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Features of the lighting spectrum influence on the productivity and biochemical composition of test fruit and leaf vegetable crops

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The work is devoted to the study of the photosynthetically active radiation spectral characteristics influence on the productivity and quality of lettuce and dwarf tomato adapted for protected ground. High pressure sodium lamps and LEDs emitting yellow light, pink light and close to sunlight spectrum were used as test options for plant illumination. Vegetable crops were grown under controlled conditions of intensive lightculture by thin-layer panoponics; the same irradiance was achieved in all variants. Using a light source simulating sunlight with a photosynthetic photon flux of $76\,\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in the 400−500 nm range, $130\,\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in 500−600 nm and $133\,\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 600−700 nm made it possible to obtain an increase in productivity by 10% for lettuce and by 23% for tomato, and also led to an increase in the content of magnesium and iron in lettuce leaves and a higher content of carbohydrates, vitamin C, crude ash in tomato fruits compared to standard sodium lamps.

Keywords: LED, tomato, lettuce, lightculture, plant products, quality, photosynthetic photon flux.

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Introduction

Vegetables are an essential source of vitamins, antioxidants and other biologically active substances. In protected ground conditions, efficient cultivation conditions may be created to allow control of biochemical composition, quantity and quality of nutrients, production potential of plant products. Optimization of illumination environment properties is still an important plant production area. Development of applications of light with various spectral composition for controlled biosynthesis of biologically valuable compounds of various purpose is a promising area [1]. Development of LED technologies, including the complex plant response to multicomponent light, facilitate the improvement of agricultural production in protected ground conditions [2].

Light controls several processes in plants such as photosynthesis, morphogenesis, metabolism, transpiration, etc., through receptor systems of phytochromes, cryptochromes and phototropines interacting with photons of certain spectral ranges of photosynthetically active radiation (PAR) [2]. Spectral composition of light is one of the essential regulatory factors of plant morphogenesis influencing the growth process intensity, tillering, rooting, metabolic process direction, etc. [3]. It is believed that photomorphogenesis processes are mainly influenced by blue emission ($\sim$ 400−500 nm), red emission ($\sim$ 600−700 nm) and far-red emission ($\sim$ 700−800 nm) absorbed by photosensitive pigments, and addition of green emission ($\sim$ 500−600 nm) causes improvement of their performance [4]. Blue light effects plant growth in general, leaf growth, stomata opening, pigment accumulation [5–7]. Green light increases antioxidant potential and facilitates fruit after-ripening [8]. Red light has the highest relative quantum efficiency of photosynthesis, it causes dry weight gain, root system growth, stem elongation, increase in leaf surface area, controls flowering duration [9], influences the chloroplast functions, plant reproduction system development [10]. Far red light may significantly influence plant growth and morphology [11] and facilitate the increase in biomass by short-term exposure, which is associated with phytochrome operation and hormonal rearrangements that also influence circadian rhythm, stomatal conductance and plant respiration [12].

In addition to the detected light quality effects on plant development, there are significant species and varietal differences in plant response to spectral composition of light environment as well as wide variability of biochemical composition depending to the light environment conditions. Reduced blue light content (lower than 20%) in the exposure spectrum may cause increased sodium content in lettuce by 70% which can result in salt imbalance and, thus, in leaf structure changes [13]. Monochromatic green light facilitates the increase in microshoot sizes and increase in propagation factor in raspberry plants, however, does not provides such effect in blackberry plants [14]. For pepper plants grown in red light, maximum height is observed, however, addition of 5% of the total blue light intensity causes the increase in the number of fruit, 9% to the increase in the total chlorophyll and antioxidant content, and 17% to the maximum carotenoid concentration [15]. Short-term night activations of red light [16] cause the increase in the active form of phytochromes, increase in the antioxidant content level, increase in tomato fruit sizes [17], absence or size reduction of root crops in short-day radish varieties [18]. For harvested crop storage, red light can slow down ethylene synthesis and facilitate ascorbate concentration reduction (associated with yellowing and ageing) in broccoli head [19]. Presence of far-red component of at lest 15% facilitates the increase in the pine strawberry flower spike length which simplifies the berry picking process [20]. Red to blue light ratio within 1.3–4.2 ensures the best implementation of antioxidant protection mechanism in grape plants, lower ratio causes increase in peroxidase activity [21]. For pine strawberry plants grown with LED supplementary lighting with red to blue spectral composition ratio 2 to 1, sugar content is 10–20% higher than for lighting with higher red component percentage [22]. And soybean cultivation under LED lamps with increased red light component and without green light component resulted in interstice extension without increase in plant weight [23].

Potential narrow-band emission from LEDs allows to assess the role of certain wavelengths in plant morphology and development, however, the increasing number of investigations shows that plants need the full visible light spectrum to implement their production potential. For example, compared with white light, separate blue, green and red light action causes reduction of Agria potato biomass accumulation by 50, 76 and 68%, moreover, white light exposure caused maximum carboxylation rate [24]. At the same time, application of light spectrum characterized by equal energy fractions in individual PAR ranges caused formation of increased number of leaves in parsley rosette, increased wet leaf weight and higher dry substance content, and in case of exposure to spectrum close to the relative spectral photosynthesis efficiency, total leaf length increase was observed due to stalk extension with retained proportions of the remaining portion of the leaf [25]. Total increase in PAR and UV-A region facilitates the growth of chlorophyll *a* and *b*, and carbohydrate content in lettuce leaves, accelerates scion development due to the increase in the number of interstices and stem weight [26]. Illumination of onion with combination of red, blue, orange and white LEDs caused higher accumulation of vitamin C compared with other options [27].

Nevertheless, LED application may also lead to negative effects — for example, for nitrate accumulation. It was noted that the efficiency of microelement extraction by tomato and lettuce leaves from nutrient solution is higher by 10–20% when illuminated by sodium lamps than when illuminated with LED lamps, in this case efficiency of microelement extraction by lettuce does not depend on light spectrum, and it is 30% higher in tomato exposed to sodium lamp light than to LED light [28].

Thus, in the modern lightculture, increasing attention is drawn to the influence of light spectrum composition not only on photosynthesis reactions and content of photosensitive pigments, but on biochemical composition characterizing the quality of cultivated plant products. Lack of certain wavelengths may cause physiological damage in plants observed during cultivation in a wide spectrum of PAR [2] — this is due to light induction of signal pathways initiating secondary metabolite accumulation, for example, flavonoids associated with immune response of plants to biotic stresses [29,30]. Therefore, crop plant production more often uses light fixtures, including not only chlorophyll absorption peaks, but all PAR ranges [31] whose role and influence mechanism are yet to be determined.

The purpose of this research was to detect the influence of full spectral composition of light environment with different light intensities in significant PAR regions on productivity and quality, characterized by biochemical composition, leaf and fruit plant crops in intensive lightculture conditions.

1. Used light sources

Currently, three main approaches to LED illumination spectrum formation can be identified [13]: 1) use of primarily red and blue LEDs providing the spectrum having high factor of correlation to chlorophyll *a* and *b* absorption spectrum; 2) use of McCree spectral plant sensitivity[32]; 3) natural sunlight spectrum simulation.

According to this, we have selected four various light spectra implemented by the following light sources: 1) HPS — „REFLAKS" (Russia) high pressure sodium lamps, 400 W, most widely used in protected ground plant production and taken as reference (Figure 1, *a*); 2) LED1 — LED light source emitting yellow light with spectrum close to sodium lamp spectrum and taking into account the averaged spectral quantum yield of photosynthesis [32] (Figure 1, *b*); 3) LED2 — LED light source emitting pink light containing red and blue region peaks corresponding to maximum chlorophyll absorption (Figure 1, *c*); 4) LED3 — LED light source with visible light spectrum composition close to sunlight (Figure 1, *d*). LED1, LED2 and LED3 were made by the Agrophysical Research Institute partners according to our recommendations and calculated light intensities and spectra taking into account plant requirements and including physiologically significant bands. LED1 contains white, amber and cyan LEDs, LED2 contains combination of red and white LEDs, and LED3 includes white LEDs with modified secondary optics using polymer phosphor (know-how).

Photosynthesis intensity is defined by the number of absorbed photons in PAR region, i. e. this is a quantum process. Therefore, photosynthetic photon variables, characterized by photosynthetic photon flux density (PPFD), rather than lighting fitting energy variables for PAR region are currently introduced extensively into the protected ground plant cultivation practice [33]. Transition from energy units to photon units is possible either by calculation based on measured light spectra of lighting fixtures [34], or using appropriate instruments, including conversion algorithm. For the purpose of this research, light spectra have been obtained using both approaches: for HPS, LED1 and LED2,

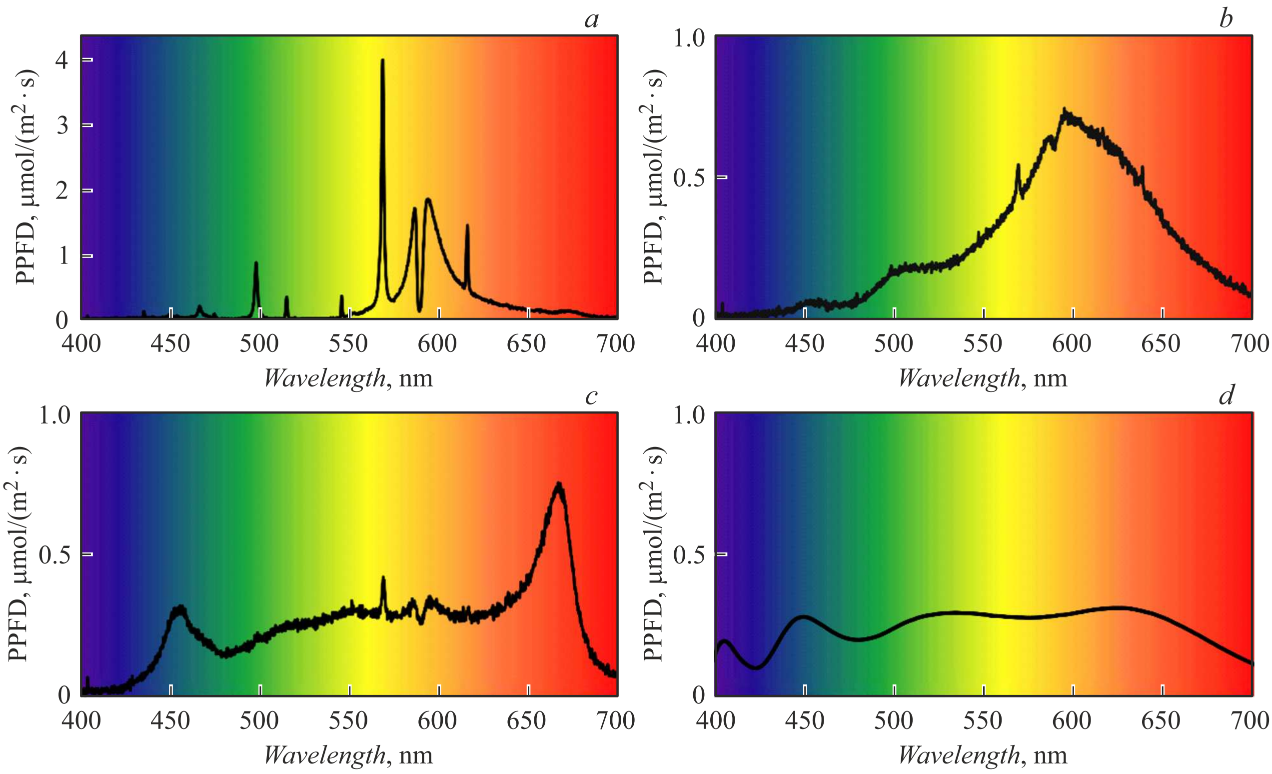

Figure 1. Emission spectra of light sources: *a* — HPS, *b* — LED1 (yellow light), *c* — LED2 (pink light), *d* — LED3 (close-to-sunlight).

Table 1. PPFD value distribution by emission ranges for used light sources

Light source	PPFD in 400–700 nm, μmol · m^{-2}s^{-1}	PPFD in 400–500 nm region		PPFD in 500–600 nm region		PPFD in 600–700 nm region	
		μmol · m^{-2}s^{-1}	% of total PPFD	μmol · m^{-2}s^{-1}	% of total PPFD	μmol · m^{-2}s^{-1}	% of total PPFD
HPS	341 ± 24	29	9	185	54	127	37
LED1	342 ± 24	23	7	156	46	163	47
LED2	332 ± 23	61	18	123	37	148	45
LED3	339 ± 21	76	22	130	38	133	40

spectra were measured in relative units using integrating sphere and Thorlabs CCS200 CCD spectrometer (USA), averaged throughout the cultivation surface and relative units are converted into PPFD, and UPRtek PG200N spectral PAR meter (Taiwan) with built-in algorithm for conversion of Wm^{-2} into μ mol · m^{-2} · s^{-1} was used to obtain spectral parameters of LED3 source. Using the obtained data, light sources were arranged in the vegetation facilities such that to ensure the same photosynthetic active photon flux rate for all options which is equal to $340 \pm 25\,\mu$ mol · m^{-2} · s^{-1} (optimum value for photophilous crops [35]) to avoid light intensity effect on plant crops. Table 1 shows the main difference of spectral characteristics of sources used — PPFD distribution over — blue, green and red ranges. The most uniform photon number relationship in each range is typical of LED3 light fixture with spectrum close to sunlight.

2. Biochemical analysis

Biochemical composition of the obtained plant products was defined by the accredited Test Laboratory of the Agrophysical Research Institute in accordance with the regulatory documents (Table 2). Crude ash, carbohydrates, nitrogen, phosphorus, potassium, calcium, magnesium were determined in % of absolute dry weight (% DW), vitamin C in mg per 100 g of fresh weight (mg/100g FW), nitrates in mg per kg of natural moisture (mg/kg FW), heavy metals and microelements in mg per kg of dry substance (mg kg^{-1} DW). Dispersion and regression analyses and other statistical processing of consolidated data are carried out using MS Excel 2010. The text and tables contain arithmetic mean values of variables and their confidence intervals at 95% probability level by *t*-test.

Table 2. Biochemical composition measurement methods for test plant crops

Measured substance or variable	Method	Reference
Humidity	Air heat drying	[36]
crude ash	dry ashing	
Carbohydrates (sugars)	Titrimetric method (Bertrand copper-reduction method)	
Nitrogen	Photometric indophenol nitrogen determination method	[37]
Phosphorus	Photometric phosphorus determination method	
Potassium	flame-photometric	
Potassium	Flame atomic absorption spectrometer	
Magnesium	Flame atomic absorption spectrometer	
Vitamin C	Titrimetric	
Nitrates	Ionometric	[38]
Heavy metals and microelements (Fe, Mn, Cu, Co, Zn, Ni, Pb, Cd)	Flame atomic absorption spectrometer	[39]

3. Experimental growing conditions for lettuce

„Sortsemovoshch" Taifun (Russia) leaf lettuce (*Lactuca sativa* L.) plants were used as the test object. Leaf lettuce has wide vitamin and mineral composition, including vitamins B and C, and calcium, boron, copper, iodine, phosphorus. Among the wide range of varieties, Taifun leaf lettuce is distinguished by quick growth, large open leaf rosette and stable yield capability even at insufficient illumination.

For the experiment, lettuce plants were grown by thin-layer panoponics method [40] in automated vegetation lighting systems equipped by light sources with various spectral characteristics (Figure 2). Light period time was 14 h per day. Air temperature was maintained within 18–20°C in day time and 16–18°C in night time, relative air humidity was 65–70% [41,42]. For watering during vegetation, 0.8 N Knop's nutrient solution was used. A community containing 30 lettuce plants (replication) was formed per 1 m^2 of vegetation lighting system. The vegetation experiment was performed twice. Harvesting was performed on day 28 after seeding. During harvesting, plant wet weight equivalent to 1 m^2, i. e. crop productivity, leaf area and plant height were recorded.

4. Light spectrum effect on lettuce productivity

The research of light spectrum effect on lettuce plants is interesting primarily in that photosynthesizing organ (leaves) parameters of lettuce are directly associated with productivity and describe the product yield [43].

Study of full-spectrum light effect with different photon ratio in blue, red and green PAR regions has shown that the highest productivity is observed for LED3 illumination option with smoother photon distribution by energies. At the same time, for light sources LED1 and LED2 it is characteristic reduction in the value of the resulting crop by 42% and 44% respectively. This is probably related to the formation smaller area of photosynthetic organs [44] — for plants illuminated with LED1, the leaf area was less by 27%, and when irradiated with LED2 — by 24%, than when using HPS lamps. In addition, the general plant height was lower by 13% and 17% compared to with control under LED1 and LED2, respectively. Wherein average leaf area under illumination with HPS lamps and LED1 practically did not differ and was about 100 cm^2, and the plant height reached 21 cm.

It follows that large fraction of photons in the red range did not provide increased productivity, while it was the PPFD ratio between light spectrum regions that played the decisive role. For LED3 option with the highest productivity, it was 1 : 1.7 : 1.8 (blue : green : red). However, high yield for lettuce plants illuminated by HPS was probably associated with the presence of illumination in far-red and IR ranges (additionally 72 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in range 700–1000 nm).

5. Light spectrum effect on biochemical composition of lettuce

Biochemical composition analysis of lettuce plants (Table 3) has shown that there are no definite differences in dry substance accumulation by lettuce leaves grown under HPS, LED2 and LED3 (weak reduction trend by 3–9%) and definitely lower content by 15% under LED1

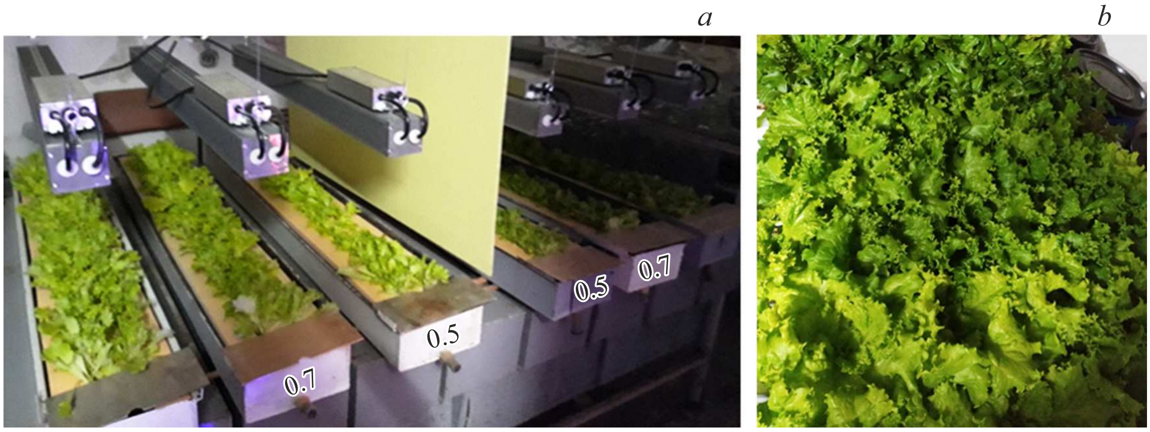

Figure 2. General view of experimental vegetation lighting systems with lettuce plants: *a* — under LED light sources, *b* — under HPS lamps.

Table 3. Biochemical composition of lettuce plants grown under light sources with different spectral composition

Parameter	Light source			
	HPS	LED1	LED2	LED3
Dry substance,%	4.7	4*	4.3*	4.55
Nitrogen, % DW	3.46	3.88*	3.69*	3.94*
Phosphorus, % DW	0.58	0.79*	0.63*	0.66*
Potassium, % DW	7.87	9.46*	7.14*	6.53*
Calcium, % DW	2.09	2.03	2.08	2.05
Magnesium, % DW	0.432	0.4*	0.484*	0.55*
Iron, % DW	109.8	95.6*	101.6*	118.7*
Sum of sugars, %DW	16.43	12.45*	13.61*	12.34*
Vitamin C, mg/100 g FW	16.69	15.35*	16.17	16.04
Nitrates, mg/kg FW	1490	1597*	1423	1551

Note: * — value is definitely different from the control (HPS lamp option) at 5% significance level.

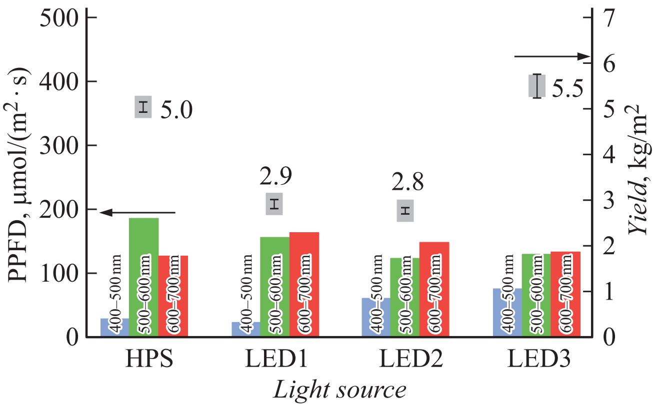

Figure 3. Productivity of lettuce plants grown under light sources with different spectral composition.

which indicates increased water content in tissues and growth of their osmotic potential due to mineral element accumulation. Thus, significant or trending increase in the form trend of nitrogen content (by 7–14%) and phosphorus content (by 9–36%) under LED light sources was detected compared with HPS lamps. At the same time, for potassium content, definite growth (by 20%) is only observed in LED1 option. Potassium content reduction trend (by 9%) was detected in LED2 option and definite reduction was detected in LED3 option. Higher content of the specified macroelements in lettuce leaves under LED1 and LED2 with drop of growth and productivity variables compared with those under HPS lamps allows to suggest lower intensity of physiological processes of the use and transformation of these compounds, and of the consumption of organic substances in plants for adaptation to light environment conditions. However, no definite differences were detected in calcium content under all LED lamps and in magnesium content under LED1 compared with HPS lamps and definite increase or increase in the form of trend of magnesium amount under LED2 and LED3 by 12–27%. It should be noted that definite reduction of carbohydrate content (by 17–25%) and vitamin C reduction trend (by 3–8%) under LED light sources. In this case, iron content reduction trend by 7–13% was observed under LED1 and LED2 and iron content increase by 8% under LED3 compared with that under HPS lamps. Probably, lettuce plant growth stimulation in LED3 option was primarily due to the increase in magnesium and iron content as well as to intensification of primary metabolism processes associated with catalytic properties of iron ions as cofactor of multiple ferments involved in large number of metabolic processes in plants. Definitely higher content of carbohydrates involved in photosynthesis and oxidation-reduction processes in lettuce leaves grown under HPS was

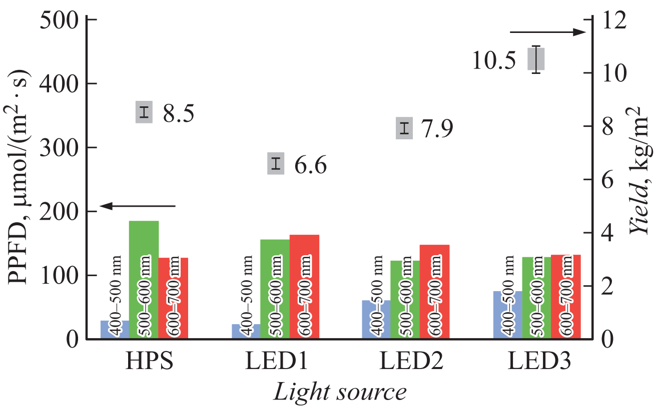

Figure 5. Productivity of tomato plants grown under light sources with different spectral composition.

indicative of sufficiently high assimilation activity of leaves (increase in leaf area, dry substance).

6. Experimental growing conditions for tomato

Natasha tomatoes bred by the „Federal Scientific Center for Vegetable Growing" (Russia) were used as the test object. These are dwarf type plants, compacts, requiring no pruning and tying, suitable for hydroponic growing method in narrow-rack and multilayer systems, also with artificial illumination.

The experimental tomatoes were grown by the thin-layer panoponics method [40] in vegetation lighting systems with various spectrum (Figure 4). Knop's solution was used for mineral nutrition. In each of the germinators with a length of 1 m, 5 plants were placed forming a plant community of 20 plants per m^2 (replication). Air temperature was maintained within 22–24°C in day time and 18–20°C in night time, relative air humidity was 75–80% [41,42]. The plants were picked on day 90 after seeding. During picking, plant productivity per 1 m^2 of the effective area of the vegetation lighting system was recorded, and biochemical composition of the fruit was determined. The vegetation experiment was performed twice.

7. Light spectrum effect on tomato productivity

The test for the effect of lighting environment with various spectral characteristics on Natasha tomato plants development in intensive lightculture has shown that the best results in terms of plant productivity were achieved when using LED3 light sources with spectrum maximally close to the solar spectrum (Figure 5). For tomato plant growing, the yield using LED3 was higher by 20% compared with control plants grown under HPS lamps. Use of LED1 and LED2, on the contrary, led to a decrease in

Table 4. Biochemical composition of lettuce plants grown under light sources with different spectral composition

Parameter	Light source			
	HPS	LED1	LED2	LED3
Humidity, %	93.1	94.5	94.1	93.8
Dry substance, %	6.9	5.5*	5.9*	6.2*
Crude ash, % DW	10.1	10.8*	10.3	10.6*
Sum of sugars, %DW	33.3	35.4*	45.8*	41.5*
Monosaccharides, % DW	31.0	35.1*	44.3*	36.2*
Disaccharides, % DW	2.3	0.3*	1.5*	5.3*
Vitamin C, mg/100 g FW	18.5	18.0	24.6*	27.5*
Nitrate, mg/kg HW	52.9	59.3*	69.7*	47.4*

Note: * — value is definitely different from the control (HPS lamp option) at 5% significance level.

productivity by 22% and 7% respectively. It is interesting to note that the plant height was similar for all variants lighting with LEDs — 28.7 ± 4.1 cm for LED1, 27.3 ± 5.2 cm for LED2, 29.5 ± 4 cm for LED3 respectively, and when irradiated with HPS lamps, plants measurements reached 38.3 ± 2.0 cm. At the same time, at approximately the same number of fruits per plant (46 ± 2). All variants showed significant differences in weight of one fruit — 7.1 ± 0.5 g for HPS, 5.6 ± 0.5 g for LED1, 7.0 ± 1.0 g for LED2, 9.5 ± 0.9 g for LED3. Increased by almost 34% fruit weight when using luminaires LED3 in comparison with the control lamps HPS speaks of the high efficiency of selected emission spectrum in this variant. Established increase in productivity of tomato plants under LED3 , probably due to amplification processes of root nutrition and redistribution of organic substances (attractions) from vegetative organs into fruits [45].

Thus, the use of LED lighting with a spectrum close to PAR solar spectrum may be preferable for protected ground which involves multilayer rack arrangement of tomatoes by means of reduced plant height with increased weight of the fruit and absence of thermal burns when plants are arranged close to each other and to the light source.

8. Light spectrum effect on biochemical composition of tomatoes

Comparative assessment of biochemical composition of Natasha tomatoes has shown their quality under all test light sources (Table 4). Thus, LED1 primarily did not caused any significant changes in the biochemical composition of fruit, except for definite reduction of dry substance content by 20% compared with that under HPS lamps. At the same time, LED2 caused considerable changes in the quality of tomatoes. Definite increase in sugar content by 38% mainly *a* *b*

Figure 4. General view of experimental vegetation lighting systems with tomato plants: *a* — under LED light sources, *b* — under HPS lamps.

due to simple sugars and in vitamin C content by 33%, ashy elements in the form of trend by 2% compared with HPS lamp option. Under LED3, change in biochemical composition of fruit was detected, i.e. definitely higher carbohydrate content by 17% was observed, due to double sugars, vitamin C content by 49%, crude ash as a trend by 5% compared with sodium lamp illumination option, and nitrate content had a downward trend (by 10%). In LED1 and LED2 options, nitrate content was higher than that under HPS lamps by 12–32%, however, under all test lighting fixtures, it did not exceed the maximum allowable concentration and corresponded to sanitary and hygienic standards of the Russian Federation.

Conclusion

According to the data obtained in other investigations, it has been shown that the light environment parameters, i.e. light spectrum characteristics, play an essential role in plant development and influence not only morphological variables, but also biochemical composition of leaves and fruit. The best results in terms of productivit and quality of plant products grown in protected ground conditions have been achieved when using light sources with spectrum close to the natural solar PAR region light.

The use of full-spectrum light source with the most smoothed photon number ratio inn blue, green and red ranges $(1:1.7:1.8)$ among all test options made it possible to get increase in productivity in the form of trend by 10% for lettuce and definite increase by 23% for tomatoes compared with reference sodium lamps. Moreover, positive changes in biochemical composition characterizing high quality of the obtained plant products were observed — increased magnesium and iron content and higher carbohydrate, vitamin C and crude ash content in tomatoes. It may be suggested that the increase in productivity during growing under LED3 light sources is associated with the change in biochemical composition as follows: primary metabolism processes are enhanced in lettuce leaves due to catalytic properties of iron, and in tomato plants — organic substance redistribution from vegetative organs into fruit.

Thus, the shown benefit of the light spectrum which is close to the solar light indicates a decisive role of entire visible spectrum wavelength range in plant life both for photosynthetic reactions, light energy accumulation and transformation and for metabolic process control and formation of biomass and biochemical composition of plant products.

Conflict of interest

The authors declare that they have no conflict of interest.

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