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Evaluation of the effect of led irradiator spectral content on the development of greenhouse plants

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Abstract. The work presents the results of an experiment studying the effect of radiation spectral content (considering its equal intensity in terms of photosynthetically active radiation) on the growth and development of greenhouse model plants. The results demonstrate that the effective development of model subjects requires the adaptation of radiation spectral content according to the growth period and plant type, unlike the illumination level. The obtained results demonstrate the necessity of the creation of adaptive irradiation unit.

1. Introduction

The effective development of plants requires a certain complex of favorable external conditions. Nature not always provides a complete set of such conditions. Hence, the humanity strives to artificially achieve them, for instance, by growing plant in greenhouses. Considering the increasing scale of greenhouse business, one of the determinative factors of its development is the implementation of energy conserving technologies, which is required by the Federal Law On energy consumption and increase of energy efficiency [1].

One of the primary subjects of energy efficiency improvement is the system of artificial illumination in greenhouses. For this reason, Russian agricultural complex demonstrates increased interest in application of LED irradiators that have been actively developing in recent years exhibiting decreasing price and augmenting luminous efficacy. Over time, initial and operational costs for LED illumination will become lower than those for conventional light sources (metal halide, sodium-vapor and fluorescent lamps). In the present time, the understanding of the whole complex of actions towards increased energy efficacy of LED-based irradiation units (IUs) for greenhouses remains unclear. In this connection, the majority of LED lamps for plants (phyto lamps) currently presented on the market [2, 3] feature the radiation spectrum primarily formed by blue (440–470 nm) and red (630–660 nm) monochromatic LEDs. Such phyto lamps like conventional light sources lack the ability of optimizing radiation spectral content, which is known to determine the energetics of photosynthesis and control this process [4-10].

The work [11] attempts to formulate the principles for increasing energy efficacy of IUs for greenhouses that are based on the following ideas:

– formation of a spectral content (by combining color LEDs) and radiation intensity necessary and sufficient for plant development with enhanced (if possible) fraction of low-energy red radiation;

– development of energy efficient, low-cost custom greenhouse plant growing LEDs and IUs on their basis (for instance, GaN-based with different combination of luminophores);
– control of spectral content, radiation intensity according to the requirements of a specific type of plant at given development stage, i.e. creation of adaptive IUs.

Practical implementation of such principles requires the understanding of the character and extent of radiation spectral content effect on the growth process at all development stages of each plant type. Such information is widely published in monographs and periodicals. Nevertheless, each of such publications has its own goals and only indirectly can be used for practical realization of energy consumption principles for IUs, especially for those based on LEDs. Real implementation requires a data bank containing the information about LED-illumination effect (for certain type of color industrial LEDs) on the plant growth processes. Such data will enable the creation of an IU with optimal basic radiation spectral content featuring adjustable color range. Such light will be more affordable. Evidently, it should contain various color LEDs and should have adjustable light flow within the boundaries of photosynthetically active radiation (PAR).

This work is aimed at substantiating the choice of industrial LEDs and their combination for creating a greenhouse adaptive lamp with optimal basic radiation spectral content. The substantiation will be based on experimental studies of the effect of LED illumination with different colors on the growth and development of model plants in phytotrons.

2. Experimental methods

Model plants were grown in three prototypes of greenhouses (figure 1), phytotrons (PhT). The analysis of the processes of growth and development of model plants involved the determination of arithmetic mean values of the following parameters: shoot height (from the ground to the first truss), width (for the widest part of a leaf) and length of a leaf (along the length of a lamina). The increment of the parameters was determined at each plant development stage by comparing the parameter value in the beginning and in the end of a stage. To decrease the error and eliminate the influence of initial seed quality, the measurements were made using two (for tomato and cucumber) and six (for lettuce) shoots.

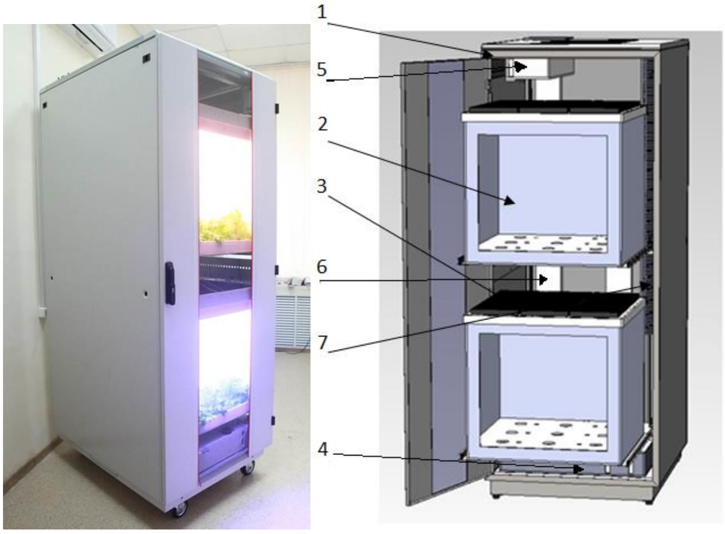

Figure 1. Prototype of “smart” greenhouse, phytotron, where 1 is the case of the research installation; 2 are phytotron cells; 3 are lamps with independent adjustment of plant irradiation regime; 4 and 5 are elements of watering system (lower and upper tanks); 6 is microclimate support system; 7 is electronic control and power supply system.

Plants in each of phytotrons were irradiated by special LED irradiators that allow forming in the process of the experiment any color gamma of the irradiation unit with the wavelength from 400 to 700 nm. Working modes of each LED comprising LED modules were constant and selected in such a way that IUs in all phytotron cells had equal total flux in the range of photosynthetically active radiation (PAR), but had different irradiation spectrum. Selection of modes was performed by altering LED current. This is the easiest and aptly controllable method for changing the intensity of LED radiation, i.e. selecting irradiation spectrum of a whole irradiation unit.

3. Results and Discussion

Were studied the growth of three types of model plants under LED irradiation: «Battler greenhouse tomato», «April greenhouse cucumber» and «Moscow greenhouse lettuce». In the course of the experiment, the duration of continuous plant irradiation during the day (phytoperiod) was 12 hours. Regarding the photoperiodic response, the chosen specimens are neutral-day plants. So, the chosen regime lies within the region of optimal duration of daylight irradiation exposure for the plants under study.

Table 1 contains the selected modes of LED module operation, illumination intensities and corresponding fluxes in the range of PAR. We should note that the spectral characteristic of plant leaf sensitivity to photosynthesis differs from that of human eye [12, 13]. Hence, the evaluation of irradiation unit efficacy using term "illumination" is not adequate and is used only for comparison purposes, since in many practical cases, greenhouse businesses specifically use illumination intensity to evaluate light flux incident at plant formation.

Table 1. LED module operation mode

No.	Operation mode	Current (mA)			E	PF_{PAR},
		Red	Blue	White	(klx)	(μmoles/m^2*s^{-1})
PhT1	continuous spectrum, prevailing red component	350	0	53	3.57	
PhT2	continuous spectrum, prevailing white component	197	0	350	4.04	120±10
PhT2	discrete spectrum, red and blue component	176	350	0	1.51	

To eliminate the influence of illumination intensity on the processes of plant growth and development, the operation modes of LEDs were selected in a such manner that photosynthetic photon flux densities (PPFD) in phytotrons with IU having different spectra were equal.

To accurately determine the photosynthesis efficiency under the influence of radiation fluxes with different spectrum, it is necessary to evaluate the PPFDs in quantum units, since elementary act of photochemical reaction is determined only by the quantity of light quanta absorbed by a chlorophyll molecule. Nevertheless, the understanding of the amount of quanta falling on the plant cover is not sufficient, for the efficacy of radiation absorption by a plant depends on the energy of incident quantum. The absorption spectrum of leaves can be represented by the absorption spectrum of chlorophyll molecule and basic pigments. Sometimes, the spectral characteristic of leaf susceptibility to incident radiation can be depicted by Sventiskiy curve [12, 13]. However, this curve is known to be non-universal, especially for different plant growth stages [5, 6, 14]. Besides, in the spectrum region where the chlorophyll molecule demonstrates no absorption, the effective absorption of incident radiation is specific for molecules of other pigments, which can transfer excitation energy to chlorophyll. Thus, at a first approximation, the estimation of the amount of energy absorbed by plants in quantum units is possible, assuming that the absorption coefficient of leaves is constant within PAR. The estimation of PAR was based on the illumination spectra of modules measured in given operation modes of LEDs by AvaSpec-2048 USB2 spectrometer (figure 2). The spectra were generated with a due consideration of spectral response characteristic of spectrometer's measuring track.

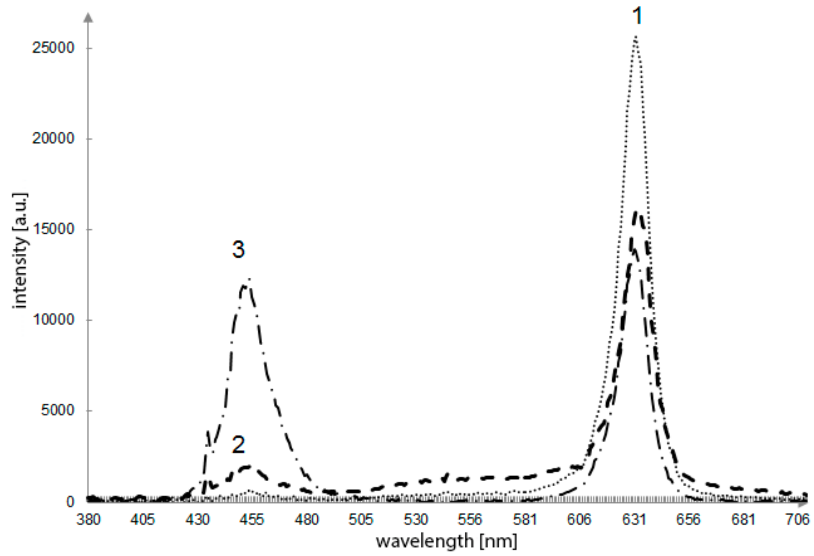

Figure 2. Radiation spectra of experimental LED modules.
1) is PhT No. 1, 2) is PhT No. 3 and 3) is PhT No. 3.

Obviously, in illumination spectra of LED modules, radiation bands in blue, green and red regions prevail. Spectrum 1 contains primarily red component of radiation and small part in blue and green regions. Spectrum 2 contains blue, green and red components of radiation spectrum. Spectrum 3 contains practically equal parts of blue and red radiation. Selection of such spectra was stipulated by the participation of these spectrum components in the process of photosynthesis. The goal of increasing the energy-efficiency is confined in selecting those compositions of blue, green and red components, which would provide for necessary conditions for photosynthesis and would be more beneficial from the point of view of LED module energy efficiency. Obviously, the long wave radiation is more effective; but application of solely long-wave radiation is impossible [4–8].

The first development stage lasts from the moment of embryo formation (i.e. up-coming plant) to the reveal of a shoot on a ground surface.

The duration of the first development stage from seeding to the appearance of a sprout on the ground surface amounted to 5, 7 and 8 days for model plants of lettuce, cucumber and tomato, respectively. The earliest shoots were found in the phytotron with PhT3 mode. The latest shoots were found in the phytotron with PhT2 mode.

The second development stage starts from the appearance of a sprout on the ground surface and ends with the formation of leaf primordia on the main stem. The results of model plant development at this stage are presented in table 2.

Table 2. Measurements at the second stage of model plant development

Phytotron	Tomato			Cucumber			Lettuce		
number	Δh (%)[a]	Δl (%)	Δb (%)	Δh (%)	Δl (%)	Δb (%)	Δh (%)	Δl (%)	Δb (%)
No. 1	92.7	84.3	38.4	90.7	84.1	88.9	88.4	76.9	66.7
No. 2	71.4	48.9	52.9	89.5	84.6	90.6	81.8	71.4	55.6
No. 3	84.6	81.4	46.7	95.2	95.9	93.3	75	71.4	50

[a] Δh is the increment of shoot height, Δl is the increment of leaf length, Δb is the increment of leaf width.

The maximum increment of tomato sprout height (Δh) was observed in the phytotron with PhT3 mode and amounted to 92.7%. The maximum increment of tomato leaf length (Δl) was observed in the phytotron with PhT1 mode and amounted to 84.3%. The maximum increment of tomato leaf width (Δb) was observed in the phytotron with PhT2 mode and amounted to 52.9%.

The maximum increment of cucumber shoot parameters was observed in the phytotron with PhT3 mode. The increment of height was 95.2%, increment of length was 95.9% and increment of leaf width was 93.3%.

The maximum increment of lettuce shoot parameters was observed in the phytotron with PhT1 mode. The increment of height in this PhT was 88.4%, increment of length was 76.9% and increment of leaf width was 66.7%.

The third development stage begins with the formation of leaf primordium of the main stem and ends with the differentiation of a growing point on the main stem. The formation of leaves at this stage almost terminates. The results of model plant development at this stage are presented in table 3.

Table 3. Measurements at the third stage of model plant development

Phytotron	Tomato			Cucumber			Lettuce		
number	Δh (%)[a]	Δl (%)	Δb (%)	Δh (%)	Δl (%)	Δb (%)	Δh (%)	Δl (%)	Δb (%)
No.1	21.6	41.7	52.9	20.4	48.8	67.8	32.5	71.7	74
No. 2	27.3	42.6	44.4	18.9	45.5	62.5	11.5	72.9	77.1
No. 3	38.4	40	43.3	14.6	40.6	60	0	59.5	75

[a] Δh is the increment of shoot height, Δl is the increment of leaf length, Δb is the increment of leaf width.

The maximum increment of tomato shoot height was observed in the phytotron with PhT3 mode and amounted to 38.4%. The length of tomato leaves in all three phytotrons increased equally (the increment was 41%). The maximum increment of tomato leaf width was observed in the phytotron with PhT1 mode and amounted to 52.9%.

The maximum increment of cucumber shoot height was observed in the phytotrons with PhT2 and PhT3 modes and amounted to 20.4% and 18.9%, respectively. The maximum increment of cucumber leaf length was observed in the phytotron with PhT1 mode and amounted to 48.8%, while the maximum increment of cucumber leaf width was observed in the phytotron with PhT1 mode and amounted to 67.8%. Thus, at this development stage, the best development conditions for cucumber were in the phytotron with PhT1 mode.

The maximum increment of lettuce leaf length was observed in the phytotron with PhT1 mode and amounted to 32.5%. The enhancement of lettuce length in the phytotron with PhT3 mode at this stage stopped almost completely. The maximum increment of lettuce leaf length was observed in the phytotron with PhT2 mode and amounted to 72.9%, while the maximum increment of lettuce leaf width was observed in the phytotron with PhT3 mode and amounted to 75%.

4. Conclusions

The presented results demonstrate that at the first and the second development stages all plant types (in addition to other colors) require a certain amount of blue (high-energy) radiation. Its fraction in IU radiation spectrum depends on the plant type and its growth time. Lettuce requires almost none of it, while tomato and cucumber at early growth stages need limited amount of it, since the increase of the fraction of blue radiation can lead to retarded plant development. At the third stage, the development of all plants requires mainly red radiation.

Thus, the presented results clearly testify that the energy efficacy of LED irradiation units can be increased by selecting an optimal radiation spectral content and consequently varying it depending on the plant growth stage, i.e. by creating adaptive irradiation units. Whilst the basic radiation spectra (i.e. those which will be adjusted afterwards) can be different for different types of agricultural plants.

The study also demonstrated the possibility of creating adaptive IUs on the basis of off-the-shelf industrial LEDs. Application of three LED types (blue, green and red) for greenhouse lamps is the most universal solution for adjusting the spectral content of the IU. However, white LEDs are known to have a fairly large fraction of blue spectrum component. Following the results of this work, this component can be sufficient for creating adaptive IU with optimal basic radiation spectrum in terms of color. Since white LEDs become more and more affordable, their implementation can be the most advantageous from the perspective of cost of greenhouse IUs. Therefore, the energy-efficient IU can be made on the basis of only white and red LEDs.

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