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The Use of Energy-Efficient Sources While Growing a Small Quantity of the Cucumber Under the Artificial Lighting Agricultural Ecosystem

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The Use of Energy-Efficient Sources While Growing a Small Quantity of the Cucumber Under the Artificial Lighting Agricultural Ecosystem

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Abstract. The research presents the results of experimental findings of cucumber growth «Partner F1» that doesn't exceed a cubic metre of quantity at artificial agroecosystems: soil was used as a substratum, there was no natural source of light, watering was provided according to plant needs. Four LED light sources with different spectra were used as luminous elements: -two sources on the basis of white light-emitting diodes with a correlated color temperature (CCT) of 4000 K and a color rendering index Ra-80 with LEDs emitting maximum optical spectrum of 625 and 630 nm in the quantitative ratio of 9:2 and 1:1; -two ones were designed using white light-emitting diodes distinguished by a measure of a CCT (3000 K and 4000 K). It was shown the possibility of cucumber development under all explored luminous spectra on the basis of morphometric measures and analysis of productivity of four plant hybrid groups that went through the whole reproduction cycle from the seed development to fruit-bearing plants. More intensive development of the vegetative parts and the early beginning of the reproductive plant stage under spectra with an extra red-blue component were identified. Plants grown under white LEDs had better state of vegetative parts on the reproductive stage.

1. Introduction

Cucumber growth in a protected environment is one of the most popular in the world. Greenhouse facilities provide population with this production throughout a year. In the conditions of the light shortage that is common to most areas in autumn and winter periods, a plenty of attention is given to the dependence of light-demanding cucumber productivity on the illumination level and specific light element placement. Only artificial lighting can be used to support the productivity of greenhouse farm ecosystem even in relatively summer regions [1].

The use of new technologies of greenhouse design and operation means complete refusal from daylight illumination while growing vegetable production. The term «photoculture» is plant growth under additional or full control lighting and that is commonly used among vegetable growers. Moreover there is an urgent issue of the profitability of plant growth under artificial lighting conditions that can be provided with the use of the efficient light sources.

In recent years the applied scientific research to create optimum conditions for plants growth while increasing energy efficiency and profitability of hothouse facilities, has found out an obvious tendency to provide new greenhouse complexes with LED lighting equipment. These days the research and experimental work is carried out both under laboratory conditions and in real greenhouse facilities [2,3].

It is known that the use of solid-state light sources provides: a long-term service of lighting elements, relatively low power consumption, opportunity to create light spectra for plants. Nowadays researchers are dealing with the following issues as how to control the composition of chemical components, ornamental features of plant color, to preserve agricultural production by means of adapted luminous fluxes produced on the basis of LED technologies, pre-sowing seed treatments under luminous fluxes



with a definite wavelength [4-6]. Meanwhile the major purpose of plant breeders is to achieve high greenhouse profitability focused on productivity of agroecosystem at minimum cost for the agricultural production due to technological process optimization of plants radiation. Under the experimental conditions the solution of such an aspect is to use luminous elements of different design due to qualitative measures: a combination of various types of lighting systems; a placement of luminous elements within light environment focused on morphological traits of cultivated plants; a selection of spectrum qualitative composition provided intensification of photosynthesis processes.

LED light sources in comparison with the conventional luminous elements used in greenhouse facilities are more mobile that allows to use them while growing plants with a multilayered position of laminae. Cucumber is a plant having long vines that is why it needs more space to grow. Researchers direct their attention to the impact of various type lighting systems on the plant growth including a cucumber as well. Combined lighting systems with the use of both common ceiling lights and vertically placed inter-row LED elements are applied at growing cucumbers in the protected agriculture. Another investigation includes cucumber growth only under the LED-based lighting conditions. A number of studies identified positive effect of using LED inter-row supplementary lighting on the plant growth [7, 8].

Our researches were conducted due to the modern tendencies of city plant-growing development called "city farming" that means to place plants near a consumer. A tall climbing cucumber requires spacious place to grow. A cucumber growth experiment under the artificial ecosystem conditions of small quantity was carried out in the investigation.

The research aim is to produce a LED emission source providing the intensification of the production process of cucumber ecosystem by means of wavelength characteristics optimization in small quantity ecosystems. The following challenges were solved to achieve this target goal: lamps with phyto-focused wavelength characteristics; the experimental investigations of cucumber growth under luminous sources with various spectral distribution.

2. Research methodology and the experiment

A cucumber, which size and biological features contributed to achieve the goal, became the object of the research to conduct such challenges. The parthenocarpic cucumber «Partner F1» was chosen as the object of the research. This hybrid is for the cultivation in the open field and protected environment. The cycle of the plant development is 45 days, from sprouting to the beginning of fructification. The cucumbers «Partner F1» have the following features: compact vines, dark-green color, torulose and smooth skin, thick hairy, 9-12 cm length. The texture is crisp and firm, without bitter taste. The cucumbers «Partner F1» may be used fresh, preserved and pickled. A small plant size, a relatively short life cycle along with a possibility of self-pollination and peculiarities of F1 hybrid are features that are appropriate for experimental researches under artificial ecosystem conditions in small quantities.

The lamp design process was based on the study of the experimental findings presented in scientific literature.

It was K A Timiryazev who began to study light characteristics as the energy source for plants growth and development in the second half of the 19th century and this research has been continued up to now. First of all, researchers are interested in the lightwave length that is a physiologically relevant factor for plants, providing high growth of plant biomass and, as a result, drawing agricultural producers' attention. A generalized spectral property of the plant leaf sensitivity to light is widely known. Investigators point out the plant sensitivity to spectral distribution of radiation sources in dependence to the plant species and the sort. While developing a LED phyto lamp, the preference in modern applied scientific research, is given to 380-490 nm and 600-780 nm wavelength ranges. However, the spectral distribution has an impact on stages of plants development: vegetative growth, anthesis, fructification. Though the data are controversial, some lamp manufactures use light emitting diodes with wavelengths which do not include the whole spectral range for the phyto lamp production. Nevertheless, most researchers think that spectral range about 500 nm is useful. The study of plants cultivation in experimental conditions conducted by N N Protasova is the classical one [9]. According to the investigation results of luminous flux impact of various spectral distribution, morphogenesis physiological causes of plants grown under different wavelength of luminous fluxes were found out: the highest rate of photosynthesis per one leaf

area unit was observed under blue light; red spectral region contributed to the intensive leaf and axial organ growth; in a green spectrum thin leaves were formed with the minority of cells and chloroplast in reference to the lamina area upon the registration of the lowest photosynthesis rate per a leaf area unit, but in reliance on chloroplast it was the highest one. Research-based recommendations were given concerning an optimal combination of plant growing lamps including blue (380-490 nm), green (490-590 nm) and red (600-700 nm) apparent spectrum range with a predominance of the red color [9]. Recent research aimed at the investigation of green LED spectrum impact on a cucumber did not produce any meaningful results while the experiments [10].

A certain amount of LEDs with a wavelength 532 nm was composed 28% in this case, 473 nm – 20% and with 660 nm wavelength – 52%. Due to N.N. Protasova's classical study, it should be noted that a plant needs light source with the definite proportion of spectra: 380-490 nm of the radiation range should be composed 20-25%, 490-500 nm – 20-25% and 600-700 nm – 60-50%. Thus, percentage ratio of spectrum quantitative components and wavelength of experimental lamps are nearly the same in this research. The experimental results probably depend on plant features or have another origin. Nevertheless, there is such a physical phenomenon as entering of green light waves through the top and low leaves that provides shaded low leaves with increased level of lighting. This phenomenon can make an important contribution to vertically cucumber growth and development. The main investigations carried out with the search purpose of effective spectrum of plant lighting are focused on the search of optimum proportion with wavelengths of blue and red ranges in a spectrum. The influence of blue light on average cucumber growth and development is proved by experiments focused on physiological measures of photosynthetic productivity of plants [11].

While the main production priority is red-blue phyto lamps, researchers determine LEDs of white spectrum as the suitable ones to grow certain plant species [12].

Due to the literary studies results four types of LED lamps focused on the plant needs to the light wave were designed. Optical radiation with blue (400-500 nm), green (500-600 nm) and special red wavelengths (625-680 nm) has a greater influence on photosynthesis.

Taking into account the above-mentioned findings, the lamps with unique current-wavelength characteristics were designed and produced (Figure 1). Luminous elements with mentioned features below were used as light sources.

The lamp type No1, contained white light emitting diodes, based on a blue chip and a yellow-green inorganic luminophore of an aluminum-yttrium garnet group. LEDs had correlated color temperature 4000K and colour rendering index 80.

The lamp type No 2 included white light emitting diodes with correlated color temperature (CCT) = 4000K and colour rendering index 80 that was similar to the lamp type No1 and blue light emitting diodes and organic luminophore, with maximum 630 nm in the red visible spectrum. The quantitative proportion of LEDs was 1:1.

The lamp «type No3» had LEDs based on a blue chip and a yellow-green inorganic luminophore that was a group of aluminum-yttrium garnet. LEDs had correlated color temperature 3000K and colour rendering index 80.

The lamp «type No4» contained white light emitting diodes which were similar to the lamp «type No1» and LEDs with blue chips and organic luminophore of red spectrum with maximum 625 nm. The proportion of LEDs quantity was 2:9.

The evaluation method required for LED lamps characteristics was based on the determination of photosynthetically active radiation (PAR) of the photon flux ($\mu\text{mol/s}$).

The photosynthetic radiation EPAR ($\mu\text{mol/s}^2$) is the quantity of photosynthesis evaluation in its influence on the plant. The photosynthetic radiation is ratio of the photosynthetic photon flux, falling onto a little surface area in relation to the whole one (photon flux density on the surface) as required by National Standards PNST 211-2017.

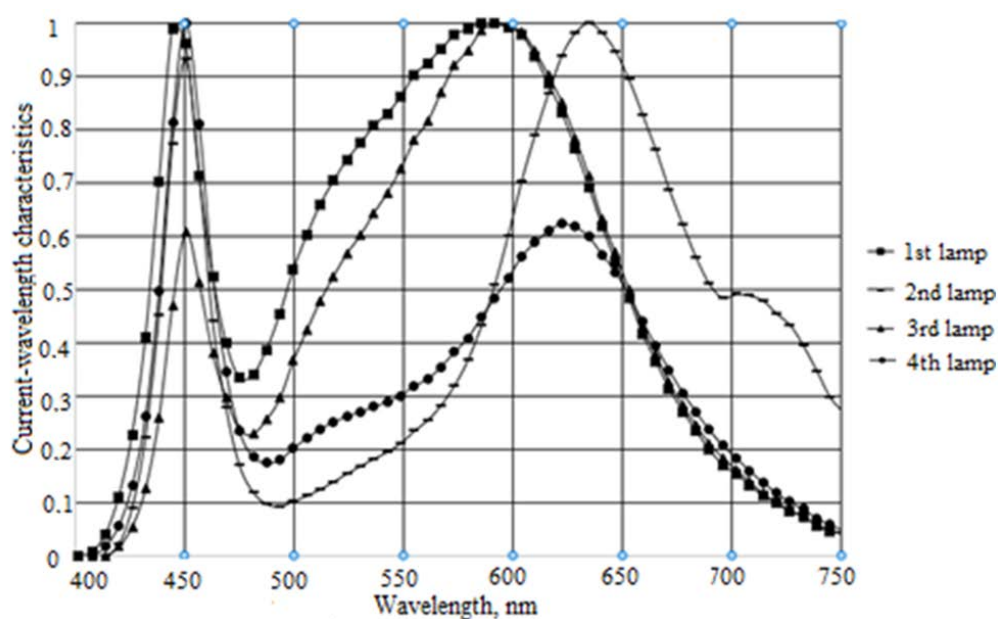


Figure 1. Spectral features of LED lamps used in the experiment

$$E_{par} = \int_{400\text{ nm}}^{700\text{ nm}} E_{\lambda} \frac{\lambda}{h \cdot c \cdot N_a} d\lambda = K \int_{400\text{ nm}}^{700\text{ nm}} E_{\lambda} \cdot \lambda d\lambda$$

E_{λ} is a spectral irradiance W/ (m²·s);

λ is a wavelength (nm);

$h = 6.626 \cdot 10^{-34}$ j·s is the Planck constant;

$c = 3 \cdot 10^8$ m/s is the speed of light;

$N_a = 6.022 \cdot 10^{23}$ mol⁻¹ – the Avogadro constant;

$K = 8.36 \cdot 10^{-3}$ mol⁻¹·j⁻¹ – the coefficient.

Lamp characteristics were worked out due to this method. Wavelength and illuminance of each lamp were measured with the TKA-VD spectrophotometer. The spectral composition of each light source was determined according to the results of spectrophotometer measurements (Figure 1). Photosynthetic radiation (EPAR) values of all lamp types were calculated according to the above-mentioned formula. Received data were summarized in table 1.

Table 1. Illuminance and PAR of LED lamps results.

Symbolic signs of lamp types	Illuminance values, lx	Photosynthetic radiation values EPAR, μmol/s ²
type № 1	3010	40.5
type № 2	3112	57.2
type № 3	2988	41.6
type №4	3000	72.1

The experiment was carried out from the 2nd of December 2016 to the 15th February of 2017.

Such morphometric parameters of plants as the shoot length, a leaf rosette diameter, the number of leaves, the leaves length along the midrib and width according to the final size of leaves were taken as evaluation criteria to determine biological effectiveness of the artificial illuminance source. Hypocotyl length, cotyledonous leaves length and width were measured from the earliest vegetative phase. The measurement scheme of the plant growth is presented in Figure 2. Color and distortion of leaves (loss of turgor) were registered due to visual observation.

Length dimensions, the diameter, the weight and the main productivity of the cucumber were used as an evaluation criterion of plant life cycle features. All morphometric data of five plants groups were measured with a caliper: four groups were grown under the artificial light source with different spectra of lighting elements, whereas the fifth control group was grown under the daylight illumination.

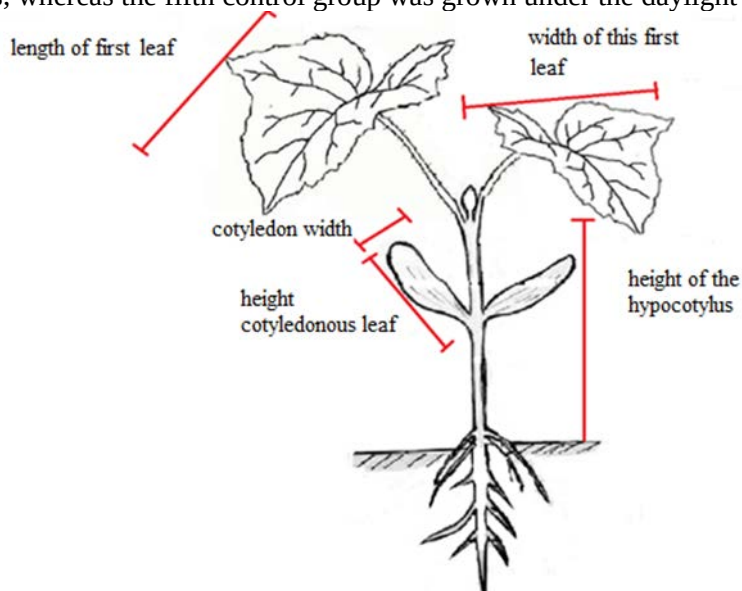


Figure 2. Morphometric parameters scheme of the cucumber growth

Cucumbers were picked up when they stopped growing, as there were no changes in data values of cucumber length and width at two fixed measurement intervals.

The research was conventionally divided into two stages. The first stage was a vegetative phase: seed germination, vegetative growth of plant parts, flowers blooming and cucumber inception. The beginning of the second stage was characterized by the emerging of the first inception, the completed fructification, leaves and stems maintenance in appropriate degree of turgor.

In the experiment, to grow cucumber plants the method of small soil quantity and constant watering was used. For this the plastic containers of 1.5 liters were used. The soil containing bog peat mixture of different decomposition levels with macro- and micro-elements was used to grow plants. The soil composition was determined due to the chemical analyses, conducted to the relevant standards (GOST): organic substance (humus) – 14.57 ± 1.46 %; concentration of essential nutrient elements; nitrate nitrogen – 64.6 ± 12.9 mg/kg; exchangeable ammonium – 6.5 ± 1.0 mg/kg; exchangeable calcium – 40.0 ± 3.0 mmol/100g; exchangeable magnesium – 43.0 ± 3.2 mmol/100g; weight percent of labile phosphorus - (P₂O₅) 790 ± 158 mg/kg; weight percent of mobile potassium - (K₂O) - 131 ± 2.0 mg/kg; pH of salt extract – 6.9 ± 0.1 ; hydrolytic soil acidity – 1.28 ± 0.15 mmol/100g.

Broad containers were filled with pure tap water. Thus, plants were supplied with a small amount of soil and water.

A group of 5 plants was placed under each light source. The distance from soil to light-emitting lamps was 25 centimeters. In the process of plant growth the lamps were raised up at some height so that the distance from lamps to plants was kept constant. During the whole process of research, the plants were exposed only to artificial lighting all day round. Inside air temperature and humidity were constantly recorded. The average indoor temperature was plus 25 degrees Celsius, whereas the average indoor humidity was 69%. A volume of each small ecosystems was about one cubic metre. Air mass was freely available. During the whole process of research, the plants were exposed only to artificial lighting all day round. Inside air temperature and humidity were constantly recorded. The average indoor temperature was plus 25 degrees Celsius, whereas the average indoor humidity was 69%.

3. Research results and analyses

During the vegetative stage, the plants, growing under the third and the fourth types of lighting, revealed better stem length in comparison to the plants growing under the other light source, used in the experiment (Figure 2).

Table 2. Growth dynamics of the cucumber stem in experimental groups.

№ measurements	The average value of the cucumber stem height under the different light sources, cm				
	Lamp type №1	Lamp type № 2	Lamp type № 3	Lamp type №4	Natural light
1	2.33±0.32	1.93±0.58	3.03±0.56	2.1±0.45	2.14±0.32
2	3.83±0.32	3.4±0.4	4.4±0.72	4.5±0.72	3.6±1.01
3	6.43±0.45	5.7±0.84	6.43±1.02	6.3±0.92	6.08±0.63
4	8.0±0.56	7.5±0.92	8.83±1.07	10.3±0.86	7.7±1.07

The growth data of a leaf lamina among experimental groups of plants were classified in the following way: the plants of group No 4 had the maximum leaf size in the length and the width; in plants of group No 2 a relatively intensive leaf width was observed and the plants growing under daylight illuminance were marked by the leaf length. The plants of group No 3 had the evident poor growth characterized by the minimum data of the average leaf length in this group (Table 3, 4).

Table 3. The index dynamic of “leaf length” of cucumber plants in experimental groups.

№ measurements	The average value of a leaf length under the different light sources, cm				
	Lamp type №1	Lamp type № 2	Lamp type № 3	Lamp type №4	Natural light
1	1.6±0.18	1.9±0.28	1.3±0.45	1.8±0.14	2.16±0.43
2	2.4±0.67	2.6±0.34	2.2±0.23	2.4±0.25	2.73±0.34
3	2.9±0.22	3.7±1.01	2.8±0.22	3.4±0.91	4.28±0.72
4	4.6±1.12	4.8±0.63	3.5±0.81	6.7±1.17	5.39±0.84

Table 4. The index dynamic of “leaf width” of cucumber plants in experimental groups.

№ measurements	The average value of a leaf width under the different light sources, cm				
	Lamp type №1	Lamp type № 2	Lamp type № 3	Lamp type №4	Natural light
1	1.2±0.16	1.1±0.16	0.9±0.17	1.05±0.28	2.69±0.34
2	2.04±0.32	2.08±0.21	2.04±0.14	2.1±0.22	3.29±0.40
3	2.9±0.22	3.7±1.01	3.09±1.51	3.7±1.15	4.43±0.7
4	4.6±1.07	4.9±0.63	4.6±1.12	5.2±1.13	4.63±1.07

Table 5. The index dynamic of “leaf rosette diameter” of cucumber plants in experimental groups.

№ measurements	The average value of leaf rosette diameter under the different light sources, cm				
	Lamp type №1	Lamp type № 2	Lamp type № 3	Lamp type №4	Natural light
1	3.66±0.62	4.16±0.32	3.5±0.40	3.56±0.91	4.3±0.62
2	4.53±0.71	5.33±0.87	5.06±0.74	5.39±0.84	5.3±1.04
3	4.9±1.07	6.6±0.91	4.5±1.04	6.3±0.45	7.2±0.92
4	7.1±1.02	7.9±1.07	7.1±0.63	8.1±0.56	8.4±1,3

On the whole, during the vegetative phase of plant it is important to emphasize that the most intensive growth of plants occurred under light source No 4 with the use of LED chips having wavelength from 445 to 660 nm and white LEDs with a CCT of 4000 K at the ratio of 9:2 according to all relevant data. The plants of group No 3 growing under the lamps with LEDs Ra-80 and a CCT of 3000 K were more stretched, having a relatively weak leaf rosette in comparison with others. This is revealed in the numerical data: the indexes of “stem length” and “leaf length” (according to mean values) in the maximum and minimum values of the whole measurement range during the process of experiment.

A growth characteristic of the hybrid “Partner F1” under various light sources at the first and the final parameters during the vegetative plant phase are shown in table 6.

Table 6. The average length of the cucumber fruit grown under the different light sources.

№ measurements	The average length of a cucumber fruit, cm				
	Lamp type №1	Lamp type № 2	Lamp type № 3	Lamp type №4	Natural light
1	0.93 ± 0.13	1.03 ± 0.17	0.6 ± 0.11	1.27 ± 0.28	0.76±1.10
2	8.0 ± 0.76	9.75 ± 1.46	8.75 ± 0.48	10.00 ± 1.96	9.2±1.46

At the early stage of fructification, plant fruits of experimental groups No 2 and No 4 outstripped other plant groups that could be explained by early blooming and fructification dates in the plant groups No 2 and No 4. The difference was 5 and 3 days respectively. At complete ripeness the average cucumber length in plants groups No 2 and 4 was bigger as well. As for the diameter of the cucumber, its final average length was 5.25±0.8cm under lamp 2 and 4.0±0.7cm under lamp No 4. The diameter under other light sources was less: 2.3±0.2cm under lamp No 1, 3.0±0.1cm – under lamp No 3, and 3.6 ± 0.2 cm under the daylight illuminance. Therefore, the plants fruits of groups No 2 and No 4 in average had maximum sizes under current conditions and corresponded to the characteristics, required by manufactures.

The number of completely ripe cucumbers on each plant in all groups is approximately the same: from 5 to 8 ones during the whole period of fructification. The weight of a grown cucumber varied from 82 to 100 grams. The general productivity in each experimental plant groups was from 558 grams (group No 3) to 743 grams (group No 2). It is significant that by the final stage of the research all plants had a larger number of fruit inception, from ten to thirteen per each plant, but these potential fruits stopped their development due to the wilting of vegetative plant parts.

It should be noted that plant habits of vegetative parts, for example, leaves during the fructification process, were kept on the plants growing under the LED light source of type No 3 (LEDs Ra-80 with a CCT of 3000 K) and plants grown under sunlight as well. Most leaves remained green during the whole

period of the research. Whereas plant leaves under other types of the spectra by the final stage of the experiment had light spots and loss of turgor in leaf cells that resulted in hanging down and dryness of a leaf lamina. We think that this fact is of interest when it concerns the increase of the vegetative growth cycle and fructification of the plant and can be purposefully researched in such experiments.

4. Conclusions

During the experimental research, cucumber seeds of the hybrid “Partner F1” went through the reproduction cycle from the seed and germ development to fruit-bearing plants. Under the experimental conditions the plant life cycle met the standards, stated by seed manufactures. The period of the fructification beginning was several days ahead of the period stated by manufactures. Cucumber sizes corresponded to the characteristics of plant species. Thus, all selected spectra for the research were, on the whole, appropriate for plant physiology in the spectral distribution of illumination.

It should be noted that lamps of “type No2” and “type No4” are most appropriate ones for quick grow of vegetative parts and the early fructification process of the cucumber “Partner F1” under artificial light and indoor conditions. Both lamps include white light-emitting diodes with a CCT of 4000 K, a colour rendering index of 80, blue LED chips and organic phosphor, emitting in red visible spectrum with 630 nm maximum and the quantitative ratio of 1:1 (type No2), 625 nm maximum and the quantitative ratio 2:9 (type No4).

During the cultivation process of the experimental hybrid “Partner F1”, a high level of vegetative parts preservation of plants (leaves and petioles) in the species growing under the light of visible white spectrum, especially warm white one (LEDs Ra-80 with a CCT of 3000 K) should be taken into account. At the final stage of the research, the plants grown under illuminance in the spectra of types No2 and No4 had a weak level of leaf turgor and were characterized by yellow color. However, characteristics of plants grown under spectra No1 and No3 were a little better in the size numbers of fruits.

Consequently, to design the standards of some illuminance for main stages of the life plant cycle during the cultivation process under completely artificial lighting conditions it is necessary to apply qualitative features of the spectral composition of a light source to increase: the growth rate and plant development in the vegetative phase; the productivity during the reproductive period and preservation of green plant parts for a long time of the final fructification stage to prolong the plant life cycle. We suppose that the best combination of luminous spectra while growing the hybrid of cucumber “Partner F1” under artificial lighting and indoor conditions includes: the spectrum of type No4 for the vegetative phase; the spectra of types No2 and No4 together with type No3 or only spectrum No3 alone for the reproductive period.

Such lighting regime will result in the intensive growth, the early fructification process and best preservation of vegetative plant parts during the reproductive period of the plant life cycle.

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