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Agrobiological Assessment of Methods and Regimes of Combine Harvesting of Oil Flax in the Conditions of Southern Steppe of Ukraine

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ABSTRACT

The article presents the results of two-year research on the dependence of a complex of quantitative and qualitative indicators of oil flax seed yield of Southern Night and Vodohray varieties, as well as seed sowing conditions on the methods and regimes of combine harvesting of the crop. The direct single-phase method of combine harvesting did not lag behind the control in terms of seed productivity per plant or M_{1000} indicator. Harvesting according to the two-phase scheme had a significant negative impact on the formation of these indicators: the M_{1000} indicator decreased by 0.5 g or 7.1% compared to the control, and the seed mass per plant decreased by 0.06 g or 15.4%. Pre-harvest desiccation in the single-phase method also negatively affected the formation of these indicators: when using Reglone Super, the M_{1000} indicator decreased by 0.7 g, Roundup by 1.0 g compared to the control; seed productivity per plant decreased by 0.07 and 0.1 g, respectively. The oil flax yield with direct single-phase harvesting was lower than the control by 0.03 t/ha or 2.1% (Southern Night variety) and by 0.04 t/ha or 3.0% (Vodohray variety). Additional desiccation of crops significantly reduced seed yield. When using Reglone Super desiccant, this reduction was 0.06–0.09 t/ha (4.5–6.4%), Roundup – 0.10–0.13 t/ha (7.5–9.2%). The two-phase harvesting method yielded lower seed yield compared to the control by 0.10 t/ha (7.1%) when growing the Southern Night variety and by 0.08 t/ha (6.0%) when growing the Vodohray variety. The oil content of seeds of both flax varieties did not differ from the control with single-phase harvesting. Desiccation of crops during single-phase harvesting led to a significant decrease in crude fat content in seeds – by 0.7–0.9% (Southern Night variety) and 0.5–0.9% (Vodohray variety). Two-phase harvesting when growing the Southern Night variety contributed to a decrease in seed oil content by 0.5%, while it did not affect this quality indicator when growing the Vodohray variety. Laboratory germination similarity and energy reached maximum values in the control and in variants of direct single-phase harvesting without desiccation of crops – 96.2 and 88.5–88.7%, respectively. Other studied methods and regimes of harvesting worsened the sowing conditions of oil flax seeds.

Keywords: oil flax, pre-harvest desiccation, combine harvesting methods, yield, seed oil content, laboratory similarity, germination energy.

INTRODUCTION

One of the most important technological elements in the cultivation of oil flax is its combine harvesting, as an irrational choice of its method or regime can undermine all the applied agronomy techniques and lead to significant crop losses. Mechanized harvesting is a resource- and energy-intensive process that accounts for 50–80% of total production and energy costs [Dudarev, 2022; Zhuikov and Melnyk, 2022]. The harvesting process is complicated by the biological peculiarity of oil flax – uneven flowering, bolls formation, and ripening. The first flower buds appear on the upper branches of the central stem and bloom earlier than others [Amangaliev et al., 2023]. Ripening of bolls follows the same sequence: bolls on higher branches ripen first, followed by those on lower branches. During the ripening period of oil flax, three main ripeness phases are distinguished: green, yellow, and full ripeness [Mirzaie et al., 2020].

From emergence to full ripeness, it takes 80–95 days depending on the variety characteristics, meteorological conditions, soil fertility, quality of soil preparation, nutrient supply for crops, and other factors. Green ripeness occurs shortly after the end of flax flowering. During this period, stems, leaves, and bolls have an intensively green color. In most bolls, seeds have formed but still have a green color and can be easily crushed by fingers. Oil flax should not be harvested in this phase. In the yellow ripeness phase, the flax field acquires a uniform light yellow color. The stem turns yellow, leaves start falling off at the bottom of the stem. The majority of bolls are yellow. Physiologically mature seeds are light brown. In this phase, oil flax can be cut into swaths for two-phase harvesting: seeds in bolls ripen during field drying and are suitable for technical and sowing purposes. In the full ripeness phase, the flax field has a brown color. All leaves on stems fall off, the stem is dry, brownish-brown, bolls are yellow-brown or brownish-brown, in rainy weather – brownish-brown. Seed formation is completed at this time, and rapid lignification of the stem occurs. Seeds are hard, shiny, acquire the typical color for the variety and start detaching from the boll's intersections. If a boll is shaken, the seeds inside rattle. In this phase, under clean weed-free crop conditions, oil flax is harvested using single-phase harvesting, i.e., direct combining [Lupova et al., 2020; Gai et al., 2023].

Harvesting oil flax is carried out using the same set of machinery as for grain crops. The period for harvesting flax falls at the end of July to early August, coinciding with grain harvests. There is no competition between crops because flax can stand until the end of grain harvests without seed spillage from bolls or stem lodging. However, delaying harvesting is not advisable as timely harvested flax seeds contain more oil and have higher germination rates. The optimal timing for direct combining is when 75% of bolls are ripe, with seed moisture content within 12–13% [Mishra and Awasthi, 2020; Omer et al., 2020].

The disadvantage of single-phase harvesting is crop losses due to poor threshing of some immature bolls and possible self-heating of the bunker mass [Ponomarova and Chygryn, 2021]. Oil flax is a crop with an unfinished type of vegetation, and in some years, after a dry period followed by heavy rainfalls in the second half of summer, secondary flowering of flax occurs. Shoots regrow on almost ripe plants, new buds, flowers, and then bolls are formed, which ripen very unevenly. Flax ripens slowly and unevenly under excessive nitrogen nutrition and late sowing dates. In this case, one should not wait for all bolls to ripen. Delaying the harvesting of flax leads to the loss of first flowering bolls, which contain more mature, filled seeds [Dai et al., 2022; Eliseev et al., 2022]. To accelerate ripening and in case of weed infestation in crops, desiccation can be applied. Crops are treated with Reglone Super (3 L/ha), Basta (2 L/ha), Roundup (2–3 L/ha) 7–14 days before harvesting. An important condition for direct combining is that plant stems should be brown and dry, as wet stems are poorly cut, blades of the cutting apparatus get clogged, and wrap around rotating parts of the combine. It is better to start mowing during the hottest period of the day [Didukh et al., 2022].

Oil flax sown using the two-phase method is harvested with significant crop contamination or regrowth of lateral shoots and secondary flowering. Mowing should start 10–12 days before full ripeness when 50–75% of bolls have ripened [Kiryluk and Kostecka, 2020]. At this time, the moisture content of bolls is 40–45%, stems – 40–60%. The advantage of windrowing is earlier harvesting (6–8 days earlier). In windrows, flax dries much faster than when ripened on the root, while seed germination qualities are not lost. During threshing, there are no losses due to under-threshing of immature bolls, resulting in improved quality of harvested products [Albota et al., 2022]. The seeds do not require drying, and yield losses do not exceed 2%. The productivity of the combine increases as dry material is threshed well, and the combine works 3–4 times more efficiently than with direct combining. There are lower labor and post-harvest costs compared to direct combining [Didukh and Albota, 2021]. In the two-phase harvesting method, flax is first mowed with mowers and laid into windrows. The field designated for harvesting should be level, rolled, and free of stones. The edges of the field should be leveled for smooth passage of the mower and combine. The mowing height is 12–15 cm. With this cutting height, the stems can support the weight of a dense windrow well and ensure its rapid and even drying. If the stems are cut too low, the windrow lies on the ground, poorly ventilated and dries unevenly, leading to seed spoilage at the bottom of the windrow, especially in case of rainfalls [Karpova et al., 2021]. Under favorable conditions, windrows dry within five to seven days, after which they are picked up and threshed by combines with pickers when the seed moisture content reaches 12–13% [Yukhymchuk et al., 2023]. Threshing un-dried windrows leads to significant yield losses due to under-threshing and wrapping of stems around rotating parts of the combine. Reducing seed moisture content to 8–10% leads to severe seed damage [Nadimi et al., 2022].

Harvesting oil flax is a crucial technological operation that affects the quality and yield of the crop. Proper harvesting helps avoid yield losses, ensure high seed quality, conserve resources, and increase the efficiency of oil flax cultivation. Therefore, it is important to follow the correct harvesting technology using appropriate equipment and methods to achieve optimal results. Our research is aimed at studying this issue.

RESEARCH METHODOLOGY

The task of the scientific research included determining the optimal method of combine harvesting of oil flax, as well as the feasibility of pre-harvest desiccation of crops regarding the impact of these technological factors on the complex of quantitative and qualitative characteristics of the crop and seed sowing conditions, namely: elements of crop structure, seed yield, raw fat content in seeds, laboratory similarity, germination energy, M_{1000} index.

The implementation of the specified list of scientific tasks was carried out by establishing a two-factor field experiment at the State Enterprise “Pioneer” in Berislav district of Kherson region on an area of 1.6 hectares during 2022–2023.

Factor A (oil flax variety) was represented by two variants: Southern Night and Vodohray, factor B (method and mode of combine harvesting) – by the following variants: three-phase harvesting (laboratory control) – manual selection of sheaf material, transportation to a stationary location, and subsequent threshing in laboratory conditions; direct single-phase harvesting; single-phase harvesting with prior application of Reglone Super desiccant at a rate of 3 L/ha; single-phase harvesting with prior application of Roundup desiccant at a rate of 3 L/ha; separate two-phase harvesting.

The experiment was set up using a split-block method with partial randomization by factor A, with a four-time repetition. The cultivation technology used in the study was traditional zonal variety recommended by the Institute of Oil Crops of NAAS.

During the research, Ukrainian State Standards were utilized:

- State Standard of Ukraine SSTU ISO 10565:2003 “Oilseed crops. Simultaneous determination of oil content and moisture. Method of spectroscopy using pulse nuclear magnetic resonance” - for determining seed oil content;
- State Standard of Ukraine SSTU 4138:2002 “Seeds of agricultural crops: methods for determining quality” – for determining seed productivity (seed weight per plant, 1000 seed weight) and seed sowing qualities (field similarity, germination energy).

For statistical analysis of experimental data, the computer program “Agrostat” was used [Ushkarenko et al., 2009].

RESULTS

Artificial acceleration of seed ripening through intensification of physiological processes leading to plant cell and intercellular moisture loss (which is the mechanism of action of most synthetic chemical desiccants available on the market), according to some authors, causes an unnatural course of ontogenesis at its final stages, negatively affecting most quantitative and qualitative indicators of agricultural crop productivity, including sunflower [Lachabrouilli et al., 2021]. In order to determine the influence of combine harvesting method and pre-harvest desiccation on elements of test flax sheaf, we conducted research, the results of which are presented in Table 1. Taking into account that the cultivation technology was identical for all experimental variants before pre-harvest desiccation, we did not investigate parameters such as the number of fruiting branches and the number of seeds in a boll in the laboratory sheaf, as these indicators were formed by oil flax plants under the influence of other factors, and the choice of combine harvesting method and mode had no effect on them.

For example, the analysis of the number of fruits on one plant allows us to conclude that factor B did not have a significant impact on its formation, and the insignificant difference between the variants of factor B did not exceed the mathematical reliability of the study. The number of bolls formed on one plant had a significant influence only from factor A: varietal characteristics of the culture resulted in the formation of an average of 19.6 bolls on one plant for the Southern Night variety of oil flax, while on Vodohray variety plants – 17.7 bolls per plant, which is 1.9 bolls or 9.7% less (Table 1).

The M_{1000} index, on the contrary, according to the results of our research, was characterized by a significant dependence on the method of combine harvesting of the crop: the accelerated loss of plant moisture led to a decrease in the value of this indicator of oil flax crop structure for all variants of factor A (variety). For example, for the Southern Night variety, the M_{1000} index reached its maximum values in the control harvesting method (three-phase laboratory) and direct single-phase harvesting without desiccant application – 7.3 and 7.2 g, respectively. Pre-harvest desiccation with Reglone Super caused a significant decrease in the M_{1000} index to 6.5 g (-0.8 g from the control), and the use of Roundup desiccant resulted in an even more significant decrease (-1.1 g compared to the control). Combine harvesting of oil flax variety Southern Night by the two-phase method also lagged behind the control variant: the M_{1000} index was 6.7 g (-0.6 g compared to the control).

A similar pattern of dependence of the M_{1000} index on the method of combine harvesting of oil flax was found for the Vodohray variety. For instance, over the years of the study, the value of this indicator for the control variant and direct single-phase harvesting without desiccant application was 7.0 g, while using Reglone Super and Roundup as pre-harvest desiccants resulted in a significant decrease (by 0.8 g and 1.0 g, respectively) compared to the control variant. Combine harvesting by the two-phase method also lagged behind in terms of the M_{1000} index (6.4 g or -0.6 g compared to the control).

The differentiated nature of the M_{1000} index values in the study variants led to a similar trend in forming the final element of the test sheaf – the seed productivity of a single oil flax plant (seed weight per plant). For example, for the Southern Night variety, the control variant (laboratory threshing) and direct single-phase combine harvesting did not show a significant difference in seed productivity per plant (0.40–0.41 g), while direct harvesting with pre-harvest desiccation using Reglone Super significantly lagged behind the control variant (seed weight per plant was 0.33 g), as well as when using Roundup desiccant (0.29 g). Combine harvesting of oil flax variety Southern Night by the two-phase method (pre-cutting into swaths with subsequent picking and threshing) was characterized by slightly higher seed productivity per plant (0.36 g), although it also significantly lagged behind the control variant and direct single-phase harvesting.

A similar pattern was observed for the Vodohray variety: for seed productivity per plant, it averaged 0.37 g/plant on control plots and plots where direct single-phase harvesting was implemented, while using the two-phase method significantly decreased this indicator to 0.30 g/plant, and additional pre-harvest desiccation during direct combine harvesting variants

Table 1. Indicators of the structure of the oil flax harvest depending on the method of combine harvesting (average for 2022–2023)

Variety (factor A)	Method of harvesting (factor B)	Number of fruits, pcs./plant	M_{1000}, g	Weight of seeds per plant, g
Southern night	Three-phase – control	19.7	7.3	0.41
	Single-phase	19.6	7.2	0.40
	Single-phase + desiccation Reglone Super	19.5	6.5	0.33
	Single-phase + desiccation Roundup	19.5	6.2	0.29
	Two-phase	19.6	6.7	0.36
Vodohray	Three-phase – control	17.7	7.0	0.37
	Single-phase	17.9	7.0	0.37
	Single-phase + desiccation Reglone Super	17.8	6.2	0.31
	Single-phase + desiccation Roundup	17.6	6.0	0.28
	Two-phase	17.7	6.4	0.30
LSD_{05}	A	0.77	0.22	0.35
	B	0.81	0.19	0.40
	AB	1.06	0.28	0.62

was also found to be ineffective: using Reglone Super reduced the indicator to 0.31 g/plant, and Roundup to 0.28 g/plant.

The averaged values of test sheaf indicators by factor A (oil flax variety) over the years of the study are presented in Figure 1. The application of direct single-phase combine harvesting method for oil flax did not show inferiority to the control variant in terms of seed productivity per plant or the M_{1000} index. Conducting crop harvesting using the two-phase scheme was characterized by a significant negative impact on the formation of these indicators: the M_{1000} index decreased by 0.5 g or 7.1% compared to the control variant, and seed productivity per plant decreased by 0.06 g or 15.4%. The use of pre-harvest desiccation with a desiccant in the direct single-phase harvesting method also negatively affected the formation of the laboratory sheaf indicators: when using Reglone Super, the M_{1000} index decreased by 0.7 g, Roundup – by 1.0 g compared to the control variant; the decrease in seed productivity per plant was 0.07 and 0.1 g, respectively. Both studied factors had a significant impact on the formation of quantitative and qualitative characteristics of the oil flax yield (Table 2).

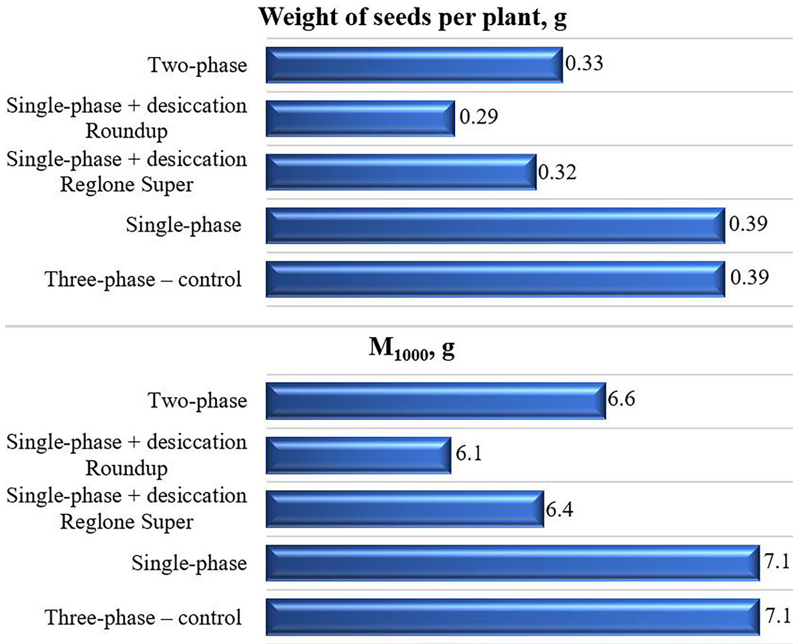

Figure 1. Average values of oil flax crop structure indicators depending on the method of combine harvesting (average for 2022–2023)

Table 2. Quantitative and qualitative indicators of oil flax harvest depending on the method of combine harvesting (average for 2022–2023)

Variety (factor A)	Method of harvesting (factor B)	Productivity, t/ha	Crude fat content in seeds, %	Total fat harvest, t/ha
Southern night	Three-phase – control	1.41	42.4	0.60
	Single-phase	1.38	42.4	0.59
	Single-phase + desiccation Reglone Super	1.32	41.7	0.55
	Single-phase + desiccation Roundup	1.28	41.5	0.53
	Two-phase	1.31	41.9	0.55
Vodohray	Three-phase – control	1.33	42.7	0.57
	Single-phase	1.29	42.9	0.55
	Single-phase + desiccation Reglone Super	1.27	42.2	0.53
	Single-phase + desiccation Roundup	1.23	41.8	0.51
	Two-phase	1.25	42.6	0.53
LSD_{05}	A	0.03	0.32	–
	B	0.03	0.24	–
	AB	0.06	0.40	–

When growing the Southern Night variety of oil flax, the application of the direct single-phase combine harvesting method showed slightly lower seed yield compared to the control variant (on average by 0.03 t/ha or 2.1%), which can be explained by minor levels of objective production losses of the grain part of the crop due to different elements of the harvesting complex within technical tolerances. Additional pre-harvest desiccation resulted in a more significant reduction in seed yield, attributed to the impact of this agricultural practice on a crucial crop structure indicator like M_{1000}. For instance, using Reglone Super led to a decrease in seed productivity of the Southern Night oil flax variety by 0.09 t/ha (6.4%) compared to the control variant, and Roundup caused a reduction of 0.13 t/ha or 9.2%. Although the two-phase harvesting method was more effective than pre-harvest desiccation, it still showed lower seed yield compared to the control variant by 0.10 t/ha or 7.1%. On average for factor B, seed productivity of the Southern Night oil flax variety in the study was 1.34 t/ha.

A similar dependence of seed yield on the method of combine harvesting was observed when growing the Vodohray variety: the maximum yield was achieved in the control variant of the study (1.33 t/ha). With direct single-phase combine harvesting, seed productivity decreased by 0.04 t/ha or 3.0%. The use of Reglone Super as a pre-harvest desiccant resulted in a more significant decrease in seed yield compared to the control (by 0.06 t/ha or 4.5%), Roundup – by 0.1 t/ha or 7.5%. Conducting combine harvesting using the two-phase method led to a decrease in this indicator by 0.08 t/ha or 6.0%. The average seed yield of the Vodohray oil flax variety for factor B in the study was 1.27 t/ha.

Based on the results obtained, a significant impact of the studied factors on the crude fat content in oil flax seeds was established. For the Southern Night variety, direct single-phase harvesting and control three-phase harvesting (laboratory threshing) did not differ in oil content in seeds (on average 42.4%). Pre-harvest desiccation due to the unnatural loss of plant moisture and acceleration of the final stages of seed ripening significantly worsened this indicator compared to the control (by 0.7% with Reglone Super and 0.9% with Roundup). The two-phase harvesting method was also deemed ineffective – the crude fat content in oil flax seeds was 0.5% lower than in the control, at 41.9%. The average crude fat content for the Southern Night variety in the study using different combine harvesting methods was 42.0% (total fat yield – 0.56 t/ha).

Analyzing the impact of combine harvesting methods on the oil content in Vodohray flax seeds, it can be concluded that there was no statistically significant difference between the control variant and the single-phase harvesting method in the study (the content ranged from 42.7–42.9%). Pre-harvest desiccation significantly reduced the crude fat content in seeds (by 0.5% with Reglone Super and 0.9% with Roundup), while the two-phase harvesting method did not differ significantly from the control variant. On average for factor B, the crude fat content in Vodohray flax seeds in the study was 42.4% with a total fat yield of 0.54 t/ha.

Averaged for factor A (variety), the main quantitative and qualitative indicators of oil flax yield are shown in Figure 2. In terms of seed yield, the most optimal combine harvesting method for oil flax was found to be direct single-phase harvesting, which outperformed other variants of factor B by 0.04–0.08 t/ha (including additional pre-harvest desiccation and two-phase harvesting). As for crude fat content in seeds, both single-phase and two-phase harvesting methods did not show a significant difference from the control variant (crude fat content ranged from 42.3–42.6%). Artificial desiccation of oil flax plants before combine harvesting significantly reduced this indicator by 0.6–0.8%. To determine the nature of the influence of combine harvesting methods on the course of physiological processes before and after harvesting ripening, basic indicators characterizing seed sowing conditions for oil flax were analyzed on average for factor A (Figure 3).

The analysis of experimental data revealed that the laboratory seed similarity index for oil flax did not differ significantly in the single-phase harvesting method compared to the control variant and averaged 96.2% over the years of the study. However, additional application of pre-harvest desiccation during single-phase harvesting of oil flax significantly decreased the seed similarity index: when using Reglone Super, the seed similarity was 95.1%, and with Roundup – 92.7%. The two-phase combine harvesting method showed a significantly higher seed similarity index compared to variants with pre-harvest desiccation (95.8%), although it slightly lagged behind both the control and direct single-phase harvesting. A similar dependency on the combine harvesting method was also observed for the seed germination energy indicator in oil

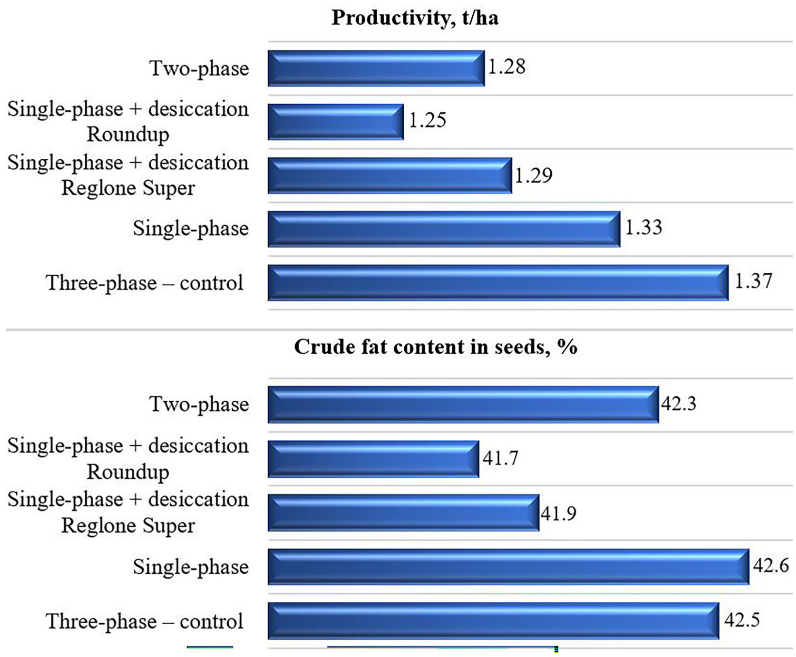

Figure 2. Average values of yield and oil content of oil flax seeds depending on the method of combine harvesting (average for 2022–2023)

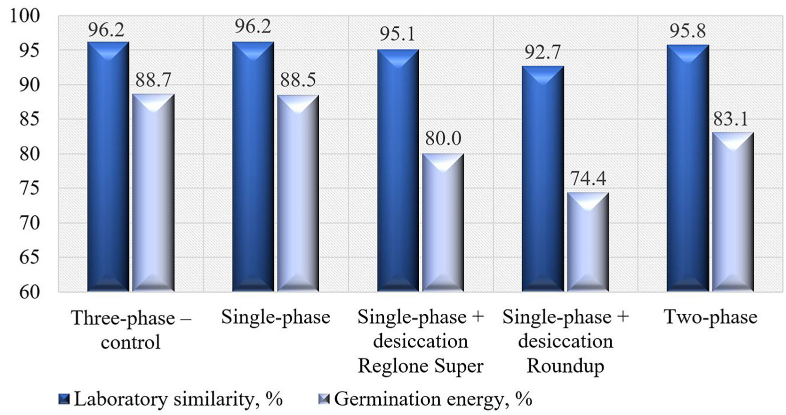

Figure 3. Sowing qualities of oil flax seeds depending on the method of combine harvesting (average for 2022–2023)

flax: the highest values were recorded in the control and direct single-phase harvesting methods (88.7% and 88.5% respectively), significantly lower in the two-phase harvesting method (83.1%), and reached minimal values in the single-phase harvesting with pre-harvest desiccation (80.0% with Reglone Super and 74.4% with Roundup).

CONCLUSIONS

The biological peculiarity of oil flax lies in the uneven flowering, capsule formation, and ripening, making the selection of an optimal combine harvesting method crucial to minimize seed yield losses. Each harvesting method has its advantages and disadvantages and should be applied based on agroclimatic and production conditions at the beginning of the oil flax harvesting period. Artificial acceleration of seed ripening through intensified plant moisture loss (using synthetic chemical desiccants) negatively affects most quantitative and qualitative indicators of oil flax productivity, as well as seed sowing conditions for the crop. In the study, direct single-phase harvesting without pre-harvest desiccation was recognized as the optimal combine harvesting method for oil flax, as it closely matched the control (three-phase laboratory method) across various evaluation criteria. The two-phase harvesting method is considered an alternative approach.

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