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Assessment of sunflower productivity depending on sowing time under the conditions of sustainable development of agroecosystems

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ABSTRACT

The article presents the results of comprehensive field research conducted in the conditions of the northeastern Forest-Steppe of Ukraine at the Institute of Agriculture of the Northeast of the NAAS to determine the optimal sowing parameters for modern sunflower hybrids, Slavson and Ravelin. Based on the analysis of variance, high statistical significance ($p < 0.001$) was established regarding the influence of sowing dates and genotypic characteristics on the formation of biometric parameters, the duration of interphase periods, and final crop productivity. It was proved that the early sowing date (April 15) ensures maximum development of vegetative mass and leaf surface area (up to 0.66 m²/plant); however, the increasing aridity of the regional climate requires an adaptive approach to selecting sowing dates to stabilize yields. Specifically, for the mid-early hybrid Ravelin, the middle and late dates (May) proved to be the most effective, with seed yields reaching 3.4–3.5 t ha^{-1}, whereas the early-maturing hybrid Slavson demonstrated a significant decrease in productivity at late sowing to the level of 1.8–2.1 t ha^{-1}. A comparison of the obtained results with international experience confirms that differentiated management of sowing dates, considering the maturity group of hybrids, is a crucial factor in optimizing yield structure and increasing the profitability of sunflower cultivation in the conditions of the left-bank Forest-Steppe.

Keywords: sunflower, sowing dates, hybrid, yield, biometric indicators.

INTRODUCTION

In recent production conditions, farmers increasingly face the necessity of sowing within extremely tight timeframes, targeting short periods of favourable weather and the availability of moisture in the topsoil [Zakharchenko et al., 2024; Butenko et al., 2025a]. A common belief is that sunflower seeds can withstand early spring frosts because their swelling and germination occur more slowly compared to maize. Consequently, early sowing dates are often perceived as safe, even under conditions of insufficient soil warming. However, practice and experimental data confirm the high risks associated with sowing sunflowers in cold soil [Ahmed et al., 2015, 2020; Ozturk et al., 2017]. At low temperatures, seeds remain in a moist environment for an extended period, leading to a decline in their sowing qualities and increasing the probability of damage by soil pathogens and pests. As a result, the field emergence rate decreases significantly [Gholamhoseini et al., 2019; Datsko et al., 2025; Butenko et al., 2025b]. Furthermore, a slow start to growth can lead to a situation where the effectiveness of seed treatments (dressings) expires before the plant forms resistant organs, increasing the risk of early disease infection, primarily the systemic form of downy mildew [Ozturk et al., 2017; Mishchenko et al., 2025].

Analysis of long-term sunflower cultivation experience in Ukraine indicates that with sufficient soil moisture, later sowing dates often ensure higher crop productivity [Trotsenko et al., 2020; Radchenko et al., 2022; Kovalenko et al., 2024]. Similar trends are observed in international research data. Even in cases where the plant did not suffer critical overcooling during the early phases, the negative consequences of early sowing still manifest in reduced yields, deterioration of seed quality characteristics, and a decrease in oil content and oleic acid levels in high-oleic hybrids [Litvinov et al., 2020; Krstić et al., 2023; Guo et al., 2023].

Sunflower cultivation remains a highly profitable direction for agricultural enterprises; therefore, increasing and stabilizing its yield is one of the primary tasks of science and production. Research on the hybrids Sumiko and Fausto in the western Forest-Steppe showed that optimal conditions for seedling emergence are formed in May. Due to low soil temperatures in April, seedlings emerged only after 20–25 days, whereas in May, this occurred twice as fast (10–13 days). Field emergence during May sowing dates was also higher (89.7–92.6%) compared to April (80.9–86.8%), despite sufficient moisture levels in both cases [Lykhochvor & Husak, 2022; Dehodiuk et al., 2024].

A study [Pinkovskyi & Tanchyk, 2021; Hryhoriv et al., 2024; Karbivska et al., 2025] conducted on ordinary chernozems in the Right-Bank Steppe (Kirovohrad State Agricultural Experimental Station of the NAAS) demonstrated that sunflower productivity directly depends on the optimization of the water regime through the regulation of standing density and sowing dates. It was established that the highest moisture reserves in the one-meter soil layer and maximum yield are ensured by a density of 60.000 plants ha^{-1}. Simultaneously, the need for a differentiated approach to selecting sowing dates was identified: for the hybrids LG 55.82 and LG 54.85, early sowing (April 6–7) proved most effective, while the hybrids LG 56.32 and Forward demonstrated the highest yield at later dates (April 13–28), highlighting the importance of considering the biological characteristics of a specific hybrid for Steppe conditions.

Analysis of scientific research and practical experience indicates that choosing the optimal sowing date for sunflowers is a critical factor determining not only the dynamics of seedling emergence but also the final productivity of the crop. At the same time, the crop's reaction to sowing dates significantly depends on the hydrothermal conditions of the region and specific genetic characteristics of the hybrids, indicating the absence of universal calendar dates and the need for an adaptive approach for each specific farm.

Modern research on sunflower sowing dates is aimed at adapting to global climate change, in particular to spring droughts and abnormally high temperatures during the flowering period. Due to rapid climate change and the emergence of new technologies, a significant list of research gaps and directions for scientific novelty has formed in this niche [Gürkan et al., 2026].

Adaptation to "temperature swings": Most of the old recommendations are based on a stable warming of the soil to 10–12 °C. However, now there are sharp returns of cold weather or anomalous warming in March-April with subsequent drought. There is a lack of models that would calculate the risks of very early sowing (4–6 °C) when using modern fungicidal treatments [Krstić et al., 2023].

Differentiated sowing dates for different maturity groups are justified by the need to take into account the specific features of the development of early-ripening and late-ripening hybrids. Each of these types has its own optimal periods for sowing, which differ significantly depending on the conditions of a particular region. Previously, such studies were often conducted for all hybrids as a single array, but this did not take into account the difference in physiological needs and reactions to temperature and agroclimatic conditions. Therefore, a point approach to determining sowing dates allows you to significantly increase the productivity and stability of crops [Lalrammawii et al., 2026].

Modeling development phases based on the sum of active temperatures involves creating a mathematical model that allows predicting the harvest date depending on the sowing date. This is especially relevant for new European hybrids that have not previously been tested in Ukraine [Lykhochvor et al., 2024].

Therefore, the aim of our research was the experimental confirmation of the influence of sowing dates on the growth, development, and productivity formation features of modern sunflower hybrids in the conditions of the northeastern Forest-Steppe of Ukraine to establish optimal sowing parameters that ensure maximum yield and seed quality.

MATERIAL AND METHODS

Field experiments were conducted during 2024–2025 at the Institute of Agriculture of the Northeast of the National Academy of Agrarian Sciences (NAAS) of Ukraine, located in the Sumy region, Ukraine (50°53'22.3"N, 34°42'34.1"E). The experimental plots are located within the northeastern Forest-Steppe, characterized by a slightly undulating lowland relief typical of the Left-Bank Lowland.

The soil cover of the experimental field is represented by typical (podzolized) chernozems formed on loess-like loams. In terms of particle size distribution, the soils are classified as medium and heavy loamy, which ensures high water-holding capacity but causes a tendency toward compaction and soil crust formation. The agrochemical characteristics of the soil (Table 1) indicate its high natural fertility. The humus content in the arable layer is 4.0%, and the overall land productivity index (bonitet) reaches 75 points. The soil solution reaction (pH_{H2O}) is 6.7, which is close to neutral and creates optimal conditions for the growth and development of sunflowers.

Table 1. Agrochemical indicators of the experimental plot soil

Parameter	Value
Soil reaction (pH_{H2O})	6.7±0.25
Humus content, %	4.0±0.15
Easily hydrolyzed nitrogen, mg/100 g of soil	11.5±1.35
Mobile phosphorus (P_2O_5), mg/100 g of soil	24.2±1.45
Exchangeable potassium (K_2O), mg/100 g of soil	18.4±2.15
Credit score	75.0±2.40

The availability of essential nutrients is at a medium level: the content of easily hydrolyzed nitrogen is 11.5 mg/100 g of soil, while mobile phosphorus compounds (P_2O_5) and exchangeable potassium (K_2O), determined by the Chirikov method, are 24.2 and 18.4 mg/100 g of soil, respectively. The combination of favorable hydrothermal indicators of the zone and the high agrochemical potential of the soils allows the research conditions to be considered representative of the northeastern Forest-Steppe of Ukraine.

Figure 1 presents a comparative assessment of weather conditions during the research years relative to the long-term average. The temperature regime during the study period (2024–2025) was characterized by a steady warming trend: average monthly temperatures in April exceeded the norm by 2.6–4.2°C, which, against the background of early vegetation recovery, created an illusion of optimal sowing conditions. However, the persistent risk of late May frosts combined with abnormal summer heat (especially in July 2024, when the temperature reached +25.4°C) proved to be suboptimal for sunflowers. Such conditions lead to a shortening of interphase periods, a decrease in pollen viability, and the inhibition of the oil formation process, confirming the necessity of adapting sowing dates to modern climate changes in the northeastern Forest-Steppe.

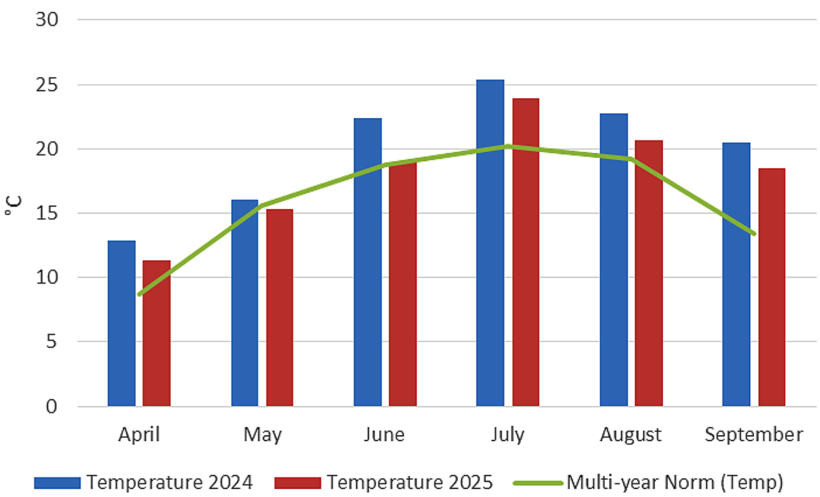

Figure 1. Dynamics of average monthly air temperature during the 2024–2025 growing seasons

The moisture regime during the research years (Fig. 2) was characterized by significant unevenness and a substantial deficit of precipitation during the critical stages of sunflower development. The 2024 growing season was marked by extreme aridity: after a relatively wet April (48 mm), a rapid decline in precipitation followed, reaching a critical minimum in July (17 mm) and August (14 mm), with a complete absence of rainfall in September. In contrast, 2025 demonstrated better moisture availability during the summer period: despite a dry start in April, the amount of precipitation from June to August was close to the long-term average, providing more favorable conditions for seed filling. Overall, the precipitation dynamics confirm the increasing aridity of the regional climate, where the total precipitation during the 2024 vegetation period amounted to only about 41% of the norm, serving as a limiting factor for yield formation.

The experimental design involved a systematic placement of variants in three replications, with a total plot area of 900 m² and a harvested (record) area of 30 m². Two hybrids of Ukrainian selection (V.Ya. Yuriev Institute of Plant Industry of the NAAS) were chosen as the objects of study: the early-maturing Slavson and the mid-early Ravelin. The scope of observations included monitoring the duration of interphase periods, biometric measurements (plant height, leaf surface area, head diameter), and analysis of individual productivity indicators.

Agricultural practices in the experiments complied with typical recommendations for the Forest-Steppe zone. The primary tillage system included stubble disking and autumn moldboard plowing to a depth of 25–27 cm, along with the application of a complex fertilizer ($N_{15}P_{15}K_{15}$) at a rate of 200 kg ha^{-1}. Pre-sowing cultivation and sowing (at a rate of 65.000 seeds ha^{-1}) were accompanied by the proportional application of fertilizers (100 kg ha^{-1}) in rows. Crop protection was based on an integrated approach: weed control was carried out using a combination of the pre-emergence herbicide Harness (3.0 l ha^{-1}) and the post-emergence herbicide Challenge (1.5 l ha^{-1}), while the phytosanitary status was maintained by applying a tank mix of Decis insecticide and Amistar Extra fungicide.

The study was conducted according to a two-factor design: Factor A – sowing dates (early – April 15 (control), middle – May 2, late – May 15); Factor B – hybrid (Slavson, Ravelin). The layout of the variants is presented in Table 2. Mathematical and statistical processing of the experimental data was performed using the analysis of variance (ANOVA) method with the specialized software package Statistica 10.0.

RESULTS AND DISCUSSION

The obtained results indicate a significant dependence of the duration of interphase periods on sowing dates and the genetic characteristics of the studied hybrids (Table 3). The "sowing-emergence" period showed a clear tendency to shorten when shifting from early (A1) to late (A3) sowing dates, which is explained by more intensive soil warming in May. Conversely, the duration of the

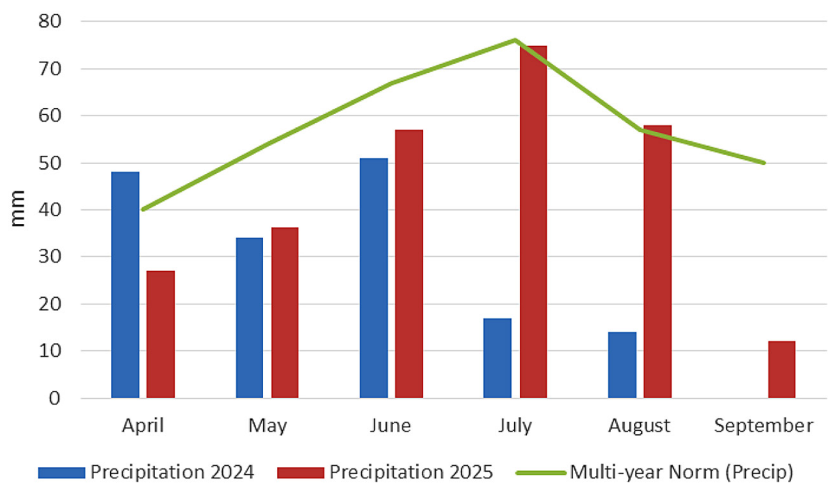

Figure 2. Distribution of precipitation during the 2024–2025 growing seasons compared to the long-term average

Table 2. Experimental design

Variant code	Factor A: Sowing date	Factor B: Hybrid
A1B1	A1 – (April 15) – Control	B1 – Slavson
A1B2	A1 – (April 15) – Control	B2 – Ravelin
A2B1	A2 – (May 2)	B1 – Slavson
A2B2	A2 – (May 2)	B2 – Ravelin
A3B1	A3 – (May 15)	B1 – Slavson
A3B2	A3 – (May 15)	B2 – Ravelin

Table 3. Descriptive statistics and multiple comparisons (Duncan's MRT) of sunflower phenological development stages (N = 18)

Variant code	Sowing–Emergence (days) M±SD	Variance	Emergence–Flowering (days) M±SD	Variance
A1B1	13.00±1.00[a]	1.00	50.00±1.00[c]	1.00
A1B2	13.00±0.00[a]	0.00	67.00±1.00[d]	1.00
A2B1	10.00±1.00[b]	1.00	51.00±1.00[c]	1.00
A2B2	10.00±0.00[b]	0.00	63.00±1.00[e]	1.00
A3B1	9.00±0.00[a]	0.00	47.00±1.00[a]	1.00
A3B2	9.00±1.00[b]	1.00	61.00±1.00[f]	1.00

"emergence–flowering" period was largely determined by the genotype: the mid-early hybrid Ravelin (B2) consistently demonstrated a longer growing season compared to the early-maturing hybrid Slavson (B1) across all sowing dates. The lowest variability in indicators was observed during the late sowing date (A3), where the combination of high temperatures and a sufficient sum of active temperatures contributed to the accelerated passage of the main stages of organogenesis for both hybrids.

For the "sowing-emergence" period, the results were divided into two main statistical subsets: the early sowing date (A1) and variant A3B1 demonstrated a significantly longer duration (13.00 ±1.00 and 9.00 ± 0.00 days, respectively), sharing index "a", while variants A2B1, A2B2, and A3B2 formed a distinct homogenous group with index "b". In the "emergence-flowering" phase, Duncan's MRT revealed a high degree of differentiation among the variants, assigning six distinct indices (a, c, d, e, f), which highlights the strong influence of the genotype on the duration of this period. Specifically, variant A1B2 reached the maximum duration (67.00 ± 1.00 days, index "d"), whereas variants A1B1 and A2B1 showed no statistical difference ($p = 0.244$), being unified under index "c". The shortest duration was recorded for variant A3B1 (47.00 ± 1.00 days, index "a"), confirming its accelerated development.

The minimal variance values (0.00–1.00) and the systematic presentation of descriptive and inferential statistics ensure the high precision of the field experiment and the reliability of the conclusions regarding the impact of sowing dates and hybrid characteristics on sunflower phenology.

The results of the analysis of variance (Table 4) confirm the high statistical significance of the influence of the studied factors on the duration of sunflower phenological phases. For both indicators – the "sowing–emergence" period ($F = 20.8$) and the "emergence-flowering" period ($F = 201.3$) – the obtained p-level values are significantly lower than the critical threshold of 0.05. In particular, the extremely high Fisher criterion value for the "emergence-flowering" phase indicates the dominant role of genotype and sowing dates in regulating the rates of vegetative development of the crop. The minimum mean square error values (0.50 and 1.00, respectively) emphasize the high precision of the experiment and the reliability of the obtained empirical data.

The analysis of biometric indicators demonstrates a significant dependence of the morphological parameters of sunflower on both the genetic characteristics of the hybrids and the sowing dates (Table 5). The highest values for all indicators were recorded during the early sowing date (A1): plant height reached 165.0–197.0 cm, and the leaf surface area amounted to 0.49–0.66

Table 4. Analysis of variance for sunflower phenological stages

Effect	Sum of squares (SS)	Mean square (MS)	SS Error	MS Error	F-value	p-value
Sowing-emergence	52.00	10.40	6.00	0.50	20.80	0.00
Emergence-flowering	1006.50	201.30	12.00	1.00	201.30	0.00

Table 5. Biometric indicators of sunflower hybrids depending on sowing dates (N = 36)

Variant code	Plant height, cm	Variance	Leaf area, m^2/plant	Variance	Head diameter, cm	Variance
A1B1	165.00±3.74	14.0	0.49±0.01	0.000080	15.80±0.42	0.18
A1B2	197.00±3.30	10.9	0.66±0.03	0.000680	18.60±0.40	0.16
A2B1	154.00±2.10	4.4	0.45±0.01	0.000080	14.25±0.47	0.22
A2B2	187.00±3.16	10.0	0.56±0.01	0.000110	17.40±0.70	0.48
A3B1	148.50±2.43	5.9	0.43±0.01	0.000200	13.20±0.51	0.26
A3B2	187.00±3.16	10.0	0.56±0.02	0.000560	16.20±0.81	0.66

m^2/plant. Shifting the sowing to later dates (A3) led to a gradual depression of growth processes, which was most pronounced in the reduction of head diameter – from 15.80 cm to 13.20 cm for the hybrid Slavson and from 18.60 cm to 16.20 cm for the hybrid Ravelin. Across all sowing dates, the hybrid Ravelin (B2) demonstrated higher biometric parameters compared to Slavson (B1), confirming its higher biological potential and morphotypic differences.

The results of the analysis of variance confirm the high statistical reliability of the influence of the studied factors on the morphological indicators of sunflower (Table 6). For all parameters – plant height ($F = 259.98$), leaf surface area ($F = 152.51$), and head diameter ($F = 71.93$) – the obtained Fisher criterion values significantly exceed the critical ones, and the significance level $p = 0.00$ indicates that the variability of these traits is caused not by random factors, but by the direct influence of sowing dates and the genotypic characteristics of the hybrids. Low mean square error (MS Error) values indicate high experimental precision and the representativeness of the sample.

The analysis of sunflower yield (Table 7) revealed significant differentiation between the experimental variants, primarily driven by the genetic potential of the hybrids and their response to sowing dates. According to Duncan's MRT, the highest productivity was achieved by the hybrid Ravelin (B2) at the late (A3) and medium (A2) sowing dates, forming the leading statistical group "a" with yields 3.50 ±0.33 and 3.38 ± 0.30 t ha^{-1}, respectively. The early-maturing hybrid Slavson (B1) demonstrated significantly lower productivity across all treatments. Specifically, its yield at the first two sowing dates (A1, A2) showed no statistical difference ($p = 0.362$), resulting in a shared index "c" (2.28–2.40 t ha^{-1}). The lowest yield was recorded for the A3B1 variant (1.93 ± 0.14 t ha^{-1}, index "d"), indicating a negative impact of late sowing on this particular

Table 7. Descriptive statistics and Duncan's MRT results for sunflower yield (N = 36)

Variant code	Yield (t ha^{-1}), M±SD	Variance
A1B1	2.28±0.15^{c}	0.021
A1B2	2.82±0.08^{b}	0.006
A2B1	2.40±0.19^{c}	0.038
A2B2	3.38±0.30^{a}	0.093
A3B1	1.93±0.14^{d}	0.020
A3B2	3.50±0.33^{a}	0.109

Table 6. Analysis of variance for sunflower biometric indicators

Parameter	SS Effect	MS Effect	SS Error	MS Error	F-value	p-value
Plant height, cm	11959.25	2391.85	276.0000	9.200000	259.98	0.00
Leaf area, m^2/plant	0.22	0.04	0.0085	0.000285	152.50	0.00
Head diameter, cm	117.91	23.58	9.8350	0.327833	71.93	0.00

Table 8. Analysis of variance for sunflower yield

Parameter	SS Effect	MS Effect	SS Error	MS Error	F-value	p-value
Yield, t ha^{-1}	11.74	2.34	1.43	0.04	49.15	0.00

genotype. The clear separation of the data into four distinct statistical subsets (a, b, c, d) with low variance values confirms the high precision of the experiment and the non-random nature of the identified advantages of the B2 hybrid under optimal sowing conditions.

The results of the analysis of variance confirm the high reliability of the influence of the studied factors on the formation of sunflower seed yield (Table 8). The calculated Fisher criterion value (F = 49.15) significantly exceeds the critical threshold, and the high statistical significance ($p < 0.001$) indicates that the variability in yield is strictly determined by the changes in sowing dates and genotype selection rather than by random factors. The low mean square error value (MS Error = 0.04) demonstrates the high precision of the field experiment and the representativeness of the obtained data. This allows for the conclusion that the studied factors are key in optimizing crop productivity, while the low SS Error (1.43) further confirms the reliability of the established dependencies across the experimental variants.

Regarding international scientific experience, research on sunflower yields in the steppe and dry-steppe zones of Kazakhstan demonstrated that early sowing dates (May 10–15) combined with fertilizer application contribute to an extension of the growing season by 3–5 days and the formation of maximum head diameter and weight. The highest yield in the steppe zone was obtained under early sowing and increased plant density (65.000 seeds ha^{-1}), indicating high ecological plasticity of modern hybrids and their positive response to intensified cultivation technologies under sufficient moisture supply. These results complement findings on the advantages of early plant development, suggesting that optimal sowing dates allow the crop to more effectively realize its genetic potential through improved yield structure parameters [Gordeyeva et al., 2023; Radchenko et al., 2024; Butenko et al., 2025c].

A study of the influence of sowing dates on morphological traits and yield components of sunflower hybrids in Romania showed that the middle sowing date – March 25 – was the most favorable for the formation of head diameter, 1000-seed weight, and yield. Early sowing (March 10) promoted a longer growing season and the formation of a larger number of leaves per plant; however, due to a deficit of precipitation during the winter-spring period, this did not ensure maximum productivity. At the same time, the hybrids' reaction to sowing dates was varied: while March was optimal for most, the hybrid FD18E41 demonstrated its highest yield (2566.3 kg ha^{-1}) with late sowing on April 10, confirming the importance of considering genetic characteristics when selecting technological parameters [Stępień-Warda et al., 2020; Radu et al., 2022].

Results of research in Turkey indicate that delayed sowing leads to an overall decrease in sunflower productivity, while the earliest sowing dates provide the maximum seed yield (3484 kg ha^{-1}) and the highest gross oil yield (1084 kg ha^{-1}). Although later sowing allowed for a higher oil content in the seeds (31.7%), the decisive factor for final oil productivity remains the high yield achieved specifically during early sowing periods [İzgi et al., 2024; Hussain et al., 2025].

CONCLUSIONS

The results of the conducted research indicate that the productivity formation of modern sunflower hybrids in the northeastern Forest-Steppe of Ukraine is closely dependent on hydrothermal conditions and sowing dates. It was established that shifting the sowing from early (April 15) to later dates (May) promotes the intensification of initial growth processes and a shortening of the "sowing-emergence" period; however, it leads to a noticeable depression of vegetative mass and a reduction in head diameter. Statistical analysis confirmed the high reliability of the "sowing date × hybrid" interaction on seed yield: while the middle and late dates proved optimal for the mid-early hybrid Ravelin (3.4–3.5 t ha^{-1}), the early-maturing hybrid Slavson demonstrated a sharp decline in productivity when sowing was delayed until mid-May. The obtained data align with international experience regarding the genotypic specificity of sunflower reaction to sowing dates, emphasizing the need for a differentiated approach to selecting sowing timing based on the biological characteristics of a specific hybrid.

In the context of the northeastern Forest-Steppe of Ukraine, the main patterns that determine the formation of the level of seed oil content were established. These parameters depend on changes in the time of the beginning of flowering caused by varying the sowing dates. In addition, an analysis was conducted and critical temperature limits were determined, which are crucial for the initial growth phases of modern high-yielding intensive hybrids. These results are important for optimizing cultivation technologies and improving the quality characteristics of the crop.

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