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Sustainable management of water resources and land in the production of pepper in the greenhouse

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Abstract

The aim of this study was to evaluate the effects of irrigation level, soil type, and microbial biostimulants on fruit weight and fruit number per plant of the pepper genotype "Moravska lepotica". The experiment was conducted during 2025 in the greenhouse of the Institute for Vegetables Crops Smederevska Palanka, on land originating from three locations important for the production of peppers in Serbia (Ruski Krstur, Donja Lokošnica and Smederevska Palanka). The experiment included a control treatment and three treatments with biostimulators (Azoter F - *Trichoderma atroviride*, Biofor active and Folisu) in three repetitions with 10 plants per treatment. Statistical analysis (ANOVA) showed a significant effect of factors and the interaction of irrigation × locality × treatment on fruit weight per plant. The highest fruit weight per plant (110.95 g) was measured at the full irrigation norm on the land from Donja Lokošnica in the Biofor active treatment. In contrast, at the reduced norm, the highest value (86.45 g) was recorded on land from Smederevska Palanka. The lowest average weight (32.22 g) was measured on the soil from Ruski Krstur in the Azoter F treatment at 50% of the irrigation norm. At the reduced irrigation norm, the highest number of fruits was obtained on Ruski Krstur with Azoter F (8.7) and Folis (7.8), while the control yielded the fewest (4.5).

Keywords: biostimulants, pepper, reduced irrigation, soil type, productive traits of fruit

Introduction

Fertile soil not only provides the necessary conditions for plant growth, but actively participates in the preservation of biodiversity, nutrient cycling, water filtration and carbon sequestration (Rajičić et al., 2023; Fausak et al., 2024; Rajičić et al., 2024). However, unsustainable agricultural land management, excessive use of chemical fertilizers and direct impacts of climate change cause soil degradation (Stojiljković et al., 2025a; Šević et al., 2025a). Soil degradation manifests itself through erosion, contamination, increased salinity, disruption of microbial communities, greenhouse gas emissions and imbalance of nutrient elements (Stojiljković et al., 2025b; Terzić et al., 2025a). These processes threaten agroecosystems in the long term, especially in regions with intensive greenhouse production. In response to these interconnected challenges, innovative, nature-based and ecologically efficient management measures are gaining increasing importance (Rajičić et al., 2025; Šević et al., 2025b). Research suggests that agrotechnical measures such as drip irrigation systems, mulching and foliar feeding contribute to better plant growth, higher yields, water savings, weed control, improved nutrient absorption and reduced soil compaction, creating a more favorable microclimate for crops (Deepthi et al., 2024).

Pepper (*Capsicum annuum* L.) is among the most important vegetable species worldwide and in Serbia (Šević et al., 2024). High nutritional value, antioxidant compound content, and intense organoleptic properties (taste, colour, aroma, and texture) make it highly sought after on the market (Brezeanu et al., 2022). The quality of pepper fruits depends on the genotype (Cvikić et al., 2024), degree of maturity, and production conditions, including applied agrotechnical measures and fertilisation systems (Bajagić et al., 2025; Elhawary et al., 2025). According to FAO data from 2021, the annual withdrawal of water from natural water resources worldwide was approximately 4250 km^3, with agriculture accounting for as much as 71.7% of total water consumption. It is estimated that the world population will reach 9 billion by 2050, posing numerous serious challenges for agriculture in providing sufficient food (Tripathi et al., 2018). To feed the human population, it will be necessary to produce about 60% more food than current levels, which will inevitably lead to a further increase in water consumption (Mancosu et al., 2015). Preservation of this resource is necessary to achieve maximum efficiency with minimal losses, thereby ensuring the long-term sustainability of agricultural production (Boyacı et al., 2025).

Rising temperatures have a negative impact on plant growth and development (Jovanović and Rančić, 2025), which often leads to insufficient development of reproductive organs due to reduced carbon assimilation (Kabir et al., 2021; Marcellini et al., 2023). Drought stress is one of the most significant abiotic limitations of agricultural productivity. Water deficiency directly impairs photosynthesis by limiting CO_2 diffusion into plant leaves under stress, due to reduced conductivity in stomatal and mesophyll tissues (Ntanasi et al., 2025). In addition, in drought conditions, there is a reduced absorption of mineral nutrients by the root system, because the low moisture content in the soil slows down the diffusion of nutrient ions from the soil to the roots. Because of the above, there is an increasingly pronounced need to develop pepper genotypes that show greater resistance to drought and, at the same time, maintain satisfactory yields and fruit quality (Gisbert-Mullor et al., 2023). In agroecological and organic production systems, special importance is given to preserving the diversity of genotypes, especially traditional and locally adapted genotypes. They represent an important genetic resource for breeding and as rootstocks, which significantly contribute to greater resistance of vegetable production in an increasingly unpredictable climate (Conti et al., 2019). Pepper belongs to plants that are extremely sensitive to water stress (Mačkić et al., 2023), so great caution is necessary when managing irrigation.

The period of lack of water during flowering and fruit setting is especially critical. In the context of climate change, characterised by an uneven distribution of precipitation and extreme temperatures (Terzić et al., 2025b), the accurate determination of the watering rate becomes crucial for stable and successful plant production (Tupajić et al., 2026). As an effective adaptation strategy, biostimulators are increasingly used - relatively new products of various formulations that positively affect vital processes in plants without direct supply of nutrients (Calvo et al., 2014; Dragičević et al., 2021). In modern plant production, their application is considered an important component of sustainable agriculture that significantly contributes to the preservation of the agroecosystem (Salachna et al., 2025). Biostimulators reduce the use of conventional mineral fertilisers, strengthen resistance to biotic and abiotic stresses and increase the synthesis of photosynthetic pigments (Janošević et al., 2017; Naqve et al., 2023). Microbiological biostimulators based on beneficial fungi and bacteria are particularly important, as they improve soil structure and microbial diversity, thereby contributing to the sustainability of production under increasingly pronounced water stress and elevated temperatures.

The aim of this study was examine the impact of reduced irrigation (50% of the full norm) and the application of different biostimulators on the components of the yield of peppers of the Moravska lepotica variety in greenhouse production conditions, with special reference to the weight of fruits per plant and the number of fruits per plant. The novelty of the research is reflected in the comprehensive analysis of the interaction between water deficit and biostimulators on the productive parameters of the Moravska lepotica variety, with an emphasis on the possibility of significantly reducing water consumption while preserving or improving yields, in parallel with reducing the use of mineral fertilisers and chemical plant protection agents and preserving the microbiological activity of the soil. This approach represents a practical model of climate-smart, resource-efficient agriculture in the context of global climate change.

Material and Methods

The research was conducted during 2025 in the greenhouse of the Institute for Vegetables Crops Smederevska Palanka (44°22′ N, 20°47′ E, 102 m above sea level), on lands from three locations known for pepper production in Serbia: Ruski Krstur, Donja Lokošnica (near Leskovac) and Smederevska Palanka. The experiment included two irrigation norms - full (100%) and reduced (50% of the total watering norm). Irrigation was implemented using the Smart Watering automated system. The system is equipped with a sensor for continuous measurement of soil moisture. The sensor automatically started the irrigation process when the lower limit of optimal humidity was reached, and stopped it after the required amount of water had been applied. The sensor is placed in pots with two drippers, ensuring a full

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irrigation norm (100%). The variant with a reduced irrigation norm (50%) was realised using only one dripper per pot.

Seedlings of the variety Moravska lepotica were transplanted into pots filled with soil from three localities, with 10 plants per treatment and three repetitions. Treatments with biostimulators were applied starting 15 days after planting, according to the manufacturer's recommendations: 1. Control - without application of biostimulators. 2. Azoter F (*Trichoderma atroviride*) – component A (120 ml/30 l of water) and component B (1.6 ml/30 l of water), applied together by watering. The first treatment is a few days after planting, then two more at intervals of 7-10 days. 3. Biofor active - dose 125 ml/10 l of water (watering and foliar application). The first treatment is a few days after planting, then two more at intervals of 7-10 days. 4. Folisu – ecological foliar treatment, dose 18.75 g/2.250 ml of water. The first treatment is a few days after planting, the second in the phase of intensive growth, and the third in the phase of fruit set.

The experiment was conducted under greenhouse conditions, with the main focus on insect and mite control. For this experiment, a monitoring-based method was used, in which the decision to apply insecticides/miticides was based on visual detection, combined with early-detection tools such as sticky traps (yellow and blue) and VARL+ traps with pheromone lures. The lures were selected for control of *Helicoverpa armigera armigera L.* and *Ostrinia nubilalis L.*, based on field history.

Agrochemical analysis of the soil was performed before setting up the experiment using standard accredited methods: pH in KCl according to Kapen, humus content according to Kotzman, total nitrogen using the Kjeldahl method, and easily accessible forms of phosphorus (P_2O_5) and potassium (K_2O) using the AL-method according to Egner-Riehm (Table 1).

Table 1. Soil nutrient availability and mechanical composition at various locations

Provision of soil with nutrients						
Locality	**Depth (cm)**	**Humus**	**N**	**Available (mg 100 g^{-1} soil)**		**pH**
		(%)	**(%)**	**P_2O_5**	**K_2O**	**KCl**
R. Krstur	0-30	2.02	0.13	37.55	52.16	7.11
D. Lokošnica	0-30	2.13	0.14	31.74	45.18	5.77
S. Palanka	0-30	2.25	0.15	38.28	39.27	5.91

Mechanical composition of soil				
Locality	**Sand**	**Fine sand**	**Powder**	**Clay**
Ruski Krstur	1.3	23.0	39.1	36.6
Donja Lokošnica	17.3	12.0	53.5	17.2
Smederevska Palanka	5.1	21.1	24.5	49.3

All three soils were low humus content (Belić et al., 2014), with a slightly acidic (Donja Lokošnica and Smederevska Palanka) to neutral reaction (Ruski Krstur) and a high content of phosphorus and potassium in all three soils. Differences in the mechanical composition were determined: the largest share of powder in the soil from Donja Lokošnica, the largest share of clay in the soil from Smederevska Palanka and an almost equal share of dust and clay in the soil from Ruski Krstur (Table 1).

Air temperature (°C) and relative humidity (RH %) were measured daily during the growing season with a digital thermohygrometer (Testo 608-H1), and the values are shown as averages per month during the research period (Figure 1).

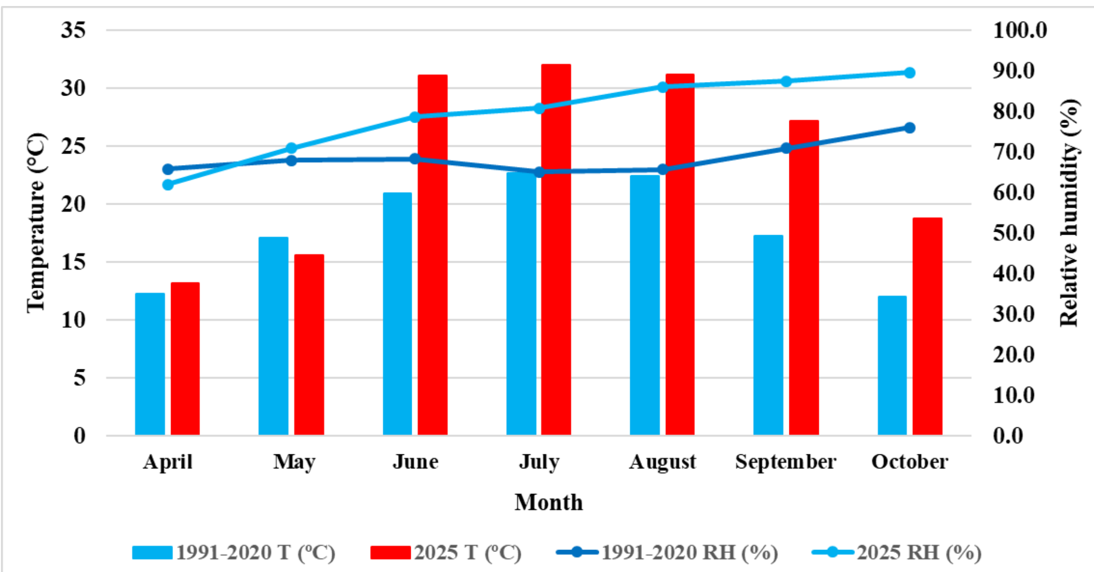

Figure 1. Average monthly air temperature and relative humidity during the growing season in 2025 and the multi-year period (1991-2020)

Average air temperatures in 2025 ranged from 13.2 °C (April) to 32 °C (July), which is significantly above the long-term average. Relative air humidity during 2025 was elevated (62.0-89.6%), with a tendency to increase during the season due to increased evapotranspiration. Analysis of microclimate parameters revealed that the relative humidity during the research period was significantly above the long-term average (65.1-76.1%).

IBM SPSS Statistics software, version 26.0, was used for the statistical analysis of the obtained data. An Analysis of Variance (ANOVA) was applied to assess the influence of locality, irrigation norm and treatment, with significance levels set at $p<0.05$ and $p<0.01$. Tukey's HSD (Honestly Significant Difference) post-hoc test was used to perform multiple pairwise comparisons between all group means at statistical significance level 0.05. It was determined which specific groups had statistically significant differences by comparing the difference between each pair of means with a calculated critical value (HSD). A compact representation is given with different letters denoting significant differences.

Results and Disscusion

The statistical analysis (Table 2) determined the influence of individual factors, as well as the interaction of irrigation × locality × treatment, on the examined characteristic, fruit weight per plant, in the Moravska lepotica. Genotype, irrigation and biostimulant treatments significantly influence the quality of pepper fruits (Elhawary et al., 2025).

Table 2. Analysis of variance (ANOVA) for fruit weight

EFFECT	SS	df	MS	F test	ProbF	Sign.
Irrigation	5847.98594	1	5847.98594	17.55454433	0.000125150	**
Locality	3127.249427	2	1563.624714	4.693704744	0.013962909	*
Treatment	4046.930319	3	1348.976773	4.049372349	0.012312878	*
Irrigation x Locality	1473.735278	2	736.8676389	2.211936856	0.121003346	ns
Irrigation x Treatment	1195.310562	3	398.436854	1.196031846	0.321799150	ns
Locality x Treatment	4346.664115	6	724.4440191	2.174643506	0.062672740	ns
Irrigation x Locality x Treatment	7711.102049	6	1285.183675	3.857877571	0.003362055	**
Total	46977.89404	71				

Note: SS-Sum of squares; df – Degree of freedom; MS-Mean Squares; F test - value calculated; ProbF – probability of F – p value; ** Highly significant at 0.01 probability level; *Significant at 0.05 probability level; ^{ns}Non significant at 0.05 probability level.

The highest average value of fruit weight per plant (Figure 2) was measured at full irrigation norm (100%) on the land from the Donja Lokošnica location in the treatment with Biofor active, and is 110.95 g, then at full irrigation norm on the land from Smederevska Palanka in the control treatment, where no biostimulator was applied (104.07 g). Regarding the reduced irrigation norm (50%) on the soil type from Smederevska Palanka in the treatment with Biofor active, the highest fruit weight was achieved (86.45 g). At the same time, the lowest average value was recorded in the soil from Ruski Krstur with the Azoter F treatment, at 32.22 g, indicating statistically significant differences between treatments. The results show that applying biostimulators can significantly increase fruit weight. The results of the research are in agreement with the results of earlier research in which the foliar application of biostimulators had a positive effect on the physical characteristics of the fruit, including greater fruit weight (Mahmood et al., 2017; Halshoy et al., 2025). Also, the positive impact of biostimulators on fruit weight was reported in the research results (Halshoy et al., 2025), and this was confirmed in the results of this research, where the treatments Biofor active, Azoter F and Folisu, in most cases, achieved better results than the control.

Reducing the irrigation norm to 50% of the norm did not result in significant losses in the Moravska lepotica genotype, especially when combined with a suitable biostimulator and soil. This coincides with the findings that reducing irrigation to a certain level (67% ETc) does not significantly affect the yield and quality of fruits (Kabir et al., 2021), and that reductions (up to 20% reduced regime) in some genotypes did not lead to significant losses (Marcellini et al., 2023). However, optimal growth and high yield still require sufficient water during critical developmental stages (Kabir et al., 2021). A greater reduction in the watering rate (by 40%) often leads to a decrease in yield due to a reduction in the number or size of fruits (Ntanasi et al., 2025), and the average weight of fresh pepper fruit decreases in conditions of water deficit (Kurunc et al., 2011). Pimentel-Pujols et al. (2026) in their research concluded that fertigation and different substrates significantly affect the agronomic characteristics of pepper in a protected area, and the type of substrate proved to be a dominant factor, especially in terms of fruit weight, and other productive properties of pepper fruit (Salachna et al., 2025).

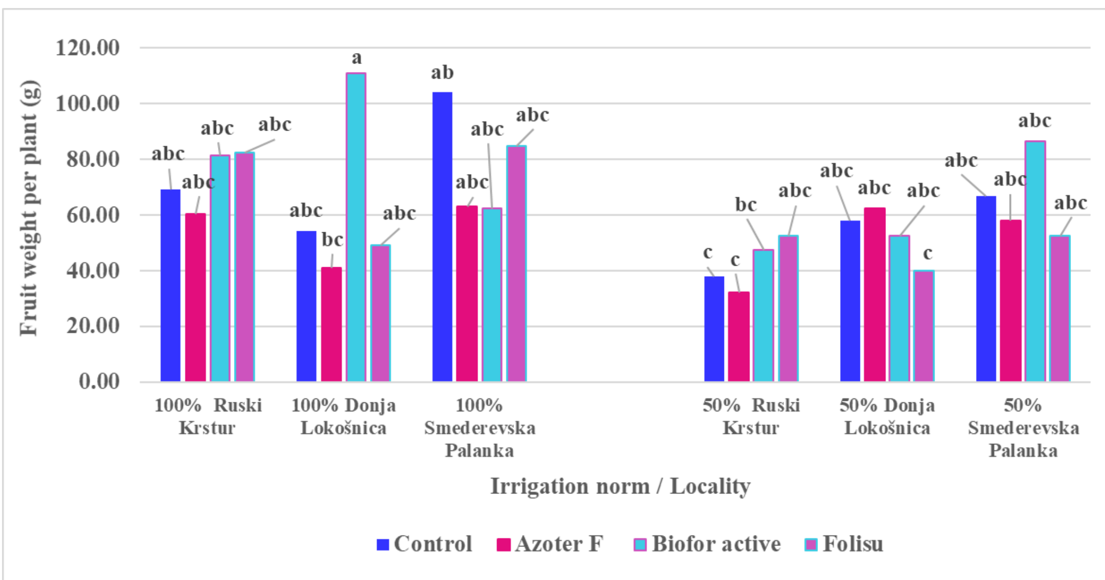

Figure 2. Average fruit weight per plant (g) at different irrigation rates and treatments during 2025. Irrigation: 100 % - full norm; 50% - reduced norm. Locality: Ruski Krstur, Donja Lokošnica, Smederevska Palanka. Treatment: Control, Azoter F, Biofor active, Folisu. Tukey's test HSD – different letters indicate statistically significant differences between treatment combinations.

Analysis of variance (Table 3) showed that the treatment had a statistically significant effect on the number of fruits per plant in the Moravska lepotica genotype.

Table 3. Analysis of variance (ANOVA) for fruit number per plant

EFFECT	SS	df	MS	F test	ProbF	Sign.
Irrigation	0.003472222	1	0.003472222	0.001014478	0.974728773	ns
Locality	10.63020833	2	5.315104167	1.552912766	0.22252087	ns
Treatment	35.75347222	3	11.91782407	3.482027928	0.023190188	*
Irrigation x Locality	6.585069444	2	3.292534722	0.961979115	0.389689287	ns
Irrigation x Treatment	7.420138889	3	2.47337963	0.722646759	0.54363568	ns
Locality x Treatment	6.897569444	6	1.149594907	0.335876881	0.914418049	ns
Irrigation x Locality x Treatment	7.262152778	6	1.210358796	0.353630252	0.904123789	ns
Total	234.09375	71				

Note: SS-Sum of squares; df – Degree of freedom; MS-Mean Squares; F test - value calculated; ; ProbF – probability of F – p value; *Significant at 0.05 probability level; nsNon significant at 0.05 probability level.

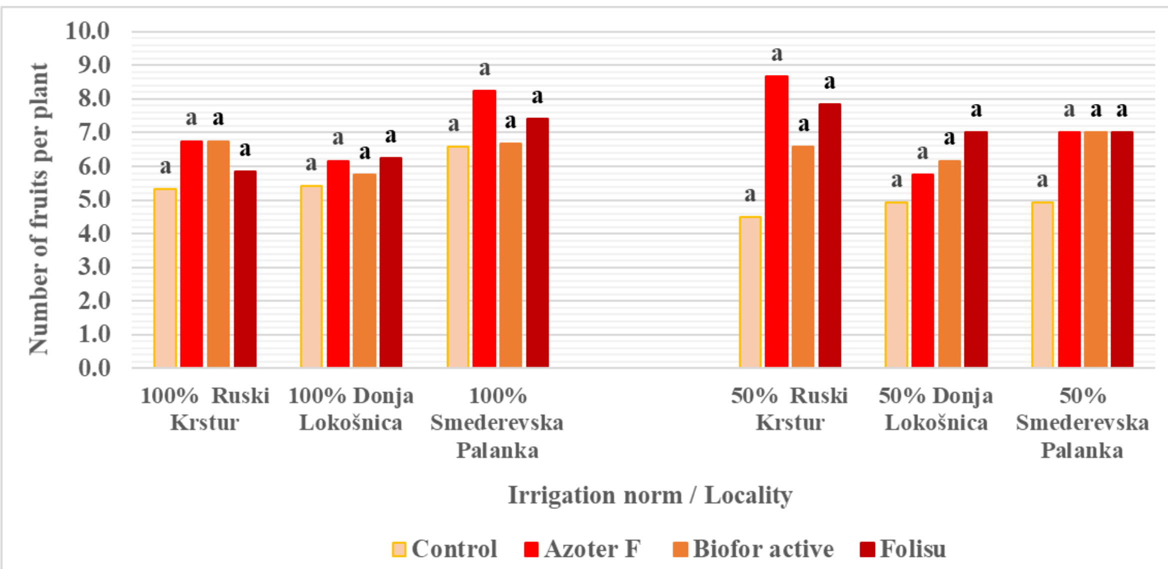

Figure 3. Average values of the number of fruits per plant under different irrigation rates and treatments during 2025. Irrigation: 100 % - full norm; 50% - reduced norm. Locality: Ruski Krstur, Donja Lokošnica, Smederevska Palanka. Treatment: Control, Azoter F, Biofor active, Folisu. Tukey's test HSD – different letters indicate statistically significant differences between treatment combinations.

Analysing the results on the number of fruits per plant (Figure 3), it can be seen that with a reduced irrigation norm, a higher number of fruits per plant was achieved on the soil type from Russian Krstur in the treatment with Azoter F (8.7) and the treatment with Folisu (7.8). In contrast, the lowest average value was observed in the control treatment (4.5). At the full irrigation norm, the highest average number of fruits was recorded for the soil from Smederevska Palanka in the Azoter F treatment (7.4). In contrast, the lowest number of fruits was measured for the soil from Ruski Krstur in the control treatment (5.3). It is particularly noticeable that, in the control treatment without biostimulators, the lowest number of fruits was recorded. This confirms the findings according to which the number of fruits per plant is significantly influenced by treatment with biostimulators ($p \leq 0.01$), with the lowest values precisely in the control (Salachna et al., 2025). Research conducted over two years with a larger number of harvests also showed positive effects of biostimulators on the number and weight of fresh fruits (Mezeyová et al., 2024), which aligns with the results of this research. The results on the land from Ruski Krstur under irrigation at a 50% watering norm show that certain genotypes, with the help of biostimulators, can maintain a high number of fruits, indicating good water-use efficiency. The high productivity of certain sweet corn genotypes under reduced irrigation norms confirms their resistance to water deficit (Tupajić et al., 2024; Tupajić et al., 2026), which is consistent with the research results. In research, the Moravska lepotica genotype showed tolerance to a reduced irrigation norm when treated with appropriate biostimulators, which opens up the possibility of applying reduced irrigation norms in pepper production without major compromises in fruit weight or number per plant.

Conculison

Based on the research, irrigation, locality and applied biostimulators significantly influenced fruit weight per plant in Moravska lepotica pepper variety. The largest fruit mass (110.95 g) was achieved at full watering rate (100%) on the land from Donja Lokosnica in the variant with the application of Biofor active. With reduced irrigation (50%), the highest mass (86.45 g) was on the land from Smederevska Palanka with the same biostimulator.

The number of fruits was the highest at 50% irrigation on the land from Ruski Krstur in the variants Azoter F (8.7) and Folis (7.8). The control variant without biostimulator produced the lowest number of fruits.

The results show that the variety Moravska lepotica with an appropriate selection of biostimulators can successfully produce sr in a reduced watering regime (50%) without a significant loss of yield, with good water use efficiency.

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United Nations 2030 Agenda for Sustainable Development, specifically with Goal 2: Zero Hunger (available at United Nations Sustainable Development Goals – Goal 2)."

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Održivo upravljanje vodnim resursima i zemljištem u proizvodnji paprike u plastenicima

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Apstrakt

Istraživanje je imalo za cilj da ispita uticaj redukovanog navodnjavanja (50 %) u odnosu na punu normu (100 %), različitih tipova zemljišta i primene mikrobioloških biostimulatora na masu ploda po biljci i broj plodova po biljci genotipa paprike Moravska lepotica. Ogled je sproveden tokom 2025. godine u stakleniku Instituta za povrtarstvo Smederevska Palanka, na zemljištima poreklom sa tri lokacije značajne za proizvodnju paprike u Srbiji (Ruskog Krstura, Donje Lokošnice i Smederevske Palanke). Eksperiment je obuhvatio dve norme navodnjavanja, tri biostimulatora (Azoter F – *Trichoderma atroviride*, Biofor active i Folis) i kontrolni tretman bez njihove primene, u tri ponavljanja sa po 10 biljaka po tretmanu. Statistička analiza (ANOVA) pokazala je značajan uticaj faktora i interakcije navodnjavanje × lokacija × tretman na masu ploda po biljci. Najveća masa ploda po biljci (110,95 g) izmerena je pri punoj normi navodnjavanja na zemljištu iz Donje Lokošnice u tretmanu Biofor active. Pri smanjenoj normi navodnjavanja, najveća vrednost (86,45 g) zabeležena je na zemljištu iz Smederevske Palanke. Najniža prosečna težina (32,22 g) izmerena je na zemljištu iz Ruskog Krstura u tretmanu Azoter F pri 50% zalivne norme. Pri smanjenoj normi zalivanja, najveći broj plodova dobijen je na zemljištu iz Ruskog Krstura sa Azoterom F (8,7) i Folisu-om (7,8), dok je u kontrolnoj varijanti dobijen najmanji broj plodova (4,5). Rezultati ukazuju da primena odgovarajućih biostimulatora, posebno Biofor active, može značajno ublažiti negativne efekte redukovanog navodnjavanja na masu ploda, dok Azoter F i Folisu imaju pozitivan uticaj na veći broj plodova u deficitarnim uslovima. Genotip Moravska lepotica pokazuje potencijal za održivu proizvodnju uz uštedu vode kada se koriste mikrobiološki preparati i odgovarajući tip zemljišta.

Ključne reči: biostimulanti, paprika, redukovana norma zalivanja, tip zemljišta, produktivne osobine ploda

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