also to its spectral composition.

Corresponding author: Edward Borowski, Department of Plant Physiology, University of Life Sciences in Lublin, ul. Akademicka 15, 20-950 Lublin, Poland, e-mail: edward.borowski@up.lublin.pl

The generally known, but still intensively studied, effect of the spectral composition of light on the processes of photosynthesis and photomorphogenesis in plants is the basis for constructing more and more perfect artificial light sources. LED (Light Emitting Diode) light is a new light source developed during the last dozen or so years. According to Morrow [2008], the LED lighting system has several unique advantages over existing horticultural lighting such as the ability to control the spectral composition, the ability to produce very high light levels with low radiant heat output, and the ability to maintain the necessary level of radiation for years without lamp replacement. Morrow [2008] as well as Hyeon-Hye Kim et al. [2004] also claim that LED diodes are safer to operate than electric lamps because they do not have glass envelopes, do not contain mercury, have a low weight and volume as well as a durable design, and are easily integrated into digital control systems. An important advantage of LEDs, in particular in Polish conditions, is their low power consumption compared to fluorescent lamps or HPS (High Pressure Sodium) lamps [Wojciechowska 2013].

The research conducted on lettuce has shown that it grows well under cool white fluorescent lamps but much worse under LEDs that emit red light. To improve plant growth under such conditions, it is necessary to supplement red light with blue light [Sharkey and Raschke 1981, Bula et al. 1991, Barta et al. 1992, Hoenecke et al. 1992, Okamoto et al. 1997, Yorio et al. 2001]. As reported by Mortensen and Stromme [1987] as well as by Schuerger et al. [1997], blue light is a growth inhibitor and induces changes in plant morphogenesis. Because this light is strongly absorbed by photosynthetic pigments [Hyeon-Hye Kim et al. 2004], a question arises how large blue light supplementation should be. In their study on lettuce seedlings, Okamoto et al. [1997] found their dry weight to be the highest at a red/blue PPFD ratio of 72/8, whereas Hogewoning et al. [2010] found that for cucumber it could not exceed 50%.

Despite that the addition of blue light clearly improves lettuce growth, but still it is not as good light as cool white fluorescent light [Yorio et al. 2001]. This suggests that other colours of light also affect the growth and development of lettuce plants. According to Hyeon-Hye Kim et al. [2004], adding green light to red and blue LED lighting had a significant role. Green light added to the other colours at an appropriate proportion increases light penetration inside the leaf rosette [Klein 1992, Smith 1993], thereby improving the penetration of carbon into the lower leaves [Sun et al. 1998]. The role of yellow light in lettuce growth is not clear, either. In their research using HPS and MH (metal halide) lamps, Dougher and Bugbee [2001a, 2001b] found yellow light (580–600 nm) to inhibit lettuce growth, whereas Hogewoning et al. [2010] did not find such a correlation.

Apart from PAR radiation, light sources used in horticulture usually emit small amounts of UV radiation and far-red light. Senger [1984] claims that the effectiveness of UV light in triggering some responses in plants can match that of blue light. But the addition of far-red light (735 nm) to both red light [Schuerger et al. 1997] and blue light [Sun-Ja Kim et al. 2004] had an adverse effect on the growth of pepper and chrysanthemum plants, respectively.

The intensity and spectral composition of light affect plant growth and development through their effects on a number of different processes, also including nutrient uptake [Hogewoning et al. 2010]. In this context, their effect on nitrogen uptake seems to be particularly interesting, since this nutrient is taken up as NO_3^-, which requires subsequent energy-consuming reduction, or as NH_4^+ ready for direct amination of keto acids [Borowski 1994a, Borowski 1994b, Borowski and Blamowski 1995]. The study on cucumber conducted by Hogewoning et al. [2010] shows a relationship between the ratio of blue to red light and the nitrogen content in leaves and their photosynthesis.

Because the use of LED diodes gives the possibility of adjusting both radiation intensity and the spectral composition of light, the aim of the present study was to compare the response of lettuce fed with nitrogen in the form of NO_3^-, NH_4^+ and NH_4/NO_3 to LED light relative to cool white fluorescent light.

MATERIAL AND METHODS

The results presented in this paper are derived from two experiments carried out in a phytotron at an air temperature of 22/18°C (day/night), a relative humidity of 70%, and a 14-hour day length. The first experiment was conducted between 21 March and 29 April, while the second experiment between 11 October and 14 November 2013.

In both experiments, lettuce plants were grown under two light arrays; one of them consisted of 12 Philips 58 W fluorescent lamps, each emitting white light, whereas the other one was composed of 32 diode lamps, each of them containing twelve 1 W LED diodes emitting light of three colours – 8 diodes emitted red light, 3 blue light, and 1 white light. In the first experiment, the light arrays emitting two types of light were placed at a height of 24 cm from the leaf tips; as a result, the irradiation of plants with fluorescent light was about 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, whereas with LED light about 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Due to a narrow stream of light from the LED lamps placed low above the plants, each pot was illuminated with a stream of light from one lamp. In the second experiment, the LED lighting array was positioned at a height of 55 cm from the plants, with the irradiation at a level similar to that emitted by the fluorescent lamps. The spectral distributions of light obtained from both types of lamps, as determined with a USB4C00684 spectrometer, are shown in Figs 1 and 2.

Lettuce seedlings, cv. 'Królowa Majowych', which were at the first true leaf pair stage, were pricked out into ϕ 18 cm pots, four seedlings in each pot, filled with a growing medium (manufactured by the company Hollas) composed of sieved and milled sphagnum peat with the addition of Hydro fertilizer, chalk, and washed fine quartz sand. Next, 32 pots were placed under fluorescent light and 32 under LED light. After 4 days, Hoagland's solution, 1% ferric citrate solution and A–Z micronutrient solution (2 cm^3 of each) were supplied to the pots. After the next 7 days, three lettuce seedlings were removed, leaving one seedling for further growth, and 4 experimental series were made under either of the types of light used. Each series consisted of 8 pots (treated as replicates) differing in the form of nitrogen added at a double rate relative to its amount of 210 mg N-NO_3 contained in Hoagland's solution: 1 – Hoagland's solution (Hoagl.) – control; 2 – Hoagl + 2N-NO_3 (plus 420 mg N in the form of $Ca(NO_3)_2$ and KNO_3; 3 – Hoagl + 2N-NH_4 (plus 420 mg N in the form of $(NH_4)_2SO_4$); 4 – Hoagl + 2N-NH_4/NO_3 (plus 420 mg N in the form of NH_4NO_3) (tab. 1). Thus, the ratios of nitrogen supplied to the growing medium as NO_3^- or NH_4^+ in the successive experimental series was as follows: NO_3/NH_4 – 1/0; 3/0; 1/2; 2/1.

Throughout the entire growth period, the growing medium moisture content was maintained at a level of 80% FWC (field water capacity) by watering the plants with distilled water to constant weight. After 6 weeks of plant growth, the photosynthetic rate was determined in the middle leaves of the rosette in 10 replicates using an LCA-4 gas analyser. During recording, the temperature in the leaf measurement chamber was approx. 25ºC, whereas the PAR flux density was similar to that used during plant growth. Then, in leaf samples collected from the middle of the rosette, the photosynthetic pigment content was determined in 4 replicates according to Arnon [1949], while the nitrate content according to Cataldo et al. [1975]. Measurements of total plant leaf area and mean leaf blade weight per 1 cm^2 (specific leaf area – SLA) were also made in 4 replicates; twenty ϕ 21 mm disks were cut with a cork borer from different aged leaves in each plant and their total area and weight were determined, and subsequently the weight of all leaves in each plant. The attempt to measure the total leaf area using a laser scanner was unsuccessful, since the surface of the leaf blades in plants grown under high intensity LED light was too folded. The above-ground parts of plants were separated from the roots, dried at a temperature of 105°C and total N content was determined in the leaf dry matter obtained using the Kjeldahl method.

The results of the analyses and determinations presented in this paper were subjected to analysis of variance for two-way cross-classification. The significance of differences between means was determined by Tukey's confidence half-intervals at $\alpha = 0.005$.

RESULTS

The results presented in Table 1 show that in the first experiment the leaf yield obtained under fluorescent light (FRS) was 2 times higher than under LED light, while in the second experiment it was about 1.6 higher. Regardless of the type of light, in both experiments plants fed with Hoagland's solution produced the lowest yield, but a significantly higher yield was obtained in plants additionally fed with a double dose of $N\text{-}NH_4$, and the highest one in plants supplied with an equivalent amount of $N\text{-}NO_3$ or $N\text{-}NH_4/NO_3$. The situation with total leaf area was similar as in the case of lettuce yield, since in the first and second experiment it was about 2.9 and 2.3 times higher under FRS light compared to LED lighting. Increased fertilization with nitrate nitrogen, ammonium nitrogen or nitrate/ammonium nitrogen significantly increased the total leaf area in the first experiment only in relation to plants supplied with Hoagland's solution (control). But in the second experiment, only plants additionally fed with $N\text{-}NO_3$ were characterized by a significantly higher value of the trait in question (tab. 2).

Unlike in the case of leaf weight and area, the specific leaf area (SLA) for plants grown under LED light was on average higher by 47.5% than under FRS light for both experiments. In the first experiment, the study found no significant differences in the value of the indicator in question resulting from nitrogen nutrition. In the second experiment, however, the leaves of control plants showed the lowest value of SLA, a significantly higher value of this measure was found in plants fertilized with $N\text{-}NO_3$ and $N\text{-}NH_4/NO_3$, and the highest value in those fed with $N\text{-}NH_4$ (tab. 3).

Table 1. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on fresh weight yield of lettuce leaves (g·plant^{-1})

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	89.7	52.2	70.9 a	97.9	67.7	82.8 a
Hoagl. + 2N-NO_3	132.2	58.4	95.3 c	140.7	78.1	109.4 b
Hoagl. + 2N-NH_4	115.7	56.1	85.9 b	125.2	72.6	98.9 b
Hoagl. + 2N-NH_4/NO_3	130.6	59.3	94.9 c	132.4	81.6	107.0 b
Mean for B	117.0 b	56.5 a		124.0 b	75.0 a	
LSD for A × B	16.6			23.1		

Values followed by the same letters are not significantly different

Table 2. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on total plant leaf area (dm^2·plant^{-1})

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	49.2	21.9	35.5 a	54.7	29.0	41.8 a
Hoagl. + 2N-NO_3	72.2	21.3	46.7 b	74.4	29.4	51.9 ba
Hoagl. + 2N-NH_4	62.3	20.9	41.6 b	66.6	26.5	46.5 a
Hoagl. + 2N-NH_4/NO_3	64.8	21.0	42.9 b	66.9	26.9	46.9 a
Mean for B	62.1 b	21.3 a		65.6 a	27.9 a	
LSD for A × B	8.9			11.2		

Values followed by the same letters are not significantly different

Table 3. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on specific leaf area – SLA (mg ·cm^{-2})

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	15.7	24.2	19.9 a	17.9	23.1	20.5 a
Hoagl. + 2N-NO_3	17.6	27.3	22.4 a	18.9	26.6	22.7 b
Hoagl. + 2N-NH_4	18.7	28.5	23.6 a	19.8	30.7	25.2 bc
Hoagl. + 2N-NH_4/NO_3	17.9	27.0	22.4 a	18.8	27.0	22.9 b
Mean for B	17.5 a	26.7 b		18.8 a	26.8 b	
LSD for A × B	n.s			3.63		

Values followed by the same letters are not significantly different

Table 4. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on leaf total N content (% D.W.)

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	2.32	2.86	2.59 a	2.25	2.72	2.48 a
Hoagl. + 2N-NO_3	3.92	4.83	4.37 b	3.85	4.48	4.16 b
Hoagl. + 2N-NH_4	4.62	5.94	5.28 c	4.41	5.53	4.97 c
Hoagl. + 2N-NH_4/NO_3	4.12	5.06	4.59 b	4.02	4.87	4.44 b
Mean for B	3.74 a	4.67 b		3.63 a	4.40 b	
LSD for A × B	0.66			0.72		

Values followed by the same letters are not significantly different

Table 5. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on leaf nitrate content (μg $NO_3 \cdot g^{-1}$ F.W.)

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	602.2	856.1	729.1 a	510.5	839.6	675.0 a
Hoagl. + 2N-NO_3	1848.7	3177.2	2512.9 d	1746.6	2674.3	2209.4 d
Hoagl. + 2N-NH_4	712.7	2068.7	1390.7 b	856.3	1847.4	1351.9 b
Hoagl. + 2N-NH_4/NO_3	1675.0	2569.4	2122.2 c	1307.5	2245.8	1776.7 c
Mean for B	1209.6 a	2167.8 b		1104.7 a	1901.8 b	
LSD for A × B	489.3			479.5		

Values followed by the same letters are not significantly different

Table 6. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on leaf photosynthetic pigment content ($mg \cdot dm^{-2}$)

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	1.40	0.77	1.08 a	1.70	1.89	1.79 a
Hoagl. + 2N-NO_3	1.95	0.91	1.43 b	2.10	2.23	2.16 b
Hoagl. + 2N-NH_4	2.34	1.34	1.84 bc	3.25	3.10	3.17 d
Hoagl. + 2N-NH_4/NO_3	1.93	1.16	1.54 b	2.16	2.70	2.43 c
Mean for B	1.90 b	1.04 a		2.30 a	2.48 b	
LSD for A × B	0.26			0.41		

Values followed by the same letters are not significantly different

Table 7. Effect of different nitrogen nutrition, type of light and level of LED light irradiation on leaf photosynthetic rate (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)

Nitrogen nutrition (A)	First experiment			Second experiment		
	type of light (B)		mean for A	type of light (B)		mean for A
	FRS	LED		FRS	LED	
Hoagl.	4.14	5.48	4.81 a	4.24	9.80	7.02 a
Hoagl. + 2N-NO_3	5.89	8.41	7.15 c	6.28	13.43	9.85 d
Hoagl. + 2N-NH_4	5.22	6.95	6.08 b	5.43	10.56	7.99 b
Hoagl. + 2N-NH_4/NO_3	5.95	8.23	7.09 c	5.40	12.03	8.71 c
Mean for B	5.30 a	7.27 b		5.34 a	11.45 b	
LSD for A × B	0.92			0.90		

Values followed by the same letters are not significantly different

The yield, total leaf area and SLA in the leaves grown under FRS light at an irradiance of 200 μmol·m^{-2}·s^{-1} showed a slightly higher value in the first experiment than in the second one. But the yield and leaf area for plants grown under LED light at an irradiance of 200 μmol·m^{-2}·s^{-1} (second experiment) was higher respectively by 32.7% and 31.0% than at an irradiance of 800 μmol·m^{-2}·s^{-1} (first experiment), whereas the SLA showed an almost identical value (tabs. 1, 2, 3).

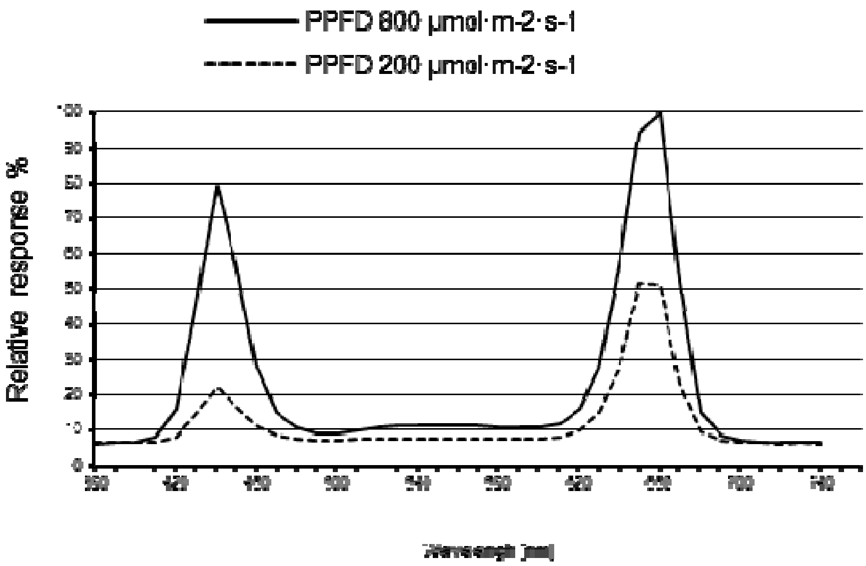

Fig. 1. Spectral distribution in relative energy of LED-s lamps

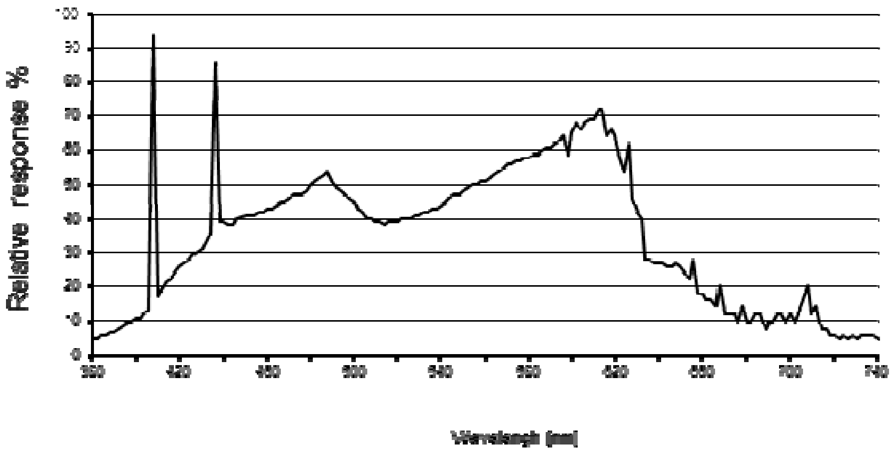

Fig. 2. Spectral distribution in relative energy of the fluorescent lamps (FRS)

In both experiments, the total N content in the leaves of plants growing under LED light was significantly higher than in the case of FRS and besides this content in the leaves at increased irradiation was higher by 0.27% compared to lower irradiation. Both in the first and second experiment, the leaves of plants additionally fed only with the ammonium form of N accumulated most nitrogen, while N accumulation was significantly lower when plants were fertilized with the nitrate form and the nitrate-ammonium form. The leaf nitrogen content in control plants was nearly half lower (tab. 4). Plants under LED light contained not only significantly more total N, but also more nitrates than those growing under FRS lamps. The high irradiation with this light promoted NO_3 accumulation in the leaves (first experiment). Regardless of the type of light used in the experiments, however, plants additionally supplied with this form of nitrogen contained most nitrates, whereas a significantly lower amount of nitrates was found in plants fed with NH_4/NO_3 and the lowest one in those fed with NH_4. The nitrate content in the leaves of control plants was on average 3 times lower (tab. 5).

FRS light had a significantly more beneficial effect on the photosynthetic pigment content in the leaves in the first experiment, whereas in the second experiment it was LED light. Irrespective of the type of light, in both experiments lettuce additionally fertilized with N-NH_4 contained the highest amount of photosynthetic pigments, while this amount was significantly lower in plants fed with N-NH_4/NO_3 and N-NO_3, and the lowest one when only Hoagland's solution was used. However, regardless of the type of light and the nitrogen form used, lettuce leaves in the first experiment contained a lower amount of pigments than in the second one (tab. 6).

The photosynthesis rate of lettuce plants under LED light with a 4 times higher level of irradiation relative to FRS light was higher by 37% than under fluorescent light (first experiment), while at a similar level of irradiation (second experiment) by as much as 114%. The effect of different nitrogen nutrition of plants on the process of photosynthesis was similar in both experiments. Additional nutrition of plants with nitrate N and nitrate-ammonium N had the most beneficial effect, but this effect was significantly worse in the case of ammonium N. The photosynthetic rate was lowest in plants fed only with Hoagland's solution (tab. 7).

DISCUSSION

A comparison of the spectral distribution of LED light and cool white fluorescent light shows substantial differences in light quality (figs 1, 2). The light emitted by LED diodes, both at a high PPFD (800 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and a low PPFD (200 $\mu mol \cdot m^{-2} \cdot s^{-1}$), contained the red and blue colours as well as trace amounts of other colours in the PAR range. On the other hand, the light of fluorescent lamps showed rather proportional percentages of individual colours with a small percentage of red colour relative to the other colours. UV radiation and far-red light were also present in its composition. Given this, it is difficult to explain the much higher leaf yield and the higher total leaf area under FRS light than in the case of LED light, since red light is well absorbed by photosynthetic pigments and is the most photosynthetically effective compared to the other colours [Yorio et al. 2001]. In their research on lettuce plants, other authors have also found lettuce to show distinctly better growth under the white light of fluorescent lamps than under LED lamps [Yori et al. 2001, Hyeon-Hye Kim et al. 2004].

Lettuce plants also exhibited a different response to LED lamps which resulted from a different level of irradiation with this light and the changed spectral composition depending at what height the lamps were positioned relative to plants. In the lamps used, 3 blue diodes and the white diode were placed in the middle of the lamp, whereas the red diodes were placed around them. Therefore, in the first experiment (800 $\mu mol \cdot m^{-2} \cdot s^{-1}$) with the low position of the lamps (24 cm from the leaf tips), the ratio of red to blue light calculated from a comparison of the peak area in the 638–663 nm range for red light and 428–453 nm for blue light was low (1.54), whereas in the second experiment (200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) with the high position of the lamps (55 cm), it was more than twice higher (3.46). This appears to be the main reason for the low yield and small leaf area in the first experiment compared to the second one. As shown by Mortensen and Stromme [1987] as well as by Schurger et al. [1997], blue light is a growth inhibitor and induces changes in leaf morphogenesis. It seems that the too high proportion of blue light in the light of LED lamps placed above the plants caused violet colouration of the leaves in 10-day lettuce seedlings (phot. 1) as well as strong undulation, chlorosis and necrosis of younger leaves at a later time (phot. 2). This could also have been caused by too high radiation (800 $\mu mol \cdot m^{-2} \cdot s^{-1}$) operating without interruption for 14 hours per day. Even though the natural light often reaches a twice higher level of radiation in the PAR range, it has a completely different spectral composition and operates with varying intensity, depending on the time of the day and the degree of cloudiness.

A decrease in irradiation to about 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from the LED lamps, making it equal to the irradiation of FRS light, distinctly increased the leaf yield and leaf area and improved the appearance of the leaves (phot. 3). Nevertheless, the value of the analysed plant traits still differed significantly from the parameters of the leaves grown under FRS lighting. The reason could still be an inappropriate (too high) ratio of blue to red

Phot. 1. 10-day lettuce seedlings in the first experiment

Phot. 2. 6-week lettuce seedlings in the first experiment

light. Studies conducted with LED lamps show that red light alone is unacceptable for the proper growth of lettuce [Bula et al. 1991, Barta et al. 1992]. To improve its growth, blue light supplementation is necessary [Sharkey and Roschke 1981, Bula et al. 1991, Barta et al. 1992, Hoenecke et al. 1992, Okamoto et al. 1997, Yorio et al. 2001]. However, a question arises what the ratio of red to blue light should be. Bula et al. [1991] reports that in the case of lettuce cv. 'Grand Rapids' grown under red LEDs 10% blue light supplementation was necessary for lettuce growth, while Okamoto et al. [1997]

obtained the highest plant dry weight at the red/blue light ratio of 48/12. Cucumber required much larger amounts of blue light. Hogewoning et al. [2010] report that with an increasing percentage of blue light relative to red light from 7% to as much as 50% the photosynthetic capacity increased, which was coupled with an increase in SLA as well as in the content of pigments and nitrogen. In the light of the research on lettuce conducted by other authors [Bula et al. 1991, Okamoto et al. 1997], this seems to be the reason for the lower values of all the plant traits in question (except for the nitrate content) in the first experiment in relation to the second one.

Phot. 3. 6-week lettuce seedlings in the second experiment

Nevertheless, the above discussion does not explain why in the second experiment lettuce produced a higher leaf yield and the leaves had a larger leaf area under FRS light than under LED lighting, in particular that the effect of types of light on the photosynthesis was opposite (tab. 7). Comparing FRS and LED light (figs 1, 2), one can presume that this was associated with the large proportion of green colour in fluorescent light, which was almost absent in LED light. Light passes easily through leaves [Klein 1992, Smith 1993], thereby increasing carbon assimilation in the lower leaves [Sun et al. 1998], and this can be important in the case of lettuce characterized by dense leaf arrangement. Hyeon-Hye Kim et al. [2004] also confirmed the beneficial effect of a 24% addition of green light to the red and blue colours. In the light of the literature, other colours present in the cool white light of fluorescent lamps, and absent in the light of LED lamps used, did not affect the growth of lettuce [Senger 1984, Schuerger et al. 1997, Dougher and Bugbee 2001a, b, Sun-Ja Kim et al. 2004, Hogewoning et al. 2010]. But the higher values of the other leaf traits in question under LED light compared to FRS light in the second experiment could have resulted from the fact that the blades of these leaves were thicker, hence the higher value of SLA and the higher photosynthetic pigment content per area (tabs. 3, 6). But this did not apply to the total N and nitrate content; the obtained results show that LED light with a high proportion of blue light stimulates nitrogen uptake, which was also found by Hogewoning et al. [2010] in the case of cucumber. LED light is also worth attention because, as shown by the present study, LED lamps used 45% less energy than FRS lighting, which is also confirmed by Wojciechowska et al. [2010].

Different nitrogen nutrition of lettuce plants did not have such a great effect on the lettuce yield and leaf traits analysed as light. The significant differences in the values of all the leaf traits analysed in the present study in control plants, as compared to the other plants, resulted undoubtedly from the fact that the amount of nitrogen supplied to the growing medium was lower by two-thirds. In the group of plants fed with the nitrogen forms used, the significantly lower leaf yield in plants fertilized with $N\text{-}NH_4$ relative to those fed with $N\text{-}NO_3$ and $N\text{-}NH_4/NO_3$ in the first experiment probably resulted from the too low ratio of red to blue light or excessive irradiation with LED light. This caused, due to chlorosis, necrosis and the holding and rolling of leaf blades, the exclusion of a part of the leaf apparatus from effective photosynthesis and, as shown by the results obtained, a decrease in the photosynthetic rate in the other regions of the leaf. It could have resulted from insufficient production of carbon chains formed in this process, which are necessary to assimilate $N\text{-}NH_4$ taken up. The presence of free NH_4^+ ions, in particular in leaves, clearly reduces plant growth [Borowski and Blamowski 1995]. It is worth noting that in the second experiment, with a PPFD reduced by about 4 times, no significant differences were found in the leaf yield dependent on the nitrogen forms supplied. At the same time, this is evidence that the high rate of photosynthesis taking place in such conditions (tab. 7) was a sufficient source of energy necessary for NO_3^- reduction and the incorporation of reduced N into amino acid synthesis. Despite, as it seems, efficient metabolization of NO_3^- ions taken up, which is evidenced by the high total N content in the leaves of these plants (tab. 4), they also contained certain amounts of nitrates (tab. 5). This can be evidence of excessive nutrition of lettuce plants (a short growing period) with this form of nitrogen. The presented correlations are confirmed by earlier research on tomato [Borowski 1994a] and lettuce [Borowski 1994b].

CONCLUSIONS

1. Under FRS light, the lettuce leaf yield was distinctly higher than under LED light at a PPFD of 200, and in particular 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Besides, the leaves grown under FRS light showed a significantly thinner leaf blade (SLA) and a lower content of photosynthetic pigments, total N and nitrates.

2. The photosynthetic rate was higher under LED light at an irradiance of 200 than at 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and significantly higher under LED light relative to FRS light.

3. Different nutrition of plants with $N\text{-}NO_3$, $N\text{-}NH_4$ and $N\text{-}NH_4/NO_3$ had a similar effect on the yield and analysed traits of lettuce leaves, regardless of the type of light and the level of irradiation with LED light.

4. LED lamps seem to be a very promising light source for plants, but they require further research on how to adapt the spectral distribution of light to their requirements.

ACKNOWLEDGEMENTS

The authors are grateful to LEDNAR-Lublin, Chemiczna 7, for free delivery of the LED lamps to these experiments.

REFERENCES

Arnon D.J., 1949. Cooper enzymes in isolated chloroplasts: Polyphenoloxidase in *Beta vulgaris*. Plant Physiol., 24, 1–15.

Barta D.J., Tibbitts T.W., Bula R.J., Morrow R.C., 1992. Evaluation of light emitting diode characteristics for space-based plant irradiation source. Adv. Space Res., 12, 141–149.

Borowski E., 1994a. Reakcja roślin pomidora na formy azotu w warunkach pełnej i zmniejszonej intensywności światła. Annales UMCS, sec. EEE, Horticultura, 2(1), 1–12.

Borowski E., 1994b. Reakcja sałaty na formy azotu w warunkach pełnej i dwukrotnie zmniejszonej wilgotności powietrza. Annales UMCS, sec. EEE, Horticultura, 2(10), 73–83.

Borowski E., Blamowski Z.K., 1995. Reakcja rzepaku na żywienie $N\text{-}NO_3$ i $N\text{-}NH_4$ podawane w różnych fazach wzrostu roślin. Annales UMCS, sec. E, Agricultura, 50(19), 137–144.

Bula R.J., Morrow R.C., Tibbitts T.W., Barta D.J., Ignatius R.W., Martin T.S., 1991. Light emitting diodes as a radiation source for plants. HortSci., 26, 203–205.

Cataldo D.A., Harocn M., Schrader L.E., Youngs V.L., 1975. Rapid colorimetric determination of nitrate in plants tissue by nitration of salicylic acid. Commun. Soil Sc. Plant Anal., 6, 71–80.

Dougher T.A.O., Bugbee B., 2001a. Differences in the response of wheat, soybean and lettuce to reduced blue radiation. Photochem. Photobiol., 73, 199–207.

Dougher T.A.O., Bugbee B., 2001b. Evidence for yellow light suppression of lettuce growth. Photochem. Photobiol., 73, 208–212.

Hoenecke M.E., Bula R.J., Tibbitts T.W., 1992. Importance of "blue" photon levels for lettuce seedlings grown under red light-emitting diodes. HortSci., 27, 427–430.

Hogewoning S.W. Trouwborst G., Maljaars H., Poorter H., van Ieperen W., Harbison J., 2010. Blue light dose-responses of leaf photosynthesis, morphology, and chemical composition of *Cucumis sativus* grown under different combinations of red and blue light. J. Exp. Bot., 61(11), 3107–3117.

Hyeon-Hye Kim, Goins G.D., Wheeler R.M., Sager J.C., 2004. Stomatal conductance of lettuce grown under or exposed to different light qualities. Annals Bot., 94, 691–697.

Klein R.M., 1992. Effects of green light on biological system. Biol. Rev., 67, 199–284.

Morrow R.C., 2008. LED lighting in horticulture. HortSci., 43, 7, 1947–1950.

Mortensen L., Stromme E., 1987. Effects of light quality on some greenhouse crops. Sci. Hort., 33, 27–36

Okamoto K., Yanagi T., Kondo S., 1997. Growth and morphogenesis of lettuce seedlings raised under different combinations of red and blue light. Acta Hort., 435, 149–157.

Schuerger A.C., Brown C.S., Stryjewski E.C., 1997. Anatomical features of pepper plants (*Capsicum annuum* L.) grown under red light-emitting diodes supplemented with blue or far-red light. Ann. Bot., 79, 273–282.

Senger H., 1984. Blue light effects in biological system. Springer-Verlag, Berlin.

Sharkey T.D., Raschke K., 1981. Effects of light quality on stomatal opening in leaves of *Xanthium strumarium* L. Plant Physiol., 68, 1170–1174.

Sun J., Nishio J.N., Vogelmann T.C., 1998. Green light drives CO_2 fixation deep within leaves. Plant Cell Physiol., 39, 1020–1026.

Sun-Ja Kim, Eun-Joo Hahn, Jeong-Wook Heo, Kee-Yoeup Paek, 2004. Effects of LEDs on net photosynthetic rate, growth and leaf stomata of chrysanthemum plantlets in vitro. Sci. Hort., 101, 143–151.
Smith H., 1993. Sensing the light environments: the functions of the phytochrome family. In: Photomorphogenesis in plants. Kendrick R.E., Kronenberg G.H.M. (eds.). Kluwer Academic Publ., Dordrecht, 377–416.
Wojciechowska R., Kołton A., Długosz-Grochowska O., Żupnik M., Grzesiak W., 2013. The effect of LED lighting on photosynthetic parameters and weight of lamb's lettuce (*Valerianella locusta*). Folia Hort., 25/1, 41–47.
Yorio N.C., Goins G.D., Kagie H.R., Wheeler R.M., Sager J.C., 2001. Improving spinach, radish, and lettuce growth under red light-emitting diodes (LEDs) with blue light supplementation. HortSci., 36(2), 380–383.

REAKCJA SAŁATY NA ŚWIATŁO FLUORESCENCYJNE I ŚWIATŁO LED NA TLE ZRÓŻNICOWANEGO ŻYWIENIA ROŚLIN AZOTEM

Streszczenie. W dwu kolejnych doświadczeniach wazonowych prowadzonych w fitotronie z sałatą odm. Królowa Majowych badano wpływ zimnobiałego światła fluorescencyjnego (FRS) przy PPFD 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ i światła LED o barwie czerwono-niebieskiej przy PPFD 200 i 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ na przebieg fotosyntezy, plon, powierzchnię liści, SLA, zawartość barwników asymilacyjnych, N-ogólnego i azotanów. Rośliny doświadczalne rosły w torfie wysokim zasilonym na początku doświadczenia pożywką Hoaglanda o pojedynczej koncentracji. Po 10 dniach od zapikowania roślin utworzono 4 serie doświadczalne różniące się formą N dodanego do podłoża w dawce 420 mg (2N): 1) pożywka Hoaglanda (kontrola), 2) Hoagl + 2N-NO_3, 3) Hoagl + 2N-NH_4, 4) Hoagl + 2N-NH_4/NO_3. Uzyskane wyniki wykazały, że plon liści sałaty przy świetle FRS był wyraźnie wyższy niż przy świetle LED o PPFD 200, a zwłaszcza 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Liście spod światła FRS wykazywały istotnie cieńszą blaszkę liściową (SLA), niższą zawartość barwników, N- ogólnego i azotanów. Fotosynteza przebiegała intensywniej w świetle LED niż FRS. Zróżnicowane żywienie roślin N-NO_3, N-NH_4 i N-NH_4/NO_3 wywierało zbliżony wpływ na plonowanie i analizowane cechy liści niezależnie od rodzaju światła i poziomu napromienienia światłem LED. Lampy LED wydają się być obiecującym źródłem światła dla roślin, ale wymaga to jednak dalszych badań dotyczących dostosowania rozkładu spektralnego światła do ich wymagań.

Słowa kluczowe: jakość spektralna, *Lactuca sativa,* plon, powierzchnia liścia, SLA, barwniki asymilacyjne, N-całkowity, azotany, fotosynteza

Accepted for print: 15.09.2014