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YIELD AND SEED QUALITY OF MILLET DEPENDING ON HARVESTING FEATURES

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Дослідження з вивчення впливу особливостей збору врожаю насінницьких посівів проса посівного проведено впродовж 2023–2024 рр. у польовій сівозміні кафедри рослинництва Уманського національного університету за схемою трьохфакторного польового досліду за градації факторів: А (сорт) – Слобожанське і Лана; В (ступінь зрілості насіння) – воскова стиглість у верхній (контроль) і середній частинах волоті; С (спосіб збору врожаю) – однофазний; однофазний з десикацією і двофазний (контроль). Встановлено, що найвпливовішим чинником, що забезпечував найбільший збір урожаю насіннєвого матеріалу в обох досліджуваних сортів виявився вибір оптимального способу збору врожаю – частка впливу на рівні 35–38 %. Дещо меншим виявився вплив строку обмолоту валків – на рівні 23–31 %. Частка впливу інших факторів та їхні взаємодії виявилися менш істотними. Одержанню найвищої врожайності (3,36–3,95 і 3,28–3,83 т/га) сприяло використання однофазного збору врожаю у поєднанні з десикацією насінницьких посівів сортів проса посівного (Слобожанське і Лана) у фазу воскової стиглості зерна в середній частині волоті. Формуванню найвищого рівня інтегрованого показника якості сприяло використання однофазного збору врожаю у поєднанні з десикацією посівів обох сортів проса посівного у фазу воскової стиглості насіння в середній частині волоті.

***Ключові слова**: просо, насіння, сорт, спосіб збору врожаю, ступінь зрілості, врожайність, посівні якості.*

Problem statement. Nowadays, due to its valuable agronomic characteristics, millet is receiving increased attention globally [1]. This crop is appreciated for its numerous health benefits, rich nutritional content, resistance to extreme climatic conditions, and minimal environmental impact. In recognition of its role in addressing global food security, the United Nations declared 2023 the International Year of Millets. In recent years, millet production has significantly increased worldwide, with India being the largest producer. Millet is highly nutritious, containing carbohydrates, antioxidants, flavonoids, carotenoids, phenolic acids, minerals, and vitamins.

Incorporating millet into a balanced diet can help manage and prevent cardiovascular diseases and diabetes due to its low glycemic index and gluten-free nature.

Analisys of resent research and publications. Under current socio-economic conditions in Ukraine, the issue of producing high-quality seed material and optimizing seed production systems for cereal crops in each region has become increasingly important [2]. Although breeders have made notable progress in developing new millet varieties, their widespread adoption is limited due to the lack of cultivation technologies adapted to regional conditions, which would support the production of seeds with high sowing quality and stable yield indicators [3].

Despite millet's high potential productivity, the imperfections in cultivation techniques in both commercial and seed-growing fields significantly limit its yield potential. Millet has a range of biological traits that cause a notable variability in seed quality. For instance, due to uneven panicle emergence and extended flowering duration, seed maturity is also uneven throughout the panicle. The heaviest and largest seeds are formed in the upper part of the panicle, although they account for only 10–20 % of the total panicle mass. The middle part is less productive but contributes around 60 % of the yield. Combined, this 70–80 % portion constitutes the foundation of the crop [4]. Due to millet's tendency to shatter, the largest and most mature seeds in the upper panicle are often lost by the time of harvest. Thus, due to asynchronous seed maturity and shattering, the timing and method of harvest play a crucial role in determining seed quality parameters.

Hence, a ***pressing task*** is to develop the theoretical foundations for forming high-quality millet seed material depending on the agroecological conditions of the growing region and threshing specifics. This approach will provide deeper insights into the causes of reduced seed viability and support yield forecasting in subsequent generations.

Considering the aforementioned, and the fact that determining optimal harvest parameters in seed-growing fields requires refinement, the aim of our ***research*** was a comprehensive study of the combined influence of harvest methods and seed maturity stage in the panicle of various millet varieties under the regional conditions of the Right-Bank Forest-Steppe of Ukraine.

Research methodology. The study was conducted during 2023–2024 in the crop rotation field of the Department of Crop Production at Uman National University. A three-factor field experiment was set up to examine the effects of harvest method characteristics on seed millet crops. The factor levels were as follows: A (variety) – Slobozhanske and Lana; B (seed maturity stage) – wax ripeness in the upper (control) and middle parts of the panicle; C (harvest method) – single-phase; single-phase with desiccation; and two-phase (control).

Winter wheat was the preceding crop. Phosphorus and potassium fertilizers were applied during autumn tillage, while nitrogen fertilizers were added during the first spring cultivation at a rate of $N_{60}P_{60}K_{60}$. Both millet varieties used in the study belong to the medium-ripening group. Sowing took place in the second ten-day period of May. The experiment had four replications with treatments arranged sequentially. Harvesting was carried out according to the research scheme, followed by grain weighing and recalculation to standard moisture and impurity content.

The single-phase harvest method involved direct combine harvesting when wax ripeness was reached in the upper and middle parts of the panicle. Reglon Super was used as the desiccant at a rate of 2.0 l/ha. In the two-phase method, seed plots were mowed into windrows, followed by threshing after three days. Yield was measured using test sheaves from 1 m² in all replications.

Field and laboratory studies, accounting, analyses, and observations were carried out in accordance with generally accepted methods [5]. The research area is characterized by unstable moisture conditions. A comprehensive assessment of moisture and temperature conditions during the research years, according to the hydrothermal coefficient (HTC) of G. T. Selyaninov, showed that the millet growing season in 2023 was slightly dry (HTC = 0.9), and in 2024 – moderately dry (HTC = 0.7). Typically, hot weather was established by the time of full ripeness, which facilitated threshing in all variants of the seed millet harvest study.

Research Results. Millet sowing during the study years was carried out within the recommended timeframe for the region — the second ten-day period of May. Adequate soil moisture reserves formed as a result of rainfall during this period, along with optimal air (+16.3…+18.6° C) and soil (+17.1…+20.2° C) temperatures, ensured a high level of field germination and the emergence of even and uniform seedlings.

On average over the two years of research, the plant density and field germination rates of millet were quite high and stable, amounting to 241–244 plants/m² and 72.7–73.5 % (Slobozhanske variety), and 241–245 plants/m² and 72.7–73.9% (Lana variety), without significant differences between the years.

Weather conditions and harvest methods had a much more pronounced effect on the final morphological structure of the seed crops. For instance, in July 2023, almost a month's worth of rainfall (61.4 mm) fell during the third ten-day period, and this, combined with relatively mild temperatures, significantly altered the seed crop structure. At the stage of wax ripeness in the upper part of the panicle, the plant survival rate was 79.7–81.3 % for Slobozhanske and 76.4–80.8 % for Lana, whereas in the more favorable conditions of 2024, it varied within 82.9–84.9 % and 82.2–84.8 %, respectively.

Depending on the applied harvest technique, it was observed that in both study years, postponing the mowing period from wax ripeness in the upper to the middle part of the panicle led to a slight decline in plant density. However, such changes were usually not critical – ranging between 1–1.5 %. Subsequently, these plant density dynamics had a direct impact on the yield level of the mother plants of both millet varieties and on the structure of that yield.

The findings demonstrated that the timing and methods of harvest had unequal effects on the yield of mother plants of the studied millet varieties (Table 1). As shown by the presented data, under the 2023 conditions, the highest yield of the studied millet varieties was achieved when using desiccation followed by direct harvesting of seed crops at the onset of wax ripeness in the upper part of the mother plant panicle. Depending on the variety, Slobozhanske had a significantly higher yield (3.95 t/ha) than Lana (by 0.12 t/ha, with LSD_{05}(A) = 0.10 t/ha).

Table 1. The influence of weather conditions on the yield of millet seed crops depending on the characteristics of harvesting, t/ha

Variety (factor A)	Harvesting method (factor C)	Seed maturity (factor B)			
		waxy ripeness in the upper part of the panicle	to control, ±	waxy ripeness in the middle part of the panicle	to control, ±
2023 year					
Slobozanske	Monophase	2.29	-1.02	2.53	-1.12
	Single-phase with desiccation	3.69	0.38	3.95	0.30
	Two-phase (control)	3.31	–	3.65	–
Average by grade		3.10	–	3.38	–
Lana	monophase	2.22	-1.09	2.71	-0.78
	single-phase with desiccation	3.54	0.23	3.83	0.34
	two-phase (control)	3.31	–	3.49	–
Average by grade		3.02	–	3.34	–
Average for the experiment		*3.21*			
LSD_{05}(total) = 0.22; LSD_{05}(A) = 0.10; LSD_{05}(B) = 0.11; LSD_{05}(C) = 0.12					
2024 year					
Slobozanske	monophase	2.02	-0.7	2.26	-0.89
	single-phase with desiccation	3.04	0.32	3.36	0.21
	two-phase (control)	2.72	–	3.15	–
Average by grade		2.59	–	2.92	–
Lana	monophase	2.08	-0.9	2.23	-0.95
	single-phase with desiccation	3.07	0.09	3.28	0.1
	two-phase (control)	2.98	–	3.18	–
Average by grade		2.71	–	2.90	–
Average on the experience		*2.78*			
LSD_{05}(total) = 0.20; LSD_{05}(A) = 0.08; LSD_{05}(B) = 0.09; LSD_{05}(C) = 0.11					

Harvesting too early – at the wax ripeness phase of the upper panicle – whether with or without desiccation, led to significant seed yield losses: 0.26–1.66 t/ha for Slobozhanske and 0.29–1.61 t/ha for Lana, with LSD_{05}(total) = 0.22 t/ha. Similarly, in 2023, the use of the two-phase harvesting method negatively affected seed yields, resulting in substantial seed shattering losses of 0.30–0.64 t/ha (Slobozhanske) and 0.34–0.52 t/ha (Lana).

However, a notable benefit of using the two-phase method was observed during early harvesting. When millet plants were mown at wax ripeness in the upper panicle and laid in swaths for three days, the drying of the leaf-stem mass improved threshing quality. Moreover, due to the ability of fully developed but immature millet seeds to ripen in swaths, seed yields increased by 1.02 t/ha (Slobozhanske) and 1.09 t/ha (Lana). Similar yield-forming trends were observed in 2024.

No significant differences were found between the two varieties – 2.76 and 2.80 t/ha. However, a notable advantage was achieved with mandatory desiccation during one-phase harvesting: 3.36 t/ha for Slobozhanske and 3.28 t/ha for Lana, or 0.21–1.34 and 0.10–1.20 t/ha more, respectively, with LSD_{05}(total) = 0.20 t/ha. The two-phase threshing method was only effective when early desiccation during the wax ripeness stage of the upper panicle was excluded: yields were 1.02–1.12 t/ha (Slobozhanske) and 0.78–1.09 t/ha (Lana).

Weather conditions also significantly influenced seed yield formation. The drought in 2024 accelerated generative processes in mother plants. In 2023, lower plant density was compensated by higher tillering due to sufficient moisture, while in 2024, dry conditions favored the development of single-stem plants.

Accordingly, the average seed crop yield in 2023 across treatments was 3.21 t/ha, compared to 2.78 t/ha in 2024. According to the results of dispersion analysis, the most influential factor in achieving high seed yield for both varieties was the harvesting method (factor C), with an impact share of 35–38 %. Slightly less influential was the threshing time (factor C), accounting for 23–31 %. Other factors and their interactions were less significant.

Laboratory testing of seed modifications due to harvesting methods and weather conditions revealed certain patterns in the formation of millet seed quality (Table 2). On average over the two years of research, the highest levels of seed viability and vigor were achieved through the application of a single-phase harvesting method combined with desiccation of the seed crops of both millet varieties at the stage of wax ripeness of seeds in the middle part of the panicle. Thus, according to laboratory germination parameters, seeds obtained under this combination of harvesting conditions corresponded to the original category, with the Slobozhanske variety showing the highest levels of this indicator – 97.0 %. The germination energy (93.3 %), germination speed (1.92 days), uniformity (24.9 seeds/day), and seedling vigor (97.8 %) were also the highest.

In the Lana variety, the best results were also observed with the combination of desiccation and direct harvesting, though under both seed ripeness phases in the panicle. At the same time, the differences between the studied seed quality indicators were minor, and in absolute terms were: laboratory germination – 95.5 % and 96.0 %; germination speed – 2.09 and 2.04 days; uniformity – 22.8 and 23.5 seeds/day; seedling vigor – 95.3 % and 95.5 %, respectively.

2. The influence of weather conditions on the sowing quality of millet varieties depending on the characteristics of harvesting mother plants, *2023–2024*

Variety (factor A)	Harvesting: Term (factor B)	Harvesting: Method (factor C)	Germination energy, %	Germination rate, days	Germination friendliness, pcs/day	Growth force, %	Laboratory similarity, %
Slobozhanske	Waxy ripeness in the upper part of the panicle	Monophase	83.7	2.38	19.8	87.8	88.8
		Single-phase with desiccation	90.8	2.02	24.3	95.8	96.5
		Diphasic	91.0	2.00	24.5	95.8	96.5
	Waxy ripeness in the middle part of the panicle	Monophase	85.8	2.21	18.8	88.5	91.3
		Single-phase with desiccation	93.3	1.92	24.9	97.8	97.0
		Diphasic	92.8	1.94	24.7	97.0	96.5
Lana	Waxy ripeness in the upper part of the panicle	Monophase	84.3	2.39	17.3	84.8	85.8
		Single-phase with desiccation	86.4	2.09	22.8	95.3	96.0
		Diphasic	84.3	2.11	22.4	92.8	94.0
	Waxy ripeness in the middle part of the panicle	Monophase	86.8	2.23	22.6	89.0	91.0
		Single-phase with desiccation	91.3	2.04	23.5	95.5	95.5
		Diphasic	91.3	2.06	23.2	95.3	95.5

The calculated integrated seed quality index confirmed that the highest quality millet seed material is formed under these harvesting parameters – 100 % and 99.9 % in the overall assessment of sowing qualities of the harvested seed yield (Fig.).

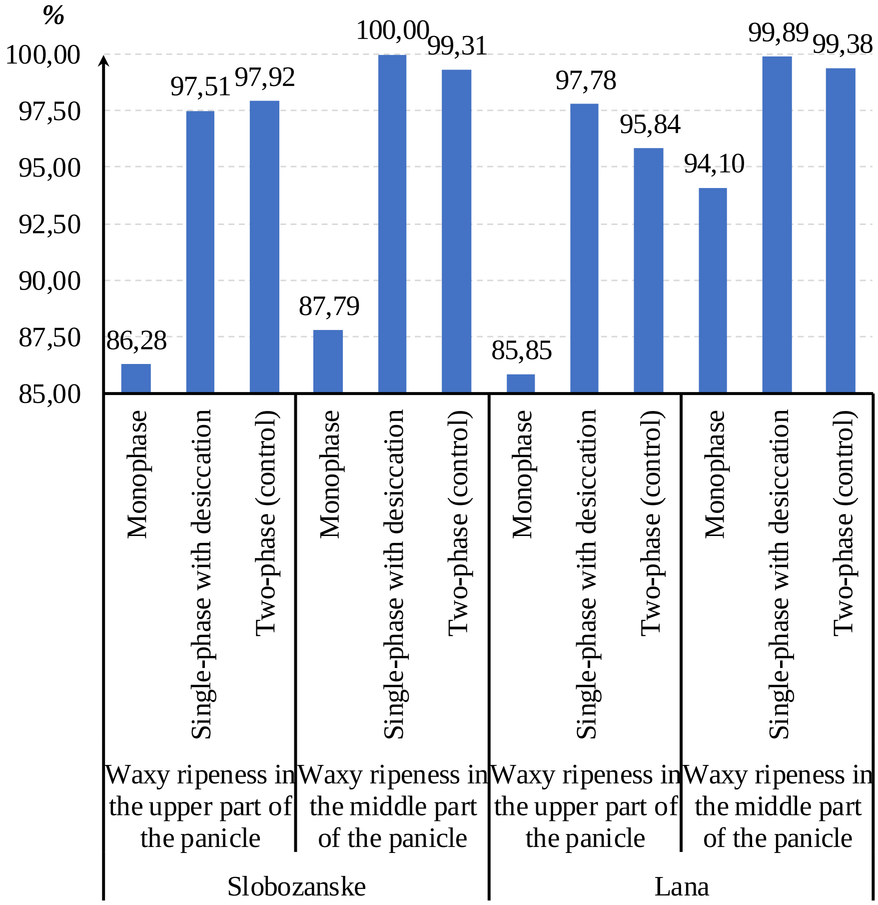

Fig. Integrated seed quality indicator formed under the influence of harvesting characteristics of seed crops of millet varieties, 2023–2024

It is also worth noting the high effectiveness of the split harvesting method when growing seed crops of both millet varieties. According to the integrated quality index, this seed ranked second under both ripeness phases – 97.9 % and 99.3 % (Slobozhanske variety) and 95.8 % and 99.4 % (Lana variety). The least appropriate method for growing millet in seed production fields was the use of direct threshing of windrows at the stage of wax maturity of seeds in the upper part of the panicle. According to the level of laboratory germination, the harvested seed material did not meet the standards for original category – 88.8 % and 85.8 % respectively for the Slobozhanske and Lana varieties.

Statistical analysis of millet seed quality indicators revealed a moderate negative correlation between laboratory germination and total ($r = -0.61 \pm 0.04$) and productive tillering ($r = -0.63 \pm 0.05$), as well as strong positive correlations between laboratory germination and 1000-seed weight ($r = 0.85 \pm 0.03$), uniformity ($r = 0.82 \pm 0.00$), and bulk density ($r = 0.77 \pm 0.01$), along with a moderate positive correlation with the yield of mother plants ($r = 0.56 \pm 0.04$).

Conclusions. 1. The highest seed yield (3.36–3.95 and 3.28–3.83 t/ha) was obtained using a single-phase harvesting method combined with desiccation of seed crops of millet varieties (Slobozhanske and Lana) at the wax ripeness stage of grain in the middle part of the panicle.

2. Although the use of the split harvesting method led to significant yield losses (0.21–0.64 and 0.09–0.34 t/ha), it proved more effective than direct windrow threshing at both ripeness stages of millet seed panicles (Slobozhanske and Lana varieties).

3. The most influential factor ensuring the highest harvest of seed material in both studied varieties was the choice of optimal harvesting method – with an influence rate of 35–38 %. The impact of windrow threshing timing was slightly lower, at 23–31 %.

4. The highest level of the integrated quality index was achieved using a single-phase harvesting method combined with desiccation of both millet varieties' seed crops at the wax ripeness stage of seeds in the middle part of the panicle.

5. Statistical analysis of millet seed quality indicators revealed a moderate negative correlation between laboratory germination and total tillering (r = -0.61 ± 0.04) and productive tillering (r = -0.63 ± 0.05), as well as strong positive correlations between laboratory germination and 1000-seed weight (r = 0.85 ± 0.03), uniformity (r = 0.82 ± 0.00), and bulk density (r = 0.77 ± 0.01), along with a moderate positive correlation with the yield of mother plants (r = 0.56 ± 0.04).

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Annotation

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Yield and seed quality of millet depending on harvesting features

*The **current task** is to develop theoretical foundations for the formation of high-quality millet seed material depending on the agroecological conditions of the growing area and the characteristics of threshing. This will help to better understand the reasons for the decrease in seed quality, and will also allow predicting millet yield in subsequent generations.*

***The purpose of the article** is a comprehensive study of the mutual influence of the harvesting method and the degree of seed ripeness in the panicle of different varieties of millet in the regional conditions of the Right-Bank Forest-Steppe of Ukraine.*

***Research methodology**. The research was conducted during 2023–2024 in the crop rotation field of the Department of Crop Production at Uman National University. The three-factor field experiment on the effect of harvesting specifics of seed crops of proso millet included the following factor gradations: A (variety) – Slobozhanske and Lana; B (seed maturity degree) – wax ripeness in the upper (control) and middle parts of the panicle; C (harvesting method) – single-phase; single-phase with desiccation; and two-phase (control). Field and laboratory studies, measurements, analyses, and observations were conducted according to generally accepted agronomic methodologies.*

***Research results**. According to variance analysis, the most influential factor ensuring the highest seed yield for both studied varieties was the choice of optimal harvesting method – with an impact share at the level of 35–38%. Slightly less influence was observed for the swath threshing time – at the level of 23–31%. The contribution of other factors and their interactions was less significant.*

***Conclusions**. The highest yield levels (3.36–3.95 and 3.28–3.83 t/ha) were achieved through the use of a single-phase harvesting method combined with desiccation of seed crops of proso millet varieties (Slobozhanske and Lana) at the wax ripeness phase of grain in the middle part of the panicle. The highest integrated quality index was also obtained through the application of a single-phase harvesting method with desiccation of both millet varieties at the wax ripeness stage of seeds in the middle part of the panicle.*

***Key words:** millet, seeds, variety, harvesting method, maturity degree, yield, sowing qualities.*