Efficiency of LED lamps used in cereal crop breeding greenhouses

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Abstract: LED lamps, which are becoming prevalent in horticulture, are also being installed in greenhouses dedicated to cereal crop breeding. However, the issue arises with the real efficiency of LED lamps. Besides high-budget programs, the smaller breeding companies in Poland face problems concerning the plant growth under LED lamps and the real costs of their exploitation. The experiment was conducted to compare seven different LED lamps and a high-intensity discharge (HID) lamp with a high-pressure sodium lamp (HPS) used as a control. For studies, two varieties of wheat, barley, and oat species were used. The plants' growth rate was assessed based on elongation growth and earing time. Plants' physiological conditions were evaluated using chlorophyll *a* (Chl *a*) fluorescence measured on dark-adapted leaves. The light spectra and intensities of tested lamps in parallel with electricity consumption were also recorded. The results showed that 1) LEDs' physical properties and luminaire construction influence the amount of electricity consumed; 2) the cereal crop species differ in lighting requirements. The less light-sensitive was oat opposite barley, with wheat of moderate sensitivity; 3) LED-6 lamp (PlantaLux S.A, Lublin, Poland) based on white diodes enriched by blue ones was the most cost-efficient and most optimal for studied species.

Keywords: greenhouse, light-emitting diodes, cost-effectiveness, cereal, *Triticum aestivum*, *Hordeum vulgare*, *Avena sativa*
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1 Introduction

Sunlight is one of the most critical factors that guarantee plants' growth and development, however in northern latitudes, from the mid-autumn to mid-spring, there is a lack of light photons of specific spectral characteristics and intensity to ensure the proper development of plants. Therefore, greenhouses used for horticulture and those used for cereal breeding must be lighted. The commonly used high-pressure sodium lamps (HPS) mainly emit yellow light, which is less effective than blue and red lights for plants' live processes. The light of blue color at wavelengths 465 nm and 454 nm, and red at wavelengths 642 nm and 662 nm is absorbed by chlorophylls (Chl) *a* and *b*, respectively. Chl *a* and Chl *b* consist of about 65% of chlorophyll antennas, and the rest is constituted by the yellow xanthophylls (29%) and orange carotenes (6%)[1]. Among other photoreceptors that allow plants to respond to environmental stimuli, there are two main types: cryptochromes, receptors of UV-A radiation and blue light, and phytochromes, receptors of red and far-red lights. Cryptochrome absorption maxima are in the range 380-440 nm depending on the chromophore composition[2]. The red light activates phytochromes, and far-infrared deactivates them. Besides the red light-sensitive antennas, the phytochromes also have blue light receptors. They are necessary not only for cryptochromes to be activated but also for regulating flowering, circadian rhythms, seed germination, seedling elongation, leaf size, shape, and number, as well as chlorophyll synthesis[3]. Thus, the replacement/ supplementation of the sunlight in the autumn-winter period by artificial light sources is a complex and essential problem[4,5].

The costs of greenhouses exploitation influence the general expenses of plants produced there. Since the greenhouses are used intensively by crop breeding companies, it also affects having a new variety. From the time, when the traditional population breeding lasted about 12 years to develop variety, was replaced in most cases by methods based on pure, genetically stable lines (derived by 5-6 generations of plants from single seeds (ssd)) or by methods based on doubled haploids (DH), the importance of cereals cultivation in greenhouse increased. When shortening the breeding time to about 7 years, the importance of a greenhouse cannot be overestimated[4,6]. Recently introduced protocols of speed breeding, enabling the growth of six generations of spring crops per year with constant greenhouse usage, pose new challenges for LED lighting suppliers[7]. So it becomes evident that such companies and the breeders who offer the best varieties bred with low financial outlays gain the advantage on the market. Breeders ahead of the competition are successful in today's agriculture. LED lighting in greenhouses might be a competitive advantage despite the relatively high cost of LED lamps installation[8].

The introduction of changes in lighting systems to the workflow of the breeding company requires monitoring of plants' physiological reactions so that in the case of high stress detected, it would be possible to react quickly. The physiological state of

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plants can be monitored by measurements of Chl *a* fluorescence, low costs, easy to carry, non-destructive, and high throughput technique. Chl *a* fluorescence is a natural phenomenon, characteristic of all photosynthetic organisms, which results from re-emitted, excess light photons. All disturbances detected in fluorescence reflect changes in the structure of chloroplast macromolecules. Those changes arise under the influence of adverse environmental stimuli and are related to redox regulation in photosynthetic organisms and energy transformation suppression in Photosystem II[9-12]. The fluorescence data interpretation is based on flux theory[13]. Data from the fast, uprising part of the Chl *a* fluorescence curve (OJIP) registered on dark-adapted leaves are recalculated into parameters, which describe different phases of light energy conversion[13-15]. Among numerous parameters, some are widely used: Fv/Fm is a variable fluorescence for dark-adapted leaves and reflects the maximum quantum yield of photosystem II (PSII); Fv/Fo is a parameter reflecting the size and number of active reaction centers of photosynthetic apparatus; (1−Vj)/Vj is a parameter which reflects the forward electron transport towards PSI; parameter Area is an area over the fluorescence OJIP curve integrated between Fo (fluorescence at starting point of illumination) and Fm (maximal fluorescence).

This article presents the efficiency of LED lighting usage in a cereal crop breeding company greenhouse. Seven LED illuminators, the high-intensity discharge (HID) lamp, and a control the high-pressure sodium lamp (HPS) were used. Separate sub-meters assessed the total amount of electricity used and the rate of plant growth, development, and plant physiological status detected by measurements of Chl *a* fluorescence.

2 Materials and methods

2.1 Materials for studies and plant growing conditions

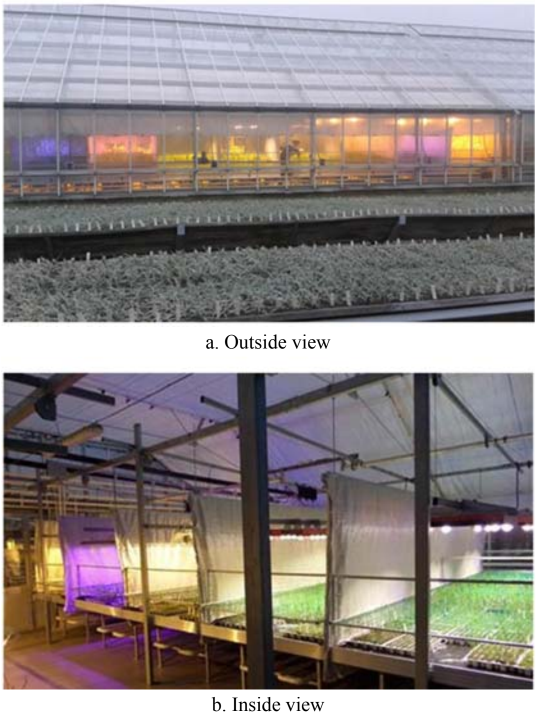
Genetically stabilized commercial cultivars were used: spring wheat Harenda and Tybalt (*Triticum aestivum* L.), spring barley Radek and Soldo (*Hordeum vulgare* L.), and oat Bingo and Navigator (*Avena sativa* L.). The experiment was conducted from October 20, 2016, to March 1, 2017. Seeds were sown in 73 cell multi-plates filled with peat soil in three replicates of each species. The tests were carried out in the greenhouse of Plant Breeding Strzelce Ltd. (HRS), Poland (52°18′41″N, 19°24′22″E). Plants were grown at the mean temperature of (22±3)°C and 80% humidity a day/night cycle of 12 h/12h from 7 a.m. to 7 p.m. The rate of plant development was determined based on plant height at fully developed flag leave, according to the scale used in UE countries to identify the phenological development stages, BBCH 37. The average value from 10 plants measured was given. The time to heading was determined in days based on first ear total formation in each repetition of the experiment.

2.2 Chlorophyll *a* fluorescence measurements

Chlorophyll *a* (Chl *a*) fluorescence was measured using PocketPEA portable fluorometer (Hansatech Instruments, King's Lynn, Norfolk, UK) for 10 plants/genotype in each replication[15]. Fluorescence was induced by saturating, red actinic light with 3.500 μmol/(m^2·s) energy. The first 3.0 s of transient fluorescence, covering more than its exponential growing part was registered with time intervals increasing from 10 μs within the first 300 μs of the measurement up to 100 ms intervals for times longer than 0.3 s. Measured parameters were Fo≈F(50 μs) (F(50 μs) is the minimal fluorescence); F1, F2, F3, F4, and F5 are the fluorescences at times: 0.05 ms, 0.10 ms, 0.30 ms, 2.0 ms, and 30 ms, respectively, after the start of actinic illumination Fo; values at 0.30 ms, 2.00 ms, and 30.00 ms responds to fluorescence at *K*, *J*, *I* points of inflections, on fluorescence transient curve; Fm=Fp represents the maximal recorded fluorescence; Tfm is the time to reach the maximal fluorescence Fm, ms; Area is the total complementary area between the fluorescence induction curve and Fm of OJIP curve. Parameters calculated and listed by PocketPEA software: Fv is the maximal variable fluorescence calculated as (Fm−Fo); Fv/Fm is the force of the light reactions; RC/ABS represents the number of active reaction centers per absorption; (1−Vj)/Vj represents a measure of forwarding electron transport; PI_{ABS} is the performance index[14]. Measurements were done at the BBCH37 phenological stage.

2.3 Lighting conditions

Nine lamps differing in the light spectrum were used in the experiment: seven LED lamps, high sodium pressure (HPS), and high-intensity discharge (HID) lamps. The LED lamps used were nominal 100 W prototypes of Neonica Ltd., Lodz, Poland, SpectroLight (Lodz, Poland), and PlantaLux (Lublin, Poland). The HPS used was 150 W (power supply-Lumatek Electronic Ballast 250 W/240 V, reflector-Adjust a Wing, light bulb-Sunmaster); the high-intensity discharge (HID) lamp was 60 W, prototype of SpectroLight (Lodz, Poland) manufacturer. The illuminators have been installed to ensure uniform light intensity on the surface occupied by multi-plates. The greenhouse chambers were shaded with a fabric to minimize daylight penetration. The multi-plates were placed under each illuminator based on the same pattern (Figure 1).



a. Outside view

b. Inside view

Figure 1 View of the lighted LED lamps greenhouse where the experiment was run the outside view and the inside view show cereal plants grown in multi-plates

At the initial stage of the experiment, the intensity and spectrum of light were measured centrally under each lamp from a distance of 0.9 m, using a spectroradiometer (GL-SPECTIS 1.0 touch) manufactured by GL-Optic Ltd. (Puszczykowo, Poland). The recorded data were processed using dedicated software (GL-SPECTRO soft). Since the LED lamps were prototypes, their characteristics in the Results section were given encoded as LED-1 to LED-7, not assigned to particular manufacturers.

Illuminators light brightness (lx), color temperature (CCT, K), radiance (W/m^2), photosynthetic active radiance (PAR, W/m^2), photosynthetic photon flux density (PPFD, μmol/(m^2·s)), the peak of the spectrum maximum (nm) and its relative value (relative units, rel. U) were recorded along with the spectrum of light sources used. The ratios of PPFD (μmol/(m^2·s) in the ranges of violet (340-430 nm), blue (431-500 nm), green (501-550 nm), yellow (551-590 nm), red (591-700 nm) and deep red (701-750 nm) were calculated on bases of spectrum integration using GL-SPECTRO soft. The electric power usage was measured by separate power consumption sub-meters and expressed in W used throughout the lamp usage, i.e., from seed germination to full first ear formation.

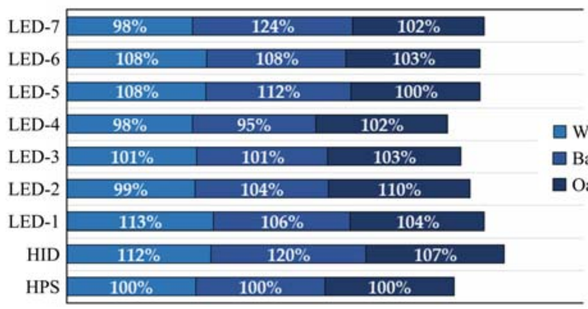
2.4 Statistical analysis

Statistical calculations were performed with Statistica® 12 package. Differences between Chl *a* parameters were evaluated based on a one-way analysis of variance and post hoc Tuckey test with $p \geq 95\%$. In contrast, parameters of plant growth were assessed by standard deviation. Because plant breeding workflow is applied to many genotypes simultaneously, the data collected for cultivars have been averaged and analyzed within species.

3 Results and discussion

3.1 Effect of LED lighting on plant elongation growth and phenology

Three cereal species were used for the studies: wheat, barley, and oat. The comparison of elongation growth under illuminators: high-pressure sodium (HPS)-control lamp, as well as high-intensity discharge (HID) and LED-1 to LED-7 lamps, revealed that plants grown under the majority of lamps were higher than under HPS-control lamp (Figure 2, Table A1). With its daily and seasonal intensities and spectra fluctuation, the natural sunlight is the best for proper plant growth and development due to plant evolutionary adaptation to particular light quality, resulting from the latitude[16]. The radiation emitted by the HPS lamp consists mainly of thermal radiation, and in the visible range, 90% of yellow one is not directly absorbed by chlorophyll antennas. The HPS nearly does not generate blue light and only a tiny share of red light[17,18].



Note: HID and LED-1 to LED-7 lamps were compared with the HPS lamp (used as a reference (100%)) in the effects on elongation growth of wheat, barley, and oat (in BBCH 37 growth stage). The absolute values of plant height (mm) are listed in Table A 1 of Appendix.

Figure 2 Comparison of elongation growth of wheat, barley, and oat plants which were grown under different illuminators

However, the HPS lamp was used as a control since it is currently proven and most often used type of illuminator in greenhouses of cereal breeding companies. In the case of wheat, the longest plants compared to HPS (control) were obtained under HID and LED-1 lamps (about 12% longer, whereas a similar growth rate was detected under lamps LED-2, LED-3, LED-4, and LED-7 lamps. The growth rate of barley plants under LED-3 and LED-4 lamps were similar to the growth rate of control. Barley plants grown under other illuminators were longer, even by 20% under HID and LED-7, Whereas oat plants were less sensitive to light spectrum and intensity. Differences in elongation growth were below 10% in all cases. In general, cereal plants grown under HID and LED lamps were satisfactory for breeding purposes because of the ease of care, although plants were toller than those produced under HPS. Not elongated cereal plants with wide leaves were considered optimal when grown in greenhouses under a single seed descent (ssd) regime[19]. It is crucial to obtain homozygotes from crossbreeding as quickly as possible, and single seeds produced by plants, are enough to receive the next inbred generations.

The comparison of the time to form the first ear revealed that none of the illuminators used at the regime of day/night length of 12 h/12 h speeded up the heading stage (Figure 3, Table A2).

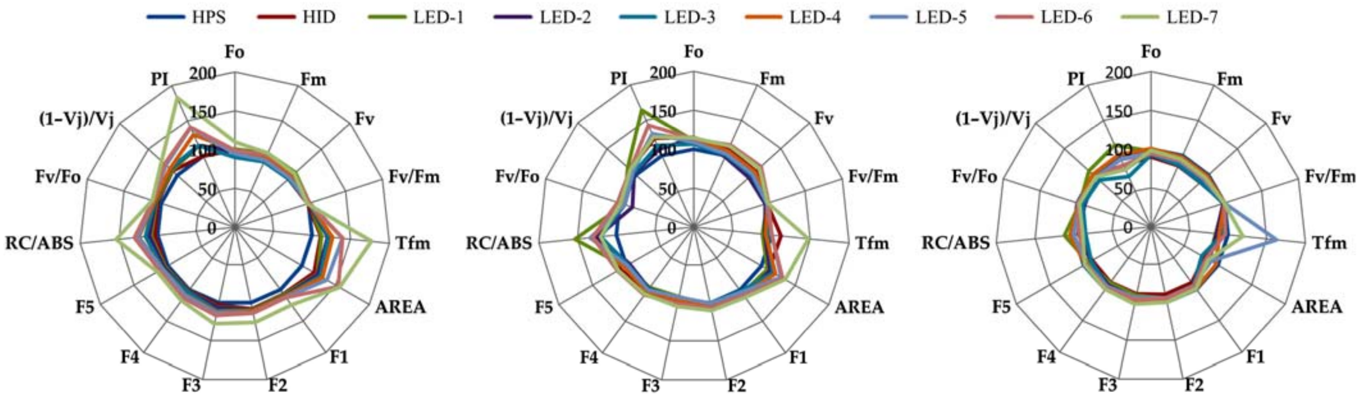
Note: HID and LED-1 to LED-7 lamps were compared with the HPS lamp (used as a reference (100%)) in the effects on time to reach the heading stage of wheat, barley, and oat species. The absolute values of time (days) are listed in Table A2 of Appendix.

Figure 3 Comparison of the time to reach the heading stage of wheat, barley, and oat plants which were grown under different illuminators (%)

Again the oat plants seemed to be the less sensitive to light used. LED-1 to LED-3 lamps did not change the oat plants' earing time compared to HPS. In contrast, LED-4 to LED-6 as well as HID lamps elongated it by about 5%. Wheat plants reacted to LED-2 to LED-6 lamps by elongation of time to earing by about 5%-7%, LED-1 by 11%, and HID lamp by nearly 20%. Barley plants were the most sensitive to light spectra with time to earing elongation by 10%-20%. The LED-7 lamp caused the largest earing time extension with the most substantial influence on wheat (time to earing 27% longer) and slightly weaker in case of barley and oat (time to earing about 20% longer): with 89 d to earing in case of wheat plants and 82 d in case of oat vs. 70 d under HPS. In the case of wheat, the most similar times to ear formation were detected under LED-4 and LED-6 lamps: 73 d and 74 d, respectively (Table A2). In general, wheat, oat, and barley cultivation, in standard ssd workflow under HPS, required 70 d to get the first fully formatted ear in case of wheat and oat and 76 d in case of barley. Usage of LED lamps elongated the time to earing by 4%-27% in wheat and 0-17% in oat and 7%-20% in barley; under LED-7 lamp development of plants of all species was the slowest (Figure 3, Table A2).

3.2 Influence of LED lighting on Chl *a* fluorescence

In general, the physiological condition of plants grown under different light sources was good, as detected by chlorophyll *a* (Chl *a*) fluorescence parameters calculated from data collected during 3 s. Measures performed on previously darkened leaves (Figure 4, Table A3). The primary and commonly used parameter Fv/Fm (force of light reactions) had values around 0.8, independently from the light source used and regardless of the species; not statistically differed by light sources in wheat. That confirms the good physiological state of plants[12]. In the case of oat plants, which did not react much to lighting sources by a fluctuation of growth rate and time to earing change, the fluorescence parameters did not fluctuate. The exception was Tfm (time to reach maximal fluorescence) 60% longer under LED-5 and 20% under LED-7 lamp. Results obtained for wheat were more diverse, with the most visible influence of LED-7. Differences in Tfm and Area, visible on the radar charts, were not significant, related to the large variance of those parameters (Figure 4, Table A3). Among the parameters of Chl *a* fluorescence, the time needed to reach the fluorescence maximal value (Tfm) was elongated, which is a symptom of some disturbances along the electron transfer chain in chloroplasts[11,20] and by that increased variance value. The index of plant performance (PI) and the number of active centers in light antennas (RC/ABS) increased by 80% and 50%, respectively, in wheat leaves and about 50% in barley. Lamps LED-5 and LED-6 also influenced the increase of most parameters of wheat leaves but to a lower extent. Chl *a* parameters detected in barley leaves varied in ranges±10% as compared with HPS lamp, beside RC/ABS and PI reaching values 50% higher.



a. Wheat b. Barley c. Oat

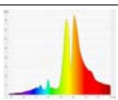
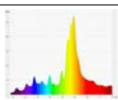
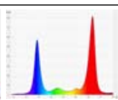
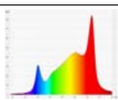
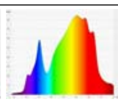
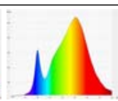
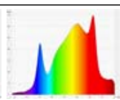
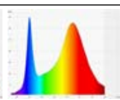
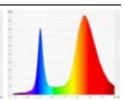
Note: HID and LED-1 to LED-7 lamps were compared with the HPS lamp (used as a reference (100%)) in the effects on Chl *a* fluoescnce parameters detected for wheat, barley, and oat species, Chl *a* fluorescence was measured on dark adapted leaves of plants in shooting stage. Presented values were calculated on bases of independent 10 measurements. The values of Chl *a* parameters and post hoc Tuckey test evaluations are listed in Table A3 of Appendix.

Figure 4 Comparison of the Chl *a* fluorescence parameters of wheat, barley, and oat plants which were grown under different illuminators

3.3 Characteristics of light sources

Seven different LED lamps were used in the experiment, with set assumptions to be suitable for the cultivation of cereals and to have the electric power consumption as small as possible. Such assignment resulted in noticeably different spectra and energy of light radiation of tested lamps (Table 1, Table A4). The most bright for the human eye, lights (>23 000 lx), were generated by LED-2, LED-3, and LED-4 lamps, about twice higher than other lamps, including HPS. The brightness of LED-1 was low (4800 lx). The color temperatures of light generated by all illuminators were in the range 1600-3400 K, with no determined value for LED-1 lamp due to the 2-band (blue and red) spectrum. The light radiance of LED-2 to LED-4 was the highest (about 90 W/m^2) and HID was the lowest (25 W/m^2). Whereas, the photosynthetic active radiation (PAR), which depends on the light spectrum, was a bit different, the highest only in the case of LED-2

Table 1 Characteristics of light sources used in this study

Characteristics		HPS	HID	LED-1	LED-2	LED-3	LED-4	LED-5	LED-6	LED-7
Parameter	Light spectra									
	Brightness/lx	13 468	7930	4807	25 212	23 573	28 418	17 792	13 112	11 646
	Color temp/K	2160	2623	--	3170	3379	3280	3431	2819	1676
	Radiometric/W·m^{-2}	42	25	52	98	84	90	64	58	66
	PAR/mW·m^{-2}	25	15	41	65	54	56	40	39	45
	PPFD/μmol·m^{-2}·s^{-1}	192	106	241	465	381	413	288	256	297
	Peak/nm	604	597	667	669	604	604	604	454	629
	Peak value/(rel. U)	428	274	822	843	421	537	348	351	485
PPFD ratios	R/V	55.23	14.29	20.63	76.92	15.95	49.52	44.03	33.93	56.17
	R/B	10.85	4.13	2.73	5.41	3.97	4.08	4.16	3.08	4.55
	R/G	12.41	5.04	12.65	4.73	3.48	3.09	3.51	5.94	19.77
	R/Y	2.13	5.04	12.65	4.73	3.48	3.09	3.51	5.94	19.77
Radiometric ratios	R/V	21.02	4.89	10.90	31.17	7.90	21.25	17.94	13.91	23.35
	R/B	8.09	3.04	1.90	3.88	2.88	2.97	3.00	2.22	3.24
	R/G	10.66	4.26	10.21	3.89	2.89	2.58	2.91	4.97	16.47
	R/Y	1.93	1.47	19.49	3.43	2.55	2.20	2.64	3.77	7.79

Note: HPS and HID lamps along with LED-1 to LED-7 lamps were used in a greenhouse experiment. The detailed characteristic of light spectra in color ranges is given in Table A4 of Appendix. PAR: Photosynthetic active radiance; PPFD: Photosynthetic photon flux density. R represents the red light; V represents the violet right; B represents the blue light; G represents the green light.

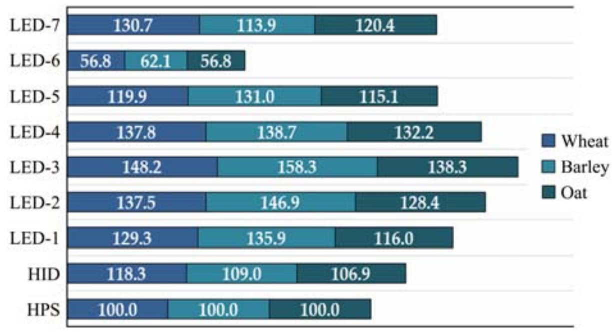
(65 W/m^2) and about 25% lower for LED-3 and LED-4, with the lowest value of HID lamp. LED-1, LED-5, LED-6, LED-7 generated PAR of about 40 whereas HPS was 25 W/m^2. The values of photosynthetic photon flux density 234 (PPFD) were in line with PAR values: the highest (465 μmol/(m^2·s)) for LED-2, about 10% and 20% lower for LED-3 and LED-4. Whereas the PPFD of the HPS lamp was about 200 and LED lamps (1, 5, 6, 7) were in the range 240-300 μmol/(m^2·s). The main peak of the light spectrum of all but one (LED-6) lamp was in the range of red light (~600 nm), whereas the LED-6 spectrum peak was in the range of blue light (~450 nm) (Table 1).

Characteristic of light spectra based on PPFD ratios in ranges of main light colors (violet V: 340-430 nm), blue (B: 431-500 nm), green (G: 501-550 nm), yellow (Y: 551-590 nm and red R: 591-700 nm) revealed also the differences between lamps. PPFD of red light was in the range of 50-280 μmol/(m^2·s) (Table 1, Table A4). Consequently, the proportion of red: blue PPFD was about 3:1 in spectra of LED-1 and LED-6, whereas other LED lamps, along with the HID lamp, contained about fourfold higher red PPFD than the blue one. HPS spectrum contains a small amount of blue and green PPFD, so the red: blue and red: green ratios were high (>10). Similarly, LED-1 and LED-7 contained a small share of green light, with red: green ratios higher than in HPS, in the case of LED-7 up to 20. In LED-2 to LED-6 lamps spectra and HID one, the red: green PPFD ratio was in the range of 3-5. In all lamps, except HPS, the red: yellow ratios were the same as red: green ones; in the HPS spectrum, the red PPFD was twice the yellow one. PPFD of violet light was tens of times smaller than the red one. Light proportions based on radiometric values had a similar layout but different number values. The red light radiometric intensity was in the range of 10-50 W/m^2 (Table 1, Table A4) with the proportion of red: blue from about 1:1 in the spectrum of LED-2, 2:1 in LED-1, 8:1 in HPS, and about 3:1 in other LED lamps. The radiometric intensity of green light was 3-4 fold lower than red once generated by illuminators: HID and LED (LED-3 to LED-7). In HPS and LED-1 green light, the radiometric intensity was 10-folds lower, and in LED-7 ones 16-times lower. Besides the LED-1 lamp for which the red:yellow ratio was 19:1 and LED-7, characterized by proportion 8:1 spectra of others, had the higher amount of yellow light in the spectrum, for HPS and HID were 1.9:1 and 1.5:1, respectively. The spectra of LED (LED-2 to LED-6) had about red:yellow of 3:1 radiometric intensity and LED-7 was 8:1.

3.4 Comparison of energy consumption by light sources during the experiment

Total energy consumption of tested lamps, measured during the time from seed germinations to the first ear appeared, differed (Figure 5, Table A5). The highest electric power consumption was generally associated with barley cultivation: LED-1 to LED-5 lamps, besides the LED-3, used about 200 kW, whereas LED-3 used 267 kW. The HPS, HID, and LED-7 used 170-190 kW. The most economical was the LED-6 lamp, which used 105 kW during barley cultivation. For wheat and oat plants, similar amounts of electricity were needed. The less efficient LED-3 lamp used 230 kW, and the most efficient LED-6 lamp used only 88 kW. Compared with HPS the LED-3 lamp was about 50% less efficient, whereas LED-6 was about 40% more efficient than HPS.

Artificial light generated by LED illuminators may not necessarily have a continuous spectrum[21]. Depending on the type and manufacturer, it can have different proportions of individual wave ranges. Continuous spectrum diodes are used due to the photomorphogenic properties of green light and also due to the greenhouse service comfort[22,23]. The spectrum generated by such LED lamps is slightly similar to the spectrum of sunlight, and its enrichment by blue and red peaks should contribute to better energy usage in photosynthesis[24]. The share of yellow light, outside the light range directly absorbed by chlorophyll antennas and dominant in commonly used HPS lamps[25], is also aimed at making the spectrum of the LED light source similar to HPS, which works well in greenhouse plant cultivation. However, the HPS lamp also generates thermal radiation, and by that temperature increases in a small area, mainly between the lamp and the top of grown plants[18]. Such increases might positively influence plant development[26]. Light has been an important factor in plant growth and end-product quality[25,27-31]. Recent reports indicate that the red-yellow-blue spectrum in lettuce cultivation gives 2-3 times acceleration of leaf growth and dry matter[29]. At the same time, the spectrum of the “white LED” covers the green light range, with the photomorphogenic role, which is important for the proper growth and development of plants[22]. The continuous spectrum generated by the “White LED” has been enriched with a blue band recognized by chlorophyll antennas and cryptochromes to inhibit the hypocotyls elongation growth[2,32]. Light generated by all tested illuminators affected plant length and time to reach the first ear negatively in the case of wheat and barley; oat plants nearly did not react to light quality, whereas barley plants reacted the strongest.



Note: HID and LED-1 to LED-7 lamps were compared with the HPS lamp (used as a reference (100%)) in power consumption for wheat, barley, and oat species. The electric power consumption (kW·h) was measured by separate sub-meters during the entire experiment from seed germination to the first complete ear formation and is presented in Table A5.

Figure 5 Comparison of the electric power consumption by illuminators (%)

On the basis of the time of first ear formation, which should be as short as possible and most uniform between studied species, the LED-4 lamp should be chosen as the best, since under other lamps, more significant differences between studied species were detected. At the same time, the LED-7 lamp should be unconditionally rejected from the list of potential cereal breeding greenhouse illuminators due to the radical extension of time needed for the first ear formation. However, as in the LED-7 case, the evaluation is final; in the case of LED-4 (or any other lamp under which plants growth is satisfactory), the electric energy consumption should be considered. Under such circumstances, only LED-6 lamps are acceptable for the cereal crop breeding greenhouse. This lamp is exceptional among those tested because only its spectrum has a peak at 454 nm in the range of blue light, which is precisely a wavelength absorbed by Chl *b*. The blue peak is narrow, so the red: blue PPFD ratio is about 3. Obtained results are complex and require further studies using i.e., Taguchi method of workflow optimization, which has been used successfully to improve the workflow of double haploid plants generation[33].

4 Conclusions

1) In this study, savings in electricity consumption by replacing HPS with LED lamps emerged from the physical properties of light-emitting diodes. However, it is also influenced by luminaire construction. In our experiment, the real energy consumption by LED lamps was higher than that declared by the lamp producer in most cases and in some cases exceeded the power consumption of HPS. Lamp testing by connecting it to an individual electricity meter could be profitable.

2) In this experiment, the most energetically efficient was the LED-6 lamp (PlantaLux S.A, Lublin, Poland), based on a white diode with a light spectrum enriched by a blue diode.

3) The radiometric (W/m^2) ratios of colors in the lamp LED-6 light spectrum were: red/violet 13.9, red/blue 2.2, red/green 5, red/yellow 3.8 (for details see Table 1).

4) The cereal crop species differ in lighting requirements. The less light-sensitive was oat in opposite to barley, the most sensitive, with wheat of moderate sensitivity; characterization was based on phenological features and analysis of Cl *a* fluorescence parameters.

5) The optimal lamp for conducting the parallel breeding works with different cereal species in the same space of a greenhouse, in our experiment, was the LED-6 lamp (PlantaLux S.A, Lublin, Poland).

6) Since LED lamps generate less heat than HPS, the need for more heating of the greenhouse should be taken into account.

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Appendix

Table A1 Wheat, barley, and oat plant height measured at BBCH 37, at fully developed flag leave

Species	Lamp	A weekly increase of plant height/mm			Average /mm
		Repetition I	Repetition II	Repetition III	
Wheat	HPS	422 412	408 388	412 388	408[ab]
	HID	460 483	440 453	442 453	455[c]
	LED-1	453 440	453 433	515 493	463[c]
	LED-2	343 413	462 422	432 363	406[a]
	LED-3	398 417	457 375	417 405	412[ab]
	LED-4	408 425	283 445	390 435	398[ab]
	LED-5	432 477	480 407	455 393	441[bc]
	LED-6	448 455	418 422	417 490	442[abc]
	LED-7	288 383	397 425	440 455	398[ab]
Barley	HPS	382 338	358 387	327 245	339[abc]
	HID	437 438	418 337	447 367	407[d]
	LED-1	360 375	350 347	353 370	359[abc]
	LED-2	377 343	278 370	378 358	351[abc]
	LED-3	348 348	340 363	387 263	342[ab]
	LED-4	377 363	297 340	310 250	323[a]
	LED-5	385 377	402 390	434 283	379[cd]
	LED-6	375 407	387 400	315 317	367[cd]
	LED-7	380 457	418 427	427 417	421[d]
Oat	HPS	408 385	473 397	380 385	405[a]
	HID	505 423	497 415	403 362	434[a]
	LED-1	452 406	425 455	402 390	422[a]
	LED-2	440 465	443 468	428 424	444[a]
	LED-3	440 390	436 393	401 447	418[a]
	LED-4	387 417	467 438	385 392	414[a]
	LED-5	402 382	492 406	415 350	407[a]
	LED-6	429 417	417 395	435 403	419[a]
	LED-7	417 425	408 393	415 415	412[a]

Note: The average values from ten measurements per cultivar are given. Harenda and Tybalt are wheat cultivars, Radek and Soldo are barley cultivars, and Bingo and Navigator are oat cultivars. The top row in the section of each lamp shows the data for the first listed cultivar whereas the lower row is for the second one. Post hoc Tuckey test evaluations are given as letters in the column of average data.

Table A2 Wheat, barley, and oat time to the formation of the first full ear in each biological repetition of the experiment

Species	LAMP	Time to earing/d			Average /d
		Repetition I	Repetition II	Repetition III	
Wheat	HPS	69 68	73 70	71 69	70[a]
	HID	84 85	80 80	81 85	83[ab]
	LED-1	75 79	78 78	76 80	78[ab]
	LED-2	75 77	76 74	76 73	75[ab]
	LED-3	75 74	76 75	77 72	75[ab]
	LED-4	72 74	75 72	73 69	73[ab]
	LED-5	75 73	73 77	74 75	75[ab]
	LED-6	75 73	76 74	75 73	74[ab]
	LED-7	92 85	85 90	87 92	89[b]
Barley	HPS	75 77	74 74	78 75	76[a]
	HID	80 86	82 84	80 87	83[bc]
	LED-1	86 93	88 90	87 92	89[de]
	LED-2	86 88	87 87	85 86	87[cd]
	LED-3	87 90	87 89	86 85	87[d]
	LED-4	83 80	85 81	83 78	82[b]
	LED-5	89 88	89 90	88 92	89[de]
	LED-6	88 90	89 89	88 91	89[de]
	LED-7	92 92	88 93	89 94	91[e]
Oat	HPS	71 72	68 70	67 74	70[a]
	HID	75 75	74 75	76 77	75[b]
	LED-1	70 70	70 70	68 69	70[a]
	LED-2	69 71	73 68	72 69	70[a]
	LED-3	72 69	69 69	70 68	70[a]
	LED-4	72 75	71 73	70 73	72[ab]
	LED-5	72 74	69 72	72 75	72[ab]
	LED-6	75 74	75 75	76 77	75[b]
	LED-7	82 79	80 84	83 81	82[c]

Note: Harenda and Tybalt are wheat cultivars, Radek and Soldo are barley cultivars, Bingo, and Navigator are oat cultivars. The top row in the section of each lamp shows the data for the first listed cultivar whereas the lower row is for the second one. Post hoc Tuckey test evaluations are given as letters in the column of average data.

Table A3 Chl *a* fluorescence parameters (in relative units) and differences evaluations based on post hoc Tuckey test

Species	LAMP	Fo	Fm	Fv	Fv/Fm	Tfm	AREA	F1	F2	F3	F4	F5	RC/ABS	Fv/Fo	(1−Vj)/Vj	PI
Wheat	HPS	4426^{ab}	22848^{a}	18423^{a}	0.806^{a}	225^{a}	329799^{a}	4383^{b}	4753^{b}	6602^{b}	11969^{c}	17798^{b}	1.137^{b}	3.903^{a}	0.470^{c}	2.577^{b}
	HID	4400^{ab}	21493^{a}	17094^{a}	0.795^{a}	250^{a}	388974^{a}	4695^{b}	5122^{b}	6802^{b}	12107^{bc}	18388^{ab}	1.176^{b}	4.086^{a}	0.507^{bc}	2.573^{b}
	LED-1	4438^{ab}	23754^{a}	19316^{a}	0.813^{a}	252^{a}	404664^{a}	4724^{b}	5153^{b}	6981^{b}	12171^{bc}	18436^{ab}	1.230^{b}	4.155^{a}	0.513^{bc}	2.947^{b}
	LED-2	4290^{ab}	22340^{a}	18049^{a}	0.806^{a}	270^{a}	407227^{a}	4810^{ab}	5173^{ab}	6994^{b}	12296^{bc}	18684^{ab}	1.261^{b}	4.197^{a}	0.524^{bc}	2.958^{b}
	LED-3	3970^{b}	21075^{a}	17106^{a}	0.812^{a}	273^{a}	418655^{a}	4820^{ab}	5201^{ab}	7275^{b}	12410^{bc}	19085^{ab}	1.317^{b}	4.207^{a}	0.528^{abc}	2.966^{b}
	LED-4	4361^{ab}	22656^{a}	18295^{a}	0.807^{a}	284^{a}	429849^{a}	4833^{ab}	5231^{ab}	7377^{ab}	12937^{abc}	19191^{ab}	1.411^{ab}	4.231^{a}	0.530^{abc}	3.362^{b}
	LED-5	4172^{b}	21678^{a}	17506^{a}	0.797^{a}	313^{a}	480913^{a}	4908^{ab}	5386^{ab}	7521^{ab}	13021^{abc}	19219^{ab}	1.428^{ab}	4.323^{a}	0.561^{ab}	3.610^{ab}
	LED-6	4377^{ab}	23326^{a}	18949^{a}	0.812^{a}	314^{a}	506797^{a}	4914^{ab}	5394^{ab}	7693^{ab}	13558^{ab}	19954^{ab}	1.477^{ab}	4.333^{a}	0.571^{ab}	3.636^{ab}
	LED-7	4344^{a}	23866^{a}	18022^{a}	0.791^{a}	397^{a}	514203^{a}	5435^{a}	5974^{ab}	8414^{a}	14038^{a}	20557^{a}	1.747^{a}	4.366^{a}	0.596^{a}	4.703^{a}
Barley	HPS	3789^{b}	20912^{a}	17123^{cd}	0.818^{ab}	267^{b}	328258^{b}	4336^{c}	4821^{b}	7230^{abc}	12427^{abc}	18310^{cd}	1.067^{c}	4.519^{ab}	0.459^{b}	2.473^{b}
	HID	4355^{a}	22716^{abc}	18361^{abc}	0.808^{b}	299^{b}	365035^{ab}	48810^{ab}	5221^{ab}	7263^{abc}	12793^{abc}	19965^{abc}	1.347^{abc}	4.220^{c}	0.533^{ab}	3.076^{ab}
	LED-1	4192^{ab}	21950^{abc}	17758^{abc}	0.809^{b}	235^{b}	356634^{ab}	4572^{abc}	4918^{ab}	6640^{c}	11967^{c}	18794^{bcd}	1.637^{a}	4.243^{bc}	0.558^{a}	4.061^{a}
	LED-2	4325^{a}	20539^{a}	16213^{d}	0.787^{c}	245^{b}	369066^{ab}	4711^{abc}	5057^{ab}	6803^{bc}	12191^{c}	17429^{d}	1.337^{abc}	3.572^{d}	0.504^{ab}	2.696^{b}
	LED-3	4016^{ab}	21033^{cd}	17017^{cd}	0.808^{b}	253^{b}	384181^{ab}	4434^{bc}	4809^{b}	6728^{bc}	12293^{bc}	17847^{d}	1.282^{bc}	4.218^{c}	0.507^{ab}	2.831^{b}
	LED-4	4231^{a}	22314^{abc}	18084^{abc}	0.810^{b}	248^{b}	396712^{ab}	4643^{abc}	5015^{ab}	6911^{abc}	12746^{abc}	18863^{abc}	1.43^{ab}	4.273^{bc}	0.525^{ab}	3.229^{ab}
	LED-5	4110^{ab}	21439^{bcd}	17379^{bc}	0.808^{b}	268^{b}	422969^{ab}	4499^{abc}	4851^{b}	6657^{bc}	12397^{abc}	18095^{d}	1.426^{ab}	4.222^{c}	0.516^{ab}	3.249^{ab}
	LED-6	4265^{a}	24124^{a}	19559^{a}	0.823^{a}	268^{b}	432326^{a}	4729^{abc}	5141^{ab}	7270^{ab}	13419^{a}	20672^{a}	1.395^{ab}	4.652^{a}	0.537^{ab}	3.544^{ab}
	LED-7	4344^{a}	23687^{ab}	19343^{ab}	0.817^{ab}	394^{a}	443049^{a}	4849^{a}	5293^{a}	7537^{a}	13294^{ab}	20493^{ab}	1.283^{bc}	4.465^{abc}	0.536^{ab}	3.132^{ab}
Oat	HPS	4324^{a}	23661^{a}	19337^{a}	0.817^{a}	317^{b}	447151^{a}	4778^{a}	5194^{a}	7196^{ab}	13004^{a}	20313^{a}	1.418^{ab}	4.471^{a}	0.545^{ab}	3.562^{abc}
	HID	3884^{a}	20322^{c}	16438^{c}	0.808^{ab}	289^{b}	352829^{ab}	4281^{a}	4635^{b}	6411^{c}	11508^{b}	17794^{c}	1.329^{ab}	4.224^{abc}	0.529^{bc}	3.076^{abc}
	LED-1	4200^{a}	22071^{abc}	17871^{abc}	0.810^{ab}	267^{b}	356470^{ab}	4566^{a}	4908^{ab}	6531^{bc}	11591^{b}	18848^{abc}	1.588^{a}	4.294^{abc}	0.584^{a}	4.087^{a}
	LED-2	4191^{a}	20997^{bc}	16306^{bc}	0.800^{b}	270^{b}	388408^{ab}	4603^{a}	4975^{ab}	6812^{abc}	12152^{ab}	18081^{bc}	1.328^{ab}	4.015^{c}	0.523^{bc}	2.869^{bc}
	LED-3	4013^{a}	20578^{c}	16565^{c}	0.804^{ab}	295^{b}	339822^{b}	4471^{a}	4885^{ab}	6905^{abc}	12449^{ab}	18080^{bc}	1.202^{b}	4.125^{bc}	0.487^{c}	2.508^{c}
	LED-4	4337^{a}	23220^{aab}	18884^{ab}	0.813^{ab}	280^{b}	434818^{ab}	4759^{a}	5132^{ab}	6022^{abc}	12837^{a}	19878^{abc}	1.484^{ab}	4.360^{ab}	0.548^{ab}	3.624^{ab}
	LED-5	4087^{a}	21795^{abc}	17708^{abc}	0.809^{ab}	317^{a}	398279^{ab}	4500^{a}	4876^{ab}	6721^{abc}	12439^{ab}	19447^{abc}	1.415^{ab}	4.315^{abc}	0.519^{bc}	3.379^{abc}
	LED-6	4075^{a}	22055^{abc}	17981^{abc}	0.815^{a}	307^{b}	368560^{ab}	4518^{a}	4918^{ab}	6933^{abc}	12734^{ab}	19593^{abc}	1.313^{ab}	4.430^{ab}	0.517^{bc}	3.074^{abc}
	LED-7	4254^{a}	22507^{abc}	18253^{abc}	0.811^{ab}	377^{ab}	382926^{ab}	4746^{a}	5187^{a}	7354^{a}	13009^{a}	20008^{ab}	1.243^{b}	4.315^{abc}	0.519^{bc}	2.861^{bc}

Note: Chl *a* fluorescence was measured on dark-adapted leaves of plants in the shooting stage. Presented values were calculated based on independent ten measurements.

Table A4 Spectroradiometric characteristics of lamps light spectra

Spectra	Parameter	HPS	HID	LED-1	LED-2	LED-3	LED-4	LED-5	LED-6	LED-7
Violet (340-430 nm)	Radiometric/W·m^{-2}	1.04	1.91	2.60	1.64	4.58	1.81	1.57	1.94	1.68
	PAR/mW·m^{-2}	0.51	0.82	2.01	0.91	2.94	1.05	0.87	1.08	0.95
	PPFD/μmol·m^{-2}·s^{-1}	2.09	3.50	7.58	3.62	12.21	4.16	3.46	4.28	3.76
	Peak/nm	430.00	429.99	429.99	429.99	429.99	429.99	429.99	429.99	429.99
	Peak value/(relative units)	24.41	42.39	234.60	67.16	147.92	83.06	62.84	85.2	81.71
Blue (431-500 nm)	Radiometric/W·m^{-2}	2.69	3.07	14.94	13,18	12.55	12.94	9.40	12.18	12.09
	PAR/mW·m^{-2}	2.39	2.79	14.50	12,00	11.60	11.80	8.59	11.30	11.40
	PPFD/μmol·m^{-2}·s^{-1}	10.64	12.10	57.18	51,46	49.06	50.48	36.64	47.12	46.45
	Peak/nm	498.35	498.35	443.48	452.41	452.41	450.18	452.41	450.18	450.18
	Peak value/(relative units)	80.15	67.14	454.2	317.29	291.96	318.81	226.55	351.08	407.49
Green (501-550 nm)	Radiometric/W·m^{-2}	2.04	2.19	2.77	13.16	12.53	14.89	9.70	5.43	2.38
	PAR/mW·m^{-2}	0.97	1.02	1.25	5.93	5.60	6.67	4.35	2.48	1.10
	PPFD/μmol·m^{-2}·s^{-1}	9.30	9.93	12.36	58.89	56.03	66.61	43.39	24.43	10.68
	Peak/nm	548.76	546.71	525.95	548.76	548.76	548.76	548.76	548.76	548.76
	Peak value/(relative units)	86.06	80.81	68.77	321.92	308.45	371.82	236.11	133.3	56.83
Yellow (551-590 nm)	Radiometric/W·m^{-2}	11.26	6.32	1.45	14.93	14.21	17.47	10.70	7.17	5.03
	PAR/mW·m^{-2}	5.52	3.2	0.72	7.39	7.04	8.66	5.3	3.57	2.55
	PPFD/μmol·m^{-2}·s^{-1}	54.31	30.72	7.13	72.86	69.37	85.3	52.25	34.57	24.5
	Peak/nm	571.05	588.88	588.88	588.88	588.88	588.88	588.88	588.88	588.88
	Peak value/(relative units)	405.36	244.31	42.86	427.66	406.16	508.39	302.04	241.13	241.06
Red (591-700 nm)	Radiometric/W·m^{-2}	21.75	9.32	28.31	51.24	36.17	38.45	28.22	26.98	39.22
	PAR/mW·m^{-2}	15.10	6.40	22.20	38.00	26.10	27.30	20.50	19.40	2.83
	PPFD/μmol·m^{-2}·s^{-1}	115.43	50.00	156.34	278.45	194.72	206.00	152.33	145.20	211.19
	Peak/nm	604.41	596.68	666.91	668.66	604.41	604.41	604.41	623.39	628.98
	Peak value/(relative units)	427.62	273.85	821.76	842.98	421.43	536.50	348.18	324.38	484.55
Deep red (701-750 nm)	Radiometric/W·m^{-2}	2.82	1.4873	1.004	2.6752	3.1812	3.2113	3.2602	3.2917	4.597
	PAR/mW·m^{-2}	0.46	0.23	0.19	0.55	0.56	0.65	0.51	0.65	0.94
	PPFD/μmol·m^{-2}·s^{-1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Peak/nm	702.60	710.76	702.60	702.60	702.60	702.60	702.60	702.60	702.60
	Peak value/(relative units)	68.32	32.23	34	95.28	87.09	106	75.55	104.18	153.77

Note: Chl *a* fluorescence was measured on dark-adapted leaves of plants in the shooting stage. Presented values were calculated based on independent ten measurements.

Table A5 The electric energy usage by lamps

Lamp type	The electric energy usage/W		
	Wheat	Barley	Oat
HPS	155 232	168 538	155 232
HID	183 662	183 662	165 960
LED-1	200 678	228 979	180 096
LED-2	213 480	247 637	199 248
LED-3	230 040	266 846	214 704
LED-4	213 840	233 798	205 286
LED-5	186 120	220 862	178 675
LED-6	88 200	104 664	88 200
LED-7	202 920	191 904	186 960

Note: HPS, HID, and LED-1 to LED-7 electricity usage throughout the entire time of the experiment, with 12 h/12 h (day/night), from germination till the first full ear formation.