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Effect of supplemental lighting spectral composition on the tomato yield in greenhouses

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Abstract

Transplants of tomato cultivar ‘Hybrid Tarasenko’ and ‘De Barao’ were grown under the additional lighting of different high-intensity light sources in greenhouses. As lighting sources were tested: mercury arc lamps with a luminophores covering (MALF 400), standard high-pressure sodium lamps (HPS 400) and high-pressure sodium lamps with additive of Cesium (HPS-Cs 400) and amalgam content: Hg-20 %, Na-75 %, Cs-5%. It was established that introduction of Cesium 5% in the amalgam composition of high-pressure sodium lamps, leads to increase of radiation intensity in red (600-700 nm) and near Infrared region to 58%. The growth dynamic and the most important morphological attributes of the transplant were investigated. Our investigations revealed that the increase of red light proportion in spectral composition of such lamp radiation promoted an intensification of tomato plants growth processes and photosynthesis. Increase in yield was result of the carried-out greenhouse experiment with tomatoes plants which is grown up when lighting by HPS-Cs 400 lamps. The yield of ‘Hybrid Tarasenko’ and ‘De Barao’ tomato cultivars, grown under HPS-Cs 400 lighting, exceeded the yield of plants grown under HPS 400 lighting by 7.4% and 6%, respectively. The irradiation of ‘Hybrid Tarasenko’ and ‘De Barao’ tomatoes plants by HPS-Cs 400 lamps promoted to the more significant yield increase on 22.8% and 24.5%, respectively, as compared with the plants cultivated under the lamps of MALF 400.

Keywords: tomato, high-pressure sodium lamps, photosynthetically active radiation, photosynthesis

Introduction

The most widespread cultures grown up in the closed soil in the majority world countries are tomatoes plants. The ways of the tomatoes production intensification at decrease in energy consumption in the closed soil, are based on plants supplemental artificial lighting. It was established that for most crops a 1% light increment results in 0.5% to 1% increase in harvestable product, including for 0.8-1% for closed soil grown vegetables [1]. The use of different spectral ranges radiation for pre-sowing seed treatment has a positive effect on the biometric parameters of plants grown and in the open soil [2]. The most important problem to achievement of high production for vegetables cultivated in closed soil is establishment and optimization of mane optical radiation parameters such as radiation spectra, light level, and photoperiod. The energy efficiency of supplemental lighting systems is reached due to use of highly effective light sources with spectral composition of radiation which favorably influences on biological processes. Among the different spectra used in supplemental lighting, red (600 to 700 nm) is often considered the most efficient in driving photosynthesis [3]. Red and far-red (700-800 nm) light are sensed by the phytochromes that trigger several morphological and developmental processes that impact productivity and yield quality [4]. However, it is established that plants do not develop normally when grown solely under monochromatic red light (“red light syndrome”). The plants lighting only by red light leads to leaf curling and decreases in photosynthetic capacity, leaf thickness and leaf pigmentation [5, 6]. The best wavelengths of visible light for photosynthesis fall within the blue range (425–450 nm) and red range (600–700 nm). The natural sunlight in greenhouses includes 27–31% of blue light, which may be sufficient even in winter [7]. Blue light produces “sun-type” leaves even when overall light intensity is low and suppresses symptoms damage of the plants and promotes to their normal development [8, 9]. It was established that addition of 6-12% of blue light against the background of the overall photosynthetic active radiation (PAR), can be advantageous for growth and yield, while adding 24% blue light can lead to inhibition of tomatoes plants [9]. A significant amount of red light (80-90%), for example, from light emitting diodes (LEDs), can lead to leaf curling and yield decreases by 3-6% concerning lighting by sources, in which radiation spectra a share of red light does not exceed 37% (lamp HPS 400) [10].

The effect of different proportions of PAR on growth and production the tomatoes plants (*Lycopersicon esculentum* cv. Tradiro F) under 100% artificial lighting was studied. Heights of tomato plants grown under the lamps with 37.3% red and 6.1% blue in PAR, for 26% exceeded height of the plants grown under the lamps with reduced portion of red light (17.1%) and increased portion of blue light (34.2%). However, chlorophyll content measurements showed that leaves had significantly on 40% higher chlorophyll than those under lamps with higher portion of blue in the spectrum (34.2%) [11].

High-pressure sodium lamps (HPS 400) are currently the predominant greenhouse lighting source due to its ability to deliver adequate photosynthetically active radiation for plant growth. HPS 400 lamps have high electrical efficiencies, a long operating life and a wide spectrum of light, which is suitable for many plant species. These lamps emit light in the visible (400–700 nm) and the invisible (700–850 nm) ranges, but the peak emission is in the yellow light (~589 nm) region. Often, high amount of yellow light causes the stem elongation of plants and worsens their quality [12]. Furthermore, HPS 400 lamps are 25% efficient, and the waste thermal energy can be used to increase ambient greenhouse temperature. It was estimated that, the heat emitted from HPS 400 lamps provided between 25% and 41% of the heating requirements for a greenhouse operation. These lamps usually require reflectors to direct the light from the lamps onto plants, thereby providing satisfactory light distribution and efficiency, but also blocking the direct sunlight from reaching the plants to avoid tissue scorching [13].

Plants are known needs in the even light distribution over the crop canopy, but in the greenhouse with high plant density, most of the supplemental lighting can only be intercepted by the upper part of the plant canopy and therefore side is necessary lighting. As a suitable source for additional lighting of tomatoes plants the combinations with HPS 400 lamps and light-emitting diodes (LED) are widely applied. The light spectrum of LEDs is a mixture of 90% red (640 nm dominant wavelength) and 10% blue (450 nm dominant wavelength). The use of such hybrid lighting promoted the increase in tomatoes productivity by 32.9%, as compares the HPS 400 lighting which lead to increase in productivity by 21.8% for 'Ruifen882' tomato cultivar as was shown in study [14]. Thus, HPS 400 are neither spectrally (deficient in blue) optimal for creation of full-fledged artificial lighting in greenhouses.

At present, light-emitting diodes (LEDs) are widely used as the basic and supplemental lighting for plant cultivation in the closed soil. LEDs have a spectral range of radiation from near-infrared (IR) to near-ultraviolet (UV). They are characterized by high radiation efficiency, long lifetime, low radiation temperature, relatively narrow radiation spectra, and short switching periods [15]. However, due to the high cost of LED lighting systems and the need for customization for the specific crops, their use is not always reasonable.

Thus, despite a numerous researches, the search for light sources with effective spectral composition of radiation, as well as optimization of the main parameters of optical radiation for the different plant species are still necessary.

This article aims to evaluate the growth dynamics and chlorophyll content of tomato plants 'De Barao' and 'Hybrid Tarasenko' cultivars grown under lighting by standard high-pressure sodium lamps (HPS 400), high-pressure sodium lamps with additive of Cesium (HPS-Cs 400), and mercury arc lamps with a luminophores coating (MALF 400).

Material and Methods

The experiment was carried out in the greenhouses of Poltava State Agrarian University, Poltava, Ukraine. Tomatoes (*Lycopersicon esculentum* Mill) of the cultivars'Hybrid Tarasenko' and 'De Barao' were sown in the trays filled with typical light loamy chernozem that served as a substrate (pH 6.9–7.0). The substrate was enriched with mineral fertilizer AQUA (Ukraine) includes the macroelements: nitrogen - 21%, phosphorus - 21%, potassium - 21%, and microelements: Mg, Fe, Mn, B, Cu, Zn, Co, Mo and amber acid.

Plants were watered when necessary. Day/night temperature till germination was 26/24 °C, and a 14-h photoperiod was maintained. After the germination, photoperiod was 16 h and the day/night temperature was 22/18 °C. The relative air humidity was 70%. After germination, tomato transplants were cultivated for 28 days being lighted by lamps with different spectral ranges of radiation: standard high pressure sodium lamps (HPS 400); high-pressure sodium lamps with additive of Cesium (HPS-Cs 400), and mercury arc lamps with a luminophores coating (MALF 400) (Table 1). The lamps were installed at a height of 2 m from the plants, the lighting surface was 15 m^2, and the distance between the lamps was 3 m. The planting density of tomatoes was 2.5 plants per square meter. The light intensity from the lamps at a seedling level was maintained at 110-130 W m^{-2}.

The morphological parameters were determined on the 28th day after germination. Five plant samples of each cultivar were selected in quadruple repetitions. Plant height was measured to the tip of the youngest leaf. The number of fully expanded leaves was counted; the first internode length was measured. The results were expressed as mean values using MS Excel software.

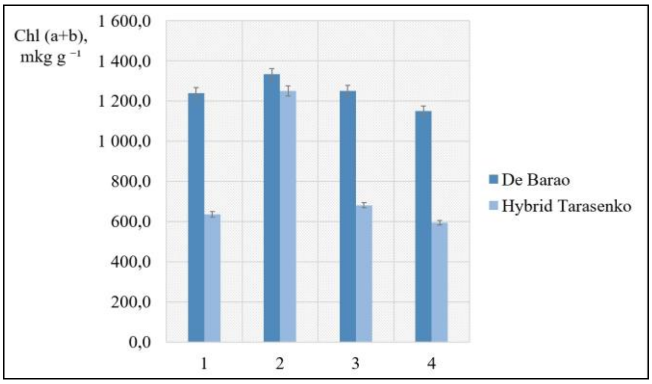
In order to determine chlorophyll content, leaves of one layer were collected at the top of a plant. Six leaf discs with a diameter of 1.6 cm were randomly collected from each leaf and these samples were used for measuring chlorophyll content. Ethanol was used as a solvent; absorbance was measured at 665, 649 and 470 nm using a UV-Vis spectrophotometer (UV-1800; Shimadzu). Chlorophyll concentration was calculated using the equations derived from [16]. Tomatoes were harvested on the 90th day.

The effect of lighting types on plant growth and leaf pigment content was assessed by one-way analysis ANOVA (variance analysis), followed by the protected Fisher's test with the least significant difference (LSD) with 95% confidence.

Results and Discussion

In the present study, high-pressure sodium lamps with addition of Cesium (HPS-Cs 400) having the discharge tube filled with the amalgam of the following composition: Hg-20%, Na-75%, Cs-5% have been offered for lighting tomato plants. These lamps have the same design as the HPS 400, but the difference is only in the filling: instead of sodium amalgam, sodium-cesium amalgam is dosed into the burner. In order to determine the optimal cesium content in the amalgam, lamps with the following amalgam composition have been manufactured: 1 – 20 at% Hg, 77 at% Na, 3 at%

Cs; 2 – 20 at% Hg, 75 at% Na, 5 at% Cs; 3 – 20 at% Hg, 73 at% Na, 7 at% Cs; 4 – 20 at % Hg, 70 at% Na, 10 at% Cs.
The effectiveness of lighting was evaluated by the pigments content in leaves of the studied tomato cultivars (Figure 1).



*1 – 20 at% Hg, 77 at% Na, 3 at% Cs
2 – 20 at% Hg, 75 at% Na, 5 at% Cs
3 – 20 at% Hg, 73 at% Na, 7 at% Cs
4 – 20 at% Hg, 70 at% Na, 10 at% Cs

Fig 1: Chlorophyll *a* and *b* content in tomato plant leaves grown under HPS-Cs 400 lamps with different cesium content in amalgam (LSD_{05}=147 mkg g^{-1})

The highest total chlorophylls content in leaves of 'De Barao' (1340 mkg g^{-1} of wet weight) and 'Hybrid Tarasenko' (1240 mkg g^{-1} of wet weight) cultivars was observed under lighting by a lamp, the discharge tube of which contained amalgam with 5 at% Cs (Figure 1). When tomato plants were lighted by lamps containing 3 at% and 7 at% Cs in the amalgam the total pigments content in leaves of 'De Barao cultivar was decreased on 7,5%. The increase in the cesium content in the lamp amalgam up to 10 at% resulted in the decrease of the pigments content by 13.4%. A similar trend of change in the total pigments content in tomatoes leaves was observed for 'Hybrid Tarasenko' cultivar. Thus, based on the obtained data, the most effective amalgam composition in HPS-Cs 400 lamps has been determined – 20 at% Hg, 75 at% Na, and 5 at% Cs.
The lamps with this amalgam composition were used in the further studies. As follow from Table 1 the addition of 5 at% Cs into the lamp amalgam leads to a redistribution of the radiation energy intensity regarding the radiation of HPS 400 lamp. The spectral distribution of the radiation energy in the PAR region of HPS-Cs 400 lamp is as follows: 14% of the radiation in the blue region (400-500 nm), 31% in the green region (500-600 nm) and 55% in the red region (600-700 nm) and near-infrared PAR region. A redistribution of the relative spectral radiation energy as a result of cesium addition to the amalgam of HPS 400 lamp is confirmed by the authors of the study [17].

Table 1: The main characteristics of the tested lamps

Lamp type	Hg, mg	Light efficiency PAR, %	Proportion of PAR,%		
			400-500 nm (Blue)	500-600 nm (Green)	600-700 nm (Red)
HPS 400	17	27	7	56	37
MALF 400	76	12	26	56	18
HPS-Cs 400	10	29	14	31	55
HPS-K-Cs-400	12	24	15	32	53

*Photosynthetic active radiation (PAR), **Mercury content (Hg, mg)

We have also tested a high-pressure sodium lamp with addition 1% potassium (K) into the amalgam. So, the following amalgam composition has been obtained: 20 at% Hg, 75 at% Na, 4 at% Cs, 1 at% K. The addition of potassium to the amalgam of HPS-Cs 400 lamp increases the radiation energy in the red spectral region (509-767 nm). The light efficiency of lamps with such amalgam is reduced, both due to the increase in the heat loss of the discharge and due to the raise of the radiation intensity in the red spectral region. Thus, HPS-Cs 400 lamps are the most suitable for improving light transmission quality, which provide the largest number of lines in the red spectral region and partially in the blue-green region, compared to HPS 400 lamps with potassium addition.
One of the important characteristics of lamps is the light efficiency in the PAR region. The indicators of lamps light efficiency with different amalgam fillings are shown in Figure 2.

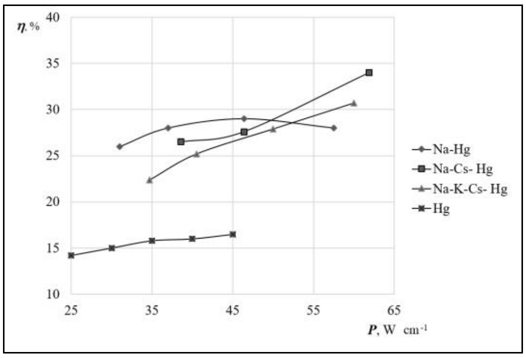


Fig 2: Dependence of light efficiency (η) on the lamps specific power (P_1) with various filling of a digit tube: Na-Hg (HPS 400); Na-Cs-Hg (HPS-Cs 400), Na-K-Cs-Hg (HPS-Cs-K 400)

As follows from Figure 2, the light efficiency(η)) of PAR under the raise of the lamp specific power (P_1) in the range of 27-60 W cm^{-1} increases for HPS 400 lamp up to 28%. The light efficiency of HPS-Cs 400 lamp exceeds this indicator of HPS 400 lamp by 1-2% at a specific power of 50-65 W cm^{-1} and is 29±2%. For HPS-Cs-K 400 lamp with addition of 1 at% potassium and 4 at% cesium in the amalgam, the light efficiency at a specific power of 50–65 W cm^{-1} is 27%, which is less than this indicator for HPS-Cs 400 lamps. It should be noted that HPS-Cs 400 lamps have a significant stability reserve during exploitation and a fairly long lifetime (25000 hours).
We have carried out a comparative analysis of the effectiveness of lighting tomato plants by HPS-Cs 400 lamps, HPS 400 and MALF 400. The lighting effectiveness has been evaluated according to the comparison of some morphological characteristics of tomato transplants (Figures 3, 4, 5), yield indicators (Figure 6, Table 2) and pigments content in plant leaves (Table 3).
Known, insufficient intensity and quality of light limit the growth and development of tomatoes, and the quality of tomatoes plants worsens under such growing conditions. Properly grown tomato seedlings should be compact, with hard stems, large and intensely green leaves. These seedlings guarantee the best possible root development after transplanting and affect the yield quality and quantity. In our experiments the stem height of tomato plants 'De Barao' cultivar being additionally lighted by HPS-Cs 400 lamps

was by 2.9% and 9.8% higher than under lighting by HPS 400 and MALF 400 lamps, accordingly.

Tomatoes of 'Hybrid Tarasenko' cultivar turned out to be more sensitive to lighting by HPS-Cs 400 lamps. The increase in the seedling height of this tomatoes' cultivar as a result of lighting by HPS-Cs 400 lamps was 5.9% and 11.9%, accordingly, comparatively to the plants lighted by HPS 400 and MALF 400 lamps (Figure 3).

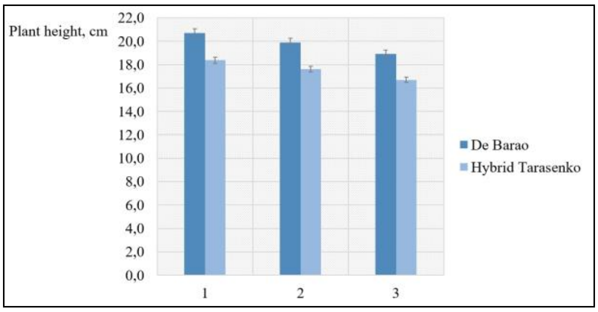


Fig 3: The height of tomato transplants seedlings grown under different light sources illumination: 1 - HPS-Cs 400, 2 - HPS 400, 3 - MALF 400 (LSD_{05}=1.2 cm)

A redistribution of the blue and red light percentage in the luminous flux of radiation in the PAR region under lighting by HPS-Cs 400 lamp in comparison with lighting by HPS 400 lamp had a significant effect on the morphological parameters of tomato transplants. Although the blue color percentage (14%) compared to red color (55%) in the radiation flux in the PAR region under lighting by HPS-Cs 400 lamp is insignificant, it nevertheless, this circumstance weakens the effect of only red light on the plant development and, due to an increase of supplemental blue light, promotes the formation of the solar type rays.

As is known, the oversaturation of red light in the radiation flux of lamps causes a significant decrease in the number and thickness of leaves, the photosynthetic pigments content [18, 19]. While lighting by lamp HPS-Cs 400, such deviations were not observed due to the addition of 14% radiation in the blue region. As confirmed in the study [18], even 7% of blue light is sufficient to prevent any dysfunctional photosynthesis. The ratio of blue and red light in the radiation of light sources is important for the regular photo morphogenesis of various plants. The experiment results proved that plants grown under lighting by HPS-Cs 400 had the largest number of fully formed leaves (Figure 4) and the longest first internode (Figure 5).

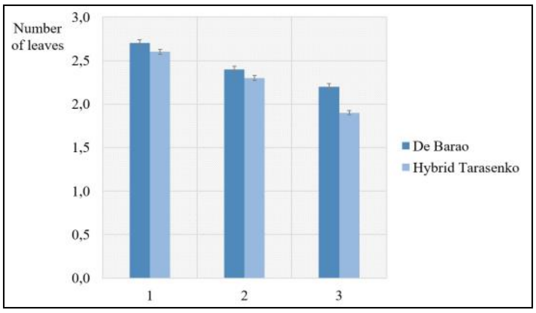


Fig 4: The number of leaves in tomatoes plants grown under different light sources illumination: 1 - HPS-Cs 400, 2 - HPS 400, 3 - MALF 400 (LSD_{05}=1.0 cm)

The number of leaves of 'De Barao' plants under supplemental lighting by HPS-Cs 400 lamps was by 7.4% and 14.8% higher than under lighting by HPS 400 and MALF 400 lamps, respectively (Figure 4). Tomatoes of 'Hybrid Tarasenko' cultivar developed even higher number of leaves under lighting by HPS-Cs 400 lamps. Obviously, the blue color that is presented in the HPS-Cs 400 lamp radiation contributed to the intensive formation of leaves on the plants of this cultivar, the number of which was by 11.5% and 19.3% higher than under lighting by HPS 400 and MALF 400 lamps, respectively. Lighting of 'De Barao' tomatoes by HPS-Cs 400 lamp had a similar effect on the length of the first internode, which was increased by 3.8% in comparison to tomato plants grown under HPS 400 lamps and by 9.5% compared to the plants lighted by MALF 400 lamps. A significant elongation of the first internode by 6.1% and 11.2%, respectively, was also observed in tomatoes of 'Hybrid Tarasenko' cultivar (Figure 5).

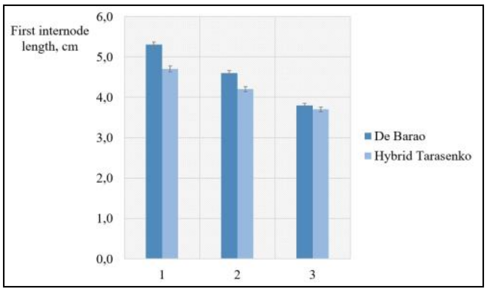


Fig 5: The first internode length of tomatoes plants grown under different light sources illumination: 1 - HPS-Cs 400, 2 - HPS 400, 3 - MALF 400 (LSD_{05}=0.9 cm)

The effect of the spectral composition of the studied light sources on the total fresh weight 'De Barao and 'Hybrid Tarasenko' tomato seedlings are shown in Figure 6. As follows from the obtained data, lighting of tomato seedlings by HPS-Cs 400 lamp increased the total fresh weight by 7.5% for 'De Barao' cultivar and by 5.9% for 'Hybrid Tarasenko' cultivar in comparison to the results of lighting by HPS 400 lamp. Lighting of tomato seedlings by MALF 400 lamp with the main radiation flux (56%) in the green region (500-600 nm) and only 18% in the red one was insufficient for the active plant growth. As a result, there was the decrease in the total fresh weight of 'De Barao' seedlings cultivar by 15.1% and 'Hybrid Tarasenko' cultivar by 9.8% in comparison with those obtained under lighting by HPS-Cs 400 lamp. Discrete influence of green light on the plant biology, regulation of vegetative development, photoperiod of flowering, modulation of stem growth, expression of chloroplast genes have been described in the study [20].

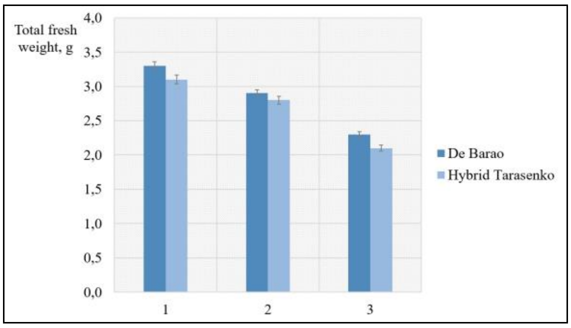


Fig 6: The total fresh weight of tomatoes plants grown under different light sources illumination: 1 - HPS-Cs 400, 2 - HPS 400, 3 - MALF 400 (LSD_{05}=0.86 cm)

The specifically effects of narrow regions of the radiation spectrum presented in the tested light sources can be estimated both on the basis of the accumulation of the total biomass of tomato plants and the yield. It is known that tomato cenoses are capable of providing a sufficiently high productivity in the red rays. We have evaluatd the tomato plants productivity depending on the spectral composition of light sources (Table 2).

Table 2: Yield of the tomatoes plants

Lamp type	Yield per plant, kg		Yield per plot square meter, kg	
	Hybrid Tarasenko	De Barao	Hybrid Tarasenko	De Barao
HPS-Cs	6,48	8,64	16,2	17,28
HPS 400	6	8,12	15	16,9
Malf 400	5	6,5	14,5	16,25

Supplemental lighting of tomato plants during the growing season by HPS-Cs 400 lamp increased the yield per one plant of ‘De Barao’ cultivar by 1.52 kg and of ‘Hybrid Tarasenko’ cultivar by 0.48 kg comparatively to the plants that were lighted by HPS 400 lamp. Yield per one tomato plant additionally lighted by MALF 400 lamps, was by 2.14 kg lower for ‘De Barao’ cultivar and by 1.48 kg lower for ‘Hybrid Tarasenko’ cultivar.

The yield per square meter of the plot provided a similar correlation. The lowest yield of both tomato cultivars per square meter was observed on the plots where plants were lighted by MALF 400 lamp (18% red light). A raise of red light percentage in the relative spectral radiation energy of HPS 400 lamp (37% red light) contributed to an increase of the yield ‘De Barao’ cultivar by 3.8% and of the ‘Hybrid Tarasenko’ cultivar by 3.4%. A significantly greater increase in tomato yield per square meter was recorded on the plots where plants were lighted by HPS-Cs 400 lamps (55% red light). An increase of tomatoes yield per square meter of this plot was 6.3% for ‘De Barao’ cultivar and 10.5% for the ‘Hybrid Tarasenko’ cultivar comparatively to the yield obtained on the plot lighted by MALF 400 lamp. Thus, our results confirm that the biomass and plant yield respond favourably to the distribution of light radiation spectral energy in the PAR region.

The informative indicator of the plants photosynthetic apparatus is the amount of pigments in the tissues, which determines their functional state and changes that occur during growth and development. The photosynthetic apparatus responds to the different light modes and intensity, adapts and has its own activity. The degree of plant sensitivity to the light of various spectral compositions can be determined by the photosynthetic pigments content [21]. Chlorophyll *a* and *b* molecules are main pigments for photosynthesis, which allow plants to absorb and transfer light energy in the reaction centers of the photosystems. Chlorophyll *b* is an accessory pigment that absorbs light energy and passes it to chlorophyll *a* to drive photosynthesis [22].

We have determined the content of chlorophylls *a* and *b* and carotenoids in leaves of 28-day-old tomato plants (Table 3). The highest Chl *a* and Chl *a*+*b* content was determined in leaves of both tomato cultivars irradiated with the HPS-Cs 400 lamp in comparison to the control. The Chl *a* and Chl *a*+*b* content exceeds these indicators in leaves of ‘De Barao’ tomato cultivar grown only under natural light by 73% and 50%, respectively, and in leaves of ‘Hybrid Tarasenko’ tomatoes by 14.8% and 21%, respectively (Table 3).

When lighting by HPS 400 lamp, the Chl *a* content in leaves of ‘De Barao’ cultivar was by 5% higher than in the control, but by 64.4% less than under lighting by HPS-Cs 400 lamp. The use of HPS 400 lamp for lighting of ‘Hybrid Tarasenko’ tomatoes resulted in the decrease of Chl *a* content both as in comparison to the control (by ~ 3%), as in comparison to the plants grown under lighting by HPS-Cs 400 lamp (by 18%). The total Chl *a*+*b* content in leaves of ‘De Barao’ tomatoes grown under lighting by HPS 400 lamp was equal to the control level, but by 50.4% less than in leaves of plants lighted by HPS-Cs 400 lamp. The photosynthetic apparatus of ‘Hybrid Tarasenko’ tomato cultivar responded positively to lighting by HPS 400 lamp, which lead to the increase in the total Chl *a*+*b* content by 3.4%. But, this indicator turned out to be 17% less than while using HPS-Cs 400 lamp.

Table 3: Effects of supplementary lighting from different light sources on chlorophyll *a* and *b* content, chlorophyll a/b ratio and carotenoids content in tomato leaves

Tomatoes cultivar	De Barao				Hybrid Tarasenko			
Lamp type	HPS 400	MALF 400	HPS-Cs 400	Control	HPS 400	MALF 400	HPS-Cs 400	Control
Chl *a*, mg g^{-1}	0,74±0,03	0,68±0,03	1,22±0,17	0,70±0,07	0,80±0,07	0,71±0,04	0,94±0,07	0,82±0,04
Chl *b* mg g^{-1}	0,21±0,02	0,17±0,07	0,21±0,03	0,25±0,08	0,30±0,05	0,23±0,08	0,34±0,06	0,24±0,05
Chl *a*+*b*, mg g^{-1}	0,95±0,03	0,85±0,07	1,43±0,04	0,95±0,03	1,10±0,02	0,94±0,03	1,28±0,13	1,06±0,37
C_t, mg g^{-1}	0,45±0,05	0,26±0,03	0,27±0,08	0,29±0,03	0,32±0,08	0,26±0,06	0,27±0,02	0,28±0,07
Chl a/b	3,50±0,41	3,90±0,22	5,71±0,4	2,80±0,65	2,70±0,38	3,10±0,67	2,80±0,52	3,40±0,46

*Control - Natural light, Chl *a* - chlorophyll ***a***, Chl *b* - chlorophyll ***b***, C_t - carotenoids

Carotenoids are represents another photosynthetic pigment group. Although they do not directly participate in the reactions of photosynthesis, but play the role of the photosynthetic antennas, participate in harvesting light energy for photosynthesis and protect the chlorophyll molecule that is sensitive to light.

The dynamics of the carotenoids content in leaves of the studied tomato cultivars in response to lighting by the different types of lamps correlates with the regularity of changes in the Chl *a* and Chl *b* content. The lowest of yellow pigment content was observed in plants leaves with a high total Chl *a*+*b* content (lighted by HPS-Cs 400 lamp). As noted above, the total content of Chl *a*+*b* in leaves of ‘De Barao’ cultivar, lightened by the HPS-Cs 400 lamp was by 50% higher than under natural light, and the carotenoids content was by 6.6% lower. However, the using of HPS 400 lamp with radiation of more yellow-red colour for lighting of this tomato cultivar promoted a significant accumulation of carotenoids in leaves, the content of which was by 53.6% higher than the control at almost permanent total Chl *a*+*b*.

The positive dynamics of ‘Hybrid Tarasenko’ tomatoes cultivar both in terms of lighting by HPS-Cs 400 lamp and

HPS 400 lamp should be noted. The use of MALF 400 lamps for supplemental lighting definitely leads to the suppression of the photosynthesis process in the leaf blade of plants, which is confirmed by a decrease Chl *a* content by 3.2% in 'De Barao tomatoes cultivar and by 15.1% in 'Hybrid Tarasenko' tomatoes cultivar. The total Chl *a*+*b* content in leaves of these tomatoes cultivars is also lower by 11.7% and 12.8%, respectively (Table 3). In the present study, HPS-Cs 400 lamp has 55% of spectral radiation energy in the red region of the PAR. The intensity of the radiation energy in this region has been increased by addition of 5% cesium into the amalgam composition. Thus, the resulting ratio of red and blue light promoted expansion of tomato leaves, stomata opening and, therefore, access to CO_2, which ultimately has enhanced photosynthesis. The obtained results are confirmed by the data of studies [23, 24]. However, the authors of the study (Yan *et al*., 2018), comparing the lighting effectiveness of 'Ruifen 882' tomatoes cultivar by HPS 400 lamps and by HPS 400 lamps with the addition of LED, the radiation spectrum of which was a mixture of 90% red (640 nm) and 10% blue (450 nm), established the opposite regularity. Lighting of tomato plants only by HPS 400 lamps boosted the chlorophyll raise by 13.1%, while hybrid lighting by HPS 400 lamps with additional illumination from LEDs – by 10% comparatively to the control. It can be assumed that a significant amount of red light resulted in the reduction of tomatoes photosynthetic ability and the decrease in their pigmentation, which correlate with the studies [5, 6]. The effectiveness by the different lamps lighting on morphological parameters of studied tomato cultivars and photosynthetic parameters, as well as chlorophyll content and as yield were evaluated by analysis of variance (ANOVA). The correlation analysis results showed that the tomatoes yield in greenhouse conditions largely depends on the ratio of the Chl a/b content in plant leaves (Figure 7).

The yield tomatoes dependence on the chlorophyll *a* content also characterized by a direct average correlation, but the correlation coefficient is 0.58. In turn, the direct correlation dependence between the Chl *a* content and the seedlings height of tomato plants (r = 0.50), the number of leaves per plant (r = 0.65), the length of the first internode (r = 0.61), and weight of the plants (r = 0.67) was established with the indicated coefficients.

According to the results of multi-factor analysis of variance, it has been revealed that the cultivars properties, the lighting factor and interaction: cultivars properties - lighting significantly affects the productivity of tomato plants. The value of least significant difference (LSD_{05}) was 0.31 kg m^{-2} for interaction factor, 0.2 kg m^{-2} for cultivar factor and 0.16 kg m^{-2} for lighting factor.

A similar dependence was observed for other parameters such as the seedlings height, the number of leaves on a plant, the length of the first internode, the mass of plants, and the photosynthetic pigments content determining during the research. Correlation analysis of these parameters indicates their close relationship, which can be used as an indication for yield predicting.

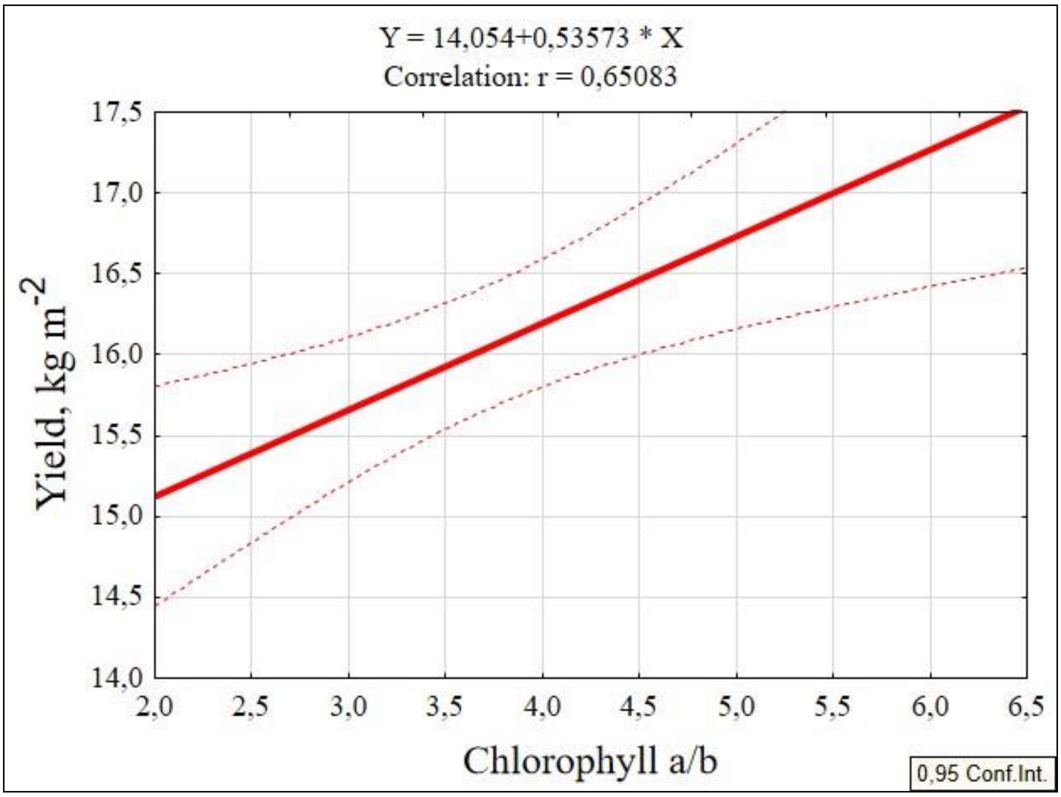


Fig 7: The tomatoes yield dependence on the ratio of the Chl a/b content in plant leaves

In particular, there is a close direct correlation between the yield, the length of the first internode and the seedlings height with r = 0.80-0.92 ($p \leq 0.01$), and between the number of leaves on the plant, the Chl *a* content and the yield with r = 0.54-0.66. Thus, taking into account the established patterns, it is possible to regulate the growing tomatoes technology using the above parameters. One of such elements is the regulation of the wavelength lighting intervals (Figure 8).

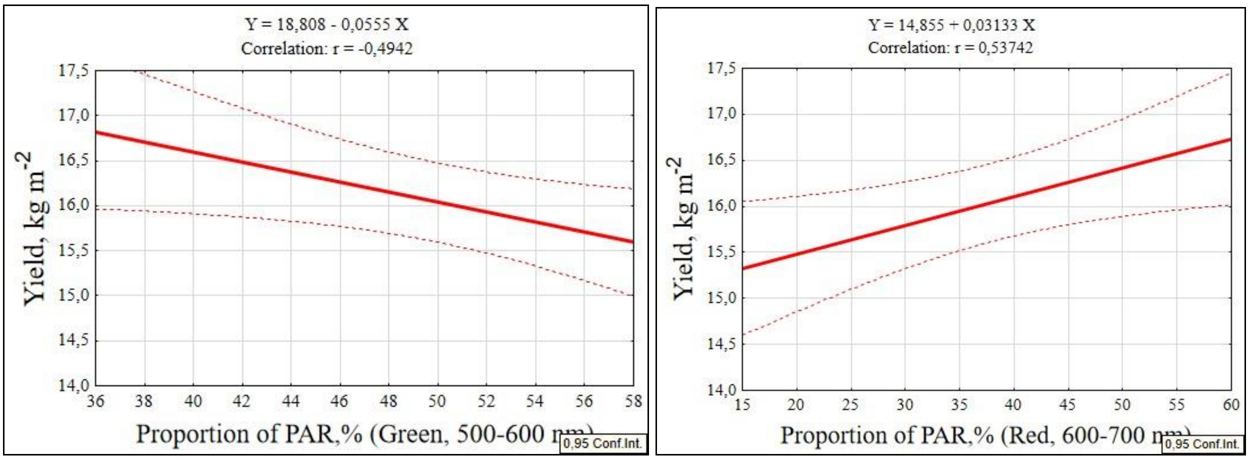


Fig 8: Regression plots of tomato cultivars yield as a function of the spectral range (green and red) wavelength in the lamps radiation, nm

Further correlation analysis of the lighting spectrum influence on the formation of yield indicators shows that the lighting spectrum composition significantly affects the value of tomatoes yield. An excessive amount of green light in lamp radiation (500-600 nm) negatively affects the tomatoes yield (r = - 0.49), while an increase of red light proportion (600-700 nm) leads to an increase in yield (r = 0.54) ($p \leq 0.05$).

Conclusions

The efficiency of supplemental lighting of tomato plants grown in greenhouses by high pressure sodium lamps with addition of 5 at% cesium in amalgam is shown. It has been determined that the introduction of 5 at% Cs into the amalgam of the lamp results in a redistribution of the spectral energy of light radiation in the PAR region comparatively to the radiation of standard high-pressure sodium lamp. The spectral distribution in the PAR region of HPS-Cs 400 lamp is: 14% (400-500 nm), 31% (500-600 nm), 55% (600-700 nm). It was shown that the raise of red light proportion up to 55% determines the significant morphological changes in tomato plants such as the increase of shoots height, the number of formed leaves, and the first internode length. A significant effect of radiation of this spectral composition on the photosynthesis has been established. The total photosynthetic pigments content in leaves of ‘De Barao’ and ‘Hybrid Tarasenko’ tomato cultivars under lighting by high pressure sodium lamp with addition of cesium was 1.4 and 2.5 times higher than under lighting by MALF 400 and HPS 400 lamps, respectively.

The additional light of the indicated spectral ranges significantly increased the tomato yield both per one plant and per plot square meter. The yield growth per one plant grown under lighting of HPS-Cs 400 lamps compared to plants lighted by HPS 400 lamps was 7.4% (‘Hybrid Tarasenko’) and 6% (‘De Barao’). A more significant yield increase was obtained at comparison to the plants illuminated by MALF 400 lamps - 22.8% for tomatoes of the ‘Hybrid Tarasenko’ cultivar and 24.5% for the ‘De Barao’ cultivar.

Conflict of interest statement

We declare that we have no conflict of interest

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