ЗЕМЛЕРОБСТВО, РОСЛИННИЦТВО, ОВОЧІВНИЦТВО ТА БАШТАННИЦТВО

AGRICULTURE, CROP PRODUCTION, VEGETABLE AND MELON GROWING

УДК 633.174:631.52:631.8(477.7)
DOI https://doi.org/10.32782/2226-0099.2026.147.1.1

THE EFFECT OF ROW SPACING AND BIOSTIMULANTS ON THE PHOTOSYNTHETIC POTENTIAL AND YIELD OF MILLET IN SOUTHERN UKRAINE

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The study examined the characteristics of millet (Panicum miliaceum L.) productivity formation depending on the spatial organization of sowing and the use of biostimulating preparations in the arid conditions of southern Ukraine during 2021–2023. The response of plants to different row spacing (15 and 30 cm) in combination with pre-sowing seed treatment with Gumicor and foliar feeding with HELAFIT-Combi was evaluated. It was shown that changing the parameters of plant placement significantly transforms the morphological structure of the agrophytocenosis, the intensity of assimilation surface formation, and the level of photosynthetic activity of crops. The narrow-row sowing method ensured an increase in growth, tillering, and photosynthetic activity, which led to a stable increase in grain yield compared to wide-row placement.

The article highlights the results of a three-year field experiment, establishes the dominant role of row spacing in yield formation, and determines the proportion of influence of the studied factors based on the results of variance analysis. It was demonstrated that optimizing the spatial structure of sowing allows for more effective realization of the potential of mineral nutrition and biostimulation, and the combination of 15 cm row spacing with the use of Gumicor and HELAFIT-Combi ensures maximum productivity – 4.06 t/ha. It was established that the contribution of row *spacing to the overall variability of yield is 76 %, which confirms its decisive importance in the system of technological measures.*

The results obtained indicate the feasibility of an integrated approach to regulating crop density and nutrition in order to increase the adaptability of the crop to moisture deficiency and high temperatures. The proposed technological elements can be recommended for industrial implementation in order to stabilize and increase millet yields in the southern regions of Ukraine.

Key words: *millet, row spacing, photosynthetic activity, biostimulants, yield, adaptive technology.*

Аверчев О. В., Нікітенко М. П. Вплив ширини міжрядь та біостимуляторів на фотосинтетичний потенціал і врожайність проса в умовах півдня України

Досліджено особливості формування продуктивності проса (Panicum miliaceum L.) залежно від просторової організації посіву та застосування біостимулюючих препаратів у посушливих умовах Півдня України протягом 2021–2023 рр. Оцінено реакцію рослин на різну ширину міжрядь (15 і 30 см) у поєднанні з передпосівною обробкою насіння препаратом Гумікор та позакореневим підживленням ХЕЛАФІТ-Комбі. Показано, що зміна параметрів розміщення рослин істотно трансформує морфологічну структуру агрофітоценозу, інтенсивність формування асиміляційної поверхні та рівень фотосинтетичної діяльності посівів. Вузькорядний спосіб сівби забезпечив підвищення показників росту, кущення та активності фотосинтезу, що зумовило стабільне зростання врожайності зерна порівняно з широкорядним розміщенням.

У статті висвітлено результати трирічного польового експерименту, встановлено домінуючу роль ширини міжрядь у формуванні врожаю та визначено частку впливу досліджуваних чинників за результатами дисперсійного аналізу. Продемонстровано, що оптимізація просторової структури посіву дозволяє ефективніше реалізувати потенціал мінерального живлення і біостимуляції, а поєднання міжряддя 15 см із застосуванням Гумікор і ХЕЛАФІТ-Комбі забезпечує максимальний рівень продуктивності – 4,06 т/га. Встановлено, що внесок ширини міжрядь у загальну варіабельність урожайності становить 76 %, що підтверджує її визначальне значення в системі технологічних заходів.

Отримані результати свідчать про доцільність інтегрованого підходу до регулювання густоти та живлення посівів для підвищення адаптивності культури до дефіциту вологи та високих температур. Запропоновані елементи технології можуть бути рекомендовані для виробничого впровадження з метою стабілізації та зростання врожайності проса в умовах південних регіонів України.

Ключові слова: *просо посівне, ширина міжрядь, фотосинтетична активність, біостимулятори, урожайність, адаптивна технологія.*

Problem statement. Row spacing is one of the key agronomic factors that directly determine the growth and development of millet (Panicum miliaceum L.). It affects the distribution of plants per unit area, light regime, availability of moisture and nutrients, as well as the interaction between plants in the crop. Smaller row spacing promotes denser plant placement, which allows for more efficient use of light and increases the intensity of photosynthesis. In turn, optimal photosynthetic potential is the foundation not only for the accumulation of above-ground and below-ground biomass, but also for the formation of high-quality grain indicators [6, c. 32].

The problem of choosing the optimal row spacing is particularly relevant for the conditions of southern Ukraine, where millet crops often face high temperatures, limited moisture supply, and unstable soil fertility. In such conditions, dense plant spacing allows for better soil moisture retention, reduces evaporation, and forms a more тоcompetitive plant structure. At the same time, overly dense crops can lead to competition between plants for resources, increased risk of disease development, and physiological stress.

In modern millet cultivation technologies, a comprehensive approach is important, combining the optimization of row spacing with the use of biostimulants and mineral nutrition. This not only increases the photosynthetic activity of the foliage, but also improves the development of the root system, which directly affects the absorption of water and nutrients during periods of critical resource shortages.

Analysis of recent studies and publications. The issue of optimizing row spacing as one of the key elements of cereal crop cultivation technology has been repeatedly highlighted in the works of domestic scientists. Studies show that the spatial arrangement of plants directly affects the formation of the photosynthetic potential of crops, the intensity of biomass accumulation, and the level of yield.

The works of M.Ya. Gumentyk (2014) have established that plant density and row spacing significantly determine the productivity of switchgrass (Panicum virgatum L.), in particular due to changes in the structure of the agrophytocenosis and the efficiency of environmental factors [1, c. 29]. The author emphasizes the importance of adapting row spacing to soil and climatic conditions and the intended use of the crop. Further research (Gumentyk, 2016) confirmed that the optimal sowing method and plant care system contribute to increased biomass yield and stability of the production process in the forest-steppe zone of Ukraine [1, c. 29].

Similar conclusions regarding the role of row spacing were obtained in studies by V. A. Mazur and Yu. Yu. Branitsky (2017), who noted the influence of sowing dates and spatial organization of sowing on the growth and development of millet plants [2, c. 19]. It has been established that changing row spacing in the early stages of organogenesis affects competitive relationships between plants and the formation of productive stems.

The scientific and production recommendations of O. V. Averchev (2008) on the cultivation of millet in the conditions of the Black Sea steppe of Ukraine emphasize the importance of agrotechnical measures aimed at preserving soil moisture, optimizing sowing dates, and maintaining a favorable water-air regime through inter-row cultivation [4, c. 6]. Given the aridity of the region, the spatial parameters of sowing are considered as a tool for regulating the microclimate of the agrocenosis.

At the same time, in modern research, the combination of agrotechnical methods with a system of mineral nutrition and biological preparations is becoming increasingly relevant. Thus, in the works of O. V. Averchev, N. E. Vasilenko, and co-authors (2019), the effectiveness of optimized nitrogen nutrition (90–110 kg/ha d. r.) and pre-sowing inoculation of seeds with biological preparations to increase the seed productivity of cereal crops has been proven [5, c. 1]. The results confirm the feasibility of integrating agrotechnical and agrochemical factors into a single adaptive cultivation system.

At the same time, for the conditions of southern Ukraine, the issue of the optimal combination of narrow-row sowing with biostimulants and mineral nutrition of millet (Panicum miliaceum L.) remains insufficiently studied. This necessitates comprehensive research aimed at determining the effect of row spacing in interaction with agrochemical factors on biometric indicators, photosynthetic potential, and crop yield [6].

The aim of the study is to determine the effect of row spacing (15 and 30 cm) on biometric indicators, photosynthetic potential, and millet yield formation in southern Ukraine, taking into account the adaptive response of plants to sowing density and agrochemical factors.

Soil conditions. The study was conducted on southern transitional to ordinary and southern low-humus chernozems formed on loess-like carbonate loams. The depth of the humus horizon was 30 cm, the humus content was 2.0–3.0 %, and the soil solution reaction was close to neutral (pH 6.8). The soils are characterized by optimal bulk density (1.15–1.29 g/cm^3), porosity of 55.6 %, and heavy loam granulometric composition, which provides favorable water-air properties. The availability of mobile forms of phosphorus is average (5–10 mg P_2O_5 per 100 g of soil), potassium is high (11–15 mg per 100 g of soil), and nitrification capacity is moderate (1–3 mg per 100 g of soil). Groundwater lies at a depth of more than 3 m. In terms of their natural properties, the soils are characterized by high potential fertility and are suitable for growing grain crops.

Experimental design. Field studies were conducted using a three-factor design. Factor A – pre-sowing treatment of seeds with Gumikor (3.0 l/ha), Gumiam-01 (2.0 l/t) and control (water). Factor B – row spacing of 15 and 30 cm with a sowing rate of 20 kg/ha. Factor C – foliar feeding of plants with Gumicor (3.0 l/ha), BIO-GEL (2.0 l/ha), HELAFIT-combi (1.0 l/ha), Gumiam-01 (0.07 l/ha) and control. Seed treatment was carried out one day before sowing, foliar feeding was carried out twice – in the tillering and panicle emergence phases of the crop.

Setting the task. Within the framework of the study aimed at increasing millet productivity and optimizing agrotechnical measures, the task was set to comprehensively assess the effect of row spacing on plant growth, development, and photosynthetic activity.

First, it was planned to determine the effect of 15 and 30 cm row spacing on key biometric indicators, including plant height, number of shoots, and leaf area, as well as to assess the net photosynthetic productivity of crops with different spatial structures. Another important task was to determine the effectiveness of the combined use of different row spacing widths, pre-sowing seed treatment with Gumicor, and foliar feeding with HELAFIT-Combi. A dispersion analysis was performed to quantitatively assess the impact of the studied factors on crop yield. Based on the results obtained, it was planned to develop scientifically sound recommendations for industrial implementation.

The implementation of these tasks made it possible not only to evaluate the effectiveness of different row spacing options, but also to offer practical recommendations aimed at increasing the productivity and environmental stability of millet cultivation in southern Ukraine.

Presentation of the main research material. During the study (2021–2023), it was established that the formation of millet productivity in southern Ukraine is the result of a complex interaction of agrotechnical factors and weather and climatic conditions. The main influencing factors were row spacing (factor B), pre-sowing seed treatment (factor A), and foliar feeding (factor C).

The first stage of the research was to establish a relationship between the spatial arrangement of plants and net photosynthetic productivity [7, c. 361]. The data obtained confirmed that narrowing the row spacing to 15 cm creates more favorable conditions for the formation of a powerful assimilation apparatus.

Table 1

Effect of row spacing on biometric indicators and net photosynthetic productivity of millet plants (average for 2021–2023)

Indicator	**Row spacing**		**Difference (%)**
	15 cm	**30 cm**	
Plant height, cm	85	78	9
Number of shoots per plant, pcs	5,2	4,1	27
Leaf area, cm^2	420	360	17
Net photosynthetic productivity, g/m^2/day	5,10	4,95	3
Grain yield, cwt/ha	38,2	31,5	21

The results of the studies confirm that narrowing the row spacing to 15 cm is a key factor in optimizing the structure of the millet agrophytocenosis, which provides a significant advantage in all biometric and physiological indicators. A more uniform distribution of plants across the area contributed to a 17 % increase in leaf surface area and a 3 % increase in net photosynthetic productivity compared to 30 cm row spacing. The data obtained indicate a more efficient use of photosynthetically active radiation and improved conditions for intraspecific plant interaction, which ultimately ensures an increase in the level of realization of the productive potential of the crop [7, c. 361].

The established direct correlation between morphological parameters (in particular, a 27 % increase in the number of shoots) and photosynthetic intensity proves that denser sowing allows plants to more fully utilize the resource potential of the environment – light, moisture, and mineral nutrition. This leads to the formation of a consistently higher grain yield (38.2 cwt/ha), which is 21 % higher than that of wide-row sowing, confirming the scientific significance of choosing a row spacing of 15 cm as a basic element of intensive millet cultivation technology in southern Ukraine.

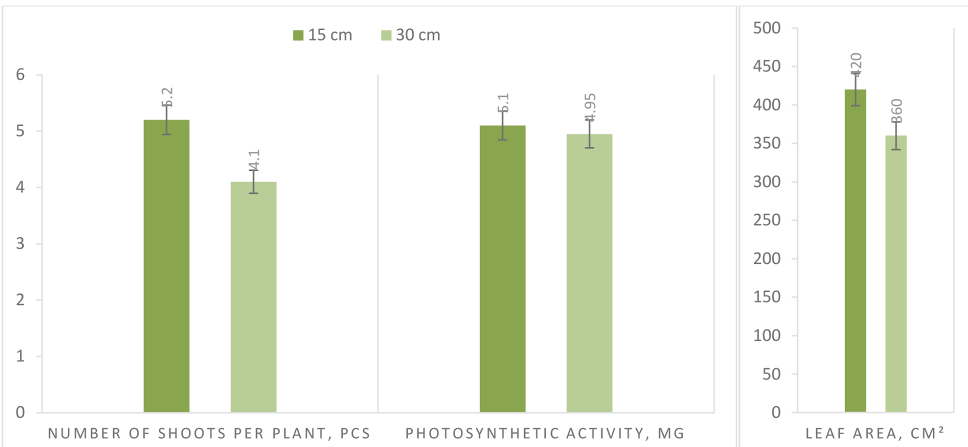

Fig. 1. Dynamics of biometric and physiological indicators of millet depending on row spacing

Analysis of the graph (Fig. 1) allows us to establish a direct relationship between row spacing and the efficiency of resource use by millet plants. The greatest discrepancy between the experimental variants was recorded in terms of the number of shoots (27 % more with narrow-row sowing) and net photosynthetic productivity (3 % more), which indicates better lighting and nutrition for each plant with a row spacing of 15 cm. The pattern shown in the figure confirms that narrowing the row spacing to 15 cm reduces the area of unshaded soil that does not participate in photosynthesis. This ensures more complete absorption of solar radiation by the leaf surface, increases the productivity of the entire crop, and creates the conditions for higher grain yields [8, c. 674].

The next step was to study how biometric advantages are realized in yield under the influence of biostimulants and weather conditions in 2021–2023 [6, c. 32].

The results of three years of observations show that row spacing is the dominant factor, accounting for 76 % of the variability in yield, according to dispersion analysis. It has been established that the transition from 30 cm to 15 cm row spacing allows for a significant increase in yield due to the optimal distribution of plants over the area and better use of resources.

Table 2

Millet grain yield by experimental variants, t/ha

Factor A (seed treatment)	Factor C (fertilization)	Factor B (row spacing)	
		15 cm	30 cm
Control	Control (water)	2,43	1,73
	HELAFIT-Combi	3,80	2,70
Gumicor	Control (water)	2,56	1,83
	HELAFIT-Combi	4,06	2,93
HIP_{05}, t/ha	0,15–0,25	0,10–0,16	

The data in Table 2 demonstrate the consistent advantage of narrow-row sowing (15 cm) regardless of the use of biostimulants. The highest yield (4.06 t/ha) is achieved by combining pre-sowing seed treatment with Gumicor and foliar feeding with HELAFIT-Combi at a row spacing of 15 cm. The difference between the row spacing options is statistically significant throughout all years: the yield at 15 cm was 28–30 % higher than at 30 cm, which is confirmed by the HIP05 values.

Dispersion analysis of the data revealed that the share of the row spacing factor (factor B) in the total variation of the trait is 76 %. The effect of pre-sowing seed treatment (factor A) was 16 %, while foliar feeding (factor C) and the interaction of factors had smaller but statistically proven values. In particular, the interaction of “pre-sowing treatment + row spacing” (AB) provided a 5 % effect, which indicates an increase in the action of biostimulants in technologically correctly formed crops.

The data obtained prove that for the conditions of southern Ukraine, narrowing the row spacing to 15 cm is a basic element of technology that maximizes the work of the photosynthetic apparatus, and the use of biological products allows this potential to be further realized even in dry years.

Conclusions and recommendations. The research has shown that reducing the row spacing from 30 cm to 15 cm significantly affects the productivity of millet due to its complex effect on the morphological and physiological indicators of plants. Closer spacing contributes to an increase in stem density, plant height, more intensive accumulation of above-ground and below-ground biomass, and an expansion of leaf surface area. This, in turn, ensures an increase in the photosynthetic potential of crops and creates the conditions for higher grain yields.

Scientific analysis of the results confirms that smaller row spacing optimizes the spatial organization of the agrocenosis, improves root system development, and promotes more efficient use of soil moisture and mineral nutrients. In the conditions of southern Ukraine, where water supply is often a limiting factor, such optimization of the crop structure is of particular importance for stabilizing crop yields.

The additional use of Gumicor and HELAFIT-Combi biostimulants increases the intensity of growth processes, activates the physiological mechanisms of plant adaptation to stress factors, and enhances the realization of their genetic productivity potential. The combination of optimal row spacing with biostimulants provides a synergistic effect, which manifests itself in increased yields and improved structural elements of productivity [9, c. 141, 10, c. 441].

To maximize millet yield in the southern regions of Ukraine, it is advisable to use a row spacing of 15 cm in combination with the biostimulants Gumikor and HELAFIT-Combi. The proposed agricultural technique is scientifically sound and can be recommended for implementation in production practice in order to increase the economic efficiency of crop cultivation.

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Дата першого надходження статті до видання: 13.01.2026
Дата прийняття статті до друку після рецензування: 13.02.2026
Дата публікації (оприлюднення) статті: 13.04.2026