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OPTIMIZATION OF THE SPECTRAL COMPOSITION OF PHYTOLAMPS IN CLOSED SOIL TO IMPROVE FOOD STABILITY IN UKRAINE IN THE CONTEXT OF POSTWAR RECOVERY

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У статті представлено результати експериментального дослідження впливу спектрального складу світлодіодного освітлення на ріст, розвиток та продуктивність овочевих культур у закритому ґрунті. Актуальність теми зумовлена значними втратами врожайності у відкритому ґрунті, через кліматичні ризики, деградацію ґрунтів та нестабільність погодних умов, а також скороченням посівних площ унаслідок воєнних дій. Ці чинники знижують ефективність традиційного землеробства, обмежуючи можливість стабільного забезпечення населення якісними овочами. В умовах контрольованого середовища теплиць ризики втрат можна мінімізувати, особливо за застосування LED-фітоламп з адаптивним спектром, що допомагає оптимізувати фотосинтетичну активність рослин та підвищити ефективність використання енергії. Метою дослідження було визначення оптимальних спектральних параметрів освітлення для підвищення продуктивності помідорів (Solanum lycopersicum, сорт «Чумак») та салату (Lactuca sativa, сорт «Одеса 75»). Експеримент проводили у навчальній теплиці з використанням LED-фітоламп потужністю 100 Вт у чотирьох режимах: повний спектр (контроль), переважно синій, переважно червоний та комбінований зі включенням інфрачервоного (ІЧ) та ультрафіолетового (УФ) випромінювання. Протягом восьми тижнів вегетації виконували щотижневі вимірювання висоти рослин, площі листкової поверхні, маси біомаси, вмісту хлорофілу, кількості квіток, маси плодів і врожайності. Статистичну обробку здійснювали методом однофакторного дисперсійного аналізу (ANOVA) з рівнем значущості $p \leqslant 0,05$. Найбільш ефективним виявився комбінований спектр, який забезпечив максимальні показники врожайності помідорів (4,9 кг/м^2) та біомаси салату (186 г/росл.), а також сприяв гармонійному розвитку вегетативних і генеративних органів. Синій спектр стимулював накопичення хлорофілу, але мав обмежений вплив на генеративні процеси, тоді як червоний посилював плодоношення, проте знижував вегетативний ріст. Отримані результати підтверджують доцільність використання адаптивних LED-фітосистем із керованим спектром як інноваційного та енергоефективного інструменту для підвищення продуктивності овочевих культур у закритому ґрунті. Це має особливе значення для післявоєнного відновлення аграрного сектору України та зміцнення продовольчої безпеки країни.

Ключові слова: *опитальне освітлення, LED-фітолампа, обмежені ресурси, овочеві культури, адаптивне агровиробництво, фотосинтез, тепличне вирощування.*

INTRODUCTION

In the context of post-war reconstruction of Ukraine, a comprehensive approach to ensuring the country's food security is of particular relevance. An important component of this process is the modernization and activation of the agro-industrial sector, in particular in regions where, due to war destruction, mine danger or climate change, open soil has become unsuitable for traditional agriculture. In this context, greenhouse vegetable growing acts as a strategically important direction, allowing for stable cultivation of vegetable products throughout the year. Greenhouse farms ensure uninterrupted supply of fresh vegetables, herbs and berries even in winter, thereby reducing dependence on imported products. This is especially critical in conditions of unstable logistics and currency fluctuations. In addition, the development of the greenhouse sector contributes to the economic revitalization of the affected territories, enabling small and medium-sized businesses to restore agricultural production at lower costs than in the case of field farming. Therefore, investments in greenhouse farming are not only tactical, but also strategic in importance for restoring Ukraine's agricultural potential.

The effectiveness of growing vegetable crops in the closed ground largely depends on the characteristics of artificial lighting. Recent scientific works [1–5] confirm the significant influence of the spectral composition of light on the physiological processes of plants: photosynthesis, biomass formation, flowering and fruiting. Unlike natural lighting, phytolamps allow you to adjust the light parameters precisely, providing optimal growth conditions by controlling the radiation spectrum. This is especially important in Ukrainian conditions with short daylight hours, limited energy supply and the need for efficient use of resources. In this regard, the study of the reaction of plants to changes in the spectral composition of light becomes particularly relevant and contributes to the development of innovative technologies for sustainable greenhouse and vertical farming.

Modern LED phytolamps make it possible to create specialized spectral lighting modes with an emphasis on red (660 nm), blue (450 nm) and other ranges that affect plant photomorphogenesis [1]. At the same time, the effectiveness of various spectral combinations depends on the type of crop, its development phase, microclimate conditions and technological approach to cultivation. Despite the wide popularity of phytolamps in greenhouse production, it has not been sufficiently studied which spectral combinations are optimal for different phases of vegetable crop development. The issue of balancing high yields and energy efficiency of lighting systems remains unresolved. This necessitates the need for adaptive, energy-efficient solutions to ensure maximum productivity in closed ground conditions.

Therefore, the aim of the work is determination of optimal spectral modes of LED phytolamps for stimulating growth and generative indicators of tomatoes and lettuce in closed soil under conditions of limited resources, to improve food stability in Ukraine in conditions of post-war recovery.

ANALYSIS OF LATEST RESEARCH AND PUBLICATIONS

LED phytolamps for irradiating plants are no different in design from conventional LED lighting devices — emitting crystals, under the influence of electric current, generate a light flux of a certain wavelength.

The difference between phytolamps and LED devices is observed in the composition of the spectrum — not a narrow interval of warm white glow like incandescent lamps, but a wide range from ultraviolet to red rays [2]. This emitted spectrum is the main advantage of LED phytolamps for plants — LEDs emit light of the spectrums most needed by indoor plants.

Phytolamps are special light sources that mimic natural sunlight and provide plants with the necessary spectrum for their growth and development. They are especially useful in conditions where natural light is insufficient, such as in winter or when growing plants indoors.

Different light spectra have a significant impact on the photosynthetic activity of plants, and this issue has been studied actively in many scientific works. In [3], the authors R. Roberta, G. Cocetta and S. Proietti examine the mechanisms by which different spectral components of light — particularly the red, blue and green spectra — can enhance or reduce the efficiency of photosynthesis in plants. Their study emphasizes the importance of light interactions with plant photosystems at the chloroplast level, where the spectral composition of light directly affects the energy balance of the photosynthetic apparatus.

In the study [4] (S. Arena, T. Tsonev) examine in detail the influence of light spectra, in particular red and blue, on the photosynthetic activity of plants. The authors emphasize that, to optimize photosynthesis, plants use different spectral components of light depending on intensity and environmental conditions.

They also emphasize the importance of the combined use of these spectra to maximize the efficiency of photosynthesis, since each spectrum stimulates different photosystems of plants.

In work [5] (L. Gennaro, B. Mele and V. Luca) focus on how the spectral composition of light, particularly the red and blue ranges, affects the rate of photosynthetic processes and overall plant growth. They focus on analyzing how changes in light intensity and spectrum can alter the productivity of photosynthesis under different conditions, particularly in laboratory experiments.

In the works [6; 7] the authors D. Shuangshuang, S. Pengfei, I. Dyachenko and L. Romanenko investigated and analyzed the effect of light on photosynthetic activity with a special emphasis on the role of photosynthetic pigments such as chlorophyll and carotenoids. The studies showed how different light spectra affect energy production in chloroplasts, which is critical for efficient photosynthesis. At the same time, it was shown that certain spectral components could both cause stress in plants and stimulate their activity under favorable conditions.

Research [8] by M. Haidekker, K. Dong and E. Mattos presented us with methods for assessing photosynthesis by measuring chlorophyll fluorescence, an accurate indicator of photosynthetic activity. They describe how different light spectra change fluorescence parameters, allowing precise measurements of the efficiency of photosynthetic processes. In particular, chlorophyll fluorescence is a very sensitive indicator for studying how light of different wavelengths affects photosynthesis.

Overall, these studies confirm that the spectral composition of light is an important factor for optimizing photosynthetic processes. The red and blue spectra are particularly important for stimulating the photosystem. Therefore, the correct use of the spectral characteristics of light is an important prerequisite for increasing yields, especially under artificial lighting conditions, such as in greenhouses or vertical farming systems.

Therefore, after analyzing the results of these works, it is possible to present new methods of plant irradiation in greenhouse conditions, which involve the optimal combination of spectral components, taking into account energy efficiency, to increase yield.

MATERIALS AND RESEARCH METHODS

The study used four spectral modes of LED phytolamps (full, blue, red and combined spectrum with IR and UV components), which were applied to tomatoes of the Chumak variety and lettuce of the Odesa 75 variety in a training greenhouse. The lamp power was 100 W, the distance to the plants was 25–30 cm, the photoperiod was 16 h/day, the light flux intensity was 400–700 $\mu mol \cdot m^{-2} \cdot s^{-1}$ depending on the growth phase. All plants were grown in a peat-coconut mixture (pH 5.8–6.2, EC 1.8–2.2 mS/cm) under standard agrotechnical conditions (t° during the day 23 ± 1°C, at night 18 ± 1°C; humidity 60–70%; drip irrigation). In each variant, 3 replicates were planted: 10 tomato plants and 15 lettuce plants.

During 8 weeks, height, number of leaves, leaf surface area, biomass mass, number of flowers, fruit mass, yield, chlorophyll content (according to Arnon) [9] and dry matter were determined. The selection of indicators took into account the biological characteristics of crops: for tomato, mainly generative parameters (number of flowers, fruit mass, yield) were evaluated, while for lettuce — vegetative (leaf surface, biomass, dry matter content). This made it possible to objectively assess the impact of spectral modes of LED phytolamps on the economic value of crops.

Statistical analysis of the results was performed using one-way ANOVA with a significance level of $p \leq 0.05$ for each culture separately. The least significant difference (LSD) test was used to determine the significance of differences between mean values [10; 11].

RESULTS AND DISCUSSION

Based on studies [11; 12], diagrams (*Fig. 1, a*) were constructed, which illustrate the influence of light waves of different lengths on the photosynthetic activity of plants. The diagrams show that blue light

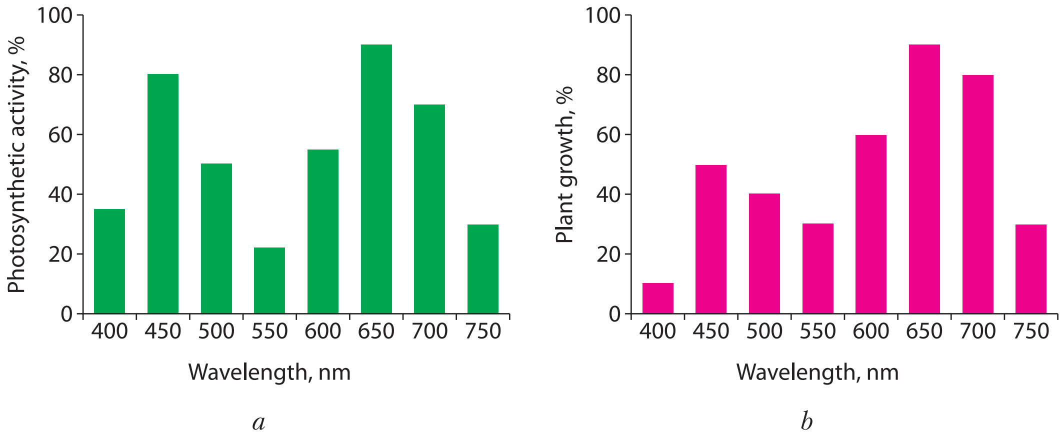

Fig. 1. Characteristics of light influence:
a — influence of light spectrum on photosynthesis; *b* — influence of light wavelength on plant growth

(approximately 450 nm) and red light (approximately 650 nm) are most effective in stimulating photosynthesis. According to the results of the study [13], we also constructed a graph (*Fig. 1, b*), which reflects the general relationship between the wavelength of light and plant growth.

The greatest growth is observed in the red (650–700 nm) and blue (450 nm) spectra, which correspond to the main photosynthetically active ranges. Thus, it makes sense to apply the combined use of these spectra in phytolamps, providing a comprehensive stimulation of growth and productive processes, which can be the basis for effective greenhouse production in the conditions of modern agricultural technologies.

Table 1. **Experimental lighting options**

Version	Spectrum type	Spectral ratio (%)
Option I	Full spectrum	100% (380–780 nm)
Option II	Mostly blue	70% blue, 30% red
Option III	Mostly red	70% red, 30% blue
Option IV	Combined with IR and UV	50% red, 30% blue, 10% IR, 10% UV

In accordance with the purpose of this work, we conducted experimental studies on the influence of the spectral composition of LED phytolamps on the growth, development and yield of vegetable crops on the basis of a training greenhouse. Tomatoes (Solanum lycopersicum variety «Chumak») and leaf lettuce (Lactuca sativa variety «Odesa 75») were selected as seedlings.

To conduct the experiment, 4 experimental lighting options were created using 100 W LED phytolamps installed at a height of 25 cm above the plants (*Table 1*).

All other growing conditions were standard and identical:

- Temperature: +23°C during the day, +18°C at night;
- Air humidity: 60–70%;
- Photoperiod: 16 hours/day;
- Substrate: peat-coconut mixture;
- Watering: drip, automated;
- Feeding: NPK12-12-18 solution with trace elements.

Parameters studied: saverage plant height (cm); number of true leaves (pcs); leaf surface area (cm^2); weight of raw biomass (g); chlorophyll a+b content (according to Arnon) (mg/g); yield (kg/m^2).

Data were collected weekly for 8 weeks of vegetation. The obtained data were subjected to statistical processing by one-way ANOVA with a significance level of $p \le 0.05$ for each crop separately.

The study found that the spectral composition of lighting significantly affects the growth, development and productivity of vegetable crops in closed ground. The summarized data on the experimental variants are presented in *Tables 2–3*.

Based on the summarized data in *Tables 2* and *3*, it is possible to construct diagrams showing influence of different spectral modes of LED phytolamps on plant height, chlorophyll content, and yield, *Fig. 2*.

The presented data show that the best results for all studied indicators were achieved when using a combined spectrum of lighting.

Table 2. **Influence of the spectral composition of phytolamps on tomato performance**

Indicator	Option I (full spectrum)	Option II (blue)	Option III (red)	Option IV (combined)
Plant height, cm	45.2 ± 2.0	38.6 ± 1.7	49.7 ± 2.3	52.4 ± 2.5
Number of flowers, pcs.	15 ± 2	11 ± 2	18 ± 3	20 ± 2
Fruit weight, g/plant	243 ± 15	211 ± 12	267 ± 17	288 ± 14
Yield, kg/m^2	4.1 ± 0.3	3.6 ± 0.2	4.5 ± 0.3	4.9 ± 0.3
Chlorophyll content, mg/g	1.82 ± 0.11	2.06 ± 0.13	1.67 ± 0.12	1.94 ± 0.10

Table 3. **Influence of the spectral composition of phytolamps on lettuce performance**

Indicator	Option I (full spectrum)	Option II (blue)	Option III (red)	Option IV (combined)
Plant height, cm	17.5 ± 1.3	14.9 ± 1.1	20.4 ± 1.5	22.1 ± 1.6
Leaf surface, cm^2	282 ± 14	316 ± 16	268 ± 13	305 ± 15
Mass of raw biomass, g	158 ± 9	134 ± 8	172 ± 10	186 ± 12
Chlorophyll content, mg/g	2.08 ± 0.12	2.47 ± 0.14	1.77 ± 0.11	2.38 ± 0.13
Dry residue, %	6.2 ± 0.3	6.5 ± 0.2	6.8 ± 0.3	7.1 ± 0.3

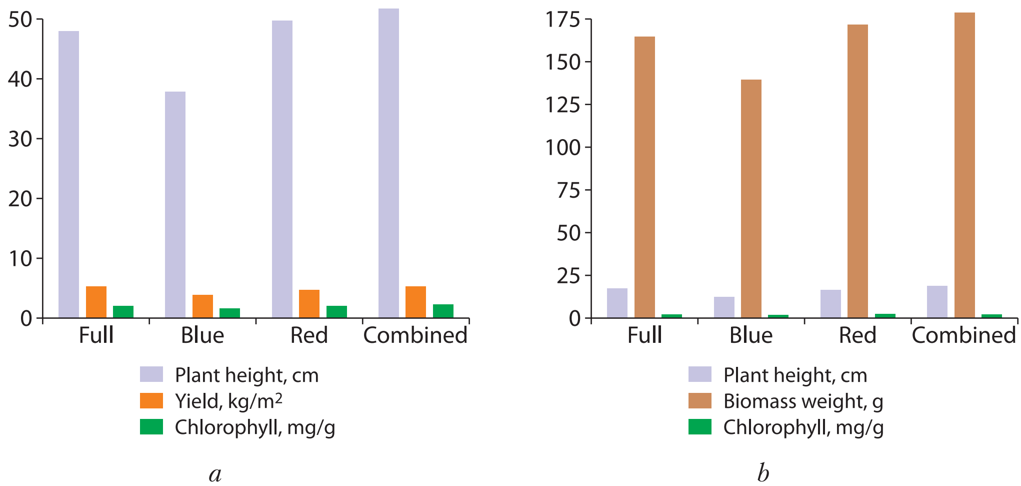

Fig. 2. Effect of the spectral composition of phytolamps on:
a — tomato; *b* — lettuce

Analysis of the results shows that it was with the combined spectrum that tomatoes demonstrated the highest values of key agrophysiological parameters. The yield in this variant reached 4.9 kg/m^2, which is 16.7% higher than the indicators of the control (full spectrum) lighting and 36% higher than the variant with a predominance of the blue spectrum.

A similar trend is observed in terms of fruit mass and the number of inflorescences. The increase in total biomass and the intensive growth of plant mass are explained by the synergistic effect of spectral components: the blue spectrum stimulates leaf development, red — promotes flowering and fruit formation, infrared improves root system growth, and ultraviolet activates plant resistance mechanisms.

Although blue light provided the highest chlorophyll concentration (2.06 mg/g), it was unable to compensate for the decrease in overall productivity, probably due to insufficient stimulation of generative processes. Red spectrum, on the contrary, significantly increased fruiting, but in the absence of sufficient vegetative support, it negatively affected the overall chlorophyll content and plant development rate.

In the case of lettuce, the advantage of the combined spectrum was also recorded, which provided the maximum indicators of biomass (186 g), height (22.1 cm) and dry matter content (7.1%), indicating harmonious growth and high quality of the product. The blue spectrum demonstrated the highest chlorophyll content (2.47 mg/g) and leaf surface area (316 cm^2), but lagged behind in terms of crop weight. This confirms that the blue range is critically important in the early stages of plant development, but the presence of red and infrared light is necessary to ensure maximum productivity.

Therefore, using adaptive LED lighting with a combination of red, blue, infrared and ultraviolet spectra creates the most favorable conditions for the balanced development of both vegetative and generative organs of vegetable crops.

CONCLUSIONS

The results of the analysis of the spectral impact of LED phytolamps on the processes of vegetable crops confirm the key role of the combined spectrum in increasing the efficiency of greenhouse cultivation. It was found that the combination of red, blue, infrared and ultraviolet light contributes to the harmonious development at the main stages of plant vegetation. The use of the combined spectrum provides the highest tomato yield (up to 4.9 kg/m^2) and lettuce biomass growth (up to 186 g per plant), while simultaneously improving quality characteristics such as chlorophyll and dry matter content.

Of particular note is the adaptability of LED phytolamps, which allow for rapid change of spectral ratio depending on the growth phase or external factors. Unlike traditional light sources, such lamps allow for precise adaptation of the spectrum in real time, which makes them not only agrotechnically efficient, but also economically beneficial for greenhouse farming. This allows for optimization of lighting, reduction of energy consumption, reduction of the need for additional equipment and increase of the overall profitability of growing crops in conditions of limited resources.

Therefore, the introduction of intelligent LED systems with adaptive spectral control should be considered as an important element of technological modernization of the greenhouse sector, especially relevant in the context of post-war reconstruction and restoration of the country’s food security and quality.

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