Usefulness of LED lightings in cereal breeding on example of wheat, barley and oat seedlings

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Abstract: The LED lightings in horticulture are becoming prevalent, due to their physical properties allowing reduction of electricity consumption and on modulation of light spectrum and frequency. At present, LED lightings are not widely used by cereal breeding companies despite the fact that use of greenhouses is very common. This is why, the present experiment was run to show the evidence of LED lightings usefulness in a cereal crops breeding processes. Spring wheat (*Triticum aestivum*, L.), spring barley (*Hordeum vulgare*, L.) and oat (*Avena sativa*, L.), one cultivar of each species, were used for the 9 week trial conducted in a greenhouse with strictly controlled temperature (22°C) and humidity (80%). As a light source, 4 LED illuminators along with a high-pressure sodium and xenon lamps and a natural sunlight in non-shadowed area of the same greenhouse were used. LED illuminators were characterized by relatively high ratio of blue/red radiation (0.6-1.3) to force the stem shortening, since cereal seedlings with such a growth habit are preferred in greenhouse cultivation of cereals. It was evidenced, that LED illuminators provided light suitable for cereals growth in a greenhouse, however each species had slightly different optimal light requirements. For wheat and barley the best impact on stem shortening and also on time to heading had a LED illuminator with high multi wave-blue radiation whereas on the leaves width the illuminator with lowest blue/red ratio. For oat seedlings a light source with highest light intensity and highest blue/red ratio seemed to be the most proper. Not much differences in seedlings growth and time to heading suggested that there is a chance for construction of one universal type of LED illuminator designed for greenhouse stages of cereal crops breeding.

Keywords: greenhouse, light emitting diodes, cost-effectiveness, *Triticum aestivum*, *Hordeum vulgare*, *Avena sativa*
DOI: 10.25165/j.ijabe.20191206.3646

Citation: Stefański P, Siedlarz P, Matysik P, Rybka K. Usefulness of LED lightings in cereal breeding on example of wheat, barley and oat seedlings. Int J Agric & Biol Eng, 2019; 12(6): 32–37.

1 Introduction

Modern cereal breeding is carried out under the strong time pressure. In classical breeding more than 15 years of time was needed to produce the new cereal cultivar, while today only about 5 years is required[1]. This acceleration results from changes in breeding tactics. At present, single seed descent (SSD) and doubled haploids (DH) are the main systems in which several generations per year are obtained using greenhouses. This paper focuses on assessment of suitability of LED lightings in facilities intended for cereal breeding.

Currently the high-pressure sodium lamps or fluorescent ones are most commonly used by cereal breeders. Sometimes xenon ones are used due to theirs energetic efficiency. Those lamps emit light that only in a small section of the electro-magnetic spectrum covers the photosynthetic demands of plants, it is because they have been designed to be friendly to the human eye. The spectrum of fluorescent lamps provides the energy captured mainly by chlorophyll *b* in the range of red light and in a much smaller scale by the antenna sensitive to the blue light, whereas the xenon lamp has quite rich blue light spectrum[2]. Almost half of the energy of those lamps is emitted in the spectral range that is not recognized by the chlorophyll antenna[3]. High pressure sodium lamps (HPS), so frequently used in greenhouses due to the high power, are in fact even less effective because they practically do not emit the blue light (450-470 nm) and their maximum efficiency consists an orange light (approx. 600 nm), which is not a very efficient energy source for the photosynthesis of green plants. An additional disadvantage is the high heat radiation resulting from their relatively low efficiency[2].

The idea of incorporating lightings built from light emitting diodes (LED) in greenhouses is becoming prevalent in horticulture[4]. Google search for the query “greenhouse grow LED” gave more than 2.5 million entries in January 2014, whereas in March 2016 more than 40 million. This results from the development of LED production technologies providing varieties of LED colors and from the economic benefits for users of such illuminators. The groundbreaking invention of efficient blue light-emitting diode was honored by Nobel Prize in physics in 2014[5]. The predominance of LEDs over current solutions is related to their physical properties, which determines a very low

Received date: 2018-07-17 **Accepted date:** 2019-09-23
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power consumption as compared to lighting systems commonly used in greenhouses[6]. Additionally light emitted by a single LED is in a very narrow range and lighting spectrum can be adjusted to the particular needs by combination of different LEDs[7]. Such an attribute can also have an influence on the reduction of the energy consumption[8]. Remarkable and important advantage, as compared to conventional HPS, is low inertia of LED illuminators, which causes that after lighting the LEDs gain almost immediately theirs full power. This trait enables a precise controlling using microprocessors[9]. Moreover, from the economic point of view, LEDs are the most efficient lightings and this is a key factor contributing to the growing demand for this type of light sources on the market[4].

The advantage of LEDs results from the possibility of any spectrum formation in LED illuminators. Two streams of the modulated blue and red light, providing radiation closely matching the chlorophyll antenna, supplemented by green light, are believed to reduce the operating costs of greenhouses. "Replacing high-intensity discharge lamps with LEDs is a catalyst for a fundamental change in plant lighting and we are on a steep learning curve to fully realize how to fully control LED technology in plant growth applications"[10].

The first experiment with the use of red LEDs in cereal cultivation was carried out in '90 of the last century. It was found that the use of blue light (obtained from fluorescent lamps, as blue LEDs have not yet been commercially produced that time), and red in the ratio of 1 : 9 enabled to obtain wheat yields comparable to those obtained using fluorescent lamps[11]. Although the scientific literature concerning photo-morphogenesis is rich[12], there is no systematic knowledge on methods of cultivation of cereal crops under the LED panels[13,14]. The main goal of our preliminary studies was determination of effects of different types of light sources on cereal seedlings growth.

2 Materials and methods

Genetically stable varieties of spring wheat (*Triticum aestivum*, L. cultivar Kamelia), spring barley (*Hordeum vulgare*, L. cultivar Radek) and oat (*Avena sativa*, L. cultivar Bingo) were used for the studies. Seeds were sown in 73 cell multi-plates propagation trays produced by Folmax (Warszawa, Poland), in 7 replications per each cultivar. The studies were conducted in a greenhouse with precisely controlled environments (temp. ±3°C and humidity ±5%) of Plant Breeding Strzelce Ltd., Co. Group IHAR in Strzelce, Poland (52°18′41″N 19°24′22.4″E). The experiment was started at Apr 27th in 2015 year and was conducted for 6 weeks. Multi-plates were placed in a greenhouse in which 4 different LED illuminators in parallel with sodium and a xenon lamp were installed. Under each of the illuminator the multi-plates were placed, based on the same pattern. The group of control plants was grown in the same greenhouse under the natural sunlight. Seedlings were grown at the mean temperature of about 22°C and 80% humidity. The following illuminators, including LED illuminators produced by Neonica, Sp. z o.o. (Łódź, Poland) and SpectroLight, Tomasz Braczkowski (Łódź, Poland) were used in the experiment: 1) High Pressure Sodium Lamp (HPS 150 W, power supply-Lumatek Electronic Ballast 250 W/240 V, reflector-Adjust a Wing, light bulb-Sunmaster); 2) Xenon Discharge Lamp (60 W, prototype of SpectroLight manufacturer); 3) Neonica GrowLED iluminator (100 W, prototype of Neonica manufacturer); 4) SpectroLight-1 LED illuminator (100 W, prototype of SpectroLight manufacturer); 5) SpectroLight-2 LED illuminator (100 W, prototype of SpectroLight manufacturer); 6) SpectroLight-3 LED illuminator (100 W, prototype of SpectroLight manufacturer).

At the initial stage of the experiment the intensity of light was measured from the distance of 1 m from the lamp at 3 points: centrally under a lamp as well as on the left and the right table edges. The results of measurements were averaged because they did not differ much from each other. The prototype-spectroradiometer produced by SpectroLight, Roman Braczkowski (Łódź, Poland), based on the Hamamatsu electronics module allowing the calculation of the desired parameters by McCamy method was used for measurements of the relative spectra distribution. All illuminators were installed in a way that ensured uniform light intensity on the surface occupied by multi-plates. The greenhouse chamber was overshadowed with black plastic to minimize the penetration of the sunlight and to indicate which illuminator is the best for proper growth of cereal seedlings. The seedlings were grown in 12/12 h day/night cycles from 7:00 to 19:00 and lightings were switched on for 12 h. The height of seedlings and width of the leaf were measured at 7 d intervals starting from 7th day after germination. The germination was carried out under the target illuminator. Statistical analysis: The experiment was run twice, in 9 week cycles, one after the other. During the first 4 weeks the measurements of seedlings growth rate were carried out. One-way Anova and LSD Student test were performed for $\alpha \leq 0.05$, using Statistica software.

3 Results and discussion

Before the experiment was started, the illuminators were compared on bases of light intensity and spectrum. Light intensity was expressed using two different units: Photosynthetic Photon Flux Density (PPFD) and illuminance. PPFD [μmol/m^2·s] is defined as number of photons of the photosynthetic active radiation (PAR), per square meter per second, whereas illuminance and luminous emittance measure the luminous flux per unit area and is expressed in lux [lx]. In photometry, this unit is used as a measure of light intensity as perceived by the human eye, according to the luminosity function in standardized model of human visual brightness perception (Ritchie 2010). As can be seen from the Table 1, the PPFD of used illuminators had the range from 77 to 157 μmol/m^2·s, whereas the luminous emittance had the eight-fold range, from 600 to 4900 lx.

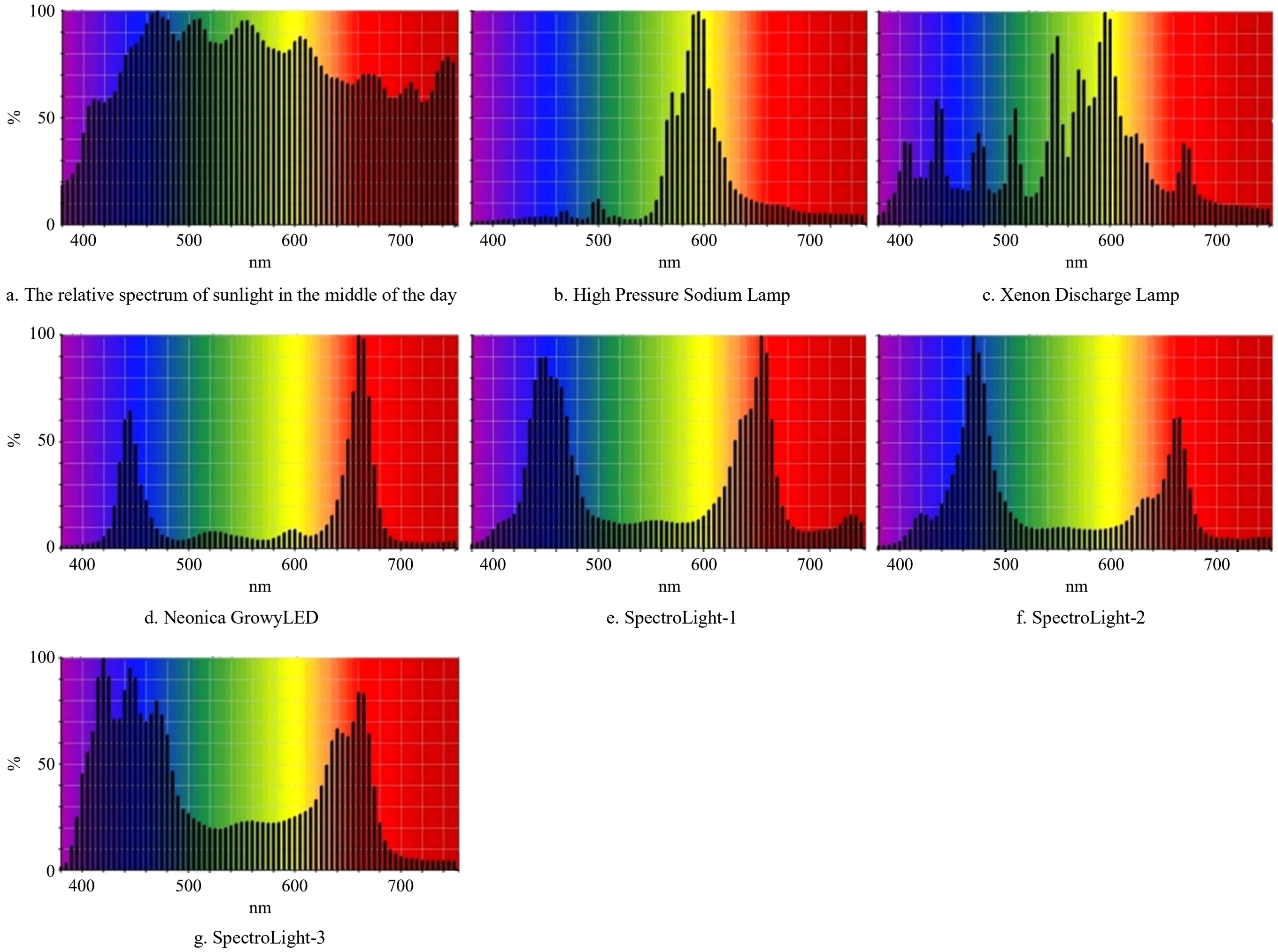
This is a consequence of the selective action of the human eye[15]. For plant breeding purposes the PPFD comparison is proper and one has to keep in mind that the assessment of light intensity by eye can be unreliable, if used for comparison of radiation generated by artificial light sources. The SpectroLight-2 LED illuminator had the highest PPFD whereas SpectroLight-1 gave the weakest light as expressed in [μmol/m^2·s]. The HPS lamp was weaker than SpectroLight-2 whereas the remaining lamps had similar PPFD, about 100 [μmol/m^2·s] (Table 1). As the light intensities of used illuminators differed, the relative spectral distribution of light sources differed as well (Table 1), what is important when considered from different points of view, i.e.: economic, physiological, sociological and environmental[15-18].

The spectrum of the visible part of the sunlight, measured outside the greenhouse, which was the control in present experiment, has the range from about 380 nm of violets bordering the high energy UV radiation, to about 780 nm of far red, neighboring the infrared. Its spectral distribution was characterized by variable proportions of particular waves changing not more than twice, dependently on the season, the time of the day and the cloud cover (Figure 1a). The artificial lights generated by illuminators had discontinuous spectra characterized by diverse proportions of particular waves (Figures 1b-1g). The high pressure sodium and xenon discharged lamp emitted heat radiation as the primary radiation, which was a great economic disadvantage of such a light sources[2]. The visible spectrum of the sodium lamp in 90% was in the range of yellow light (560-620 nm). No blue light and only small amount of the red light, which were directly captured by the chlorophyll antennas, were generated by such lamps.

Table 1 Light intensity measured from the distance of 1 m

Illuminator	Light intensity		Light spectrum characteristics (relative values)				
	[μmol·m^{-2}·s^{-1}]	[lx]	V/R	B/R	G/R	Y/R	DR/R
Control/ Mid-day Summer Sunlight	0.8-1.5 k	32-100 k					
High Pressure Sodium Lamp	138	850	0.04	0.12	0.15	2.04	0.20
Xenon Discharge Lamp	108	600	0.35	0.69	0.57	1.61	0.23
Neonica GrowyLED	105	2549	0.03	0.58	0.12	0.11	0.17
SpectroLight-1 LED	77	2300	0.1	0.98	0.22	0.20	0.19
SpectroLight-2 LED	157	4900	0.13	1.27	0.51	0.25	0.16
SpectroLight-3 LED	108	2650	0.49	1.14	0.37	0.33	0.10

Note: High Pressure Sodium Lamp (HPS 150 W), Xenon Discharge Lamp (60 W), Neonica GrowyLED, SpectroLight-1, SpectroLight-2, and SpectroLight-3. The illuminators characteristics is shown as the relative quantum ratios of ranges: violet 380-420 nm (V), blue 425-480 nm (B), green 485-540 nm (G), yellow 545-600 nm (Y), red 605-680 nm (R) and deep red 685-750 nm (DR).



a. The relative spectrum of sunlight in the middle of the day
b. High Pressure Sodium Lamp
c. Xenon Discharge Lamp
d. Neonica GrowyLED
e. SpectroLight-1
f. SpectroLight-2
g. SpectroLight-3

Figure 1 The relative spectral distribution of light sources used in the experiment

The xenon discharge lamp generated light with peaks across the whole spectrum of visible light. Although a lot of energy is emitted in the form of yellow-green light, also some blue and red lights was generated. The LED illuminators predestined for plant growing purposes should be characterized by spectra corresponding to absorbance maxima of the chlorophyll antennas, in ranges of blue and red light waves. The LED illuminators used in present experiment were characterized by two main peaks of blue and red lights. In Neonica GrowyLED the blue peak was nearly twice smaller than the red one, whereas SpectroLight illuminators were characterized by equal blue and red peaks as in SpectroLight-1, dominating single blue peak, in SpectroLight-2 and dominating triple violet-blue peak in SpectroLight-3 LED illuminator (Table 1, Figure 1d-1g). The illuminators differed slightly in deep red light

(685-750 nm), partially covering a range of far red (710-850 nm). The lowest share (10%) of deep red in red spectrum was detected under the SpectroLight-3 illuminator.

All LED illuminators used in present experiment were characterized by increased value of blue/red ratio as compared to typical horticulture LED illuminators characterized by 10%-30% participation of blue light in total spectrum[19]. Such an increased ratio of blue LEDs was presumed to force the shortest stem length since cereal seedlings with such a growth habit are preferred in greenhouse cultivation of cereals. Blue light morphogenetic signals are perceived by cryptochromes and results in inhibition of hypocotyl growth[20]. The ratio of different LEDs (mostly B, G and R) consist an important signal for the growth, development, and biosynthesis of secondary metabolites in plants. It was established that the supplemental green LEDs in combination with red and blue LEDs can improve lettuce growth[21,22], so it was the reason of green LED supplementation.

There is no doubt that the natural sunlight with its intensity and spectrum changing seasonally, matches the best plant requirements due to plant evolutionary adaptation to particular latitude. Artificial lighting should allow for a proper plant growth. Not too elongated cereal seedlings with wide leaves were considered as optimal when grown in the greenhouses. After 7 d of growth the wheat seedlings responded in a clearest way; the shortest stems were developed under the LED illuminator SpectroLight-3, characterized by rich blue spectrum and its relative intensity about 15% stronger than the red one. Whereas the wheat leaf was the widest in seedlings grown under the sunlight. Within the first week of the experiment barley seedlings did not respond to light characteristics while oat seedlings were most elongated under the xenon discharge lamp (Table 2).

After 14 d of growth the seedlings of wheat and barley became slightly elongated as compared to control, whereas the growth of oat seedlings became suppressed by artificial light, excluding Neonica GrowyLED characterized by lowest blue/red ratio. In opposite, the width of the oat leaves after 2 weeks under the artificial lights became and remained significantly restricted till the end of the experiment (Table 2).

Table 2 Comparison of average seedlings height and average leaf width of seedlings of spring wheat, spring barley and oat plants grown in the greenhouse under natural light (control) and in darkened part of the same greenhouse illuminated by artificial lightings

Illuminator	Wheat				Barley				Oat			
	Average seedlings height/mm		Average leaf width/mm		Average seedlings height/mm		Average leaf width/mm		Average seedlings height/mm		Average leaf width/mm	
7 d												
Control	184,7	bc	4,7	a	160,0	a	7,5	a	163,5	ab	5,8	a
High Pressure Sodium	183,6	bc	4,4	ab	170,0	a	6,5	b	159,0	b	4,9	b
Xenon Discharge	212,1	a	4,3	ab	173,0	a	7,5	a	182,5	a	4,9	b
Neonica GrowyLED	202,0	a	4,3	ab	173,0	a	7,4	a	171,5	ab	5,3	ab
SpectroLight-1 LED	192,5	ab	4,3	ab	166,5	a	7,3	a	171,5	ab	4,9	b
SpectroLight-2 LED	184,5	abc	4,2	b	160,5	a	7,0	a	158,0	b	4,9	b
SpectroLight-3 LED	170,0	c	4,4	ab	164,5	a	7,3	ab	152,5	b	5,1	b
14 d												
Control	320,8	c	4,6	ab	261,2	d	7,5	a	306,1	a	6,7	a
High Pressure Sodium	356,3	abc	4,7	ab	287,1	cd	6,9	ab	256,4	c	5,3	b
Xenon Discharge	336,9	abc	4,8	ab	351,4	a	7,5	a	305,7	ab	5,3	b
Neonica GrowyLED	374,5	ab	5,0	a	343,5	a	7,4	a	270,0	bc	5,3	b
SpectroLight-1 LED	362,1	abc	4,4	b	332,5	ab	7,3	ab	313,0	a	5,5	b
SpectroLight-2 LED	382,4	a	4,8	ab	303,0	bc	6,7	b	247,0	c	5,3	b
SpectroLight-3 LED	329,3	bc	4,5	b	316,6	abc	5,7	ab	266,6	c	5,3	b
21 d												
Control	401,1	b	6,5	a	332,0	cd	7,8	ab	360,0	d	10,0	a
High Pressure Sodium	494,5	a	5,1	b	346,2	bc	7,2	cd	377,0	cd	6,0	cd
Xenon Discharge	474,5	a	5,1	b	381,0	ab	7,5	abc	406,0	abc	6,3	bc
Neonica GrowyLED	487,5	a	5,4	b	406,5	a	7,4	bcd	435,0	a	5,9	cd
SpectroLight-1 LED	494,0	a	5,1	b	412,5	a	8,0	a	427,0	ab	6,7	bc
SpectroLight-2 LED	495,5	a	5,1	b	355,5	bc	6,9	d	357,0	d	5,3	d
SpectroLight-3 LED	460,5	a	4,9	b	398,0	a	7,5	abc	394,5	bcd	7,2	b
28 d												
Control	424,0	d	7,3	a	346,5	d	8,1	ab	395,0	d	10,0	a
High Pressure Sodium	566,5	ab	5,5	c	418,5	c	7,6	c	510,5	abc	7,0	c
Xenon Discharge	558,0	ab	5,8	bc	459,5	ab	7,8	bc	501,0	bc	7,3	c
Neonica GrowyLED	555,5	ab	6,1	b	472,0	a	8,4	a	543,4	ab	7,3	c
SpectroLight-1 LED	535,5	bc	5,8	bc	475,0	a	8,4	a	520,5	abc	7,5	c
SpectroLight-2 LED	585,5	a	5,8	bc	435,0	bc	7,1	d	473,0	c	5,6	d
SpectroLight-3 LED	517,5	c	5,8	bc	435,5	bc	7,8	bc	557,0	a	8,5	b

Note: The averages from 10 independent measurement were compared using t-Student test (LSD) for $\alpha \leq 0.05$.

In response to 21 d illumination by artificial light, wheat and barley elongation growth was faster as compared to sunlight, whereas wheat leaf width was suppressed by all artificial lights and barley by all but SpectroLight-1. The oat seedlings elongation was suppressed by all but SpectroLight-1 artificial lightings and leaves width by all artificial illuminators (Table 2).

At the end of the 4th week (28 d) wheat seedlings grown under the SpectroLight-3 was 20% longer than in those grown in the sun, while under the SpectroLight-2 the stem was 40% longer than in control even though that illuminator had the strongest light intensity and the highest blue/red ratio. Interestingly, wheat plantlets grown under the high pressure sodium lamp were not the shortest at all, as expected at the start of the experiment. Barley seedlings responded to artificial light partially different. Under high pressure sodium lamp seedlings were the shortest among those grown under artificial lighting (but c.a. 1/5 longer than under natural light) followed by 5% in average longer seedlings grown under both: SpectroLight-2 and SpectroLight-3. It should be noted that, in opposite to wheat, seedlings grown under the SpectroLight-2 were equal to that grown under SpectroLight-3. Additionally the width of barley leaves grown under the Neonica GrowyLED and SpectroLight-1 were wider than in control (Table 2). Oat seedlings had the shortest (under artificial lighting) stem and at the same time the narrowest leaves when grown under SpectroLight-2, whereas the SpectroLight-3 influenced the longest stem formation and quite wide leaves (only 15% narrower than leaves from control conditions).

Detected differences in seedling growth were in parallel with the time of heading. The shortest time (58 d), was needed by control barley plants as well as by those grown under high sodium pressure lamp (Table 3). The longest period (65 d), was taken by wheat plants grown under SpectroLight-2 LED illuminator. Control wheat plants needed one day more to heading than control barley, whereas those grown under SpectroLight-3 and Neonica GrowyLed needed 2 d more. Wheat grown under SpectrLight-1 needed 61 d to head emergence and under high sodium pressure and xenon discharge lamps 62 d. Barley responded to grow under xenon discharge lamp and SpectroLight-2 by emerging in 60th day after sowing. Neonica GrowyLED influenced on barley heading in 61st whereas SpectroLight-1 in 62nd day after sowing. For oat number of days to head emergence was: 59 for control and SpectroLight-2, 60 for conventional lamps, 61 for SpectroLight -1 and -3, and 62 for Neonica GrowyLED (Table 3).

Table 3 Number of days to heading of spring wheat, spring barley and oat grown in the greenhouse under natural light (control) and in darkened part of the same greenhouse illuminated by artificial lightings

Illuminator	No of days to heading		
	Wheat	Barley	Oat
Control	59	58	59
High Pressure Sodium Lamp	62	58	60
Xenon Discharge Lamp	62	60	60
Neonica GrowyLED	60	61	62
SpectroLight-1 LED	61	62	61
SpectroLight-2 LED	65	60	59
SpectroLight-3 LED	60	59	61

As it can be seen from presented results, the requirements for light spectrum and intensity are changing with plant age. Preferable rapid leaf area expansion, needed for most effective light photons capture, should go along with prevention of excessive stem elongation[23]. The SpectroLight-3 illuminator was the most effective during the 1st week of wheat seedlings growth as compared to Control, while the Neonica GrowyLED - for oat seedlings, which grew in the same way as in the sun. Those illuminators differed mainly in quantity and in spectrum of blue light (Table 1). The growth rate of barley seedlings were not differentiated between control and studied illuminators at the beginning of the experiment. Further weeks of seedlings growth gave variable results. Considering days to emergence as well as seedlings elongation growth, it seems that SpectroLight-3 was optimal for wheat and barley; whereas, SpectroLight-2 for oat growing.

The quantitative aspects of blue light spectrum and light intensity have to be considered to understand the growth dynamic of cereal seedlings under LED illuminators[24]. Additionally, the ratio of red to far red, affecting the phytochrome-mediated responses should be taken into account as well[23]. A thorough understanding of those interactions is essential for construction of light sources optimal for cereal plant growth and development[14,24]. Obtained results do not discredit LEDs as light sources in greenhouses dedicated for cereal breeding.

4 Conclusions

Tested LED illuminators provided light suitable for crop growth in greenhouses in the framework of breeding processes, however each species had slightly different light requirements for optimal growth.

For wheat and barley the best impact on stem shortening and also on time to heading had SpectroLight-3 LED illuminator with high multi wave-blue radiation whereas on the leaves width the illuminator with lowest blue/red ratio (NeonicaGrowyLED).

For oat seedlings SpectroLight-2 LED illuminator with highest light intensity and blue/red ratio, seemed to be the most proper.

Acknowledgements

This work was supported by the National Centre for Research and Development, Poland (grant PBS3/B8/19/2015). Results are planned to be a part of PhD thesis of Piotr Stefański, MsC. Eng. The authors declare any actual or potential conflict of interest.

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