

Sustainable aspects of millet (*Panicum miliaceum*) productivity: Optimization of sowing rate and mineral nutrition

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ABSTRACT

This study focuses on developing a resource-saving technology for cultivating millet (variety Omriyane) in the North-Eastern Forest-Steppe of Ukraine by optimizing mineral fertilization and seeding rates. The relevance of the work is driven by millet's multifaceted significance (food, feed, and industrial uses) and its critically low proportion in the region's crop structure due to outdated agricultural practices and the high cost of fertilizers. Five-year field experiments, conducted on typical chernozem soil, demonstrated that the level of mineral nutrition is the crucial factor in determining millet productivity. It was established that applying the most intensive (calculated) fertilizer rate ensures maximum morphological parameters (plant height, grain count) and, consequently, the highest crop yield. The seeding rate factor, while influencing plant stand density, had a less pronounced effect on the final yield. The main conclusion is that to fully realize the potential of the Omriyane millet variety in the North-Eastern Forest-Steppe, it is necessary to implement an intensive mineral nutrition system combined with an increased seeding rate. This approach will ensure stable productivity growth and enhance the economic efficiency of cultivating this valuable crop.

Keywords: *Panicum miliaceum*, fertilizer rates, seeding rate, yield, 1000-seed weight, climatic conditions, variety.

INTRODUCTION

Millet is a crop of great importance in the national economy. The grain of this crop is used for the production of groats, which is a valuable food product for people [Hassan et al., 2021]. Millet has not only food value but also feed value. Grain, by-products of groat production, as well as straw and hay, which are not inferior to hay from annual cereals in terms of nutritional value, are used for feed purposes. Millet grain is used in the distilling and brewing industries. Sugar, starch, protein preparations, etc., are made from millet. In addition, grain crops provide nutritious feed for livestock—millet chaff, which is used in mixtures

with other feeds. Millet straw is fed to animals, and grain to poultry [Daduwal et al., 2024; Kolisnyk et al., 2024; Butenko et al., 2025]. Millet is a valuable agricultural crop not only because of its high yield. Its husks serve as raw material for obtaining substances widely used in the production of polish, shoe creams, and insulating materials, confirming millet's multifunctionality in the national economy [Tripathi et al., 2022; Hryhoriv et al., 2024].

Despite the value of millet, its specific gravity among grain crops in the Forest-Steppe is critically low, accounting for only 1.5–2.0%. The vast majority of agricultural producers grow this crop on small areas (10–30 ha) as part of general

plantings, ignoring modern agrotechnologies [Gumentyk, 2020; Voitovyk et al., 2023; Radchenko et al., 2024]. Such outdated practice does not allow for achieving high productivity, improving grain quality, or increasing overall economic efficiency. To unlock millet's potential, it is vitally necessary to adapt its cultivation technology to specific soil and climatic conditions. This includes optimizing fertilizer rates, methods and timing of sowing, testing the effectiveness of herbicides, and evaluating the interaction of all these factors, especially for new varieties, with the goal of resource conservation.

It is also important to consider the region of millet cultivation; the articles by Prysiazniuk et al., (2021); Drobot and Vysochanska, (2024); and Voytovyk et al., (2024) investigated the average statistical indicators of millet yield depending on the region over ten years. It is impossible to definitively state the most suitable region for cultivating this crop, but it can be said with high probability that both the lowest and the highest yields were obtained in regions with the most favorable weather conditions, particularly optimal temperature and moisture. However, not only climatic conditions affect the yield of the studied crop. Thus, Prisyazhnyuk et al. [2023] proved in their work that using liming (a quarter rate) allows for high yields in the Vinnytsia region, and thanks to plowing under crop residues, over 40% of macronutrients were returned to the soil. The research by Kulyk et al., (2022); Mishchenko et al., (2022); and Kovalenko et al., (2024a) proved that the most optimal method for cultivating millet in the central Forest-Steppe zone would be the use of wide-row sowing and a fertilizer rate of $N_{45}P_{60}K_{60}$. Therefore, millet is capable of yielding high harvests in various regions of Ukraine, provided intensive agricultural technology is applied. However, due to the significant reduction in fertilizer use in agriculture, caused by their excessive cost, there has been an urgent need to review existing recommendations for the fertilization system, including millet. To ensure the economic feasibility of resource use, the development of a resource-saving technology for mineral fertilizer application for millet in the North-Eastern Forest-Steppe is relevant. Therefore, this study, which combines the optimization of fertilizers with different seeding rates of the Omriyane variety, is extremely important.

MATERIAL AND METHODS

The research was carried out in the field crop rotation of the Sumy Institute of Agricultural Production on typical chernozem during 2020–2024.

The arable soil layer (0–20 cm depth) is highly fertile. The humus content is 3.9%. The soil reaction is neutral (salt pH 6.9), and its acidity is very low (hydrolytic acidity according to Kappen – 3.4 milligram-equivalents per 100 grams of soil). The soil has a high nutrient retention capacity (adsorption capacity – 35.11 milligram-equivalents). The content of easily available nitrogen according to Cornfield is moderate (11.2 milligrams per 100 grams). The availability of mobile nutrient forms is increased for phosphorus (16.3 mg P_2O_5 per 100 g of soil) and medium for potassium (10.2 mg K_2O per 100 g of soil) according to the Chirikov method.

Over the five-year period (2020–2024), the average weather conditions during the growing season (March–August) were characterized by a moderately warm spring transitioning into a hot summer with adequate but uneven moisture distribution. On average, early spring (March) was cool (2.7 °C) and showed the greatest precipitation deficit (12.4 mm). Subsequently, temperatures rose rapidly (up to 14.7 °C in May), with April being the wettest month of spring (58.4 mm). The summer period was consistently hot (temperatures ranged from 21.2 °C to 22.6 °C), with July being the warmest month. At the same time, June, with an average of 84.4 mm of rainfall, was the wettest month of the entire season, providing the main moisture resource for crop development in early summer. In the second half of summer (July–August), precipitation levels decreased but remained moderate (46.5 mm and 52.8 mm, respectively), indicating the absence of a prolonged mid-season drought despite high temperatures (Figure 1).

The experiments with millet of the Omriyane variety were conducted according to the scheme shown in Table 1. The cultivation technology followed standard practices for the northeastern Forest-Steppe zone of Ukraine.

The research methodology was based on several widely accepted scientific methods. The visual method was used for operational monitoring of the phenological development of plants. The measurement method was the primary approach for obtaining quantitative data required for agronomic analysis: it included

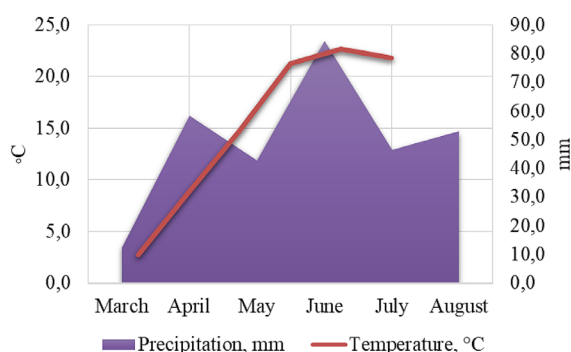


Figure 1. Climatic conditions for millet cultivation during 2020–2024

determining plant density, detailed analysis of plant structure (productivity parameters), and recording final yield. Meanwhile, the calculation method was applied to determine mineral fertilizer rates and assess plant survival during the growing season. The obtained quantitative data were processed using mathematical and statistical methods to verify reliability and evaluate the strength of factor influence with the Statistica 10.0 software. Field experiments were standardized and carried out on plots of 40 m² with four replications.

RESULTS AND DISCUSSION

The first analyzed indicator concerned plant density at harvest, depending on the seeding rate and fertilizer application. The data shown in Figure 2 indicate that in the control treatment, the highest average plant density was observed at a seeding rate of 3.5 million seeds ha⁻¹ (ranging from 289 to 355 plants/m²), while at 2.5 million seeds ha⁻¹, the values were the lowest (186–252 plants/m²). The highest plant density was obtained under the calculated fertilizer rate N₁₁₀P₉₀K₉₀ + N₃₀, where, at a seeding rate of 3.5 million seeds ha⁻¹, density reached 353–364 plants/m², which indicates a positive effect of intensive nutrition

on plant survival until harvest. The results of the Duncan's post-hoc test for millet plant density show that the seeding rate is a statistically significant and dominant factor that has the greatest influence on the final density (Table 2). In particular, the lowest density values recorded at the seeding rate of 2.5 million seeds ha⁻¹ differed significantly from all other variants, regardless of fertilizer application. Conversely, the highest seeding rate (3.5 million seeds ha⁻¹) provided the maximum density and also differed significantly from the lowest rate. Regarding the effect of mineral fertilizers, at both the lowest (2.5 million seeds ha⁻¹) and highest (3.5 million seeds ha⁻¹) seeding rates, their application (all three nutrient levels) did not result in statistically significant differences in plant survival.

The highest values of plant height (134.93 cm), number of grains per plant (333.20 pcs), and 1000-grain weight (7.24 g) were obtained with the calculated fertilizer rate N₁₁₀P₉₀K₉₀ + N₃₀. The treatment with N₄₅P₄₅K₄₅ also improved the parameters compared with the control, though to a lesser extent. Among the seeding rates, the highest values were recorded at 3.5 million seeds ha⁻¹, indicating a tendency toward the formation of more developed plants under denser sowing, although without statistically significant differences. Overall, the results confirm the decisive role of nutrient level in shaping the structural elements of yield (Table 3).

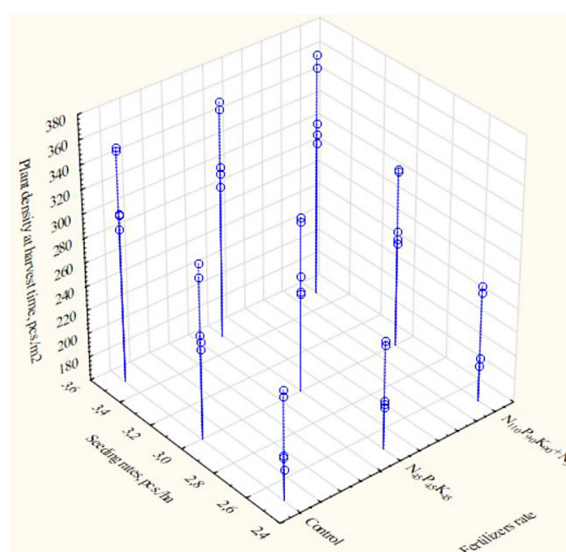


Figure 2. Millet plant density at harvest depending on seeding rate and fertilization

Table 1. Scheme of the two-factor experiment

Factor A sowing rate	Factor B fertilizer rates
2.5 million seeds ha ⁻¹	Control (no fertilizer application)
3.0 million seeds ha ⁻¹	N ₄₅ P ₄₅ K ₄₅ (recommended rate)
3.5 million seeds ha ⁻¹	N ₁₁₀ P ₉₀ K ₉₀ + N ₃₀ (calculated rate)

Table 2. Results of Duncan's post-hoc comparison of average millet plant densities

No.	Fertilizers rate	Seeding rates, pcs. ha ⁻¹	1	2	3	4	5	6	7	8	9
1	Control	3		0.027064	0.015664	0.781359	0.025740	0.017011	0.648907	0.030761	0.014921
2	Control	2.5	0.027064		0.000046	0.016246	0.882081	0.000043	0.011000	0.897470	0.000036
3	Control	3.5	0.015664	0.000046		0.025145	0.000061	0.984265	0.031577	0.000054	0.911616
4	N ₄₅ P ₄₅ K ₄₅	3	0.781359	0.016246	0.025145		0.017387	0.028285	0.835087	0.019299	0.025502
5	N ₄₅ P ₄₅ K ₄₅	2.5	0.025740	0.882081	0.000061	0.017387		0.000055	0.012654	0.976363	0.000049
6	N ₄₅ P ₄₅ K ₄₅	3.5	0.017011	0.000043	0.984265	0.028285	0.000055		0.038279	0.000055	0.921061
7	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	3	0.648907	0.011000	0.031577	0.835087	0.012654	0.038279		0.013478	0.035909
8	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	2.5	0.030761	0.897470	0.000054	0.019299	0.976363	0.000055	0.013478		0.000045
9	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	3.5	0.014921	0.000036	0.911616	0.025502	0.000049	0.921061	0.035909	0.000045	

Table 3. Effect of seeding rate and fertilization on plant height, number of grains per plant, and 1000-grain weight

Version	Level	Plant height, cm	Number of grains on average per plant, pcs.	Weight of 1000 grains, g	p-level
Fertilizers rate	Control	125.13	245.40	6.92	< 0.05
Fertilizers rate	N ₄₅ P ₄₅ K ₄₅	128.27	289.73	7.16	
Fertilizers rate	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	134.93	333.20	7.24	
Seeding rates, pcs. ha ⁻¹	3	129.27	291.80	7.14	0.32
Seeding rates, pcs. ha ⁻¹	2.5	124.40	273.87	6.99	
Seeding rates, pcs. ha ⁻¹	3.5	134.67	302.67	7.19	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	Control	123.60	243.80	7.18	0.99
Fertilizers rate*seeding rates, pcs. ha ⁻¹	Control	121.60	231.60	6.72	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	Control	130.20	260.80	6.86	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	N ₄₅ P ₄₅ K ₄₅	131.20	298.60	6.98	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	N ₄₅ P ₄₅ K ₄₅	121.00	269.80	7.18	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	N ₄₅ P ₄₅ K ₄₅	132.60	300.80	7.32	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	133.00	333.00	7.26	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	130.60	320.20	7.06	
Fertilizers rate*seeding rates, pcs. ha ⁻¹	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	141.20	346.40	7.40	

The obtained research results demonstrate a significant effect of fertilization level on crop yield, while the seeding rate had a less pronounced effect (Table 4). In the control treatment without fertilizers, yield ranged from 2.436 t ha⁻¹ (at 2.5 million seeds ha⁻¹) to 2.944 t ha⁻¹ (at 3.5 million seeds ha⁻¹). The application of N₄₅P₄₅K₄₅ increased yield by an average of 0.3–0.4 t ha⁻¹ compared with the control, reaching 3.354 t ha⁻¹ at the highest seeding rate. The highest yield values were recorded under the calculated fertilization rate N₁₁₀P₉₀K₉₀ + N₃₀, where yield ranged from 3.202 to 3.832 t ha⁻¹, depending on the seeding rate.

The analysis of variance (ANOVA) confirmed a statistically significant effect of the fertilization factor ($F = 4.39$; $p = 0.01$), while the seeding rate factor did not have a significant influence on yield

($F = 2.20$; $p = 0.12$). Thus, increasing the level of mineral nutrition contributed to a steady increase in yield, while changes in seeding density only slightly adjusted this indicator.

The study of the effects of fertilization and seeding rate on crop yield has been conducted by scientists around the world. In particular, researchers in China demonstrated that high application rates of NPK fertilizers (160, 90, and 150 kg ha⁻¹, respectively) led to a significant increase in the yield of the JG21 variety compared to the control [Litvinov et al., 2020; Karbivska et al., 2022a; Xing et al., 2023]. Another study [Zheng et al., 2024; Kovalenko et al., 2024b], conducted on two millet varieties (JGNo.21 and LZGNo.2) under low nitrogen conditions, found that for JGNo.21, all types of fertilizers

Table 4. Average yield data of Omriyane Millet variety depending on seeding rate and fertilization

No.	Fertilizers rate	Seeding rates, pcs. ha ⁻¹	Yield, t ha ⁻¹
1	Control	3.0	2.752
2	Control	2.5	2.436
3	Control	3.5	2.944
4	N ₄₅ P ₄₅ K ₄₅	3.0	3.024
5	N ₄₅ P ₄₅ K ₄₅	2.5	2.724
6	N ₄₅ P ₄₅ K ₄₅	3.5	3.354
7	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	3.0	3.582
8	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	2.5	3.202
9	N ₁₁₀ P ₉₀ K ₉₀ +N ₃₀	3.5	3.832
SS	5.22	2.61	
MS	2.61	1.30	
F	4.39	2.20	
p	0.01	0.12	

improved agronomic traits. Nitrogen and complex fertilizers decreased starch content while increasing protein content, whereas phosphorus and organic fertilizers had the opposite effect. Nitrogen and complex fertilizers also reduced viscosity parameters, while phosphorus and organic fertilizers improved them. The amino acid content in JGNo.21 increased under the influence of complex and nitrogen fertilizers. For the LZGNo.2 variety, complex, nitrogen, and organic fertilizers significantly increased amino acid content, while phosphorus fertilizers reduced it. In contrast, sticky viscosity increased under the influence of phosphorus fertilizers and decreased under nitrogen treatment. Research conducted in Senegal [Karbivska et al., 2022b; Faye et al., 2023; Radchenko et al., 2023] showed that grain yield improvement was mainly influenced by planting density, variety, and fertilizer combinations. Regardless of the variety, increasing the planting density up to 25,000 holes per hectare significantly boosted grain yield (up to 1.600 kg ha⁻¹). The highest yields across all environments were achieved with the application of N₇₀P₁₀K₁₉ combined with 2.5 t ha⁻¹ of cow manure. A field study on millet in Italy investigated the effects of different nitrogen fertilizer levels (0, 50, 100, and 150 kg ha⁻¹ of nitrogen) and planting densities (55, 111, and 222 plants per m²) on morphological and yield characteristics. The study found that the highest grain and total yield indicators were achieved under the highest nitrogen level combined with the greatest planting density [Hryhoriv et al., 2022; Palchetti et al., 2023].

CONCLUSIONS

The results of a five-year study of the millet variety Omriyane grown on typical chernozem soil in the North-Eastern Forest-Steppe region showed that the level of mineral nutrition is a decisive and statistically significant factor in forming both the elements of yield structure (plant height, number of grains, weight of 1000 grains) and final yield. It was found that the highest yield (3.83 t ha⁻¹) was achieved with the calculated, most intensive fertilizer rate (N₁₁₀P₉₀K₉₀ + N₃₀) combined with the maximum seeding rate (3.5 million seeds ha⁻¹), which was also the dominant factor in ensuring high plant density. In contrast to fertilization, the seeding rate had a minor effect on the yield itself. Thus, to fully realize the potential of millet in the region, despite economic challenges, it is vital to implement an intensive mineral nutrition system that ensures stable increases in crop productivity.

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