The influence of the light spectrum on the growth and development of greenhouse plants on the example of cucumber culture (Cucumis sativus L., Cucurbitaceae family)

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Abstract. The aim of the work is to develop the lighting mode for the cucumber photoculture. The developed lighting mode should intensify the production process by optimizing spectral characteristics of the light sources used at different stages of the life cycle of the plant. The authors conducted experiments on the cultivation of cucumber culture under conditions of small ecosystems with artificial illumination. As the lighting sources, LED elements with phyto-oriented spectra were used. Based on the dynamics of phenological and morphometric parameters and productivity of plants, the authors conclude that pre-sowing irradiation provided a positive effect on seed germination. Artificial lighting sources with additional red LEDs (625 nm in the ratio 9:2) accelerated the development of the vegetative and generative systems. Illumination by white spectrum LEDs (Ra80, CCT 3000 K) contributed to improving the efficiency of photosynthesis processes and extended the period of active life of the plants. The authors proposed variants of artificial lighting with the use of light sources composed of LEDs of different spectra for the effective cultivation of cucumber according to different stages of plant life cycle.

1. Introduction
Cucumber is one of the most popular cultures in the world among the ones grown in greenhouse conditions. Therefore, the provision of a light resource is especially important. Even in relatively sunny regions, the productivity of greenhouse agrocenoses in this period can be maintained only with the use of artificial light [1]. The concept of “photoculture”, the cultivation of plants with additional or fully controlled lighting, firmly entered the terminology of vegetable growers and business executives. At the same time, the question of the profitability of growing plants under artificial lighting remains topical; the profitability is supposed to be ensured by the use of efficient light sources.

Applied studies aimed at providing optimal conditions for the development of plants and increasing the energy efficiency and profitability of greenhouses revealed in recent years a tendency to use LED lighting equipment in new greenhouse complexes. Nowadays, research and experimental works are carried out in laboratory and in real conditions of greenhouses [2].

It is known that LED elements ensure a long service life of lighting equipment, relatively low energy consumption, and ability for mobile adjustment of light spectra for the needs of plants. At present time, researchers are addressing issues of managing the content of chemical components, decorative features of plant coloring, and preservation of agricultural products using adapted light
fluxes created on the basis of LED-technologies, pre-sowing treatment of seeds with light fluxes with specific wavelength [3, 4].

LED light sources, compared with traditional lighting elements used in greenhouses, are quite mobile, which makes them especially suitable for growing plants with a multi-layered arrangement of leaf blades. One of the research trend is consideration of cucumber cultivation in conditions of LED lighting only. A number of studies revealed a positive effect of using additional inter-row LED lights on the growth of cucumber culture [5, 6].

The present work was carried out in accordance with modern trends in the development of urban plant growing, the city-farming, which implies growing of plants directly near the consumer. In this study, an experiment was conducted on growing cucumber culture in artificial ecosystem of small volume.

The aim of this work is to develop the lighting mode for cucumber photoculture, ensuring the intensification of its production process by optimizing the spectral characteristics of the light sources used at different stages of the plant life cycle. Achieving this goal involved solving of the following tasks: selection of the light spectrum and irradiation conditions for pre-sowing seed treatment; designing of lamps with phyto-oriented spectral characteristics; conducting experimental studies on the pre-sowing treatment of seeds followed by the cultivation of cucumber culture under light sources with different spectral composition.

2. Materials and methods
In this work, the parthenocarpic cucumber culture “Partner F1” was selected as an object of the study. Based on patent search, literature data, and the results of previous experimental studies conducted by the authors of the work, a method for pre-sowing treatment of cucumber seeds was developed.

Infrared radiation is widely used in research works for pre-sowing treatment of seeds. It is known that electrothermal radiation at processing temperature of up to 55 °C can increase biological activity of seeds, reduce infection by phytopathogens, and does not damage the tissue and the structure of the object. The effect of the biological action of infrared radiation is largely determined by the following parameters: the maximums of the radiation wavelength, the distance from the source of infrared heating, the processing temperature, the duration of exposure [7, 8].

In the present experiment, the pre-sowing treatment of seeds was carried out by LED sources of the red and infrared spectra with wavelengths of 630 and 840 nm taken in a ratio of 21:16, respectively. The time of treatment was 10 minutes.

In the modern applied research, the preference for creating phyto-illumination is given to wavelengths in the ranges of 380-490 and 600-780 nm. Modern works aimed at studying the influence of the green spectrum LEDs on cucumber culture did not reveal any significant effect [9-11]. The share of LEDs with a wavelength of 532 nm in this case was 28%, of 473 nm – 20%; with a wavelength of 660 nm – 52%. It should be noted that in the classic works of N.N. Protasova, the recommended ratio of spectra was the following: the share of radiation with a wavelength of 380-490 nm should be 20-25%, 490-500 nm – 20-25%, and 600-700 nm – 60-50%, respectively. Thus, the percentages of the qualitative components of the spectrum and the wavelengths of the experimental light sources in these studies were approximately similar. The results may depend on the characteristics of the plant culture or on different reasons. However, there is a physical phenomenon such as the penetration of green light waves through the upper leaves to the lower ones providing the shaded lower leaves with an increased level of light. For a vertically developing cucumber, this can make a significant contribution to the growth and development of the plant. The main studies performed in order to find effective spectrum of plant illumination are aimed at finding the optimal ratio of radiation with wavelengths relating to blue and red parts of the spectrum. The effect of blue light on the normal growth and development of plants, cucumber in particular, was confirmed by experiments aimed at studying the physiological parameters of the photosynthetic activity of plants [12-14].
With the main orientation of phyto-illumination producers to the blue-red component, researchers consider white-spectrum LEDs as optimal for the growth of certain plant species.

Lighting elements with the following characteristics were used as the light sources.

The 1st lamp (type 1) contained white LEDs based on a blue glowing crystal and a yellow-green inorganic luminophore (type of yttrium aluminum garnet). Correlated color temperature of the LEDs was 4000 K; color rendering index was 80.

The type 2 lamp contained white LEDs similar to those of the type 1 lamp with correlated color temperature of 4000 K and color rendering index of 80. It also contained LEDs with blue glowing crystals and organic luminophore emitting light in the red part of the optical spectrum with a maximum wavelength of 630 nm. The quantitative ratio of the LEDs was 1:1.

The type 3 lamp contained LEDs based on a blue glowing crystal and a yellow-green inorganic luminophore (type of yttrium aluminum garnet). Correlated color temperature of the LEDs was 3000 K; color rendering index was 80.

The type 4 lamp contained white LEDs similar to those of the type 1 lamp and LEDs with blue luminescent crystals with an organic red luminophore emitting light in the red part of the optical spectrum with a maximum wavelength of 625 nm. The quantitative ratio of the LEDs was 2:9, respectively.

The spectral composition of each of the light sources was determined according to the spectrocolorimeter readings. The values of photosynthetic irradiation EPAA are presented in table 1.

The first experiment was conducted in the period from December 2016 to mid-February 2017. The second experiment on pre-sowing seed treatment followed by the cultivation of cucumber plants was carried out in the period from March to May 2017. Sample sizes (N=50) were used in each experiment for statistically significant the obtained results.

To determine the biological efficiency of the source of artificial lighting, the morphometric parameters of plants were taken as the evaluation criterion. As a criterion for assessing the characteristics of the generative stage of the life cycle of each group of plants, the authors used the values of length, diameter, and weight of fruit and total productivity. Fruits were harvested after they stopped growing, which was indicated by unchanged values of the length and width of the fruit, according to the results of two consequent measurements (the measurements were performed with a daily interval).

The second experiment had two stages. The first stage was considered vegetative. It began from the emergence of seedlings, followed by the development of vegetative parts of the plant. The appearance of the first flowers and cucumber ovary was regarded as the end of the stage. The second stage began from the appearance of the first ovary. The suspension of fruiting and reduction of turgor content in the green parts of the plant (leaves and stem) below the proper degree was regarded as the end of the stage.

For cultivation of cucumber plants in the experiment, the authors applied a technique using small volumes of soil and providing plants with constant irrigation. The efficiency of photosynthesis processes was studied by measuring the chlorophyll fluorescence parameters using a PAM fluorimeter.

### Table 1. The illuminance values and PAA calculated values of the LED lamps.

| Type of lamp | Illuminance value, lux | Photosynthetic irradiation value Epaa, µmol/s² |
|--------------|------------------------|-----------------------------------------------|
| 1            | 3010                   | 40.5                                          |
| 2            | 3112                   | 57.2                                          |
| 3            | 2988                   | 41.6                                          |
| 4            | 3000                   | 72.1                                          |

### 3. Results and discussion
Seeds in both groups began to germinate on the 3rd day after sowing. From the 3rd to the 9th day after planting, the germination in the group that did not undergo pre-sowing treatment was more intensive. However, on the 11th day, the treated seeds demonstrated 100% germination, while the final germination of untreated seeds reached only 80%.

Further monitoring of the development of seedlings placed under the red-blue spectrum light source (type 4 lamp) and the control group grown under natural light revealed that the type of lighting was a decisive factor for plant growth. Plants placed under LED sources developed more intensively than those grown under natural light. The factor of pre-sowing seed treatment did not have significant effect on the growth of plants at subsequent stages of development. This is evidenced by the timing of the appearance of true leaves. The results show that all plants (with pre-sowing treatment and without it) growing under LED lighting had a true leaf on the 15th day after planting, while some plants growing under natural lighting had only cotyledon leaves.

According to the results of measuring the size of cotyledonous leaves, it can be noted that the leaves of the plants grown under artificial lighting were larger than those grown under natural light.

**Table 2.** The arithmetic mean value of size of cucumber leaves in the experimental groups, cm.

| Number of days since sowing | Group of seedlings with pre-sowing seed treatment and lighting by type 4 lamp | Group of seedlings with lighting of type 4 lamp without pre-sowing seed treatment | Group of seedlings with pre-sowing seed treatment and with natural light | Control group of seedlings |
|-----------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------|
| 8                           | 5.2                                                                      | 5.09                                                                           | 5.04                                                               | 4.75                     |
| 12                          | 6.65                                                                     | 6.61                                                                           | 6.26                                                               | 5.94                     |
| 15                          | 7.88                                                                     | 7.53                                                                           | 6.98                                                               | 6.94                     |

According to the results of the second series of the experiments, at the vegetative stage of development, plants growing under the lamps of types 3 and 4 surpassed by the length of the stem the plants growing under other light sources participating in the experiment.

The growth rates of the leaf blade in the experimental groups of plants were distributed during growth as follows: the maximum length and width of the leaf were observed in plants of the 4th group; relatively intensive growth was observed in plants of the 2nd group (in terms of leaf width) and in plants of the control group (in terms of leaf length). A pronounced lag in growth was observed in plants of the 3rd group, which is reflected by the minimum values of the leaf length on average for this group (Tables 3, 4).

**Table 3.** The dynamics of the indicator “length of leaves” of cucumber plants in the experimental groups.

| Number of days since sowing | The average value of the leaf length of the plants grown under different lamps, cm |
|----------------------------|--------------------------------------------------------------------------------------|
|                            | Type 1 lamp  | Type 2 lamp  | Type 3 lamp  | Type 4 lamp  | Control group |
| 15                         | 1.6          | 1.9          | 1.3          | 1.8          | 2.16          |
| 20                         | 2.4          | 2.6          | 2.2          | 2.4          | 2.73          |
| 25                         | 2.9          | 3.7          | 2.8          | 3.4          | 4.28          |
| 30                         | 4.6          | 4.8          | 3.5          | 6.7          | 5.39          |

**Table 4.** The dynamics of the indicator “width of leaves” of cucumber plants in the experimental groups.

| Number of days since sowing | The average value of the leaf length of the plants grown under different lamps, cm |
|----------------------------|--------------------------------------------------------------------------------------|
|                            | Type 1 lamp  | Type 2 lamp  | Type 3 lamp  | Type 4 lamp  | Control group |
| 15                         | 1.2          | 1.1          | 0.9          | 1.05         | 2.69          |
| 20                         | 2.04         | 2.08         | 2.04         | 2.1          | 3.29          |
Overall, according to all of the considered indicators, the most intense growth during the vegetative phase of plant development was observed for plants grown under the type 4 light source. Plants of the third group looked elongated and had a relatively weakly developed leaf blade compared to the other groups. This is reflected by indicators “stem length” and “length of leaves” (by average values). The values of these indicators are maximal and minimal, respectively, among the entire measurement range obtained during the experiment. Measurement results obey the normal distribution law.

Measurement of the characteristics of chlorophyll fluorescence on a PAM fluorimeter is one of the fastest and most informative methods, which gives the most complete picture of the state of the plant's photosynthetic apparatus. Comparison of the main fluorescence parameters of cucumber plants grown under red light (Type 4 lamp) and white light (Type 1 lamp), showed that white light, in general, led to greater efficiency of photosystem II: the maximum and effective quantum yield of PS II (Fv / Fm, Y (II)), as well as the photochemical quenching coefficient qP in the variant with white light turned out to be higher than in the variant with red light (Figure 1). Moreover, the most significant differences were noted for ETR - the speed of relative electron transport. To process the experimental results, the statistical Mann-Whitney tests were used.

However, the coefficient of non-photochemical quenching qN in the variant with white light also turned out to be significantly higher than in the variant with using red light. This may be due to the fact that white light illumination, along with an increase in the overall intensity of photosynthesis, also necessitated the protection of the photosynthetic apparatus of plants from high-intensity light and the dissipation of part of the energy in the form of heat.

![Figure 1](image_url)

**Figure 1.** The influence of red and white light on the chlorophyll fluorescence in the cucumber leaves.

* – Differences with the previous variant are reliable according to the Mann-Whitney test (p<5%)/

The characteristics of growth of cucumber hybrid “Partner F1” under different light sources, registered on the first and last measurements at the generative stage of plant development are presented in Table 5.

|                | 25  | 2.9 | 3.7 | 3.09 | 3.7 | 4.43 |
|----------------|-----|-----|-----|------|-----|------|
|                | 30  | 4.6 | 4.9 | 4.6  | 5.2 | 4.63 |

|                | 25  | 2.9 | 3.7 | 3.09 | 3.7 | 4.43 |
|----------------|-----|-----|-----|------|-----|------|
|                | 30  | 4.6 | 4.9 | 4.6  | 5.2 | 4.63 |
At the initial stage of fruiting, the fruits of the plants of the 2nd and 4th groups developed faster than the fruits of other groups of plants, which can be explained by early terms of beginning of flowering and fruiting. The difference in these terms was 5 and 3 days, respectively. The average size of fruits at full maturity was also greater in the 2nd and 4th groups. As for the diameter of cucumber fruits, the average final dimensions were: 5.25±0.8 cm under the 2nd lamp and 4.0±0.7 cm under the 4th. Under other light sources the diameter was smaller: 2.3±0.2 cm under the 1st lamp, 3.0±0.1 cm under the 3rd, and 3.6±0.2 cm under natural light. Thus, the fruits growing on the plants of group 2 and group 4 reached on average maximal sizes for given growing conditions.

It should be noted that the vegetative parts of the plants (leaves during fruiting) were visually in better condition in the cases of natural light and LED light sources of the 3rd type (Ra80 LEDs with a correlated color temperature of 3000 K). The authors suppose this fact to be of interest when considering the issue of extending vegetation and fruiting season of plants and may be studied further in special experiments.

### 4. Conclusion

According to the results of the research, it was established that pre-sowing treatment of seeds with the red and infrared spectra ensures high germination of cucumber plants without affecting its timing. The growth of plants at next stages of development was largely determined by the characteristics of the lighting elements, which served as the light resource for the plant.

The seeds of cucumber hybrid “Partner F1” in the course of the experiment went through a full cycle of development from seeds and seedlings to fruiting plants. Under the experimental conditions, the length of the plant life cycle corresponded to the length declared by the seed producers; the dates of the beginning of fruiting in experimental studies were several days ahead of the dates declared by the producers; fruit sizes were consistent with varietal characteristics. Therefore, in general, all the spectra used in the experiments corresponded to the physiological needs of plants in terms of spectral composition of illumination.

Type 2 and type 4 lamps should be considered as the most suitable for achieving high growth rate of vegetative parts and early beginning of fruiting of cucumbers “Partner F1” under conditions of artificial illumination in greenhouse.

The suitable combinations of light spectra for growing “Partner F1” cucumber culture under artificial lighting in greenhouse conditions are the following: at the vegetative developmental stage - type 4 spectrum, at the generative stage - type 2 and type 4 spectra in combination with type 3 spectrum or type 3 spectrum only. This lighting mode will contribute to intensive growth of plants and early start of fruiting, it will also enable one to keep vegetative parts of the plant at the generative stage of its life cycle in a better state.

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