

ENHANCING GREENHOUSE PEPPER PRODUCTION USING PRE-TRANSPLANT LED TREATMENTS

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Abstractt

Pepper (*Capsicum annuum* L.) is a widely cultivated vegetable whose growth and development are significantly modulated by light quality. This study aimed to evaluate the effects of different LED light treatments during the seedling stage on pepper subsequent development and yield after transplanting into a greenhouse. Commercial sweet pepper variety Morava was used as the plant material. At the phenological stage of first true leaf formation, the plants were placed in closed plant growth chambers under four light treatments: multispectral white light-emitting diodes (W LEDs), monochromatic blue LEDs (B LEDs), red LEDs (R LEDs), and a mixed (50:50% ratio) red and blue LEDs (RB LEDs). The seedlings were cultivated for either 20 or 27 days under a 12/12 h (light/dark) photoperiod at a controlled temperature of 23 ± 2 °C. After 20 and 27-day exposure periods, five uniform seedlings per treatment were transplanted into larger plastic pots and transferred to a greenhouse, where they were grown under natural daylight for an additional 51 and 44 days, respectively. At the full maturity stage, the number of fruits and yield per plant, chlorophyll content, and total soluble sugar content were recorded. The results show that the number of pepper fruits per plant was significantly influenced by both the light treatment and its interaction with the duration of light exposure. In contrast, the fruit weight, total soluble sugar content, and chlorophyll content depended exclusively on the duration of exposure to the light treatments. A 27-day red light treatment applied at the first true leaf stage significantly increased fruit number and weight while proving statistically equivalent to other leading treatments in optimizing sugar and chlorophyll accumulation.

Key words: *Capsicum annuum* L., Morava cultivar, artificial lighting, vegetable, yield, chlorophyll content, soluble sugar content

Introduction

Pepper (*Capsicum annuum* L.) represents one of the most economically significant cultivated species and holds great importance in human nutrition, both in fresh and processed forms, due to its exceptional nutritional value.

Pepper fruits are characterized by a high content of essential vitamins (A, C, B3, B6, and K), carbohydrates, carotenoids, anthocyanins, amino acids, and minerals (Kang, 2013).

In addition to genetic factors, the nutrition-

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al value of the fruit is influenced by environmental conditions, particularly light quality and intensity. The process of photosynthesis relies on utilizing sunlight to transform carbon dioxide and minerals into organic molecules (Figueroa et al., 2016). The primary products are carbohydrates, which, through various metabolic pathways, serve as precursors for the synthesis of other organic compounds. Bosland (2012) highlights that pepper achieves optimal growth under light within the 400–700 nm spectrum, with approximately 35% PAR (photosynthetically active radiation), and an 18-hour photoperiod. Wien and Stützel (2020) note that while fluorescent and high-intensity discharge (HID) lamps were previously used as supplementary light sources in protected cultivation, light-emitting diodes (LED) technology,

featuring red, green, and blue spectral regions in various combinations, currently predominates. In specially designed closed cultivation systems (plant factories), this serves as the sole light source. Research by Serrano (2023), Zhang et al. (2026), Demirsoy et al. (2018), and Liu et al. (2022) emphasizes that different spectral components exert distinct influences on the growth and fruiting of peppers.

This study aimed to investigate the effects of different light treatments and exposure durations on Morava pepper seedlings, as well as their subsequent development, yield components, and physiological characteristics of the plants and fruits after transplanting into a greenhouse.

Material and Methods

Plant Material and Experimental Design

The research was conducted in 2024 at the Institute for Vegetable Crops Smederevska Palanka, Serbia. The commercial sweet pepper (*Cap-sicum annuum* L.) variety Morava, obtained from the same institute, was utilized as the plant material.

Seeds were sown in 100 plastic pots filled with a commercial substrate (Pindstrup Mosebrug A/S, Denmark). At the first true leaf stage, the plants were transferred to closed plant growth chambers. Inside the growth chambers, four distinct light treatments were applied using light-emitting diodes (LEDs) with varying spectral compositions: multispectral white (W), monochromatic blue (B), monochromatic red (R), and a mixed red and blue spectrum (RB, 50:50% ratio). Plants were cultivated in the plant growth chambers at a temperature of $23 \pm 2^\circ\text{C}$, with a 12-hour photoperiod (12 h light, 12 h dark). The plants were manually irrigated, and substrate moisture was rigorously regulated to prevent drought stress.

After 20 and 27 days of cultivation in closed plant growth chambers, pepper seedlings were transplanted into bigger plastic pots and removed to the greenhouse, where they were

cultivated for the next 51 and 44 days, respectively, under natural daily light.

Morphological and Physiological Measurements

At 51 and 44 days after transplanting, respectively, the number of fruits per plant, fruit weight, leaf chlorophyll content, and soluble sugar content in fruits were measured. These measurements were performed on five uniform replicate plants per light treatment and exposure duration.

The fruit weight was measured using an IoT-Line Precision Balance 572-31 technical scale (Kern & Sohn GmbH, Balingen, Germany). Chlorophyll content was measured utilizing a Portable Chlorophyll Meter CM-B (BioBase Industry, Shandong Co., Ltd., Jinan, China). The chlorophyll content measurements were expressed in SPAD units. The soluble sugar content was measured using a Refractometer HI 96801.

Statistical analysis

In order to evaluate the effects of various light treatments, exposure duration, and their interaction on the pepper plants, a two-way

analysis of variance (ANOVA) was conducted. Treatment means were compared using Duncan's multiple range test at significance levels of $p < 0.01$ and $p < 0.05$. These analyses were performed using SPSS software, version 22.0

(IBM Corp., Armonk, NY, USA). Additionally, Pearson's linear correlation coefficient was calculated to determine the relationships among the evaluated traits.

Results and Discussion

Light, as one of the key environmental factors, can play both supportive and detrimental roles in plant growth, development and yield components (Ruban, 2015; Landi et al., 2020; Liu et al., 2019, 2022; Nie et al., 2023). The results of this study showed that both light treatments (L) and the interaction between light treatment (L) and exposure duration ($L \times E$) had statistically significant effects on

the number of fruits per plant. However, the analysis of variance (ANOVA) revealed that fruit weight, total soluble sugar content, and SPAD values depended solely on the duration of light exposure (E). In contrast, neither the individual effects of the light treatments (L) nor the interaction ($L \times E$) had a statistically significant impact on these traits (Table 1).

Table 1. Analysis of variance for the number of fruits per plant, fruit weight, chlorophyll content (SPAD units), and total soluble sugar content

Tabela 1. Analiza varijanse za broj plodova po biljci, masu plodova, sadržaj hlorofila (SPAD jedinice) i sadržaj rastvorljivih šećera

Source of variation	df	NFPP		FW (g)		TSSC (° Brix)		CC (SPAD units)	
		MS	F	MS	F	MS	F	MS	F
LT (L)	3	14.93	3.71*	922.94	1.14 ^{ns}	2.57	1.66 ^{ns}	11.72	1.60 ^{ns}
ED (E)	2	7.04	1.75 ^{ns}	5076.79	6.29*	9.00	5.81*	134.43	18.32**
Repetition	2	3.50	0.87 ^{ns}	1305.44	1.62 ^{ns}	0.84	0.59 ^{ns}	13.21	1.80 ^{ns}
$L \times E$	3	23.49	5.84**	1776.70	2.20 ^{ns}	1.37	0.88 ^{ns}	9.52	1.30 ^{ns}
Error	14	4.02	-	806.98	-	1.55	-	7.34	-
Total	23	-	-	-	-	-	-	-	-

LT – Light treatment; ED - Exposure duration; NFPP - number of fruits per plant; FW - fruit weight; TSSC - total soluble sugar content; CC - chlorophyll content; ** Significant at $p < 0.01$ level; * Significant at $p < 0.05$ level; ^{ns} Non significant

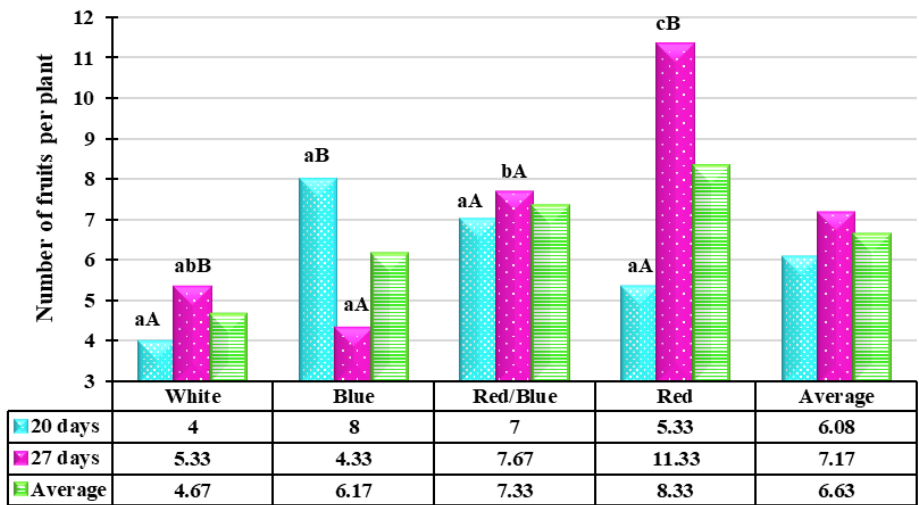
The significant role of exposure duration highlights that the total amount of light received over time has a greater influence on the regulation of plant primary metabolism and biomass distribution than simply altering narrow-band spectral qualities. According to Langton et al. (2003), while the quality of light activates specific photomorphogenetic pathways, the duration of light exposure determines the total energy availability needed for structural and biochemical changes. Supporting this concept, Luković et al. (2024a) have confirmed that the use of energy-efficient white and blue LEDs over an 18–25-day period enhanced let-

tuce seedling quality, which directly leads to higher yields and improved plant quality.

Consistent with these findings regarding the impact of exposure time, our research demonstrated that extended light treatment duration also positively affected the number of fruits in pepper plants, similar to results reported by Chen et al. (2022) and Liu et al. (2022). In the treatment of 20 days of plants exposure to LEDs, the highest number of fruits per plant was recorded in plants grown under the B LEDs, whereas the lowest number was observed under W LEDs. However, when the exposure duration was extended to 27 days, the

plants' response to the different light treatments changed: the maximum number of fruits per plant was now observed under R LEDs, while the minimum was recorded under B LEDs (Figure 1). The observed variations in plant response throughout the treatment reveal a significant interaction between the light spectrum and exposure duration. This demonstrates that the impact of light treatment on fruit formation is directly dependent on the duration of LED exposure. Hogewoning et al. (2010), Luković et al. (2024b), and Zheng et al. (2024) have found

that B LEDs initially stimulated early flowering by activating specific light receptors, which accelerates the transition of the plant into the reproductive stage. However, extended exposure to B LEDs can inhibit apical dominance and limit carbohydrate transport. In contrast, R LED promotes continuous branching through phytochrome-mediated processes, ensuring a sustained supply of nutrients to developing fruits over time (Katircioğlu et al., 2019; Azizi et al., 2025).

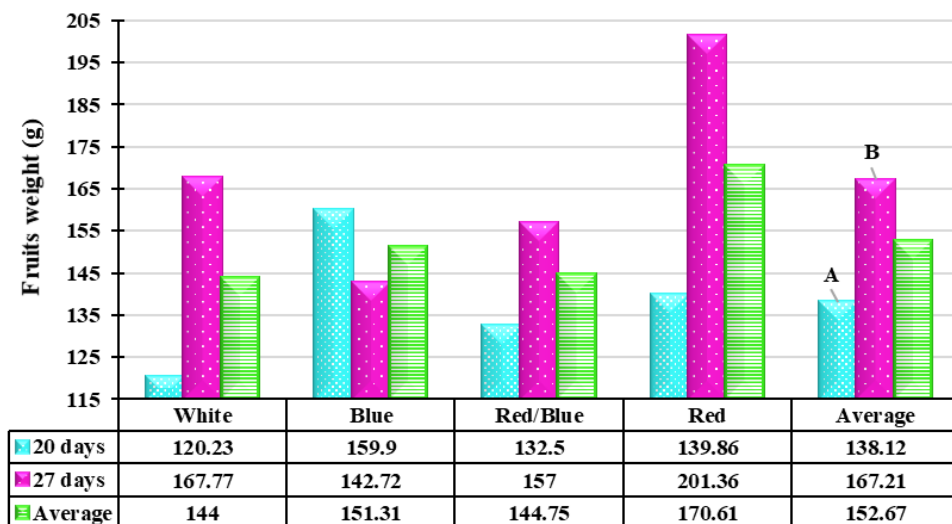


Legend: Different lowercase letters within column (a, b, c) denote statistically significant differences between light treatments within the same exposure duration, while different uppercase letters within column (A, B) denote statistically significant differences between the plant exposure duration within the same light treatment ($p < 0.01$).

Figure 1. Average number of fruits per plant by light treatments and exposure durations.
 Grafikon 1. Prosečne vrednosti broja plodova po bilji po svetlosnim tretmanima i dužini izlaganja.

The weight of the fruit was also influenced by LED exposure duration. With the exception of the B light treatment, the extended 27-day exposure resulted in higher fruit weights across all groups compared to shorter exposure duration (Figure 2). The highest fruit weight was observed under R LEDs, confirming that prolonged exposure to this spectrum can significantly enhance fruit development and increase

biomass accumulation. In contrast, extended exposure to B LEDs had a negative effect on both fruit number and weight compared to the shorter exposure period. These findings suggest that prolonged exposure to blue B LEDs during early developmental stages can adversely affect fruit formation and biomass accumulation, ultimately leading to reductions in both yield and fruit weight.



Legend: Different uppercase letters within column (A, B) denote statistically significant differences in the plant exposure duration to different lights ($p < 0.05$).

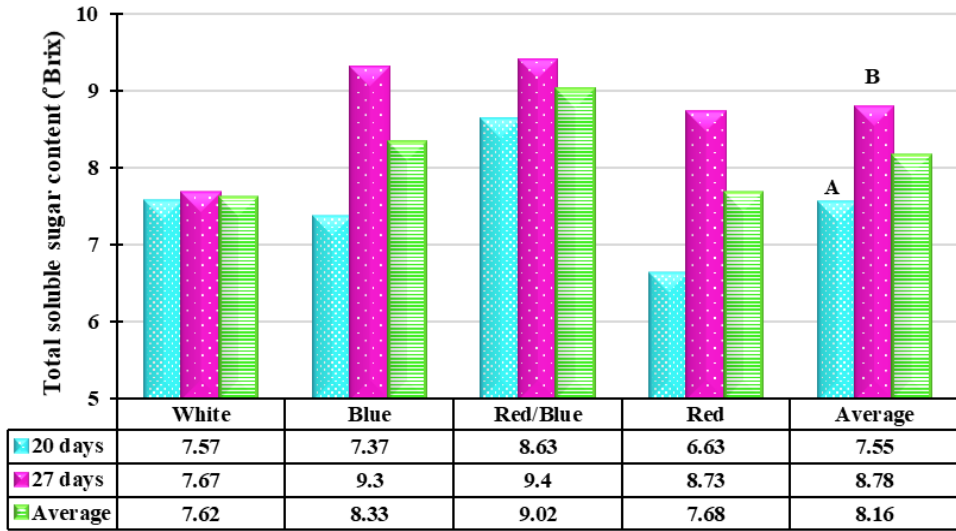
Figure 2. Average values of fruit weight per plant by light treatments and exposure durations.

Grafikon 2. Prosečne vrednosti mase plodova po biljci po svetlosnim tretmanima i dužini izlaganja.

Monochromatic R LEDs are highly efficient at driving the quantum yield of photosynthesis, leading to higher starch accumulation and enhanced cell expansion in fruit tissues (Wien and Stützel, 2020). Conversely, long-term monochromatic B LEDs are known to restrict leaf area development and stomatal conductance under certain photoperiods, creating a carbon-limiting environment that triggers abortive mechanisms or severely limits individual fruit biomass allocation (Serrano, 2023).

As demonstrated by Wang et al. (2016), the combination of red and blue photons (RB) optimizes photosynthetic efficiency and enhances the activity of key enzymes responsible for sugar synthesis in lettuce, while Kim and Son (2022) have shown that supplementation with

red, blue and far red LEDs could increase total soluble sugar in sweet pepper. Unlike single wavelengths or overly broad spectra, which can depress photosynthesis or dilute carbohydrate reserves, the RB spectrum establishes an ideal balance that ensures a steady and efficient source-to-sink translocation of carbohydrates. Our findings strongly corroborate this. The RB treatment yielded the highest total soluble sugar content across both exposure durations. Conversely, the lowest sugar accumulation was observed under R LEDs at day 20 and under W LEDs at day 27 (Figure 3). Furthermore, prolonged exposure to the light treatments consistently exerted a positive impact on the total soluble sugar content.

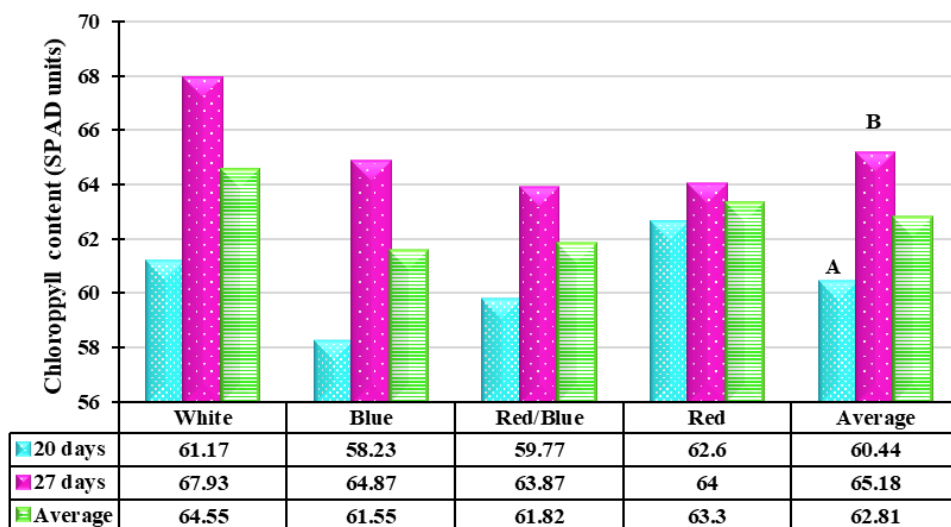


Legend: Different uppercase letters within column (A, B) denote statistically significant differences in the plant exposure duration to different lights ($p < 0.05$).

Figure 3. Average values of total soluble sugar content per plant by light treatments and exposure durations. Grafikon 3. Prosečne vrednosti sadržaja ukupnih rastvorljivih šećera po biljci po svetlosnim tretmanima i dužini izlaganja.

The chlorophyll content increased across all light treatments with longer exposure times, indicating that prolonged treatment has a positive effect on the synthesis of photosynthetic pigments. The highest chlorophyll content was observed in plants exposed to W LEDs, whereas the lowest value was observed under the RB light treatment (Figure 4). Broad-spectrum W LEDs include green and yellow wavelengths that possess superior tissue-penetrating capa-

bilities compared to red or blue photons. This deep penetration stimulates chloroplast development throughout the entire leaf mesophyll rather than just the upper epidermis, resulting in elevated SPAD values (Smith et al., 2017). On the contrary, the narrow-band RB spectrum can induce local acclimation stress or trigger feedback inhibition of pigment synthesis due to localized energy imbalances between Photosystem I and II (Naznin et al., 2019).



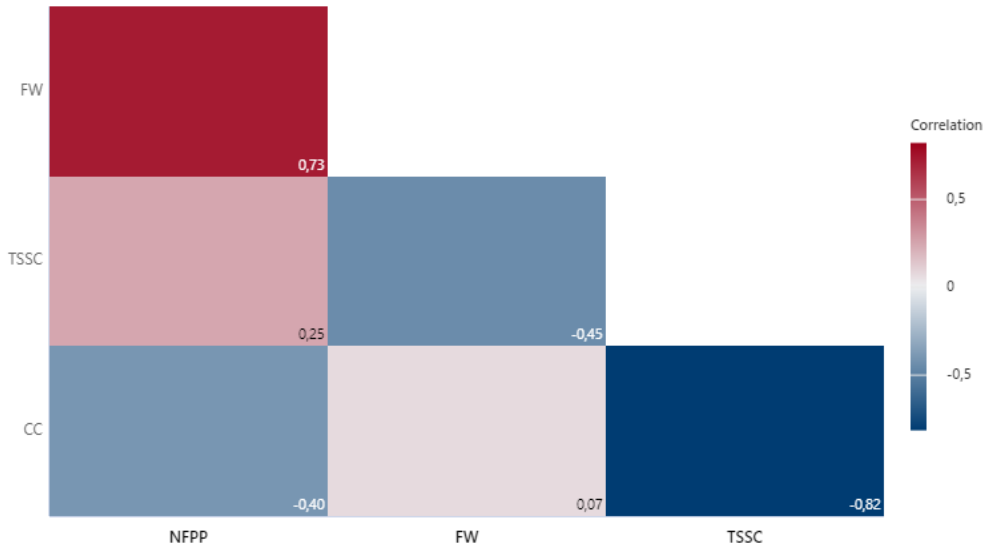
Legend: Different uppercase letters within column (A, B) denote statistically significant differences in the plant exposure duration to different lights ($p < 0.01$).

Figure 4. Average values of chlorophyll content (SPAD units) per plant by light treatments and exposure durations.

Grafikon 4. Prosečne vrednosti sadržaja hlorofila (SPAD jedinice) po biljci po svetlosnim tretmanima i dužini izlaganja.

The degree of association among the studied traits in pepper plants was assessed using Pearson's correlation coefficient (Figure 5). A highly significant negative correlation was found between leaf chlorophyll content and total soluble sugar in fruits ($r = -0.82^{**}$). This

strong negative correlation suggests a feedback mechanism: when plant produce too much sugar, it slows down the genes responsible for making chlorophyll to keep its metabolism balanced (Paul and Pellny, 2003).



Legend: NFPP – number of fruits per plant; FW – fruit weight; TSSC – total soluble sugar content; CC – chlorophyll content.

Figure 5. Correlation between the yield components and physiological features of pepper.
Grafikon 5. Korelacije između komponenti prinosa i fizioloških karakteristika paprika.

Additionally, fruit weight exhibited a strong positive correlation with the number of fruits per plant ($r = 0.73^{**}$), confirming the interdependence of this yield component. Conversely, a moderate negative correlation between total

soluble sugar and fruit weight ($r = -0.45$) suggests that enhanced fruit biomass accumulation is not necessarily accompanied by a concurrent accumulation of sugars in the fruit.

Conclusion

The results of this research confirm that the spectral composition of light and exposure duration are important modulators of pepper yield and quality. Specifically, the R light treatment during the first true leaf stage for 27 days resulted in significant increases in both number of fruits per plant and fruit weight. Notably, while the RB light treatment yielded the highest total soluble sugars, its effect was statistically equivalent to that of the R light treatment, indicating that R LEDs are sufficient to optimize sugar accumulation. Similarly, the highest chlorophyll content achieved under W LEDs showed no significant variation compared to R LEDs, further confirming the beneficial impact of the red spectrum on the physiological parameters of pepper plants.

The documented positive correlation between the number of fruits per plant and fruit weight underscores that an increase in fruit number directly drives higher overall yield. In contrast, the negative correlation between chlorophyll and total soluble sugars indicates different regulatory pathways for photosynthate partitioning.

Based on these results, it can be concluded that a 27-day R light treatment initiated at the first true leaf stage significantly enhances the regulation of physiological and productive traits, providing a strategic approach for maximizing both the yield and quality of pepper.

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Author contribution

Conceptualization, K.L., S.A. and A.R.; Methodology: K.L., S.A. and A.R.; Data curation: K.L. and A.R.; Formal analysis, K.L.; Investigation, K.L., S.A., V.P. and A.R.; Resources, S.A., D.C., and N.Đ.; Supervision, K.L., S.A. and A.R.; Visualization, K.L., V.P. and A.R.;

Validation, K.L., S.A., V.P., D.C., K.B. and A.R.; Funding acquisition, K.L., S.A., V.P., D.C., N.Đ. and A.R.; Roles/Writing - original draft, K.L., V.P. and A.R.; Writing - review & editing, K.L., S.A., V.P., D.C., N.Đ., K.B. and A.R.

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POBOLJŠANJE PROIZVODNJE PAPRIKE U STAKLENIKU KORIŠĆENJEM LED TRETMANA PRE RASAĐIVANJA

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Sažetak

Paprika (*Capsicum annuum* L.) je široko gajena povrtarska kultura čiji su rast i razvoj značajno uslovljeni kvalitetom svetlosti. Cilj ovog istraživanja bio je da se procene efekti različitih LED svetlosnih tretmana primenjenih u fazi rasada na kasniji razvoj i prinos paprike nakon presađivanja u staklenik. Kao biljni materijal korišćena je komercijalna sorta slatke paprike Morava. U fenofazi formiranja prvih stalnih listova, biljke su postavljene u zatvorene komore za gajenje biljaka i primenjena su četiri tretmana svetlosti: multispektralne bele LED diode (W LED), monohromatske plave LED diode (B LED), crvene LED diode (R LED) i mešavina (odnos 50:50%) crvenih i plavih LED dioda (RB LED). Rasad je gajen tokom 20 ili 27 dana u fotoperiodu od 12/12 h (svetlost/tama) na kontrolisanoj temperaturi od 23 ± 2 °C. Nakon perioda izloženosti od 20 i 27 dana, po pet ujednačenih biljaka rasada po tretmanu presađeno je u veće plastične saksije i prebačeno u staklenik, gde su gajene pod prirodnim dnevnim svetlom još 51, odnosno 44 dana. U fazi pune zrelosti zabeleženi su broj plodova po biljci i masa plodova po biljci, sadržaj hlorofila, kao i ukupan sadržaj rastvorljivih šećera. Rezultati ovog istraživanja ukazuju na to da je na broj plodova po biljci značajno uticao i svetlosni tretman i njegova interakcija sa dužina izlaganja, dok su masa plodova, ukupan sadržaj rastvorljivih šećera i sadržaj hlorofila zavisili isključivo od dužine izloženosti tretmanima svetlosti. Tretman crvenom svetlošću u trajanju od 27 dana primenjen u fazi prvih stalnih listova značajno je povećao broj plodova po biljci i masu plodova, pri čemu u sadržaju hlorofila i ukupnih rastvorljivih šećera nisu zabeležene statistički značajne razlike u odnosu na ostale najefikasnije tretmane.

Ključne reči: *Capsicum annuum* L., sorta Morava, veštačko osvetljenje, povrće, prinos, sadržaj hlorofila, sadržaj ukupnih rastvorljivih šećera

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