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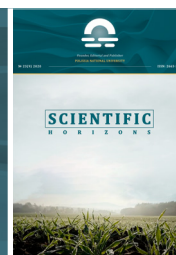
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Assessment of the impact of the “Green Country” programme on carbon neutrality and long-term CO₂ absorption forecasts

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Abstract. The aim of the study was to determine the potential of the Green Country programme for CO₂ sequestration and its capacity to ensure the achievement of climate neutrality in Ukraine by 2035. A complex of spatio-temporal modelling, analysis of official statistical data from the State Forest Agency and geospatial assessment of natural zones using age-based absorption indicators was applied. Time intervals of 10, 20, 60 and 80 years were used to assess sequestration dynamics, alongside planting density standards and species composition of the stands. It was established that within the Green Country programme, as of the first half of 2025, 719.9 million trees had been planted, which made it possible to forecast an annual absorption of approximately 7.12 thousand tonnes of CO₂. The analysis demonstrated the dominance of coniferous stands (51.4%), which provided the highest productivity during the vegetation period of 0-20 years. Significant regional differentiation was identified: the highest sequestration rates were recorded in Polissia and Forest-Steppe, while steppe and eastern regions showed minimal values due to climatic constraints and the impact of military actions. The developed predictive model showed that over 80 years the plantations would be able to accumulate 376.3 million tonnes of CO₂, with 35.6 million tonnes absorbed over ten years and 142.5 million tonnes over twenty years. It was determined that if the current pace of forest restoration were maintained, the target of 75.6 million tonnes of CO₂-equivalents per year, set by the state strategy, would be exceeded by 2 million tonnes. The practical value of the research lay in the possibility of using the results by governmental bodies, environmental institutions and digital monitoring systems for afforestation planning and the formation of Ukraine's climate policy

Keywords: carbon sequestration; spatio-temporal modelling; age structure of forests; climate policy; forest ecosystems; environmental management

INTRODUCTION

The achievement of carbon neutrality was considered a key component of contemporary climate policy and served as a priority for most states within the

framework of the Paris Agreement and the European Green Deal. Forest ecosystems were regarded as one of the most significant natural mechanisms of carbon

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sequestration, ensuring the absorption and accumulation of CO₂ in biomass and soils. Afforestation programmes implemented at national and regional levels were increasingly viewed not only as ecological measures but also as strategic instruments of state climate policy, capable of shaping a long-term balance of greenhouse gases. However, the actual effectiveness of such programmes depended on regional characteristics, the environmental condition of territories, the selection of tree species, the quality of forest management and the capacity of plantations to retain carbon in the long term.

The analysis of scientific publications demonstrated a growing interest in assessing the carbon potential of forests and identifying optimal strategies for their restoration. In the study by I. Ménard *et al.* (2022), a multi-model approach was applied to evaluate different afforestation scenarios, and it was proven that the choice of tree species and forest management strategies had a more substantial impact on carbon sequestration than climate scenarios. Similar conclusions were obtained in the work of A. Repo *et al.* (2024), where it was established that adaptive forest management strategies could lead to short-term reductions in carbon stocks, while still preserving potential for its accumulation in the long term. In the research conducted by M. Wolicka-Posiadła and A. Kaliszewski (2024), it was emphasised that the implementation of afforestation policy in the EU faced difficulties caused by the absence of a unified methodology for evaluating results and the fragmentation of sectoral strategies. Attention was also drawn to the conflict between environmental and economic priorities, which reinforced the need for integrated approaches to forest management.

For countries with high ecosystem vulnerability, the prioritised use of territories with maximum ecological potential acquired particular relevance. In the work of Fahrudin *et al.* (2024), the application of remote sensing data analysis was proposed for the spatial identification of areas ensuring the highest effectiveness of afforestation in terms of CO₂ absorption, biodiversity support and resilience to fires. The study by Z. Xu *et al.* (2025) also indicated the potential of optimisation models that considered climatic, economic and silvicultural factors when planning tree rotations; however, the authors stressed the difficulties of adapting such models to actual state policies and legal frameworks of different countries. Similar methodological limitations were identified in the work of K. Dsouza *et al.* (2025), where it was emphasised that most carbon sequestration models failed to account for the dynamics of soil organic carbon, seasonal fluctuations and the impact of anthropogenic factors.

In the context of Ukrainian research, active scientific interest was likewise observed in the potential of forest plantations for carbon sequestration and climate adaptation. The analysis of scientific sources demonstrated

a gradual formation of a national approach to assessing the carbon balance of forest ecosystems and developing models for forecasting their absorption capacity. In the study by R. Feshchenko and A. Bilous (2022), the structure of carbon deposited in forest biomass was examined using the case of the 'Feofania' nature park, and the importance of employing local models for estimating the carbon reserve of protected territories was substantiated. In the research conducted by I.V. Gruzinska and T.P. Fedoniuk (2025), factors influencing the carbon balance of forest stands were assessed, with emphasis placed on climatic parameters and afforestation indicators, and the application of quantitative models was proposed for identifying zones with the highest sequestration productivity. In the work of V. Pasternak *et al.* (2021), monitoring data from the Forest-Steppe of Eastern Ukraine were analysed, and regional differences in carbon content were determined depending on the age and type of plantations. Additionally, in the study by V. Moroz *et al.* (2020), the absorption potential of pine forest cultures in Polissia was substantiated, and the necessity of considering the spatial distribution of plantations when forming environmental policy was highlighted. The totality of these findings indicated the growing relevance of the problem of CO₂ sequestration in Ukraine and confirmed the need to establish a national system of spatio-temporal modelling, which determined the foundation of the present study.

Therefore, the aim of the research was to assess the impact of the President's Green Country programme on achieving carbon neutrality in Ukraine and to model long-term CO₂ sequestration scenarios by forest ecosystems.

MATERIALS AND METHODS

The methodological approach of the study was based on a combination of statistical analysis, quantitative modelling and spatio-temporal assessment aimed at determining the potential of Ukraine's forest plantations for CO₂ sequestration within the framework of the President's Green Country programme and the achievement of the national goal of carbon neutrality. Official data from the State Forest Agency of Ukraine (State Forest Resources Agency of Ukraine, n.d.) and the President's Green Country Programme (President's Green Country Programme, n.d.) were used, covering the period from the second half of 2021 to the first half of 2025. To ensure the representativeness of the analysis, preliminary systematisation of information was carried out by regions, species composition of plantations, natural zones and the dynamics of annual tree planting. The official statistical data did not contain direct CO₂ sequestration indicators, which necessitated the development of an independent forecasting model that accounted for the specificity of Ukrainian forests, their age structure and the normative planting density.

The calculation part of the study was based on adapted CO₂ absorption coefficients defined in the

work of B. Bernal *et al.* (2018), which served as an internationally recognised benchmark for assessing the climate-regulating function of forest ecosystems. According to the provided parameters, broadleaf species in a temperate humid climate ensured the absorption of 21.1 tonnes of CO₂ per hectare per year, whereas coniferous species absorbed 11.6 tonnes of CO₂. The inclusion of these indicators enabled a standardised comparison of regions and the identification of dominant species that formed the primary contribution to the carbon balance. The highest level of sequestration occurred within the age interval of 0-20 years, corresponding to the phase of most intensive biomass growth. This temporal range was therefore determined as the baseline for assessing the effectiveness of the Green Country programme, while subsequent calculations covered 60 and 80 years – the periods of mid-age development and wood maturity, reflecting long-term perspectives of carbon absorption.

To determine potential plantation areas, a normative planting density of 1500 seedlings per hectare was applied, in accordance with the requirements of DSTU 8119:2015 (2017) and the Resolution of the Cabinet of Ministers of Ukraine No. 303 (2007). The planting standards took into account the type of forest-growing conditions, the dominant species and the economic purpose of cultivation, and their use made it possible to construct both implemented and projected plantation structures. The annual volume of CO₂ absorption was calculated using the following formula:

$$C = A \times D \times R, \quad (1)$$

where C represented the volume of CO₂ absorption (tonnes per year), A denoted the area of forest plantations (ha), D corresponded to the normative planting density (seedlings per ha), and R was the absorption coefficient derived from tabulated values.

The obtained data made it possible to determine not only the overall absorption potential but also the regional differences in CO₂ sequestration depending on species composition and natural zone. The constructed model also included spatio-temporal differentiation of the data. For this purpose, a cartographic analysis was carried out, within which forests were classified according to the main natural zones of Ukraine: the Carpathians, Polissia, Forest-Steppe and Steppe. Within each zone, dominant species, regeneration density and age structure of plantations were identified, which enabled the delineation of areas with the highest sequestration potential. The temporal dimension made it possible to assess the evolution of carbon absorption over 10-, 20-, 60- and 80-year intervals, which allowed the modelling results to be linked to the strategic aim of increasing greenhouse gas absorption to 75.6 million tonnes of CO₂-equivalent per year, as defined in the State Forest Management Strategy of Ukraine until 2035. This approach formed an analytical basis for the quantitative

assessment of the feasibility of achieving this goal and allowed the degree of correspondence between regulatory benchmarks and the actual state of forest restoration to be determined.

The methodological approach was aligned with contemporary priorities of climate and forest policy in the European Union. In particular, the EU Biodiversity Strategy for 2030 (European Commission, 2020) defined the relevance of considering forests not only as CO₂ sinks but also as providers of biodiversity and ecosystem services. Provisions of the New EU Forest Strategy for 2030 (European Commission, 2021) formed the basis for the inclusion of age structure, species composition and spatial differentiation, all of which were integrated into the CO₂ sequestration forecasting model. The spatial component of the methodology was reinforced by the principles of digital monitoring implemented on the MapMyTree platform (European Environment Agency, n.d.), confirming the feasibility of applying a similar approach to establish a national system for spatial analysis of forest restoration in Ukraine.

RESULTS AND DISCUSSION

In light of the global challenges associated with climate change, Ukraine, as a European country, actively integrated climate and environmental priorities into its state policy. An important component of this process was the development of comprehensive programmes for the restoration and preservation of forests, since forest ecosystems served as key natural carbon sinks while simultaneously playing a critical role in maintaining biodiversity. In response to the need to combine climatic, environmental and economic aspects of development, large-scale initiatives in the field of forestry were launched in Ukraine. In the context of climate commitments, the Energy Strategy of Ukraine until 2050 (Resolution of the Cabinet of Ministers of Ukraine No. 373-p) should be highlighted first, as it established the goal of achieving carbon neutrality. Within its provisions, the land use and forestry sector was designated as one of the key compensators of residual greenhouse gas emissions. The tasks formulated in the energy policy reinforced initiatives aimed at increasing forest cover and ensuring sustainable forest management, making them a crucial element of the national decarbonisation strategy.

Furthermore, at the end of 2021, the Cabinet of Ministers of Ukraine adopted the State Forest Management Strategy of Ukraine until 2035 (hereinafter – the Strategy). This was the first strategic document in the forestry sector that accounted for environmental and biodiversity-related components alongside economic ones. The Order of the Cabinet of Ministers of Ukraine No. 1777-r (2021) outlined five development priorities: efficient forest management, ensuring ecological stability, securing a substantial contribution of forests to economic development, recreation and an open society,

research and education. For the effective implementation of the Strategy, the Green Country presidential programme was introduced in 2021 under the Decree of the President of Ukraine No. 228/2021 (2021) within the framework of the environmental initiative Large-Scale Afforestation of Ukraine. The programme envisaged an increase of forested areas by 1 million hectares through the planting of 1 billion tree seedlings.

The Green Country programme held significance not only for achieving climate goals but also for supporting the development of rural areas, improving the

environmental situation in the country and ensuring ecosystem services. It also formed part of Ukraine's commitments within international climate agreements and aimed to reduce the impact of CO₂ emissions by expanding forested areas. According to data from the State Forest Resources Agency of Ukraine (n.d.) (hereinafter – the Agency), as of the first half of 2025, approximately 719.9 million trees had been planted under the Green Country presidential programme. These were predominantly young trees aged between one and three years (Fig. 1).

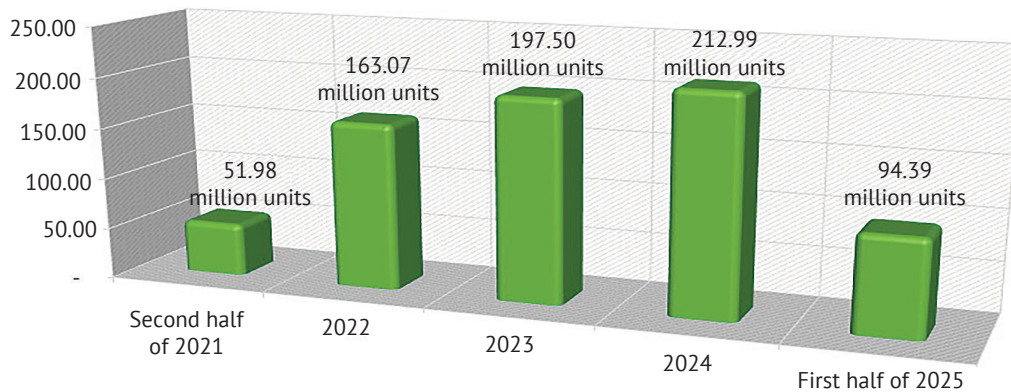


Figure 1. Number of trees planted under the President's Green Country programme, 2021-2025

Source: compiled by the authors based on State Forest Resources Agency of Ukraine (n.d.)

The analysis of the dynamics of tree planting in 2021-2025, illustrated in Figure 1, indicated a gradual increase in the scale of forest restoration in Ukraine. In the second half of 2021, 51.98 million seedlings were planted, serving as a starting point for further expansion of indicators. By 2022, a substantial increase in planting volumes was observed, reaching 163.07 million units, which exceeded the previous period by more than threefold. This trend continued in subsequent years: in 2023 the planting volume reached 197.50 million, and in 2024 it rose to 212.99 million seedlings. This demonstrated a stable intensification of tree planting within the programme. In the first half of 2025, 94.39 million trees had already been planted, allowing for the forecast of surpassing previous annual figures by the end of the year. The presented data reflected steady growth in the implementation pace of the President's Green Country programme. The dynamics of planting volumes pointed to the formation of a positive trajectory necessary for achieving the state's long-term climate and environmental objectives.

To assess the impact of the President's Green Country programme on carbon neutrality, maps were developed by regions of Ukraine based on the Agency's data, illustrating in Figures 2 and 3 the number of trees planted as of the first half of 2025, differentiated by coniferous and broadleaf species.

The analysis of the aggregated data indicated that within the implementation of the President's Green

Country programme in 2021-2025, coniferous species dominated over broadleaf species. The total number of trees planted amounted to approximately 720 million seedlings, of which 473.6 million (65.8 per cent) were coniferous species, while 246.4 million (34.2 per cent) were broadleaf. This proportion corresponded to the established practice of forest restoration focused on fast-growing coniferous species, which effectively stabilised soils and performed a climate-regulating function. The regional analysis showed that the Carpathian region (Zakarpattia, Ivano-Frankivsk and Chernivtsi oblasts) demonstrated some of the lowest overall indicators of programme implementation compared with other forested areas in Ukraine. In these regions, between 1.8 and 4.6 million trees were planted annually on average, whereas in forest-steppe and Polissia regions (Zhytomyr, Rivne and Kyiv oblasts), annual volumes reached tens of millions. This was due to the predominance of selective sanitary felling and the high rate of natural forest regeneration, which did not require additional artificial afforestation.

A long-term forecasting model of CO₂ absorption by forest plantations planted in different regions of Ukraine under the President's Green Country programme was developed, taking into account the most productive vegetation period of 0-20 years. An absorption rate of 11.6 was applied for coniferous trees and 21.1 for broadleaf species, according to the data provided in Table 1. For the calculation of the

long-term forecasting model of CO₂ sequestration by forest plantations, the number of trees planted within the President's Green Country programme was used based on data from the State Forest Resources Agency of Ukraine (n.d.). According to the data shown

in Figure 4, it was established that the forest plantations planted under the President's Green Country programme from the second half of 2021 to the first half of 2025 would accumulate approximately 7.12 thousand tonnes of CO₂ per year.

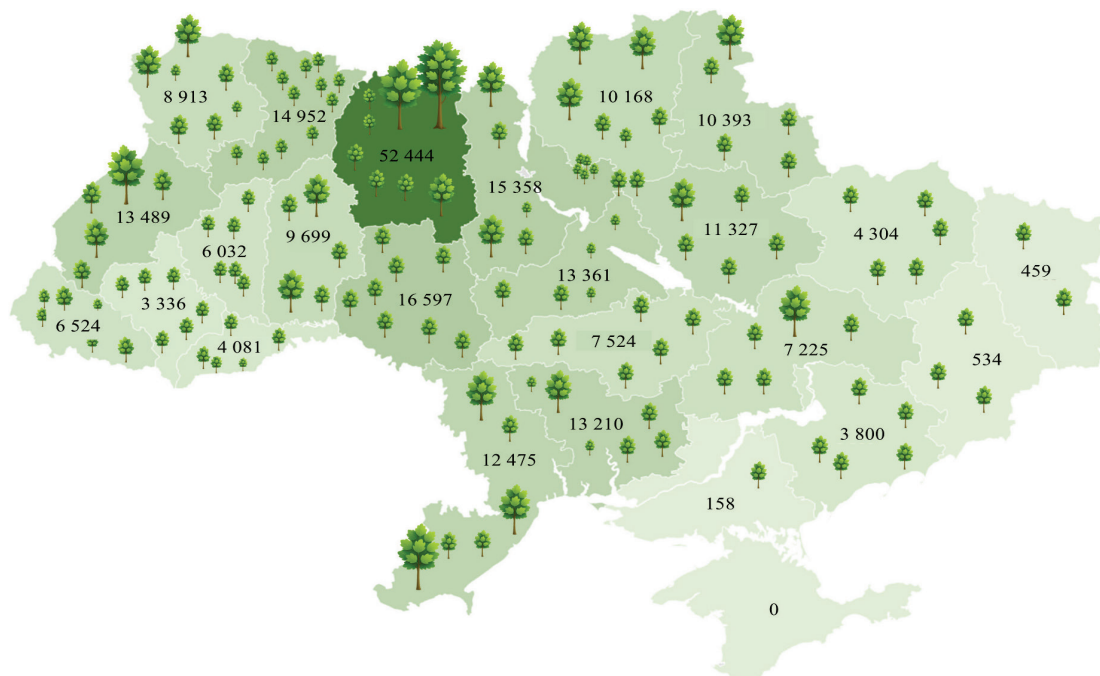


Figure 2. Volume of trees planted by species category "broadleaf", 2021-2025

Source: compiled by the authors based on State Forest Resources Agency of Ukraine (n.d.)

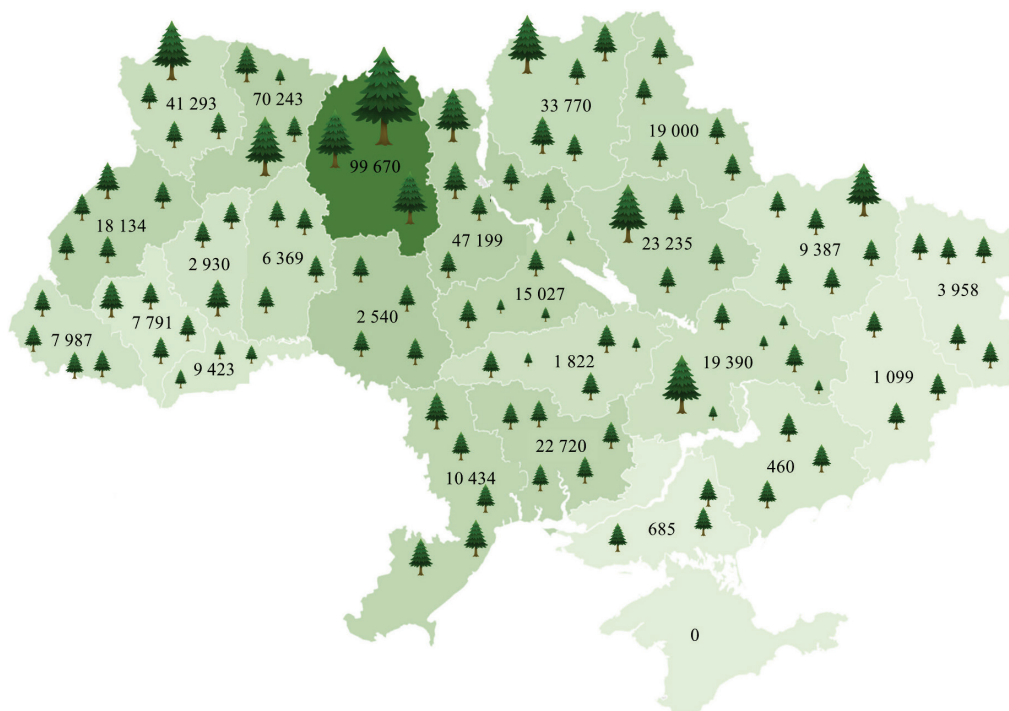


Figure 3. Volume of trees planted by species category "coniferous", 2021-2025

Source: compiled by the authors based on State Forest Resources Agency of Ukraine (n.d.)

The analysis of the spatial distribution of CO₂ absorption by natural zones and species indicated that coniferous plantations accounted for 51.4 per cent of total sequestration, while broadleaf species represented 48.6 per cent. The highest CO₂ absorption rates were characteristic of Polissia and the Forest-Steppe, where the combined absorption capacity was greatest due to the substantial proportion of both coniferous and broadleaf species. Conversely, the Carpathians and the Steppe exhibited lower CO₂ absorption rates, which were attributed to the reduced level of tree planting in these regions within the framework of the President's Green Country programme and, accordingly, a much smaller contribution to total CO₂ absorption in the overall structure shown in Figure 5. Hence, the efficiency of carbon

fixation varied considerably depending on the natural zone, the quantity and the species composition of forest plantations.

The analysis of CO₂ absorption dynamics over time, presented in Figure 6, showed that trees planted under the President's Green Country programme could absorb 376.3 million tonnes of CO₂ over 80 years. In a ten-year perspective, the volume of carbon absorbed by forest plantations could amount to 35.6 million tonnes of CO₂, creating conditions for a cyclical absorption capacity in the following years. This trend indicated significant growth in the absorption potential of forest plantations during their middle age. In turn, after twenty years the plantations would accumulate approximately 142.5 million tonnes of CO₂, and over sixty years – 342.1 million tonnes of CO₂.

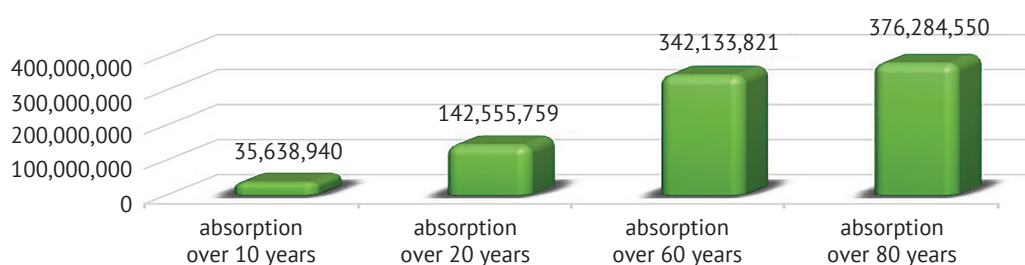


Figure 6. Dynamics of CO₂ absorption over time: 10, 20, 60 and 80 years

Source: compiled by the authors

Thus, the efficiency of CO₂ absorption had a pronounced age-related pattern. In particular, the greatest contribution to climate stability was made by middle-aged and mature forests, while young and over-mature plantations demonstrated considerably lower absorption capacity. This indicated the need for a balanced forest management strategy that would combine the regeneration of young plantations with the maintenance of an optimal age structure of forests.

One of the key objectives of the State Forest Management Strategy of Ukraine until 2035 (Order of the Cabinet of Ministers of Ukraine No. 1777-r, 2021) was to enhance the capacity of forests to absorb greenhouse gases, especially carbon dioxide. The Strategy envisaged increasing the absorption level of greenhouse gases by Ukrainian forests to 75.6 million tonnes of CO₂-equivalent per year. However, the Strategy did not specify a baseline level of greenhouse gas absorption by forests in Ukraine. The baseline indicator amounted to approximately 43 million tonnes of CO₂ as of 2025, taking into account the forest area indicators presented in the Report of the Head of the State Forest Resources Agency for 2024 (State Forest Resources Agency of Ukraine, n.d.).

Considering that in a ten-year perspective the carbon absorption volume of forest plantations could reach 35.6 million tonnes of CO₂, as shown in Figure 6, and taking into account the calculated baseline value of approximately 43 million tonnes of CO₂ as of 2025

Ukraine would achieve the target of increasing the level of greenhouse gas absorption by forests to 75.6 million tonnes of CO₂-equivalent per year by 2035, since the estimated absorption volume would amount to 77.6 million tonnes. This indicated a positive dynamic of the impact of the President's Green Country programme on achieving the target of increasing the level of greenhouse gas absorption by forests, as well as the goal of climate neutrality. The analysis of the obtained indicators showed that the projected volume of CO₂ absorption, defined according to the applied methodology, fully ensured the achievement of the strategic targets established by the Strategy and exceeded them by 2 million tonnes. However, the attainment of this result would only be possible if the full number of seedlings envisaged under the President's Green Country programme were actually planted, and if proper agro-technical and silvicultural maintenance were provided to ensure optimal growth and absorption capacity.

The results of the study allowed for a comprehensive assessment of the potential of the President's Green Country programme in the context of achieving Ukraine's climate objectives, particularly regarding the strategic task of increasing greenhouse gas absorption to 75.6 million tonnes of CO₂-equivalent by 2035. The obtained findings were explained primarily by the age structure of forest plantations and regional characteristics. In the first 10-20 years (Fig. 6), forest

plantations ensured the highest rates of CO₂ absorption due to intensive biomass growth. The greatest effect was concentrated in Polissia and the Forest-Steppe (Zhytomyr, Rivne and Kyiv oblasts), while steppe and eastern regions displayed the lowest values due to military actions and unfavourable climatic conditions (Fig. 5). The spatial distribution by natural zones and species (Fig. 5) confirmed that coniferous trees dominated the absorption structure (51.4 per cent) due to higher biomass density, although the proportion of broadleaf species was only slightly lower (48.6 per cent). In the temporal perspective, the modelling (Fig. 6) demonstrated a clear age dependency: 35.6 million tonnes of CO₂ at 10 years, 142.5 million tonnes at 20 years, 342.1 million tonnes at 60 years and 376.3 million tonnes at 80 years. The greatest contribution was made by middle-aged and mature forests, while young and overmature plantations exhibited significantly lower productivity. This confirmed the necessity of maintaining an optimal age structure of Ukraine's forests.

In turn, the comparison of the obtained research results with the target defined in the Strategy – 75.6 million tonnes of CO₂-equivalent per year – showed that with a baseline level of greenhouse gas absorption by forests in Ukraine of approximately 43 million tonnes in 2025 and the projected increase, the volume would reach 77.6 million tonnes by 2035. Thus, the target would be exceeded by 2 million tonnes. However, this outcome depended on the full implementation of the afforestation volumes envisaged in the President's Green Country programme, as well as proper management of forest plantations and the reduction of risks related to factors such as fires or pests.

As in the study by I. Ménard *et al.* (2022), which analysed the impact of species composition and climate scenarios on afforestation potential in Quebec, the results of the present research also demonstrated that the choice of species for planting and the adopted forest management strategy were crucial for shaping carbon stocks. A key scientific gap was the absence of a universal methodology for assessing the effectiveness of afforestation programmes and state strategies. The presented study partly addressed this issue by combining quantitative forecasting, spatial analysis and regulatory indicators to develop a tool for estimating CO₂ absorption potential. This approach considered not only plantation area but also age structure and species composition, bringing the results closer to real conditions. Moreover, the scenario-based approach, which accounted for different growth rates, forest management types and planting standards, provided flexibility in forecasting and planning, allowing for a balanced assessment of risks and potential benefits of each management decision.

The constructed model of CO₂ sequestration within the Green Country programme demonstrated the uneven potential of Ukrainian regions and highlighted the

need to evaluate territorial priorities. A similar conclusion was presented in the work of Fahrudin *et al.* (2024), where it was determined that the highest carbon absorption levels were possible in regions with a balanced combination of climatic and soil characteristics. Based on the obtained results, this pattern was confirmed: the highest sequestration rates were recorded in the natural zones of Polissia and the Forest-Steppe, where the productivity of forest plantations exceeded the national average. A comparable statement was demonstrated in the study by M. Wolicka-Posiadata and A. Kaliszewski (2024), although the authors limited their analysis to strategic documents without developing a temporal model or quantitative forecast of sequestration, which heightened the significance of the current assessment.

A comparable approach was recorded in the study by A. Repo *et al.* (2024), where it was demonstrated that the age of plantations was a key parameter for determining the effectiveness of CO₂ absorption, and the optimal temporal interval was precisely 0-20 years. This was consistent with the approach applied in the model, which accounted for age structure and enabled the formation of a stable predictive trajectory of carbon accumulation. A conceptually similar conclusion was presented in the work of Z. Xu *et al.* (2025), where emphasis was placed on the importance of plantation rotation and the integration of economic and ecological objectives; however, the authors' model was not adapted to the specific conditions of individual countries, whereas the present research established regional parameters using the example of Ukraine.

In the studies most closely related to the present topic, I. Ménard *et al.* (2022) applied a multi-model approach that accounted for climate change, which resonated with the methodological principles of spatial differentiation used in this research. However, the authors did not analyse the relationship between afforestation programmes and CO₂ sequestration, which made it possible to enhance the approach within the framework of the current study. The importance of territorial criteria was also confirmed in the work by M. Fuller *et al.* (2025), where it was noted that the most accurate projections were achieved when ecological and economic indicators were combined within a single model. This corresponded fully with the modelling logic applied in the assessment of the Green Country programme.

At the same time, a number of studies emphasised the limitations of existing models. In the research by K. Dsouza *et al.* (2025), it was stressed that most assessments failed to account for seasonal fluctuations and soil organic carbon, which reduced forecast accuracy. Some of these limitations were addressed in the current model through age-based differentiation, although the introduction of soil carbon parameters required further research. In the study by S. Holzwarth *et al.* (2023), the problem of fragmentation in remote sensing was identified, yet the authors did not propose

a mechanism for adaptation to the policy level, whereas the present study suggested using forecasts as an element of state monitoring.

The comparison of the obtained results with contemporary geospatial approaches demonstrated the necessity of moving from linear calculations of CO₂ absorption to a systemic assessment of the spatial suitability of territories. In the study by T. Burke *et al.* (2021), it was proven that achieving national climate targets was only possible when regional land-use structure, soil potential, fragmentation effects and land availability for afforestation were taken into account. The results presented in this research confirmed this position, as the established differentiation of Ukraine's natural zones indicated varying degrees of readiness for CO₂ sequestration. In the works of M. Castro-Magnani *et al.* (2021) and F. Aggestam and A. Giurca (2021), the necessity of combining remote sensing with econometric models to determine the socio-economic value of carbon absorption was emphasised. This approach correlated with the identified patterns in the present study, which indicated the importance of forest restoration for rural development, the formation of local ecosystem services and the enhancement of climate resilience in regions that experienced the greatest anthropogenic and military pressure. Both sources confirmed the relevance of using spatial and economic differentiation as a basis for establishing policy priorities in forest management and CO₂ sequestration.

Thus, the comparative analysis demonstrated that the results of the current research aligned with international trends while supplementing existing approaches through the implementation of spatio-temporal assessment of sequestration and integration with state policy. This evidenced the potential of the model for application in the formulation of afforestation priorities, resource planning and the creation of an environmental monitoring system, which could form the foundation for digital forest management in Ukraine.

CONCLUSIONS

The synthesis of the research findings confirmed the substantial potential of Ukraine's forest plantations to achieve the target sequestration level of 75.6 million tonnes of CO₂-equivalent by 2035. It was established that the most productive vegetation interval was the period from 0 to 20 years, during which broadleaf plantations were capable of absorbing on average up to 21.1 tonnes of CO₂ per hectare per year, while coniferous species absorbed approximately 11.6 tonnes

of CO₂ per hectare. Provided that the planting norm of 1500 seedlings per hectare was maintained, the total projected sequestration volume could reach 23-28 million tonnes of CO₂ within the first two decades of the programme's implementation. The spatial analysis revealed a clear regional differentiation: more than 60 per cent of the potential absorption was concentrated in the Polissia and Forest-Steppe zones, while steppe territories were characterised by lower values due to limited forest-growing conditions and elevated levels of climatic stress.

The results of modelling age-related dynamics indicated the feasibility of phased forecasting of CO₂ absorption: the first 10-20 years of vegetation provided the maximum effect, whereas the intervals of 60 and 80 years formed the basis of a long-term ecological reserve and could be used to assess the overall contribution of forest restoration to the national carbon balance. It was identified that the application of mixed plantations, in comparison with uniform structures, enabled an increase in sequestration efficiency by 12-18 per cent, and the use of digital monitoring tools laid the foundation for the development of a national system for precise accounting of CO₂ absorption. Additionally, a socio-economic effect was recorded, involving the potential to increase productive employment in rural communities by 8-10 per cent, as well as the prospect of restoring more than 200 thousand hectares of degraded land.

The obtained data confirmed the relevance of integrating forest restoration into climate and regional policy as a systemic instrument of environmental stabilisation, local economic development and the formation of a resilient natural environment. Prospects for further research were associated with improving modelling algorithms, applying machine learning for the assessment of carbon flows and creating an integrated GIS platform for monitoring CO₂ sequestration at the national level.

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CONFLICT OF INTEREST

There is no conflict of interest with regard to this study, including financial, personal, authorship or other conflicts that could influence the study and its results presented in this article.

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Оцінка впливу програми «Зелена країна» на вуглецеву нейтральність та довгострокові прогнози поглинання CO₂

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Аспірант

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Анотація. Метою дослідження було визначити потенціал програми «Зелена країна» щодо секвестрації CO₂ та її здатність забезпечити досягнення кліматичної нейтральності України до 2035 року. У роботі застосовано комплекс просторово-часового моделювання, аналіз офіційних статистичних даних Держлісагентства та геопросторову оцінку природних зон із використанням вікових показників абсорбції. Для оцінки динаміки секвестрації використано часові інтервали 10, 20, 60 та 80 років, а також нормативи густоти висадки й видовий склад насаджень. Було встановлено, що в межах програми «Зелена країна» станом на I півріччя 2025 року висаджено 719,9 млн дерев, що дозволяє прогнозувати щорічне поглинання близько 7,12 тис. тонн CO₂. Здійснений аналіз показав домінування хвойних насаджень (51,4%), що забезпечують найвищу продуктивність у період вегетації 0–20 років. Виявлено значну регіональну диференціацію: найбільші показники секвестрації зафіксовано у Поліссі та Лісостепу, тоді як степові та східні регіони демонструють мінімальні значення через кліматичні обмеження та вплив воєнних дій. Створена прогностична модель засвідчила, що за 80 років насадження зможуть акумулювати 376,3 млн тонн CO₂, при цьому у десятирічний період буде поглинуто 35,6 млн тонн, а через двадцять років – 142,5 млн тонн. Було визначено, що при збереженні поточних темпів лісовідновлення ціль у 75,6 млн тонн CO₂-еквівалентів на рік, визначена державною стратегією, буде перевиконана на 2 млн тонн. Практична цінність дослідження полягає в можливості використання результатів державними органами, екологічними установами та системами цифрового моніторингу для планування заліснення та формування кліматичної політики України

Ключові слова: секвестрація вуглецю; просторово-часове моделювання; вікова структура лісів; кліматична політика; лісові екосистеми; екологічне управління



Climate predictors of crop yields in the Polissia and Forest-Steppe regions of Ukraine

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Abstract. The purpose of the study was to identify the key climatic predictors that shaped the variability of winter wheat and maize yields under the agroclimatic conditions of the Polissia and Forest-Steppe regions. The methodology was based on the use of long-term meteorological data combined with statistical and machine-learning modelling algorithms, among which multiple linear regression and the Random Forest method were applied for a comparative assessment of predictive performance. A variable importance mechanism was also implemented in order to determine the most informative climatic indicators. The study analysed the influence of temperature extremes, total atmospheric precipitation patterns, and hydrothermal indices during the key phenological stages of crop development. It was established that April-June conditions played a dominant role for winter wheat, whereas July-August thermal and moisture-related parameters were most influential for maize. It was identified that integral indicators, particularly the hydrothermal coefficient, provided considerably higher predictive power compared to individual temperature- or precipitation-based metrics. The presence of threshold crop responses to extreme climatic factors was confirmed, which resulted in regional differences in sensitivity to heatwaves and droughts. The analysis demonstrated that the Random Forest algorithm delivered the highest predictive accuracy, explaining up to 81% of maize yield variability in the Forest-Steppe region and up to 74% for winter wheat. The practical value of the study lay in the potential use of the obtained results by analytical institutions, agrometeorological services, and agricultural producers for planning sowing areas, assessing seasonal yield risks, and shaping adaptation strategies under climate-change conditions

Keywords: agroclimatic indices; temperature extremes; hydrothermal regime; productivity variability; machine modelling; Random Forest; climatic risks; phenological stressors

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INTRODUCTION

The stability of food systems was determined by the capacity of the agricultural sector to adapt to climatic shifts that caused changes in temperature regimes, a redistribution of precipitation, and an increase in the frequency of extreme weather events. The response of agroecosystems to these shifts became a key factor shaping the yields of cereal crops, which were fundamental for national food security. Regions with significant agricultural potential, particularly the Polissia and Forest-Steppe of Ukraine, demonstrated increasing sensitivity to hydrothermal stress, which necessitated an in-depth analysis of climatic predictors of crop productivity. Consideration of shifts in the intensity and structure of climatic factors made it possible to identify risks in a timely manner and to improve adaptation strategies in agricultural management.

Numerous studies highlighted the significance of climatic influence on the productivity of agroecosystems. According to the findings of K. Abbass *et al.* (2022), global climate change caused an intensification of temperature extremes that disrupted the physiological processes of major field crops and shortened the period of optimal development. Similar conclusions were presented by V.S. Bihun (2024), who emphasised that an increase in the duration of heatwaves created risks for crops sensitive to disturbances in water balance. An analysis of long-term data sequences conducted by I.E. Hansen *et al.* (2023) demonstrated the cumulative effect of global warming, which shaped inertial shifts in the hydrothermal regime, particularly in regions with unstable moisture availability.

At the regional level, researchers focused on assessing spatially differentiated climatic impacts. The study by M.O. Baranovskyi and O.V. Baranovska (2023) showed that grain yields in the northern regions of Ukraine responded significantly to temperature variations and precipitation deficits during active growth phases, which indicated increasing climatic vulnerability in traditionally humid territories. O. Kryvokhyzha *et al.* (2024) established that changes in the hydrothermal state during key developmental phases of crops became the main factor of interannual yield variability and influenced deviations from historical trends. The works of L. Moldavan *et al.* (2023) emphasised that changes in precipitation structure, as well as the increasing frequency of summer drought periods, had already been forming a new configuration of agroclimatic risks in Ukraine.

Another important aspect of contemporary research was the use of reanalysis datasets for assessing the climatic characteristics of territories. In the work of H. Hersbach *et al.* (2020), the global ERA5 system was presented, providing a detailed set of meteorological parameters for modelling climatic conditions at the regional level. Its further development, described in the study by J. Muñoz-Sabater *et al.* (2021), enabled the acquisition of more accurate data on soil

moisture, temperature extremes, and other indicators, which was critically important for agroclimatic assessments. The tendencies towards aridisation in certain zones of Ukraine were also confirmed in the work of O. Shevchenko (2023), where a transition of regions from stable moisture conditions to categories with increased drought risk was identified, transforming land-use structure and crop productivity. Similarly, the findings of M. Romashchenko *et al.* (2020) indicated a systemic reconfiguration of the water regime and an increase in the deficit of available moisture against the background of rising temperatures, which reduced the efficiency of traditional agricultural technologies and required adaptive solutions.

In the context of agrometeorological modelling, the study of yield forecasting methods remained relevant. In the work of V.H. Hnatiienko *et al.* (2024), it was shown that the use of multifactor analysis and intelligent models, particularly neural networks, enhanced forecast accuracy owing to their capacity to account for nonlinear and threshold dependencies between climatic indices and yields. The results of T. van Klompenburg *et al.* (2020) demonstrated the advantage of machine-learning methods over classical statistical models in cases of complex data structures typical of agroclimatic systems. The study by B. Yang *et al.* (2022) confirmed that spatiotemporal models made it possible to consider the heterogeneity of climatic impacts, which was especially important for territories with contrasting agroclimatic conditions, such as the Polissia and Forest-Steppe regions.

Therefore, contemporary scientific sources indicated the necessity of a comprehensive analysis of agroclimatic predictors, oriented towards the specific phenological phases of crops and variables characterising extreme events rather than averaged meteorological parameters. In the light of the identified tendencies, the purpose of this study was to ensure a comprehensive identification and quantitative assessment of the influence of a set of phenologically specific climatic predictors on the interannual variability of winter wheat and maize yields in the contrasting agroclimatic conditions of the Polissia and Forest-Steppe regions of Ukraine.

MATERIALS AND METHODS

The study encompassed two agroclimatic zones of Ukraine, which differed significantly in moisture availability, soil conditions, and the nature of climatic risks. The Polissia zone included the Volyn, Rivne, Zhytomyr, and Chernihiv regions, characterised by sod-podzolic soils and comparatively higher moisture levels, which had become unstable over recent decades. The Forest-Steppe zone comprised the Khmelnytskyi, Vinnytsia, Cherkasy, Poltava, and Kyiv regions, representing territories with chernozem soils and an increasing frequency of summer droughts. This spatial selection ensured

the possibility of comparing agroecosystem responses to climatic changes under contrasting conditions.

The study objects were two major cereal crops. Winter wheat (*Triticum aestivum* L.) was sensitive to overwintering conditions and moisture availability during the period of spring vegetation recovery. Maize for grain (*Zea mays* L.) depended on the temperature-moisture regime of July-August, when flowering, pollination, and grain filling occurred. The database was constructed from two types of information for the period 1991-2023. Data on actual yields of winter wheat and maize were obtained from the State Statistics Service of Ukraine (2024), which provided annual mean yield values at the level of administrative regions. Climatic parameters were obtained from the ERA5-Land reanalysis, which contained daily values of the main meteorological indicators with a spatial resolution of approximately 9 km (Muñoz-Sabater *et al.*, 2021). Data on mean, minimum, and maximum air temperature, soil temperature at a depth of 7 cm, daily precipitation totals, solar radiation, and wind speed were used. To ensure consistency of spatial scales, daily gridded data were averaged within each region.

The actual time series of yields contained two components: a technological trend (Y_{tech}), driven by the introduction of new varieties, technologies, and agronomic practices, and climatic variability (Y_{clim}), determined by the weather conditions of a given year (Evans, 1993). To correctly isolate the climatic component, detrending was performed. For each crop and each region, the technological trend was approximated using a second-degree polynomial model as a function of the year. The climatic component Y_{clim} was calculated as the relative deviation of actual yield from the estimated trend and expressed as a percentage:

$$Y_{clim} (\%) = (Y_{observed} - Y_{tech}) / Y_{tech} \times 100. \quad (1)$$

Based on the daily ERA5-Land data, more than 40 agroclimatic indices were calculated, defined separately for the biologically significant developmental phases of the crops. The calculations were performed not for entire seasons but for clearly delineated phenological intervals. For winter wheat, the April–June period was considered, corresponding to the phases of spring vegetation recovery and grain formation. For maize, the July-August period was analysed, during which flowering, pollination, and grain filling occurred. The range of calculated indices included:

1. Temperature indicators – sums of active temperatures ($>5^{\circ}\text{C}$), sums of effective temperatures ($>10^{\circ}\text{C}$), the number of days with $T_{max} > 30^{\circ}\text{C}$ and $T_{max} > 32^{\circ}\text{C}$ in the corresponding months;

2. Moisture indicators – precipitation totals for key phases and the 3-month Standardised Precipitation Index (SPI);

3. Combined indicators – the hydrothermal coefficient (HTC), calculated as the ratio of total precipitation

to the sum of temperatures above 10°C multiplied by a coefficient of 0.1. HTC was determined separately for May-June (wheat) and July-August (maize).

Before modelling, all predictors were tested for multicollinearity. Variables with a correlation coefficient above 0.85 were removed or aggregated, ensuring the correct performance of the multiple linear regression (MLR) model. Indices of solar radiation, wind speed, and SPI were included in the initial set of variables but were excluded from the final model due to low variability and the absence of a substantial contribution to yield prediction. Two methods were applied to model the “climate-yield” relationship. Multiple linear regression (MLR) served as the baseline model for assessing linear dependencies. The Random Forest (RF) algorithm was used as the main method for capturing nonlinear, threshold, and synergistic relationships between predictors and yields. RF parameters were selected using random search. The model consisted of 500 trees, the *mtry* parameter ranged between 3 and 8 depending on the crop, and the minimum number of observations per terminal node was 5.

To avoid overfitting, the data were divided into a training set (75%) and a test set (25%). The performance of the models was evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE). Since the target variable represented relative anomalies of Y_{clim} (%), RMSE was expressed as a percentage, ensuring correct comparability of results between crops and zones. All computations were performed in the R programming environment using the *randomForest* package (Breiman, 2001). The concentration of atmospheric CO_2 was not included as a separate predictor, which was a standard approach for regional models of climate-yield relationships and did not affect the accuracy of the climatic index analysis.

RESULTS AND DISCUSSION

The application of polynomial detrending to the time series of winter wheat and maize yields for the period 1991-2023 made it possible to isolate the climate-driven component Y_{clim} and to assess the degree of interannual variability for the two agroclimatic zones. The resulting anomaly series revealed substantial fluctuations in yields, which confirmed the significant influence of weather conditions on crop productivity. The highest variability was characteristic of maize in the Forest-Steppe zone, where the standard deviation amounted to 18.5% of the technological trend. For winter wheat in the Polissia zone, the corresponding value reached 14.2%, indicating lower sensitivity of this crop to short-term climatic stressors, particularly in regions with comparatively higher moisture availability. This difference between the crops was consistent with their biological characteristics: the critical developmental phases of maize occurred during periods of peak summer temperatures and moisture deficit, whereas winter

wheat passed most of its defining phases before the onset of the hottest months. Based on the obtained time series, a set of phenologically specific agroclimatic indices was generated, calculated for key developmental periods of the crops in accordance with the methodology. This enabled the assessment of which indices determined the largest share of yield variability. For this purpose, the Random Forest algorithm was applied, within which the predictors were ranked according to the decrease in model accuracy (Mean Decrease in Accuracy).

For winter wheat in both agroclimatic zones, the top predictors included indicators describing the thermal and moisture conditions of early summer and spring: the number of days with temperatures above 30°C in June, precipitation totals for May and April, the hydro-

thermal coefficient for May-June, and the minimum soil temperature in winter. For maize, the decisive role belonged to the conditions of the second half of summer during flowering and grain filling: the hydrothermal indices for July and August, the number of days with Tmax above 35°C in July, precipitation totals for July, and the mean July temperature. The obtained results were fully consistent with the biological nature of the crops: for winter wheat, spring vegetation conditions were critical, whereas for maize, the temperature-moisture balance during the formation of generative organs was decisive. The evaluation of model performance was conducted on an independent test sample (25% of the data), using the coefficient of determination (R^2) and the root mean square error (RMSE), as required by the methodology. The indicators are presented in Table 1.

Table 1. Performance indicators of MLR and RF models on the test sample

Model	Crop	Crop	R^2 (test)	RMSE (% test)
MLR	Winter wheat	Polissia	0.52	12.5
RF	Winter wheat	Polissia	0.71	8.9
MLR	Winter wheat	Forest-Steppe	0.55	14.1
RF	Winter wheat	Forest-Steppe	0.74	10.2
MLR	Maize	Polissia	0.49	15.0
RF	Maize	Polissia	0.68	11.5
MLR	Maize	Forest-Steppe	0.60	16.2
RF	Maize	Forest-Steppe	0.81	9.8

Source: developed by the authors

The analysis of the presented indicators demonstrated a consistent advantage of the Random Forest models over the linear models. For all crops and zones, the R^2 values of the RF models exceeded the corresponding MLR values by 0.16-0.21, while the RMSE was lower by 20-35%. The highest predictive accuracy ($R^2 = 0.81$) was provided by the models for maize in the Forest-Steppe zone, where the variability of yield was almost entirely determined by the climatic conditions of July-August. The superiority of the RF approach was methodologically expected: most agroclimatic indices had a nonlinear nature of influence, complex interactions and numerous threshold values (for example, sharp changes in productivity after exceeding temperature thresholds of 30-35°C), which could not be correctly represented by linear regression.

The obtained results confirmed that the decisive contribution to yield formation was made by the conditions during the reproductive phases of the crops. The presence of hydrothermal balance indices, extreme temperature indicators and cumulative precipitation values among the top predictors reflected the synergistic character of plant responses to the combination of thermal and moisture-related stresses. It was the ability of the RF algorithm to account for these interactions that ensured the high accuracy of the modelling.

The identified limitations of this study logically followed from the methodological choices applied. The spatial aggregation of ERA5-Land data to the regional level smoothed local microclimatic differences, and the use of a polynomial trend might not have captured abrupt changes in agricultural technologies in specific years. Furthermore, the models did not incorporate short-term adaptive actions by farmers or the potential effect of increasing atmospheric CO₂ concentration on the photosynthetic activity of the crops.

The identified patterns were consistent with global tendencies regarding the impact of climate change on agricultural crops, as outlined in the IPCC reports. In the document Climate Change and Land (2019), it was emphasised that the increasing frequency of heatwaves, the alteration of moisture regimes and the rise in the amplitude of climatic variability constituted key threats to agricultural systems. A similar dependence was confirmed by the obtained results: indices that characterised the combination of heat and moisture possessed the highest predictive weight, whereas extreme temperatures during critical developmental phases caused sharp productivity losses. The high sensitivity of yields to temperature thresholds aligned with the findings of R. Guntukula (2020), where it was demonstrated that major field crops in India responded more strongly to

short-term thermal anomalies than to average seasonal changes in temperature. A comparable pattern in the present results was exhibited by temperatures of 30–35°C, which caused the most pronounced deviations from trend-based values. The differences concerned the structure of climatic influence: in India, the decisive factor was the seasonal dynamics of monsoons, whereas in Polissia and the Forest-Steppe, short but intense episodes of heatwaves were the determining elements.

The sensitivity of maize to the hydrothermal regime of July and August was consistent with the findings of H. Gurkan *et al.* (2020), where it was established that similar periods of heat and precipitation deficit substantially reduced sunflower yield in Turkey. The common element was the phase-specific nature of crop responses: the most prominent influence occurred during the generative phases of development. At the same time, in Turkish conditions, the dominant factor was soil moisture deficit, while the influence of temperature was mitigated by the different climatic structure, which represented a key distinction from the situation in the Ukrainian Forest-Steppe. The patterns established for winter wheat corresponded with the findings of K. Heil *et al.* (2020). The authors noted that rising summer temperatures combined with alterations in the water balance led to significant yield fluctuations on loess soils in Central Europe. In their long-term experiment, the prominence of the soil factor was higher; however, atmospheric conditions remained the principal drivers of productivity, which fully corresponded to the directions of change identified in the present analysis.

The advantage of the Random Forest models confirmed the patterns described by V. Konduri *et al.* (2020), where machine learning models were shown to capture complex nonlinear and threshold relationships between climatic variables and crop yields with considerably higher accuracy. The high accuracy of the models for the Forest-Steppe reflected precisely the nonlinear structure of interactions characteristic of maize during periods of thermal stress. The use of phenologically specific indices was consistent with the approaches outlined by N. Kussul *et al.* (2020), who emphasised the need for high-temporal monitoring of vegetation states based on satellite imagery. The correlation with the conclusions of M. Yemelyanov *et al.* (2022) was also evident: the authors demonstrated that shifts in climatic regimes directly affected the spatial structure of crop distribution in Ukraine.

Additional confirmation was identified in the results of O. Zhygailo *et al.* (2021), where a decline in sunflower productivity under elevated temperatures in the Northern Steppe of Ukraine was described. Similar mechanisms of heat stress were evident in the established patterns for maize, which may have indicated a gradual shift of climatic zones. The synthesis of results demonstrated their clear consistency with contemporary scientific principles presented in the study by

V. Pepeliaev *et al.* (2023). In that work, the authors modelled the responses of various crops to changes in mean annual temperatures and established that even minor deviations from optimal thermal regimes were capable of causing abrupt changes in productivity. A comparable threshold-type influence of temperature was also detected in the present analysis: yield indicators decreased sharply after exceeding critical limits during the phase of active biomass accumulation. The distinction lay in the climatic context: in the modelling conducted by V. Pepeliaev *et al.*, the dominant factor was long-term warming, whereas in the regions examined in Ukraine, short and intensive heatwaves were more decisive.

Significant attention was drawn to the findings reported by T. Telo da Gama (2023), where the systemic significance of soil characteristics in either amplifying or mitigating climatic stressors was highlighted. The author substantiated that soil degradation, reductions in organic matter and deterioration of soil structure intensified the negative impact of thermal and moisture anomalies on crop productivity. A comparison of the established results with these principles indicated that within Polissia, soil properties partially compensated for moisture deficits, whereas in the Forest-Steppe they amplified the effect of heat stress. The common feature in both cases was the decisive role of the hydrothermal balance as a fundamental regulator of crop performance.

The study by N. Brannigan *et al.* (2022) focused on modelling erosion processes under future climate change and showed that the instability of temperature and precipitation was capable of transforming not only yield levels but also the structure of agro-landscapes. It was particularly emphasised that the increasing intensity of rainfall combined with summer heatwaves produced a spatially uneven distribution of productivity. A similar pattern of heterogeneity was identified in the analysis of Ukrainian regions, where intensifying climatic variability led to increased spatial contrasts in crop yields. At the same time, the mechanism of these disparities differed: in the work of N. Brannigan *et al.*, water erosion played the dominant role, whereas in Polissia and the Forest-Steppe, thermal and moisture deviations during the generative development of crops were the prevailing drivers.

Overall, the synthesis of findings indicated that the obtained patterns were fully aligned with the contemporary scientific consensus: the productivity of cereal crops was determined by the combination of temperature extremes, water regime and their synergy, while machine learning methods provided the most relevant tools for forecasting these complex interactions.

CONCLUSIONS

A comprehensive analysis of the climatic predictors of winter wheat and maize yields under the conditions of Polissia and the Forest-Steppe made it possible to

identify the patterns that determined crop responses to key weather factors. The application of statistical and machine-learning modelling methods demonstrated that the yields of both crops were formed mainly under the influence of integrated thermal and moisture indicators and extreme temperature regimes characteristic of critical phenological phases. The greatest contribution to the variability of winter wheat yields was provided by the number of days with temperatures above 30°C in June, the amount of precipitation in April-May and the hydrothermal coefficient in May-June. For maize, the decisive factors were the hydrothermal indicators of July-August, the frequency of temperature extremes above 35°C and the precipitation regime during the period of intensive grain filling.

The comparative evaluation of models demonstrated a substantial advantage of the Random Forest algorithm over multiple linear regression. Models constructed using Random Forest explained between 68-81% of yield variability, which confirmed the nonlinear nature of the relationships within the "climate-yield" system and the presence of critical sensitivity thresholds. The high predictive accuracy for maize in the Forest-Steppe indicated that yields in this region were largely determined by weather conditions in the second half of

summer. At the same time, the increasing importance of drought indices for Polissia served as evidence of climatic shifts that brought the conditions of the region closer to those of more southern climatic zones.

The obtained results emphasised the importance of using combined and extreme indices rather than mean seasonal meteorological parameters for yield forecasting. The applied methodology confirmed the effectiveness of machine-learning approaches in identifying key climatic dependencies and detecting nonlinear responses of agricultural crops. Prospects for further research lay in the transition from regional to pixel-level yield models, the integration of satellite data, the analysis of soil characteristics, the study of agronomic adaptation measures and the development of early-season risk-forecasting systems for agricultural production.

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Кліматичні предиктори урожайності сільськогосподарських культур Полісся та Лісостепу України

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Анотація. Метою роботи було визначення ключових кліматичних предикторів, які формують варіабельність урожайності озимої пшениці та кукурудзи в агрокліматичних умовах Полісся й Лісостепу. Методологія ґрунтувалася на використанні багаторічних метеорологічних даних у поєднанні зі статистичними та машинними алгоритмами моделювання, серед яких застосовувалися множинна лінійна регресія та Random Forest для порівняльної оцінки прогнозової ефективності. Також було реалізовано механізм визначення важливості змінних із метою встановлення найбільш інформативних кліматичних індикаторів. У ході дослідження було проаналізовано вплив температурних екстремумів, сумарного режиму атмосферних опадів та гідротермічних індексів у ключові фазові періоди розвитку культур. Було встановлено, що для озимої пшениці домінуючу роль відігравали умови квітня-червня, тоді як для кукурудзи найбільше значення мали теплово-вологісні параметри липня-серпня. Було виявлено, що інтегральні показники, зокрема гідротермічний коефіцієнт, забезпечують значно вищу прогностичну вагу порівняно з окремими температурними чи опадовими метриками. Було підтверджено наявність порогових реакцій культур на екстремальні кліматичні фактори, що зумовлювало відмінності між регіонами за рівнем чутливості до теплових хвиль і посух. Було узагальнено, що алгоритм Random Forest забезпечив найбільшу точність прогнозування, пояснюючи до 81 % варіабельності врожайності кукурудзи в Лісостепу та до 74 % – озимої пшениці. Практична цінність роботи полягає у можливості використання отриманих результатів аналітичними центрами, агрометеорологічними службами та агровиробниками для планування посівних площ, оцінювання ризиків сезонної урожайності та формування адаптаційних стратегій в умовах кліматичних змін

Ключові слова: агрокліматичні індекси; температурні екстремуми; гідротермічний режим; варіабельність продуктивності; машинне моделювання; Random Forest; кліматичні ризики; фазові стресори



Optimisation of mineral nutrition norms for sunflowers to increase yield

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Abstract. The aim of the study was to determine the optimal mineral nutrition rates for sunflower that ensured maximum yield and stable seed quality indicators within the Forest-Steppe zone of Ukraine. The methodology involved a two-year field experiment with four fertilisation variants (control, $N_{120}K_{80}$, $N_{120}P_{80}K_{80}$ and $N_{150}P_{80}K_{80}$), the assessment of morphometric parameters and yield, as well as laboratory analysis of the chemical composition of seeds. Statistical processing of the results was carried out using a comparative analysis approach with an evaluation of the relative increase in indicators compared to the control. It was found that sunflower responded to the level

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of mineral supply already at the early stages of development, with a strengthening effect during the formation of reproductive organs. It was established that the diameter of the head served as a sensitive indicator of fertilisation efficiency, with the highest values recorded under the $N_{120}P_{80}K_{80}$ variant. The yield dynamics were examined and a clear advantage of complete mineral nutrition was identified, ensuring an 83.3% increase in yield compared to the control. The oil output per hectare was analysed and found to rise to 0.73 t/ha under optimal fertilisation, indicating the efficient realisation of the crop's potential. It was summarised that excessive nitrogen supply did not always provide additional benefits, as it might lead to a redistribution of nutrients towards vegetative mass. It was confirmed that balanced NPK nutrition contributed not only to high yield formation but also to stable oil accumulation in seeds. The practical significance of the study lay in the possibility of applying the obtained recommendations by agricultural producers and agronomic services to optimise sunflower nutrition systems under conditions of climate change and resource constraints

Keywords: fertilisation; seed quality; oil content; photosynthetic activity; head diameter; agrotechnologies

INTRODUCTION

Sunflower (*Helianthus annuus* L.) was classified as a strategically important oilseed crop in Ukraine, as it formed the basis of the export potential of the agricultural sector and ensured food stability. Improving seed quality and cultivation efficiency was essential for industrial processing, while changing climatic conditions and unstable water regimes intensified the need for adapted plant nutrition technologies. The system of mineral nutrition served as a key factor in yield formation, maintenance of biochemical balance in the soil, and enhancement of plant tolerance to stress conditions. Therefore, the optimisation of fertiliser rates for modern sunflower hybrids was considered a relevant direction in agrarian science and practice, determining the efficiency of soil resource utilisation and production profitability.

Scientific studies confirmed a strong relationship between mineral element application rates and the morphological parameters of sunflower. According to V. Tsyhanskyi (2020), the adjustment of the soil nitrogen-phosphorus regime promoted proper development of seed chambers and increased the stability of reproductive growth. Similar conclusions were reported in the study by V. Hanhur *et al.* (2022), which demonstrated that the combination of NPK in balanced rates stimulated head growth and ensured uniform yield structure. It was evidenced that during the flowering stage, nutrient deficiencies most significantly disrupted the productive potential of the crop. The research by V. Petrenko *et al.* (2023) traced the territorial differentiation of oil content, confirming the dependency of seed quality on phosphorus availability. Several authors focused on the bioenergetic aspects of nutrition. According to V. Hanhur and O. Kosminsky (2024), proper dosing of mineral fertilisers influenced water consumption and the intensity of photosynthesis, which was particularly important in the Forest-Steppe zone.

One important aspect concerned the response of hybrids to mineral fertilisation. The significance of sowing time and nutritional management was highlighted in the work of O. Trembitska *et al.* (2025), where a combination of agrotechnical factors ensuring maximum

crop productivity was established. It was also essential to consider the risks associated with excessive nitrogen input. According to O. Sydiakina and M. Ivaniv (2023), exceeding the optimal fertiliser rates led to hypertrophic growth of vegetative biomass, which reduced seed quality and the efficiency of nutrient use. Hence, the need emerged to determine the threshold of technological feasibility for fertiliser application.

In international studies, particular emphasis was placed on the microbiological processes responsible for nutrient assimilation. The research by Y. Sun *et al.* (2025) revealed a dependence between the structure of the microbial community and phosphorus nutrition, which indirectly influenced the formation of reproductive organs. This position aligned with the findings of L. Hellal *et al.* (2025), who demonstrated that the combination of potassium and trace elements was capable of accelerating oil accumulation in seeds even under unstable water supply. The importance of a comprehensive approach to mineral nutrition was emphasised, with consideration of physiological, soil, and microbiological factors.

Thus, previous studies outlined general tendencies of increased sunflower reactivity to mineral nutrition; however, the parameters of optimal fertilisation rates for the soil and climatic conditions of the Forest-Steppe zone of Ukraine remained insufficiently specified. In this context, scientific interest was directed towards assessing the efficiency of different nutrition systems with regard to the physiology of modern hybrids and the stability of yield quality indicators. Therefore, the aim of the research was to determine the optimal mineral nutrition rates for sunflower that ensured the highest yield and superior seed quality under the experimental conditions.

MATERIALS AND METHODS

The research was conducted in 2023-2024 on the premises of BEL-AGRO LLC, located in the Berdychiv district of Zhytomyr region within the Forest-Steppe zone. The climate of the area was moderately continental with sufficient moisture, yet characterised by an unstable

distribution of precipitation during the vegetation period, which necessitated the optimisation of mineral nutrition to ensure stable sunflower productivity. The experimental plot was predominantly composed of dark grey podzolised soils, with the following nutrient contents recorded at the beginning of vegetation: nitrogen – 98 mg/kg (DSTU ISO 14255:2005, 2006), phosphorus – 104 mg/kg (DSTU 7865:2015, 2016), potassium – 112 mg/kg of soil (DSTU 7865:2015, 2016), and soil pH – 5.8 (DSTU 8346:2015, 2017). Four nutrition variants were established in the experiment, forming a gradient of NPK availability: control (no fertiliser), $N_{120}K_{80}$, $N_{120}P_{80}K_{80}$, and $N_{150}P_{80}K_{80}$. The experimental scheme allowed the assessment of not only the overall fertilisation effect but also the determination of the threshold of technological feasibility for nutrient application.

The experimental design aimed to determine the limit of technological expediency for mineral element application and to verify whether the increased nitrogen dose was economically justified. Fertilisers were applied both during primary tillage and as supplementary feeding. The sources of nutrients were ammonium nitrate (34.6%), double superphosphate (40%), and potassium chloride (60%). The research object was the hybrid sunflower 'Sumiko', sown within the optimal period for the cultivation zone at a rate of 55 thousand seeds per hectare and a row spacing of 70 cm. Agro-technical practices were implemented according to regionally accepted technology.

Plant monitoring was carried out throughout the vegetation period with the recording of reproductive

organ development, while primary measurements were conducted during the full maturity phase. The impact of mineral nutrition was assessed according to three groups of indicators:

- morphometric characteristics – head diameter as an indicator of reproductive potential formation;
- productivity – yield (t/ha) and weight of 1000 seeds;
- seed quality properties – oil content and oil output per unit of area.

Oil content was determined under laboratory conditions using mechanical pressing, which enabled the identification of the actual volume of oil potentially obtainable from 1 hectare of crops. Statistical data processing was conducted using comparative analysis with the calculation of relative increases in indicators compared to the control variant. This approach enabled the evaluation of both the agronomic and technological feasibility of each fertilisation level and the identification of the optimal boundaries for mineral fertiliser application. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

The conducted research demonstrated that the application of mineral fertilisers had a positive effect on this indicator. In the variant without fertiliser application, the head diameter measured 14.8 cm, which was the lowest among all experimental treatments. This indicated insufficient plant nutrition, which restricted growth and hindered the development of reproductive organs (Fig. 1).

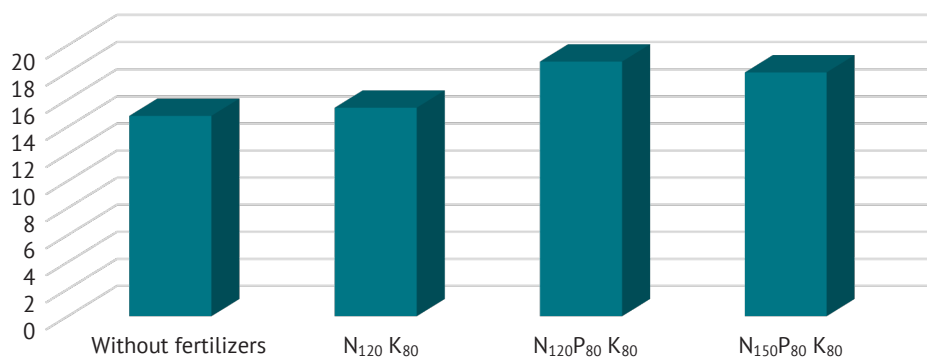


Figure 1. Head diameter at the full seed maturity stage of sunflower, cm (average for 2023-2024)

Source: created by the authors

The application of nitrogen-potassium fertilisation at a rate of $N_{120}K_{80}$ increased the average head diameter to 15.4 cm, which exceeded the control by 0.6 cm. This confirmed the positive role of nitrogen and potassium in the formation of generative organs. The largest head diameter was recorded in the treatment with complete mineral nutrition – $N_{120}P_{80}K_{80}$ – where it reached 18.8 cm. Compared to the control, this value was higher by 4.0 cm (27.0%), indicating a substantial

effect of phosphorus in combination with nitrogen and potassium on the development of the reproductive part of the plant. In the variant with an elevated nitrogen rate ($N_{150}P_{80}K_{80}$), the head diameter measured 18.0 cm, which also significantly exceeded the control (by 3.2 cm), although it was slightly lower than the optimal fertilisation variant. This may indicate that excessive nitrogen nutrition did not always provide an additional advantage and could lead to the redistribution of

nutrients towards vegetative biomass. Overall, the strongest positive effect on head diameter was observed in the $N_{120}P_{80}K_{80}$ treatment, which confirmed the expediency of applying a complete complex of mineral fertilisers in balanced rates.

The formation of high sunflower yield depended on a range of factors, among which rational mineral nutrition was one of the key determinants. Properly selected doses and proportions of nutrient elements – primarily nitrogen, phosphorus, and potassium – supported full plant growth and development, the formation of generative organs, and consequently an increase in yield and improvement in seed quality indicators. Therefore, particular importance was attached to studying

the response of modern sunflower hybrids to different fertilisation backgrounds, which enabled the scientific substantiation of optimal agrotechnical practices to achieve maximum productivity under specific soil and climatic conditions. The obtained results demonstrated a significant influence of mineral fertilisation on sunflower yield. The lowest yield was recorded in the control variant, where no fertilisers were applied – 1.8 t/ha (Fig. 2). The application of nitrogen-potassium fertiliser at the $N_{120}K_{80}$ rate increased the yield to 2.2 t/ha, which represented a 0.4 t/ha (22.2%) rise compared with the control. This confirmed the important role of nitrogen and potassium in the processes of growth, photosynthesis, and seed formation.

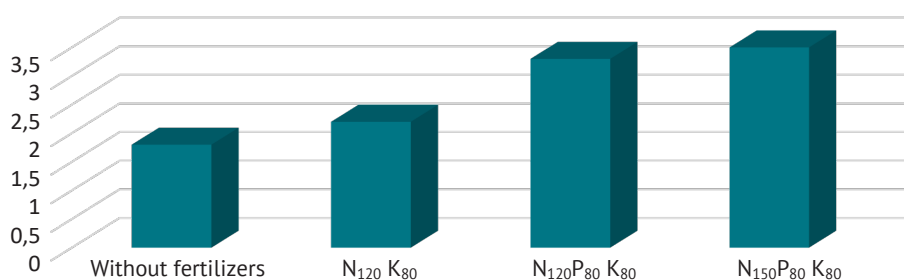


Figure 2. Effect of different fertiliser rates on sunflower seed yield, t/ha (average for 2023-2024)

Source: created by the authors

The highest efficiency was demonstrated by the treatments with complete mineral nutrition. In the $N_{120}P_{80}K_{80}$ variant, the yield reached 3.3 t/ha, which exceeded the control by 1.5 t/ha (83.3%). The application of an increased nitrogen rate in the $N_{150} P_{80}K_{80}$ treatment resulted in the maximum yield – 3.5 t/ha, which was 1.7 t/ha (94.4%) higher than the control and 0.2 t/ha (6.1%) greater than in the previous variant. According to the research findings, a clear trend was identified in the alteration of the chemical composition of sunflower seeds under the influence of different mineral fertilisation rates and the weather conditions of the cultivation years. The most pronounced variations occurred in the indicators of crude protein content and oiliness, which were the key quality parameters of oilseed raw material. During dry years, when plants experienced water deficit in critical development stages (flowering and seed filling), a reduction in seed fat

content was observed due to the disruption of photosynthetic processes and lipid assimilation.

The application of mineral fertilisers contributed to more active oil accumulation in sunflower seeds. The most significant increase in oil content was observed when balanced fertiliser rates were used, namely $N_{120}P_{80}K_{80}$ or $N_{150} P_{80}K_{80}$, which supplied the plants with essential nutrients throughout the entire vegetation period. The oil output was determined under laboratory conditions using a mechanical press. The lowest oil content recorded during the research period – 40.7% – occurred in the unfertilised variant. Under the $N_{150} P_{80}K_{80}$ treatment, the oil content was 8.6% higher than in the control, while under complete mineral fertilisation it was 6.4% higher, and 2% lower compared with the increased nitrogen rate. The calculation of oil yield per hectare of sunflower seed was performed (Fig. 3).

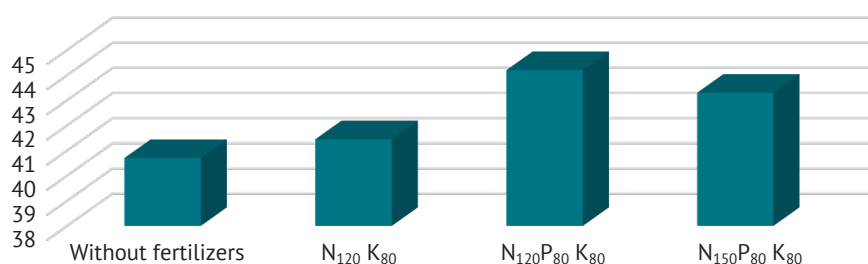


Figure 3. Oil output from seeds depending on different fertiliser rates, % (average for 2023–2024)

Source: created by the authors

Over the two years of field research, the amount of oil that could be obtained from 1 hectare of sunflower crops was determined. On average, this indicator reached 0.73 t/ha, which was considered a rather high result for this zone. The highest oil output was recorded in the variants where mineral fertilisers were applied at optimal and elevated rates. Under optimal mineral nutrition, the oil yield increased by 37.5% compared with the control treatment, where no fertilisers were applied. Even better results were observed under the elevated fertiliser rate, where oil yield rose by 44.4% relative to the control and by 6.9% compared with the $N_{120}P_{80}K_{80}$ variant. This indicated that the application of mineral fertilisers had a positive effect not only on seed yield but also on oil content.

The obtained results indicated that balanced mineral nutrition using the full fertiliser complex at the $N_{120}P_{80}K_{80}$ rate provided the most pronounced positive impact on morphometric parameters, yield, and oil output of sunflower under Forest-Steppe conditions. The increase in head diameter to 18.8 cm and the rise in yield to 3.3-3.5 t/ha corresponded well with the position that an optimal nutrition regime formed not only the mass of the yield but also the structure of reproductive organs. Similar trends were described in the monograph by Ye. Domaratskyi *et al.* (2020), which emphasised that an environmentally balanced system of sunflower fertilisation, with a focus on balanced NPK rates, ensured a substantial productivity increase alongside stable soil conditions.

The sunflower's sensitivity to the mineral nutrition background identified in the research correlated with the findings of O. Sakharchuk and L. Garbar (2018), who demonstrated that the optimisation of nutrition conditions could increase yield by 60-90% compared with the control due to the rational proportion of nitrogen, phosphorus, and potassium. In the conducted study, the yield increase reached 83.3% in the $N_{120}P_{80}K_{80}$ treatment and 94.4% in the $N_{150}P_{80}K_{80}$ treatment, which fell within the range comparable to the cited data. However, the results additionally highlighted that excessive nitrogen nutrition was not accompanied by a corresponding improvement in morphometric parameters, particularly head diameter.

The plant response to different nutrition variants also corresponded to the concept of resource provision in productivity formation, as outlined in the study by G. Pinkovsky *et al.* (2019), where it was demonstrated that a fertilisation system could simultaneously maintain soil fertility and ensure consistently high yields, provided crop rotation constraints were observed. The obtained data confirmed that under dark grey podzolised soils with moderate nutrient content, only complete mineral fertilisation enabled the realisation of the hybrid's productive potential. In this context, the results aligned with the conclusions of Z. Dehtiarova (2023), who emphasised that an increased share of

sunflower in short-rotation crop rotations without balanced fertilisation led to soil depletion and a reduced crop response to mineral fertilisers.

The established dependency of yield and oil output on mineral nutrition rates was consistent with the findings of Ye. Domaratskyi *et al.* (2022), which highlighted the pivotal role of water consumption and nutrition in the productivity formation of high-oleic hybrids under increasing climatic variability. In the present study, higher fertiliser rates contributed to better utilisation of moisture and more stable yield formation, which was indirectly supported by the findings of L. Harbar *et al.* (2025), where it was shown that the water consumption regime of sunflower was significantly influenced by technological elements, including nutrition. Overall, the observed increase in yield and oil output could be regarded as the combined effect of mineral provision and water regime.

The improvement in morphometric parameters recorded in the treatments with complete mineral nutrition supported the conclusions of L. Harbar and V. Avramchuk (2024) concerning the sensitivity of hybrids' biometric parameters to nutrition conditions and growth regulators. In both cases, the enhancement of biometric characteristics was viewed as a key link mediating the influence of agrotechnical practices on yield level. In the conducted research, head diameter proved to be a sensitive indicator that clearly responded to changes in NPK rates, with the highest values recorded under balanced combinations of nitrogen, phosphorus, and potassium. Comparison of the study results with the data of H. Drobitko *et al.* (2024) revealed certain differences in approach. While their research focused on resource-saving technologies combined with adapted hybrids in southern regions, the present study concentrated on classical mineral nutrition under Forest-Steppe conditions. However, both studies highlighted that the effectiveness of technology was determined by the interaction between varietal-hybrid characteristics and a properly selected fertilisation system.

The data by V. Gurtovenko (2025) indicated that sunflower productivity in the Right-Bank Forest-Steppe depended not only on nutrition but also on the system of primary tillage and the use of soil herbicides. The current research complemented this perspective by clarifying that under standard technology, the $N_{120}P_{80}K_{80}$ treatment could be considered a baseline for achieving consistently high yield indicators without excessive nitrogen input. A promising direction for further optimisation of nutrition involved the integration of mineral fertilisers with biological preparations, as confirmed by the research of V. Bolokhovskiy *et al.* (2024), where the possibility of increasing nutrient use efficiency and reducing chemical load through biological agents was demonstrated. In combination with the conclusions of Yu. Shkatula and

A. Kravets (2025), who examined mineral nutrition of sunflower in an agroecological context, the results of the present study indicated the feasibility of transitioning from mere intensification of NPK rates to the development of balanced nutrition models focused on agroecosystem sustainability.

Taking into account the conclusions of L. Xue *et al.* (2023) regarding differences in the chemical composition of edible oils and the importance of qualitative parameters of the lipid fraction, the increase in seed oiliness and oil output in the variants with complete mineral nutrition acquired not only agronomic but also technological significance. This highlighted that the optimisation of sunflower mineral nutrition should be viewed as a tool for enhancing the competitiveness of raw materials in the edible oil market rather than solely as a means of increasing gross yield. The conducted analysis confirmed the key role of balanced mineral nutrition in sunflower productivity formation. The most effective rate was $N_{120}P_{80}K_{80}$, which ensured an optimal balance of yield and seed quality without excessive resource expenditure. Alignment of the results with modern research confirmed the scientific validity of the experiment and its practical relevance for agro-technologies in the Forest-Steppe zone of Ukraine.

CONCLUSIONS

The conducted research confirmed that the mineral nutrition system was a decisive factor in shaping sunflower yield and seed quality characteristics. It was established that the crop response to NPK supply levels manifested already at the early stages of morphogenesis and intensified during the formation of generative organs, demonstrating a direct dependence of productive potential on the optimisation of mineral nutrition. A detailed analysis of morphometric indicators showed that head diameter, plant height, and leaf apparatus development were sensitive indicators of fertilisation efficiency. The lowest values of these parameters were recorded in the control treatment, indicating limitations

in reproductive organ development under conditions of insufficient nutrition.

The optimal response was observed in the $N_{120}P_{80}K_{80}$ treatment, where not only an increase in biometric indicators was recorded, but also the highest yield level. The elevated nitrogen rate ($N_{150}P_{80}K_{80}$) ensured the maximum yield increase; however, the results indicated a likely shift toward excessive vegetative growth at the expense of seed quality, emphasising the need to identify an economically and physiologically justified nutrient balance. Analysis of the chemical composition of seeds demonstrated that balanced nutrition promoted active accumulation of protein and oil, and optimal fertiliser rates could compensate for climatic stresses, which was particularly important in zones with unstable moisture regimes.

The determination of oil yield per hectare confirmed the high effectiveness of optimal fertilisation, which resulted in a 37.5% increase compared with the control. The synthesis of results indicated that the $N_{120}P_{80}K_{80}$ combination created the most favourable conditions for realising the genetic potential of the hybrid and maintaining the agroecological sustainability of production. The research demonstrated that a rational nutrition system was key to production intensification without compromising seed quality or soil fertility. A promising direction for further studies involved the analysis of adaptive mineral nutrition schemes considering climate fluctuations and the use of biostimulants in combination with NPK systems.

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CONFLICT OF INTEREST

The authors of this study declare that there is no conflict of interest.

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Оптимізація норм мінерального живлення соняшнику для підвищення врожайності

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Анотація. Метою дослідження було встановити оптимальні норми мінерального живлення соняшнику, які забезпечують максимальну врожайність та стабільні якісні показники насіння в зоні Лісостепу України. Методологія включала проведення дворічного польового експерименту з чотирма варіантами удобрення (контроль, $N_{120}K_{80}$, $N_{120}P_{80}K_{80}$ та $N_{150}P_{80}K_{80}$), визначення морфометричних показників, урожайності та лабораторний аналіз хімічного складу насіння. Статистична обробка результатів здійснювалася за принципом порівняльного аналізу з оцінкою відносного приросту показників відносно контролю. У ході роботи було визначено, що реакція соняшнику на рівень мінерального забезпечення проявляється вже на ранніх фазах розвитку та посилюється при формуванні репродуктивних органів. Було встановлено, що діаметр кошика є чутливим індикатором ефективності живлення, а найбільші значення цього показника зафіксовано у варіанті $N_{120}P_{80}K_{80}$. Було досліджено динаміку урожайності та виявлено чітку перевагу повного мінерального живлення, яке забезпечило приріст урожайності на 83,3 % порівняно з контролем. Проаналізовано вихід олії з 1 гектара посівів, який збільшився до 0,73 т/га за оптимального удобрення, що свідчить про ефективну реалізацію потенціалу культури. Було узагальнено, що надмірне азотне живлення не завжди забезпечує додаткову перевагу, оскільки може спричинити перерозподіл поживних речовин у бік вегетативної маси. Підтверджено, що збалансоване NPK-живлення сприяє не лише формуванню високого врожаю, а й стабільному накопиченню олії у насінні. Практична цінність дослідження полягає у можливості використання отриманих рекомендацій агровиробниками та агрономічними службами для оптимізації системи живлення соняшнику в умовах змін клімату та ресурсних обмежень

Ключові слова: удобрення; якість насіння; олійність; фотосинтетична активність; діаметр кошика; агротехнології



Variability and adaptability of winter soft wheat lines according to thousand-grain weight

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Abstract. The search for winter wheat genotypes with a high and stable expression level of valuable agronomic traits, including thousand-grain weight, is a relevant task for breeders under conditions of agricultural intensification. The aim of the study was to identify winter wheat lines with a high level of expression of thousand-grain weight and high adaptive indices for further use in breeding practice. Mathematical and statistical methods and regression analysis were used in the calculations. The adaptability of the lines was assessed by the integrated index of adaptability rating, using a set of stability and plasticity estimates. Contrasting weather conditions in 2019/20-2022/23 made it possible to identify adaptive lines for large grain size. It was found that the highest (47.9 g) mean thousand-grain weight was observed in the 2022/23 season, which was favourable in terms of weather conditions, and the minimum (41.3 g) in the dry 2019/20 season. A significant variability of trait expression was revealed depending on the conditions of the year (53.7%), genotype (27.3%) and

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the interaction (13.6%). Lines ER 60667, ER 60724 and LIUT 60680, which significantly exceeded the experiment mean, were identified. According to the regression coefficient, the lines were divided into three groups: highly plastic ($b_i = 1.06-1.60$), stable ($b_i = 0.36-0.96$) and medium-plastic ($b_i = 0.97-1.04$). From a practical point of view, the most valuable lines in terms of the trait were the most adaptive ones – highly plastic ER 60667, ER 60724 and the low-plastic LIUT 60680. An increased level of adaptability was noted for the medium-plastic lines LIUT 60430 and LIUT 60734 with an optimal response to improved growing conditions. The selected genotypes are valuable initial material in breeding for adaptability in terms of thousand-grain weight. Taking into account the yield level and the complex of traits, the obtained genotypes can be submitted as new winter wheat varieties for State varietal testing at the Ukrainian Institute for Plant Variety Examination (UIPVE)

Keywords: wheat; meteorological conditions; regression coefficient; phenotypic stability; homeostasis; breeding value

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a vital crop that ensures food security worldwide and is a globally important source of nutrients. As noted by A. El Baouchi *et al.* (2024), wheat end-use products play an important role in human nutrition, providing up to 20% of daily protein intake and 21% of caloric intake. The authors also emphasise that the expected increase in the world's population to 9 billion people by 2050 will require an increase in global wheat production by about 70%. A. Ingver *et al.* (2024) underline that yield is the main breeding target, while quality traits that determine the nutritional value and technological properties of grain are also important. To meet the growing demand for wheat consumption, it is necessary to focus on breeding improvement strategies aimed at key parameters: yield, adaptability, grain size, and quality characteristics, including morphological traits of the caryopsis and protein content. Climate change poses a serious threat to crop production worldwide; therefore, varieties adapted to specific regions are needed. According to A.C. Kyrtzizis *et al.* (2022), new varieties must combine high stable yield with the necessary quality traits. This can be achieved only by using appropriate parental components in breeding programmes.

Genotype plays an important role in the formation of yield and grain quality. O.L. Ulich *et al.* (2022) state that productivity is determined by the plant's potential and its ability to realise this potential under specific growing conditions. The yield level of wheat is closely related to such complex traits as earliness, vernalisation period, photoperiod response, plant height and tolerance to abiotic stresses. However, the linear dimensions of the caryopsis, as shown by I. Al-Ashkar *et al.* (2023), also play an important role in raising yield and correlate with it due to the stability and influence on grain mass. According to V. Torianyk and V. Vasilenko (2023), thousand-grain weight is a species-specific indicator that largely depends on the variety and seed formation conditions. In cereals, it indirectly determines grain size and filling, the technological qualities of the variety and its productivity, and also indirectly characterises increased drought tolerance.

Therefore, despite the low level of modification variability, evaluation of breeding material for adaptability in terms of grain size is necessary when creating new adaptive varieties under conditions of climate warming. B.M. Sewore and A. Abe (2024) demonstrated the importance of selecting genotypes that are stable under temperature stress.

In conformity with Yu.O. Chernobai and V.K. Riabchun (2022), despite different inheritance types of this trait depending on the parents' genotypes, selection for thousand-grain weight is effective in genera closely related to wheat. For example, in winter rye considerable success has been achieved in fixing the trait over many years. X. Hu *et al.* (2023) emphasise that phenotyping for thousand-seed weight in combination with modern genome sequencing technologies (GBS) makes it possible to predict inheritance of this trait in hybrids and thus increase breeding efficiency by forecasting and selecting only promising crossing combinations. In addition, J. Ma *et al.* (2025) state that significant progress has been made in identifying quantitative trait loci that can also be used for selection at the genetic level. Therefore, the aim of this work was to determine the degree of variability of the trait "thousand-grain weight" in winter wheat lines and to identify those lines most adaptive to changing environmental conditions.

MATERIALS AND METHODS

The study was carried out in 2019/20-2022/23 in the fields of the breeding crop rotation of the Winter Wheat Breeding Laboratory at the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Agrarian Sciences of Ukraine (MIW). The material for the study comprised eighteen breeding lines of winter wheat under competitive testing, differing in vegetation period length, morphological characteristics and potential yield level compared with the reference variety Podolianka. Sowing was performed with an SN-10C drill after soybean as the preceding crop, in the first ten-day period of October, under less dry weather conditions. The seed sowing rate was 5.0 million viable seeds per hectare. The accounting plot area was 10 m², and the

experiment was laid out in four replicates. The material was harvested with a Hege-125 combine. Records and observations were carried out in accordance with the method of State variety testing (Tkachyk, 2016). Thousand-grain weight was determined on RADWAG AS 220. R2 analytical scales (CAS MWP-300; max.: 300 g; min.: 0.2 g; e = d = 0.01 g).

To determine the influence of year conditions on trait formation, the following indices were used: "hydrothermal coefficient" (HTC), "environment index" (EI) and "relative environment index" (REI) (Vlasenko *et al.*, 2012).

$$REI = 100\% + (Pr - \bar{P})/\bar{P}100\%, \quad (1)$$

where Pr is the biometric indicator of the mean value of a specific trait for all lines in a particular year; \bar{P} is the mean value of the trait for all lines over the entire study period.

The optimum value was taken as 100%. When the values fluctuate within 83-117% (favourable conditions according to HTC) the values are close to the norm; below 83% the values are significantly low, above 117% the values are significantly high; 58-83% and 117-133% indicate moderately unfavourable conditions; below 58% and above 133% indicate unsatisfactory conditions. Statistical analysis was performed using STATISTICA 8.0 software. The "Descriptive Statistics" function was used to calculate the main statistical parameters – mean (\bar{X}), minimum (x_{min}), maximum (x_{max}) and standard deviation (σ).

$$\bar{X} = \sum x_i / n, \quad (2)$$

where x_i is the trait value; n is the total number of variants (sample size).

Significant differences and the coefficient of variation (V) were calculated according to Dospekhov (1985):

$$V = (\sigma/\bar{x}) * 100, \quad (3)$$

where \bar{x} is the genotype-averaged arithmetic mean; σ is the standard deviation.

Indices of stress tolerance ($x_{lim} - x_{opt}$) and genetic flexibility ($(x_{opt} + x_{lim})/2$) were determined according to the equations of Rosielle & Hamblin (1981), taking x_{lim} as the lowest value and x_{opt} as the highest value. The indices of homeostasis (Hom) and breeding value (Sc) were calculated following Hangildin & Litvinenko (1981):

$$Hom = (\bar{x} \times \bar{x})/\sigma, \quad (4)$$

$$Sc = (\bar{x} \times (x_{lim}/x_{opt})), \quad (5)$$

where \bar{x} is the genotype-averaged arithmetic mean; σ is the standard deviation.

Ecological plasticity (bi) and phenotypic stability (S^2_{di}) were assessed according to Eberhart &

Russell (1966). The regression coefficient (b_i) was calculated using the formula:

$$b_i = \sum_j Y_{ij} I_j / \sum_j I_j^2, \quad (6)$$

where b_i is the regression coefficient of thousand-grain weight for each i th genotype in the environment; Y_{ij} is the thousand-grain weight of the i th genotype under any j conditions; I_j is the environmental index, i.e. the difference between the mean value of thousand-grain weight for all genotypes under these conditions (year) and the overall mean for the experiment.

The variance of deviations from the regression line (S^2_{di}) was calculated as:

$$S^2_{di} = \sum (Y_{ij} - (\bar{x} + b_i I_j))^2 / (n - 2), \quad (7)$$

where Y_{ij} is the actual thousand-grain weight (g) of the i th genotype under any j conditions; \bar{x} is the genotype-averaged arithmetic mean; b_i is the regression coefficient (thousand-grain weight); I_j is the index of the j -th conditions.

Ranking of statistical indicators was carried out according to Snedecor (1961), with ranks denoted as Z . The mean trait value in the experiment, or the mean numerical value of a statistical indicator, was used as the baseline for comparison in the analysis. To assess the level of adaptability and differentiate it according to characteristics of different dimensions and units of measurement, an integrated parameter – the "variety adaptability rating" (VAR) – was calculated (Vlasenko *et al.*, 2012). To calculate the adaptability rating of breeding lines in terms of thousand-grain weight, it was necessary to normalise the arithmetic mean of thousand-grain weight by dividing it by the mean value of the sum of ranks, so that the contribution of high genetic potential would be decisive in this integrated parameter. In the rank assessment, higher positions were assigned to the following indicators: with higher numerical values – (\bar{X}), (x_{min}), (x_{max}), ($x_{opt} + x_{lim}$)/2, (Hom), (Sc), with lower values – ($x_{lim} - x_{opt}$), (V), (S^2_{di}). According to the regression coefficient, the highest rank was assigned to breeding lines with a plasticity value (bi) closest to 1.0. Ranks decreased with increasing deviation from unity in both directions – upward and downward.

Weather conditions during the study period differed from long-term averages in terms of moisture supply and temperature regime (Table 1). In 2019/20, 374 mm of precipitation fell during the vegetation period, in 2020/21 – 597 mm, in 2021/22 – 468 mm and in 2022/23 – 769 mm, with a long-term average of 615 mm. At the same time, an increased (+0.4°C to +2.0°C) mean air temperature was noted in different years relative to the norm, as well as dry conditions before sowing, at sowing and in spring after the resumption of vegetation.

Table 1. Meteorological indicators of the vegetation period of winter wheat in 2019/20–2022/23

Month	Amount of precipitation per month, mm					Average monthly air temperature, °C				
	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	Precipitation LTA, mm	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	Temperature LTA, °C
VIII	10	8	88	84	53.9	20.4	21.1	20.5	21.6	20.4
IX	12	21	19	118	56.6	15.8	18.5	13.2	12.9	14.5
X	7	22	18	30	40.3	11.0	13.2	7.6	8.2	8.7
XI	17	28	26	81	40.1	4.8	3.8	4.8	3.8	2.1
XII	36	38	63	43	42.3	2.8	-0.3	-1.1	0.2	-1.6
I	20	57	23	11	36.9	0.8	-2.3	-1.2	-0.1	-3.4
II	40	49	9	28	31.8	2.4	-4.7	1.7	-0.5	-2.2
III	15	28	10	46	34.2	6.6	2.3	2.3	5.2	2.3
IV	48	47	86	85	44.9	9.5	7.7	8.4	9.3	9.8
V	92	87	29	21	51.4	12.8	14.5	14.6	15.5	15.7
VI	57	100	42	39	84.8	21.7	20.1	20.7	19.7	19.3
VII	21	111	55	184	71.7	21.7	23.3	20.4	20.9	21.1
X	31	50	39	64	49.1	10.9	9.8	9.3	9.7	8.9
Total for the vegetation period	374	597	468	769	588.9					
HTC for the vegetation period	0.6	1.03	0.8	1.52						
HTC for IV–VI	0.80	2.5	0.80	0.90						

Note: LTA – long-term average; VP – vegetation period; HTC – hydrothermal coefficient

Source: compiled by the authors based on data from the Myronivka Agrometeorological Station

The 2019/20 period was characterised by drought conditions (HTC = 0.6) under elevated temperature regimes, which had a significant negative impact on winter wheat yield formation. Early spring vegetation recovery (2 March) took place under severe drought: in March, the moisture deficit was 24 mm with an air temperature increase of +4.2°C above the norm. In April, the average monthly indicators were within the norm – 48 mm of precipitation and 9.5°C respectively. May had sufficient precipitation (92 mm) but a lower temperature regime (-2.9°C below the norm), which led to a prolonged ear formation period (18-28 May). In June, 57 mm of precipitation fell, with a moisture deficit of 30 mm and an average air temperature of 21.7°C (+2.4°C above the norm). A prolonged June drought during the grain formation and filling stages, combined with high daytime temperatures (26.8°C, absolute maximum – 33.7°C), caused a reduction in grain size and fullness.

In 2020/21, a slightly elevated temperature regime (+0.9°C above the norm) and sufficient precipitation (597 mm; HTC = 1.03) improved plant moisture supply and contributed to the formation of an adequate productivity level. Spring vegetation began on 26 March. March was cold, with a large number (15 days) of frosts, ranging from -2.2°C to -7.8°C. In April, a temperature drop was observed, with night frosts reaching -0.2°C to -2.1°C (first decade). May was marked by reduced temperatures and significant daily fluctuations, with differences reaching 18.5°C, resulting in a delay in the onset of heading (25-30 May) and uneven flowering. In June and July, adverse weather conditions such as local heavy rains and squalls led to partial lodging of winter wheat crops.

The 2021/22 period was defined as a year of mild drought (HTC = 0.9) with a precipitation deficit of 121 mm and an annual mean air temperature close to the norm. Vegetation resumed on 21 March under adequate moisture supply and average air temperatures. In April and May, the air temperature was 1.4°C and 1.0°C below the long-term average respectively, while in June it exceeded the norm by 1.5°C. April showed excessive moisture, with precipitation exceeding the norm by 41.0 mm. However, from May to July a precipitation deficit of 82 mm was recorded (compared with the long-term average of 208 mm). The beginning of heading was noted between 21 and 26 May. Overall, insufficient moisture was observed during the spring–summer vegetation period (HTC = 0.8).

The 2022/23 period was excessively wet (HTC = 1.52). Early spring vegetation recovery (8 March) under gradually rising temperatures (1.9°C above the norm) promoted good root development and the formation of a strong vegetative mass. During the spring–summer period, a moisture deficit was observed (30-45 mm for May–June). April precipitation (198% of the norm) under near-average air temperature, evenly distributed across the first two decades, had a positive effect on grain yield levels. Climatic summer began in mid-May. The start of heading was recorded between 20 and 25 May. Adverse weather conditions were observed in July, with record high air temperatures (32.1°C) and excessive moisture (260% of the norm; HTC = 2.8), accompanied by thunderstorms and squalls. Favourable hydrothermal conditions during the winter wheat vegetation period significantly contributed

to the formation of a high productivity potential. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Phenotypic plasticity is the ability of a genotype to show phenotypic variability under different environmental conditions (Saieed *et al.*, 2024), which is inherent in a limited number of economically valuable traits (Han *et al.*, 2025). It is an important property that is extremely necessary as a component of the varietal profile under conditions of intensification of agriculture. That is, it is the ability to respond positively to the optimisation of important agrometeorological or agrotechnical measures. At the same time, the results of individual studies indicate that genomic regions associated with yield do not fully overlap with regions associated with its phenotypic plasticity (Giordano *et al.*, 2025). This makes it possible to assume that, at least partially, selection for high plasticity may be effective. As a rule, the greatest attention of researchers is

directed towards the analysis of the interaction of the yield trait and environmental factors, to which a significant number of publications are devoted. However, the general patterns of this interaction may differ considerably if the variability of each trait is considered separately. The most plastic components of the yield structure in wheat are the traits “number of ears per plant” and “number of spikelets per ear”, as well as “thousand grain weight” (Saieed *et al.*, 2024). Therefore, the study of the patterns of the inheritance may be important for understanding yield formation under diverse conditions. In this process, various statistical approaches to the analysis of the adaptive potential of the studied trait may be effective.

In the present study, weather conditions had different effects on the formation of grain size in winter wheat lines. Over the years of the study, thousand grain weight varied within quite a wide range (36.7-52.1 g), with a mean value of 44.4 g. It was established that the lowest mean value (41.3 g) was observed in the dry 2019/20 season with an environmental index $EI = -3.15$ g, and a slightly higher one (42.3 g, $EI = -2.15$ g) in 2020/21 (Table 2).

Table 2. Degree of expression and variation of thousand grain weight (g) in winter wheat lines, 2019/20-2022/23

Line name	Weight of 1000 grains, g				\bar{X}
	Year				
	2020	2021	2022	2023	
Podolyanka, standard	40.8	43.0	46.3	48.2	44.6
ER 60667	44.1	45.3	50.8	52.1	48.1
ER 60724	43.0	46.7	50.2	50.6	47.6
LIUT 60734	45.5	42.9	51.2	49.5	47.3
ER 60793	40.2	46.8	47.8	50.1	46.2
LIUT 60815	40.7	41.2	48.4	50.5	45.2
LIUT 60355	41.7	43.1	48.1	47.0	45.0
LIUT 60680	41.9	44.2	45.1	48.3	44.9
LIUT 60430	42.5	41.8	46.3	48.7	44.8
LIUT 60608	42.0	42.3	45.6	49.2	44.8
LIUT 60816	37.1	42.4	47.4	48.7	43.9
LIUT 60510	40.9	41.9	45.2	47.7	43.9
LIUT 60766	38.9	41.6	46.6	48.6	43.9
LIUT 60763	42.5	41.9	42.9	48.2	43.9
LIUT 60412	40.9	39.7	45.1	46.3	43.0
LIUT 60181	42.4	40.7	43.1	44.8	42.8
LIUT 60492	40.2	39.7	43.7	44.9	42.1
LIUT 60729	41.8	39.0	41.5	43.4	41.4
LIUT 60702	36.7	39.9	44.3	42.9	41.0
\bar{X}	41.3	42.3	46.3	47.9	44.4
max	45.5	46.8	51.2	52.1	48.1
min	36.7	39.0	41.5	42.9	41.0
CV	5.2	5.2	5.8	5.2	4.4
EI	-3.18	-2.12	1.86	3.44	
REI	93	95	104	108	
HIP ₀₅			2.52		

Note: \bar{X} , max, min – mean, maximum and minimum value of the indicator, g; CV, % – coefficient of variation (Dospekhov, 1985); EI – environmental index, g; REI – relative environmental index, % (Vlasenko *et al.*, 2012)

Source: compiled by the authors

Significantly higher values (46.3 g, EI = 1.86 g) were recorded in 2021/22, and the maximum ones (47.9 g, EI = 3.44 g) – in the meteorologically favourable 2022/23 season, which indicated the potential for grain size in this set of lines. Over the study period, under the conditions of 2019/2020 and 2020/2021, a small proportion of lines formed a 1000 grain mass of less than 40 g – 16.7% and 22.2% respectively. The largest range of variation in 1000 grain mass was in 2021/22 (41.5-51.2 g) and 2022/23 (42.9-52.1 g), and the smallest – in 2020/21 (39.0-46.8 g). At the same time, the level of variability of the trait was low (CV, % = 5.3-6.0%) and depended on the hydrothermal conditions of the year. The REI value, calculated for the trait, indicates that the conditions of the growing seasons for grain formation and filling were within the normal range – 93%, 95%, 104% and 108%. According to the REI value (53%, 107%, 99% and 140%), the nature of the factor's effect on yield level was clearer – 3.39 t/ha, 6.82 t/ha, 6.29 t/ha and 8.89 t/ha respectively. The results of analysis of variance reliably confirmed the considerable influence of the year (53.7%) and genotype (27.3%) and of the interaction (13.6%) on the formation of 1000 grain mass in the winter wheat lines. The high contribution of the first factor to the level of variability of the trait was confirmed by the significant difference in the mean value for the trial in years with contrasting weather conditions (the dry 2019/20 and the favourable 2022/23 seasons). Similar studies carried out on common wheat cultivars in the Canadian prairies under different moisture regimes also confirmed the large contribution of the year and, in particular, of the water regime to the expression of thousand grain mass and other traits related to yield (Sangha *et al.*, 2025).

During the study period, the more large-grained lines belonged to the erythrosperrum variety type. Lines that differed significantly from the trial mean and from the standard Podolianka were: with higher values – ER 60667 (48.1 g), ER 60724 (47.6 g), LIUT 60734 (47.3 g); with lower values – LIUT 60729 (41.4 g) and LIUT 60702 (41.0 g). The other eleven lines formed grain of a size comparable with the standard and with the trial mean. The considerable influence of genotype

on expression of the trait in the above-mentioned lines was confirmed by the ranking (first to third place each year). Among these lines, ER 60667 was distinguished by the maximum 1000 grain mass in the favourable 2023 season and in the trial overall – 52.1 g and 48.1 g respectively. This line belongs to the group with a short vegetation period: every year it headed first among the studied assortment, three days after the local early-ripening control cultivar (Myronivska rannostyhla). In the other lines, the heading stage occurred five to six days later, almost simultaneously with the standard Podolianka. The maximum value in the trial was obtained in the line LIUT 60734 under the dry conditions of the 2019/2020 growing season as a whole and in April-June 2022 – 45.5 g and 51.2 g respectively, which indicates its tolerance to moisture deficit and its ability to respond adequately to stress.

Analysis of adaptability parameters made it possible to identify winter wheat lines that combined a high 1000 grain mass, as an important indicator of productivity, with resistance to changing environmental conditions. The maximum level (x_{max}) of the trait (43.4-52.1 g) in the vast majority (83%) of lines was observed in the favourable 2022/23 season (Tables 2, 3). Nine lines exceeded the standard Podolianka, of which the best were ER 60667 (52.1 g), ER 60724 (50.6 g) and ER 60793 (50.1 g). One of the important indicators of adaptability is the genotype's resistance to stress, which is characterised by the level of minimum values under unfavourable conditions (x_{min}). Under the difficult (drought) weather conditions of 2019/20, eight lines together with the standard formed a minimum 1000 grain mass of 36.7-40.9 g. A smaller response (41.7-42.5 g), which indirectly characterises increased drought tolerance, was observed in the remaining lines. The highest lower threshold of the studied trait (x_{min}) was recorded in LIUT 60734 (45.5 g), ER 60667 (44.1 g) and ER 60724 (43.0 g) (Table 3). In 2020/21, under late heading in over-moistened conditions in May-June against a background of reduced temperature regime and partial lodging (5-7 points) of the stands, a 1000 grain mass of less than 40 g was observed in the tall lines LIUT 60412, LIUT 60492, LIUT 60702 and LIUT 60729.

Table 3. Parameters and adaptability rating for 1000 grain mass in winter wheat lines, 2019/20-2022/23

Line name	Statistical parameters											
	\bar{X} -Z	x_{max} -Z	x_{min} -Z	$(x_{max} + x_{min})/2$ -Z	$x_{min} - x_{max}$ -Z	CV-Z	Hom-Z	Sc-Z	b_1 -Z	S^2_{diff} -Z	ΣZ -Z	VAR
Podolianka, st.	44.6-9	48.2-10	40.8-9	44.5-10	-7.4-11	7.4-10	600-9	37.7-10	1.04-4	0.33-3	8.5	5.244-9
ER 60667	48.1-1	52.1-1	44.1-1	48.1-1	-8.0-13	7.3-9	583-11	40.7-1	1.25-10	0.13-1	4.9	9.811-1
ER 60724	47.6-2	50.6-3	43.0-2	46.8-3	-7.6-12	7.8-12	640-6	40.5-2	1.06-5	2.06-13	6.0	7.938-2
LIUT 60680	44.9-7	48.3-9	41.9-5	45.1-7	-6.4-6	4.2-1	760-3	38.9-5	0.77-9	1.62-11	6.3	7.123-3
LIUT 60430	44.8-8	48.7-7	41.8-6	45.3-5	-6.9-9	6.6-5	618-8	38.5-7	1.00-1	0.95-7	6.3	7.115-4

Table 3. Continued

Line name	Statistical parameters											
	$\bar{X} - Z$	$x_{max} - Z$	$x_{min} - Z$	$(x_{max} + x_{min})/2 - Z$	$x_{min} - x_{max} - Z$	CV-Z	Hom-Z	Sc-Z	$b_1 - Z$	$S^2_{di} - Z$	$\sum Z - Z$	VAR
LIUT 60734	47.3-3	51.2-2	42.9-3	47.1-2	-8.3-14	8.9-14	593-10	39.6-3	1.00-1	6.42-18	7.0	6.754-5
LIUT 60355	45.0-6	48.1-12	41.7-7	44.9-9	-6.4-5	7.1-7	661-5	39.0-4	0.91-6	1.71-12	7.3	6.161-6
LIUT 60608	44.8-8	49.2-6	42.0-4	45.6-4	-7.2-10	6.7-6	595-18	38.2-8	1.03-3	1.15-8	7.5	5.970-7
LIUT 60510	43.9-10	47.7-13	40.9-8	44.3-11	-6.8-8	7.7-11	619-7	37.7-10	0.98-2	0.24-2	8.2	5.357-8
LIUT 60181	42.8-13	44.8-16	40.7-10	42.8-15	-4.1-1	5.0-2	1076-1	38.8-6	0.44-13	1.43-10	8.7	4.914-10
LIUT 60763	43.9-11	48.2-11	41.9-5	45.1-8	-6.3-4	7.3-9	661-5	38.1-9	0.72-11	4.90-17	9.0	4.875-11
LIUT 60492	42.1-14	44.9-15	39.7-12	42.3-16	-5.2-3	5.9-3	691-4	37.2-11	0.79-8	0.47-6	9.2	4.579-12
ER 60793	46.2-4	50.1-5	40.2-11	45.2-6	-9.9-17	8.0-13	503-13	37.1-2	1.14-7	7.48-19	10.7	4.320-13
LIUT 60815	45.2-5	50.5-4	40.7-10	45.6-4	-9.8-16	12.6-17	410-16	36.4-14	1.57-14	0.40-5	10.5	4.305-14
LIUT 60412	43.0-12	46.3-14	39.7-12	43.0-13	-6.6-7	7.2-8	579-12	36.9-13	0.97-3	1.31-9	10.3	4.175-15
LIUT 60729	41.4-15	43.4-18	39.0-13	41.2-17	-4.4-2	5.0-2	943-2	37.2-11	0.36-16	2.99-14	11.0	3.766-16
LIUT 60766	43.9-10	48.6-8	38.9-14	43.8-12	-9.7-15	10.4-15	433-15	35.2-15	1.40-12	0.38-4	12.0	3.660-17
LIUT 60702	41.0-16	44.3-17	36.7-16	40.5-18	-7.6-12	6.5-4	497-14	33.9-16	0.96-4	3.34-15	13.2	3.102-18
LIUT 60816	43.9-11	48.7-7	37.1-15	42.9-14	-11.6-18	12.2-16	365-17	33.4-17	1.60-16	3.62-16	14.6	3.007-19
\bar{X}	44.4	48.1	40.7	44.4	7.4	7.6	622.4	37.6	1.0 0	2.15	8.5	

Note: \bar{X} – mean value of thousand grain weight, g; Z – rank; x_{max} , x_{min} – maximum and minimum thousand grain weight, g; $(x_{max} + x_{min}) / 2$ – compensatory capacity; $(x_{min} - x_{max})$ – stress tolerance, g; CV – coefficient of variation, %; Hom – homeostasis; Sc – selection value of the genotype; b_1 – coefficient of linear regression; S^2_{di} – mean-square deviation; $\sum Z$ – sum of ranks; VAR – variety adaptability rating; LIUT – *Lutescens*; ER – *ErythrospERMum*

Source: compiled by the authors

The level of resistance of the lines to stressful growing conditions is an important indicator, which shows the difference between the minimum and maximum value of the trait with a negative sign. The smaller it is, the higher the stress tolerance, or stability, and the wider the range of adaptive possibilities of the genotype (Rosielle & Hamblin, 1981). The indicator $(x_{min} - x_{max})$ ranged from -4.1 g to -11.6 g. The highest resistance and stability were manifested by the lines with a low level of x_{max} – LIUT 60181 (-4.1 g), LIUT 60729 (-4.4 g), LIUT 60492 (-5.1 g). These lines were also characterised by low variability of this trait according to the coefficient of variation (CV) as a relative indicator of variability (5.0-5.9%). In the vast majority of lines, the level of thousand grain weight varied slightly (CV = 4.1-10.4%), except for LIUT 60816 and LIUT 60815, with medium variability (12.2% and 12.6% respectively) and with the highest value of stress tolerance – -11.6 g and -9.8 g respectively. The mean coefficient of variation in the experiment, 7.6%, confirmed the low variability of the trait. The characterisation of the lines in terms of stress tolerance is complemented by the index of genetic flexibility $(x_{lim} + x_{opt})/2$, which reflects the average yield of genotypes in contrasting (optimal and limiting) conditions and characterises the compensatory capacity, and indicates the degree of correspondence between the genotype and the environment. The highest index of genetic flexibility in contrasting conditions was found in lines ER 60667 (48.1 g), ER 60724 (47.0 g) and

LIUT 60734 (46.7 g), which had the highest minimum and maximum values of the trait. When studying and analysing the ecological stability and adaptability to different environments of winter wheat varieties, other researchers selected varieties with maximum productivity and yield stability, which indicates the relative effectiveness of this method (Konovalova *et al.*, 2024).

The term homeostasis (Hom) is understood as the ability of plants to maintain internal balance and realise the genetic potential of a variety under changing environmental conditions (Hangildin & Litvinenko, 1981). It is known that genotypes with high homeostasis (Hom) respond less to the deterioration of conditions and respond well to the improvement. Hom is calculated as the ratio of the genotype-averaged arithmetic mean to the mean square deviation. The analysis of variability in terms of homeostasis and resistance to unfavourable external environmental factors for thousand grain weight showed that its highest value was in winter wheat lines LIUT 60181 (Hom = 1076), LIUT 60729 (Hom = 943) and LIUT 60680 (Hom = 760). That is, the realisation of the genetic potential took place under different growing conditions, which is important in the period of global climate change. With the help of the breeding value indicator (Sc), it is possible to identify genotypes that combine a high or medium thousand grain weight with its stable realisation under variable growing conditions. The assessment according to this indicator showed a range of variation within 33.4-40.7.

The lines with the best breeding value were ER 60667 ($Sc = 40.7$); ER 60724 ($Sc = 40.5$); LIUT 60734 ($Sc = 39.6$).

Important characteristics of the adaptability of genotypes to environmental conditions are the ecological plasticity and stability (Hangildin & Litvinenko, 1981). Plasticity is assessed by the regression coefficient (b_i), which is a criterion for assessing the level of ecological plasticity and indicates the reaction of the genotype to changes in growing conditions. According to this indicator, the lines were divided into three groups: intensive type ($b_i > 1$); stable ($b_i < 1$) and adapted to different conditions ($b_i = 1$). The higher the value of b_i , the more sensitive the genotype is to changes in growing conditions, for example, to the level of agronomic practices, mineral nutrition, etc. Genotypes with $b_i > 1$ and its variation from 1.06 to 1.60 can be considered intensive for this trait, which respond strongly to changes in environmental conditions. With $b_i < 1$, which is close to zero, the genotype reacts less to changes in environmental conditions than the average of the studied assortment. Lines with low b_i values (0.36-0.96) showed only a weak response to improved growing conditions, which determines the value in terms of stability, because under minimal inputs such lines can still achieve maximum productivity. Lines with a regression coefficient within 0.97-1.04, together with the standard Podolianka, were more adapted to various environmental conditions and optimally (adequately) responded to the changes. The highest rank for this parameter was held by lines with b_i closest to one. In the study by N. Săulescu *et al.* (2025), nine semi-dwarf winter wheat varieties were evaluated in 63 multifactor field trials conducted in different regions of Romania during 2021-2024. Yield data were analysed using analysis of variance (ANOVA) to assess the effects of environment, genotype, and the interaction. Phenotypic plasticity and stability were determined by such indicators as the coefficient of variation, Wricke's ecovalence, Finlay-Wilkinson regression coefficients and rank dispersion. In addition, regression and correlation analyses were used to assess the response of varieties to environmental conditions and to identify relationships between stability and plasticity indicators. The results showed considerable variation between varieties, with some combining high yields with increased stability under different growing conditions.

In the study by C. Adams *et al.* (2025), yield, plasticity, and stability of 45 winter wheat varieties were analysed based on the results of many years of field trials in the north-western USA. Using Finlay-Wilkinson regression analysis, the authors revealed significant differences between varieties in the response to environmental conditions and established that the main share of yield variation (over 80%) was due precisely to the influence of the environment. On the basis of regression coefficients, an integrated performance indicator was developed, which makes it possible to effectively rank varieties by a combination of high yield,

plasticity, and stability. Similar results on yield variation were obtained in the present study.

The variance of trait stability (S^2_{di}), defined as the mean-square deviation from the regression line, reveals the degree of variability of the studied genotypes and the degree of stability of the response to environmental conditions. The closer the S^2_{di} indicator is to zero, the less the empirical values of the trait differ from the theoretical ones located on the regression line. The range of variation in the differences in thousand grain weight according to the stability parameter was 0.13-7.48. Genotypes with the lowest S^2_{di} values for the trait can be considered more stable under different environmental conditions. According to the combination of the two above-mentioned indicators, the lines with higher stability, compared with the mean ($S^2_{di} = 2.15$) value in the experiment, were: intensive – ER 60667 ($b_i = 1.25$, $S^2_{di} = 0.13$), LIUT 60815 ($b_i = 1.57$, $S^2_{di} = 0.40$), LIUT 60766 ($b_i = 1.40$, $S^2_{di} = 0.38$); stable (low-plastic) LIUT 60492 ($b_i = 0.79$, $S^2_{di} = 0.47$); medium-plastic – LIUT 60510 ($b_i = 0.98$, $S^2_{di} = 0.24$), LIUT 60430 ($b_i = 1.00$, $S^2_{di} = 0.95$), LIUT 60412 ($b_i = 0.97$, $S^2_{di} = 1.31$). Low stability coefficients were recorded in ER 60793 ($b_i = 1.14$, $S^2_{di} = 7.48$), LIUT 60734 ($b_i = 1.00$, $S^2_{di} = 6.42$), LIUT 60763 ($b_i = 0.72$, $S^2_{di} = 4.90$), LIUT 60702 ($b_i = 0.96$, $S^2_{di} = 3.34$), LIUT 60816 ($b_i = 1.60$, $S^2_{di} = 3.62$), LIUT 60729 ($b_i = 0.36$, $S^2_{di} = 2.99$). Thus, not all lines that were characterised by lower plasticity indicators ($b_i = 0.36-0.96$), which may indicate the stability, also had low stability coefficients (S^2_{di}), stress tolerance ($x_{min} - x_{max}$) and coefficient of variation (CV). Therefore, to select the best genotypes, it is necessary to take into account all adaptive statistical parameters.

For a comprehensive assessment of the level of adaptability of winter wheat lines according to parameters that characterise its various features, non-parametric statistical methods and the generalised indicator "variety adaptability rating" – VAR (Demydov *et al.*, 2023) were used. Lines that had the best ratio of thousand grain weight and statistical parameters of adaptability occupied higher positions in the variety adaptability rating. Determining the position of lines in the VAR (taking into account the genetic potential of this trait) showed that the most adaptable were the intensive ER 60667 and ER 60724, which were distinguished by the highest mean, maximum and minimum values of the trait. The class with the highest overall adaptive capacity also included the lines: homeostatic, low-plastic LIUT 60680 and medium-plastic LIUT 60430 and LIUT 60734 with an optimal response to improved growing conditions. All of these lines occupied higher positions in the VAR ranking (1st-5th). The next group with medium overall adaptive capacity for this trait included the lines that occupied 6th to 11th positions in the ranking, among which LIUT 60181 and LIUT 60492 were distinguished by increased stability according to the indicators ($x_{min} - x_{max}$), CV, S^2_{di} . The remaining lines belonged to the class with low overall adaptive capacity (12th-19th

positions). These lines in the experiment had poorer values of statistical parameters, both in terms of the individual values and in terms of the mean rank in the ranking. Within this group, the highly plastic genotypes LIUT 60815, LIUT 60766 had increased stability of the trait, whereas ER 60793, LIUT 60816 had low stability. The obtained data demonstrate some differences in the ranking of genotypes according to the sum of the mean rank values of the calculated statistical parameters and the combined indicator “variety adaptability rating”, which confirms the significant contribution of the genotype to the formation of the trait “thousand grain weight”.

Thus, stability is one of the basic traits that is evolutionarily necessary for survival in interaction with a changing external environment. Some researchers point to an analogy of such a process in the creation of varietal mixtures, because in nature pure populations are rarely found, whereas mixtures of genotypes and even species predominate. Under artificial mixtures, the spike density changed the most, which had a positive effect on the plasticity of thousand seed weight, yield and biomass, and a negative effect on protein content. In practice, it is quite realistic to increase thousand seed weight by means of long-term repeated selection, but it should be borne in mind that the constant increase of this trait must be analysed in combination with other traits of yield structure.

CONCLUSIONS

Based on the results of the conducted study, it can be stated that assessment of adaptability according to grain size can be an important component of the breeding process in creating new adaptive winter wheat varieties under climate change conditions. A significant range of variation in thousand grain weight of winter wheat lines was revealed, depending on the weather conditions of the year and genotype. Reliable differences in genotype response to changes in year conditions were established. The maximum mean value over the study period was recorded in the favourable 2022/23 season. A significant influence of year (53.7%), genotype (27.3%) and the interaction (13.6%) on the formation of large grain was confirmed. Lines ER 60667 (48.1 g), ER 60724 (47.6 g), LIUT 60734 (47.3 g) differed significantly from the mean experimental value in the

direction of increasing the trait. For the studied set of genotypes grown in the Forest-Steppe zone under certain agrometeorological conditions, it was determined that high values of adaptability parameters, namely the mean value for the experiment, maximum and minimum values, compensatory ability, stability of realisation and response to growing conditions, made it possible to identify winter wheat lines that combined high thousand grain weight with resistance to environmental changes. The best according to the integrated assessment based on the variety adaptability rating (VAR) were the intensive lines ER 60667 (early-ripening, stable), ER 60724 and LIUT 60680 (homeostatic). The class with the highest overall adaptive ability also included the medium-plastic lines LIUT 60734 and LIUT 60430, adapted to different growing conditions. The selected lines are valuable initial material in breeding for adaptability according to thousand grain weight. In the course of the study, the best winter wheat samples in terms of plasticity, ER 60667 and ER 60724, were selected; these samples can be submitted for state variety testing at the UIPVE (Ukrainian Institute for Plant Variety Examination) in 2026. Given the importance and objectivity of evaluating genotypes according to adaptability parameters in different environments, it is planned to continue studying the initial material created for a complex of valuable traits at the final stages of the breeding process. The use of selection by thousand grain weight at the early stages of the breeding process makes it possible to select genotypes with high yield potential and production value, which has been confirmed by the example of the Myronivka breeding centre.

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CONFLICT OF INTEREST

All authors declare no conflict of interest in writing the article.

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Мінливість і адаптивність ліній пшениці м'якої озимої за масою 1000 зерен

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Анотація. Пошук генотипів пшениці озимої, які мають високий і стабільний рівень прояву цінних господарських ознак, в тому числі маси 1000 зерен, є актуальним завданням для селекціонерів в умовах інтенсифікації сільського господарства. Мета роботи передбачала виділення ліній пшениці озимої із значним рівнем прояву маси 1000 зерен та високими адаптивними показниками для подальшого використання в селекційній практиці. У обрахунках використовували математично-статистичні методи, регресійний аналіз. Оцінку адаптивності ліній проводили за інтегрованим показником рейтингу адаптивності, використовуючи сукупність оцінок стабільності та пластичності. Контрастні погодні умови 2019/20–2022/23 рр. дали можливість виділити адаптивні лінії за крупнозерністю. Досліджено, що найвищу (47,9 г) середню масу 1000 зерен спостерігали в сприятливому за погодними умовами 2022/23 р. а мінімальну (41,3 г) – у посушливому 2019/20 рр. Виявлено значну варіабельність прояву ознаки залежно від умов року (53,7 %), генотипу (27,3 %) та їх взаємодії (13,6 %). Визначено лінії EP 60667, EP 60724 і ЛЮТ 60680, які суттєво перевищували середній показник по досліді. За коефіцієнтом регресії лінії розподілили на три групи: високопластичні ($b_i = 1,06-1,60$), стабільні ($b_i = 0,36-0,96$) і середньопластичні ($b_i = 0,97-1,04$). Практичну цінність за ознакою мають найбільш адаптивні лінії – високо пластичні EP 60667, EP 60724 та низькопластична ЛЮТ 60680. Підвищений рівень адаптивності відмітили для середньопластичних ліній ЛЮТ 60430 і ЛЮТ 60734 з оптимальною реакцією на покращення умов вирощування. Виділені генотипи є цінним вихідним матеріалом у селекції на адаптивність за масою 1000 зерен. З урахуванням рівня їх урожайності та комплексу ознак отримані генотипи можуть бути передані як нові сорти пшениці озимої на державну кваліфікаційну експертизу в Український інститут експертизи сортів рослин (УІЕСР)

Ключові слова: пшениця; метеорологічні умови; коефіцієнт регресії; фенотипічна стабільність; гомеостатичність; селекційна цінність



Herbicide impacts on bee pollination and yield interactions in sunflower production

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Abstract. This study aimed to quantify and compare the effects of soil-applied and post-emergence herbicide programmes on bee visitation and seed yield of sunflower hybrids under contrasting seasonal conditions in the Eastern Steppe of Ukraine. Field experiments were conducted during 2022-2024 in Vasylivka (Dnipropetrovsk region), using three hybrids (Biloba CLP, NK Neoma, Suvex), a hand-weeded control, two soil-applied programmes (Primextra TZ Gold + Yastryb; Eclipse + Filder) and several post-emergence options (Helianthex, Stels, Challenge, Pulsar Flex, Granstar) applied according to label instructions. Managed colonies were stocked at 5 hives ha⁻¹ with standardised flight distance. Pollinator activity during anthesis was monitored using 24 GoPro cameras (10:00-12:00; four days; three replicates) and expressed as visits head⁻¹ 10 min⁻¹, while yield (t ha⁻¹ at 7% moisture) was assessed post-harvest. Weather conditions varied markedly, including severe drought in 2024. The control treatment recorded the highest bee visitation (mean 6.11 visits head⁻¹ 10 min⁻¹). Soil-applied programmes reduced visitation by 29-56%, with the smallest decrease under Primextra TZ Gold + Yastryb (-29%) and the largest under Eclipse + Filder (-56%). Post-emergence treatments reduced visitation by 33-86%; Challenge (0.4 L ha⁻¹) had the least impact (-33%), whereas Helianthex (45 g ha⁻¹) showed the greatest reduction (-82%). Visitation was strongly influenced by year (\approx 4.5-5.0 in 2022-2023 vs 1.28 in 2024). Yield responses partially diverged: among soil-applied options, Eclipse + Filder showed the smallest mean reduction (-0.31 t ha⁻¹; -8%), followed by Primextra TZ Gold + Yastryb (-0.35 t ha⁻¹; -9%); among post-emergence options, Stels performed best (-0.58 t ha⁻¹; -15%), outperforming Challenge (-0.76 t ha⁻¹; -20%) and Helianthex (-27%). Overall, soil-applied herbicides were associated with lower risk to pollinator activity and yield compared with post-emergence ALS/imidazolinone chemistries, while drought exerted a dominant limiting effect on both processes. Integrating pollinator-sensitive herbicide selection with seasonal risk management may help sustain ecosystem services and productivity

Keywords: sunflower; bee visitation; herbicide programs; pollinator attractiveness; yield

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INTRODUCTION

Sunflower (*Helianthus annuus* L.) had been recognised as a crop of strategic significance, serving as a major source of vegetable oil and export revenue in Ukraine. Its economic relevance depended not only on genetic improvement and agronomic technologies but also on reliable pollination processes, which determined yield formation and oil quality (Amarilla *et al.*, 2025). The increasing climatic instability, intensification of herbicide regimes and fragmentation of pollinator habitats had intensified the vulnerability of pollination services, positioning sunflower cultivation at the intersection of agronomy and ecosystem functioning. Within this context, the need to identify cultivation practices that preserved pollinator activity while ensuring agronomic performance had emerged as a major research priority.

Pollination by insects, primarily *Apis mellifera*, had been shown to markedly improve seed set, oil content and commercial quality parameters. According to the findings of G.J. Brewer *et al.* (2023), bee visitation enhanced seed weight and germination capacity. L.D. Amarilla *et al.* (2025) demonstrated that pollination significantly increased yield components and oil concentration. In Ukraine, analogous patterns were reported: I.M. Kulynych and T.M. Soloviova (2021) observed 20-47% increases in hybrid seed productivity under managed bee pollination, while P. Herasymiuk *et al.* (2025) found that exclusion of pollinators reduced seed weight by up to 2.3 times and decreased overall yield by 57%. These observations confirmed that pollinator presence constituted a critical agronomic factor in sunflower production systems.

Environmental conditions had also been demonstrated as key determinants of pollination efficiency. X. Chen *et al.* (2023) established that moisture deficit and heat stress altered photosynthetic activity, flowering dynamics and nectar secretion, leading to lower visitation rates. Similar effects were reported by Q. Ali *et al.* (2024), who indicated that water deprivation and sowing time jointly affected plant–pollinator relationships and seed yield. Landscape structure further shaped pollinator communities: K. Lajos *et al.* (2021) demonstrated that habitat simplification and monocropping reduced insect diversity and sunflower visitation. This aligned with global assessments suggesting broad dependence of agricultural systems on pollinator-mediated services (Silva *et al.*, 2021).

The influence of chemical inputs – including herbicides – had increasingly been recognised as a constraining factor for pollinator behaviour. Evidence from L. Russo *et al.* (2023) indicated that herbicide use reduced nectar quality and visitation frequency. Sublethal effects of neonicotinoids on wild bees and yield formation were recorded by M.S. Saleem *et al.* (2023), while L.T. Ward *et al.* (2023) reported negative impacts of seed treatments even when chemical residues were not detected in floral tissues. At the broader

agroecological scale, S. Boinot *et al.* (2024) identified that herbicide intensity reduced floral diversity and constrained pollinator networks. Although these studies advanced current understanding, most were conducted outside sunflower systems or under controlled conditions, leaving limited evidence on the interaction between herbicide programmes and pollination dynamics under real field conditions.

Research on mitigation strategies highlighted opportunities for preserving pollinator activity within intensive production systems. The establishment of flower strips and semi-natural vegetation had been shown to promote bee visitation and stabilise yield formation in sunflower (Mota *et al.*, 2022). More recent work by D. Bertleff *et al.* (2025) demonstrated that organic farming and habitat diversification differentially affected wild pollinators and honeybees, resulting in improved crop performance. N-fertilisation and plant nutrition were also suspected to interact with pollination processes: P. Wu *et al.* (2021) established that soil nitrogen availability and bee abundance jointly modulated fruit quality in high-input agricultural landscapes, suggesting analogous dynamics for sunflower hybrids.

The Eastern Steppe of Ukraine represented a particularly vulnerable production zone. Drought, high temperatures and chemical stress coincided during the growing season, impairing nectar secretion and increasing hybrid sensitivity to herbicide exposure. Niche analyses of keystone pollinators conducted by D. Li *et al.* (2024) further highlighted the climatic risks facing *Apis mellifera* populations. Despite the prevalence of these conditions, few studies had directly examined how contrasting herbicide programmes shaped pollination and yield outcomes in Eastern Europe. Most prior research had investigated either pollination benefits or pesticide effects in isolation, without integrating them in long-term field conditions. Therefore, a clear knowledge gap remained concerning how weed-control chemistry influenced bee behaviour and hybrid-specific yield under diverse hydrothermal regimes.

Given the agronomic dependency of sunflower on pollinators and the operational necessity of herbicide use, identifying safe management strategies had become a critical requirement for sustainable production systems. The study aimed to generate practical evidence supporting herbicide strategies that safeguard pollinator activity while maintaining high agronomic performance.

MATERIALS AND METHODS

Research was conducted during 2022-2024 at the experimental field of the State Institution “Institute of Grain Crops of the National Academy of Agrarian Sciences of Ukraine” (Vasylivka, Dnipropetrovsk Oblast; coordinates: 48.2769004 N, 34.9405689 E). The trial covered three consecutive growing seasons characterised

by contrasting hydrothermal conditions. Experimental plots measuring 21.5 m × 2.8 m were established in a randomised block design with three replications.

Sowing of the sunflower hybrids Biloba CLP, Suvex, and NK Neoma was carried out simultaneously according to the scheme presented in Table 1.

Table 1. Experimental design for evaluating honeybee pollination of sunflower under different herbicide-based weed management technologies

Herbicide technology	Hybrid
Control (hand weeding)	Biloba CLP
	NK Neoma
	Suvex
Soil-applied herbicide (Primextra TZ Gold (Atrazine, 320g/ml +S-Metolachlor, 400 g L ⁻¹) 4,5 L ha ⁻¹ + Yasryb (Glyphosate potassium salt, 441 g L ⁻¹)2,0 l/ha	Biloba CLP
	NK Neoma
	Suvex
Soil incorporated: Eclips (Prometrin, 500 g L ⁻¹) 2,0 L ha + Filder (propisochlor, 720 g L ⁻¹) 2,0 L ha	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Helianthex (galoxyphen-methyl, 68.5 g L ⁻¹) 45 g ha ⁻¹	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Stels (Flurochloridone, 250 g L ⁻¹) 0,35 L ha ⁻¹	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Challenge (Aclonifene, 600 g L ⁻¹) 0,4 L ha ⁻¹	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Pulsar Flex (Imazamox, 25 g L ⁻¹) 1.6 L ha ⁻¹	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Granstar (Tribenuron-methyl, 750 g kg ⁻¹) 40 g ha ⁻¹	Biloba CLP
	NK Neoma
	Suvex

Source: developed by the author

The study was conducted under conditions including a control treatment (hand weed removal) and the application of various herbicides (soil-applied and post-emergence) that were applied in accordance with the manufacturer's recommendations. Bee colonies were established in the experimental field at a rate of 5 colonies per 1 ha. The colonies were positioned so that the route length from the apiary to all experimental plots was the same. For the purpose of recording bee visits, GoPro video cameras were installed on the plots under study during the sunflower flowering period. A total of 24 cameras were installed. Video recording was carried out from 10:00 to 12:00 (30 min for each replication + 30 min for moving the equipment) and over four days. In total, the cameras were set in three replicates. After analysing the video camera data, indicators of flower attractiveness to bees were analysed and a point-based scoring system was developed (the mean number of visits per head per 10 minutes, where 1 visit was equivalent to 1 point and 10 visits to 10 points), and yield (in t ha⁻¹, 7% moisture) was assessed for the three sunflower hybrids: Biloba CLP, NK Neoma, Suvex.

The experimental period (2022-2024) was characterised by considerable variability in climatic conditions, particularly in the amount and monthly distribution of precipitation, which directly affected sunflower growth and yield (Table 2). In 2022, the total precipitation during the growing season (April-September) was 209.3 mm, which was significantly lower than the long-term average (by 23.7 mm). The main deficit occurred in May (19 mm) and June (29 mm), causing water stress at critical growth and development stages such as early vegetative growth, flowering, and seed filling. These conditions led to reductions in yield and oil content. In 2023, precipitation for the same period totaled 246 mm, exceeding the long-term average by 13 mm. Precipitation in April (102 mm) substantially exceeded the long-term average by 57 mm, providing adequate moisture for early plant development. However, a pronounced moisture deficit was observed in May and June. July precipitation (42 mm) partially offset the water shortage but simultaneously caused lodging in some plots, which negatively affected yield. In 2022 and 2023, the sums of active temperatures (1559 and 1651°C days) were sufficient for medium-early hybrids (1700-2100°C days).

Table 2. Average daily temperature (°C) and total precipitation (mm) during the study period, 2022-2024

Year	Month						Difference from the long-term average
	April	May	June	July	August	September	
Average daily temperature (°C)							Sum of active temperatures (°C days)
2022	11.8	16.4	21.6	24.3	23.8	17.2	+71 (1559)
2023	12.0	17.2	22.0	25.0	24.5	18.0	+163 (1651)
2024	15.5	16.4	23.2	26.6	24.6	21.0	+610 (2098)
3-year average	12.1	16.7	22.3	24.5	23.8	17.4	+281 (1769)
Long-term average	11.8	16.4	20.2	22.4	21.6	16.2	0 (1488)
Total precipitation (mm)							Precipitation deviation from the long-term average (mm)
Year	April	May	June	July	August	September	
2022	45.3	19.0	29.0	35.0	46.0	35.0	-23.7
2023	102.0	29.0	29.0	42.0	30.0	14.0	+13
2024	14.0	12.0	29.0	44.0	1.6	11.0	-121.4
3-year average	53.8	20.0	29.0	40.3	39.2	29.7	-21
Long-term average	45	29	34	42	45	38	0

Source: developed by the author

In 2024, precipitation during the growing season totaled 111.6 mm, which is 121.4 mm below the long-term average. The moisture deficit was especially pronounced in May (12.0 mm) and August (1.6 mm), which are critical periods for vegetative growth and seed filling. The sum of active temperatures reached a level optimal for medium-maturing hybrids (2100-2300°C-days), indicating unfavorable thermal conditions for the medium-early hybrids used in the study. Additionally, the lack of precipitation substantially affected sunflower development, leading to reduced yield and deterioration of quality.

RESULTS AND DISCUSSION

The control treatment (hand weeding) provided the highest average attractiveness to bees (6.11 visits per head per 10 minutes). The application of herbicides reduced this indicator in all treatments, although the magnitude of the effect depended on the product used (Table 3). Thus, soil-applied herbicides generally caused a reduction in bee visitation to sunflower heads by an average of 29–56%. The smallest negative effect

was observed with the tank mix of Primextra TZ Gold 4.5 L ha⁻¹ + Yastryb 2.0 L ha⁻¹, under which bee visitation decreased by an average of 29% compared with the control. At the same time, the tank mix of Eclipse 2.0 L ha⁻¹ + Filder 2.0 L ha⁻¹ led to an even more pronounced decrease in attractiveness to bees: in this variant, visitation decreased by an average of 56% compared with the control.

The post-emergence herbicides under study showed an even more negative impact, reducing the attractiveness of sunflower plants to bees by 33-86%. The smallest impact among the post-emergence treatments was recorded with Challenge at 0.4 L ha⁻¹, where bee visitation to heads decreased by an average of 33% relative to the control, whereas the variant with Helianthex at 45 g ha⁻¹ had the worst effect – the attractiveness to bees decreased by an average of 82%. It is worth noting that bee visitation of sunflower plants depended greatly on the growing year. In the favorable years 2022 and 2023, average visitation of heads was 4.5-5.0 per 10 minutes, whereas in the drought-prone 2024 season this indicator averaged 1.28 per 10 minutes (Table 3).

Table 3. Effect of herbicide programs on attractiveness to bees (2022-2024)

Herbicide technology (A)	Hybrid (B)	Attractiveness to bees, visits per head (10 min) each year (C)				Mean increase relative to the control	
		2022	2023	2024	average	ct/head	%
Control (hand weeding)	Biloba CLP	7.00	9.00	2.00	6.00	-	-
	NK Neoma	7.00	9.00	5.00	7.00	-	-
	Suvex	6.00	9.00	1.00	5.33	-	-
	Average	6.67	9.00	2.67	6.11	-	-
Soil-applied herbicide (Primextra TZ Gold 4.5 L ha ⁻¹ + Yastryb 2.0 L ha ⁻¹)	Biloba CLP	6.00	6.00	2.00	4.67	-1.33	-22
	NK Neoma	5.00	8.00	2.00	5.00	-2.00	-29
	Suvex	5.00	4.00	1.00	3.33	-2.00	-37
	Average	5.33	6.00	1.67	4.33	-1.78	-29

Table 3. Continued

Herbicide technology (A)	Hybrid (B)	Attractiveness to bees, visits per head (10 min) each year (C)				Mean increase relative to the control	
		2022	2023	2024	average	ct/head	%
Soil-applied herbicide: Eclipse 2.0 L ha ⁻¹ + Filder 2.0 L ha ⁻¹ .	Biloba CLP	4.00	3.00	1.00	2.67	-3.33	-56
	NK Neoma	4.00	3.00	1.00	2.67	-4.33	-62
	Suvex	5.00	3.00	0.00	2.67	-2.66	-50
	Average	4.33	3.00	0.67	2.67	-3.44	-56
Post-emergence herbicide: Helianthex 45 g ha ⁻¹ .	Biloba CLP	3.00	1.00	0.00	1.33	-4.67	-78
	NK Neoma	2.00	1.00	0.00	1.00	-6.00	-86
	Suvex	1.00	1.00	1.00	1.00	-4.33	-81
	Average	2.00	1.00	0.33	1.11	-5.00	-82
Post-emergence herbicide: Stels 350 mL ha ⁻¹ .	Biloba CLP	4.00	4.00	1.00	3.00	-3.00	-50
	NK Neoma	4.00	5.00	3.00	4.00	-3.00	-43
	Suvex	4.00	4.00	0.00	2.67	-2.66	-50
	Average	4.00	4.33	1.33	3.22	-2.89	-47
Post-emergence herbicide: Challenge 0.4 L ha ⁻¹ .	Biloba CLP	5.00	6.00	1.00	4.00	-2.00	-33
	NK Neoma	4.00	8.00	1.00	4.33	-2.67	-38
	Suvex	5.00	6.00	1.00	4.00	-1.33	-25
	Average	4.67	6.67	1.00	4.11	-2.00	-33
Average	Biloba CLP	4.83	4.83	1.17	3.61	-	-
	NK Neoma	4.33	5.67	2.00	4.00	-	-
	Suvex	4.33	4.50	0.67	3.17	-	-
	Average	4.50	5.00	1.28	3.59	-	-
Post-emergence herbicide: Pulsar Flex 1.6 L ha ⁻¹ .	Biloba CLP	4.00	6.00	0.00	3.33	-2.67	-44
	NK Neoma	4.00	7.00	1.00	4.00	-3.00	-43
	Suvex	-	-	-	-	-	-
	Average	-	-	-	-	-	-
Post-emergence herbicide: Granstar 40 g ha ⁻¹ .	Biloba CLP	-	-	-	-	-	-
	NK Neoma	-	-	-	-	-	-
	Suvex	3.00	7.00	0.00	3.33	-2.00	-37
	Average	-	-	-	-	-	-
LSD ₀₅	A – 0.24; B – 0.19; C – 0.21; AB – 0.46; AC – 0.44; BC – 0.41; ABC – 0.66						

Source: developed by the author

The reduction in bee visitation observed after soil-applied herbicides likely reflects indirect physiological and ecological effects rather than acute toxicity. Primextra TZ Gold (containing S-metolachlor and atrazine) and Yastryb (metolachlor + terbutylazine) act primarily through inhibition of photosynthetic and lipid-synthesis pathways in weeds. Their relatively low volatility and limited translocation explain why the decline in bee visitation (-29%) remained moderate – these products rarely cause visible phytotoxicity or changes in sunflower floral morphology. In contrast, the Eclipse + Filder combination includes active ingredients with higher persistence and stronger systemic uptake (metazachlor + dimethenamid-P + clomazone), which can temporarily influence plant metabolism, especially under limited soil moisture. Clomazone, known for its vapour-phase activity and bleaching effect, may reduce nectar secretion and pigment synthesis, making the flowers less visually attractive to bees.

The pronounced decline in bee visitation after post-emergence herbicide use (Helianthex, Pulsar Flex, Challenge, Stels, Granstar) is likely associated with foliar absorption and short-term physiological

stress on the sunflower plants. Helianthex (a sulfonylurea herbicide) inhibits acetolactate synthase (ALS), a key enzyme for amino acid synthesis, and even sublethal phytotoxic stress can reduce nectar and pollen production. Additionally, sulfonylureas are known for residual activity on non-target species, which can slightly modify floral scent profiles important for bee orientation. Conversely, Challenge (aclonifen) has low volatility and limited systemic mobility, explaining its relatively smaller effect (-33%). It acts through inhibition of carotenoid biosynthesis but with minimal impact on floral physiology at label rates. Climatic conditions also played a critical role. The strong decline in bee visits during 2024 corresponded with high air temperatures (>32°C) and a Selyaninov hydrothermal coefficient below 0.5, which constrained nectar secretion and reduced overall pollinator activity. Under drought, both nectar volume and sugar concentration in sunflower florets decrease sharply, which may explain why differences between herbicide treatments were less distinct that year.

Among the soil-applied herbicides, the smallest reduction in yield compared with the control was

observed with the combination Eclipse 2.0 L ha⁻¹ + Filder 2.0 L ha⁻¹. The decrease in mean yield for this treatment was 0.31 t ha⁻¹ (8%), which was the lowest among the soil-applied herbicide schemes studied (Table 4). Under this treatment, hybrid yields were close to the control: for NK Neoma the mean was 3.83 t ha⁻¹ (-0.21 t ha⁻¹ relative to the control), for Suvex 3.61 t ha⁻¹ (-0.12 t ha⁻¹), and for Biloba CLP 3.17 t ha⁻¹ (-0.59 t ha⁻¹). The second most effective soil-applied herbicide was the combination Primextra TZ Gold 4.5 L ha⁻¹ + Yastryb 2.0 L ha⁻¹, which resulted in an average yield reduction of 0.35 t ha⁻¹ (9%) compared with the control. Among

the post-emergence herbicides, the best results were obtained with Stels 0.35 L ha⁻¹, where mean yield decreased by only 0.58 t ha⁻¹ (15%) relative to the control. For Suvex the yield was 3.45 t ha⁻¹ (-0.28 t ha⁻¹ vs. control), for NK Neoma 3.34 t ha⁻¹ (-0.69 t ha⁻¹), and for Biloba CLP 2.99 t ha⁻¹ (-0.77 t ha⁻¹). The second most effective post-emergence treatment was Challenge 0.4 L ha⁻¹, which caused an average yield reduction of 0.76 t ha⁻¹ (20%). The treatment with Helianthex at 45 g ha⁻¹ had the most negative effect on the yield of all sunflower hybrids among the post-emergence herbicides studied (-27%) (Table 4).

Table 4. Yield of sunflower hybrids as affected by herbicide application, t ha⁻¹ (2022-2024)

Herbicide technology (A)	Hybrid (B)	Year (C)			Mean increase relative to the control		
		2022	2023	2024	Average	t ha ⁻¹	%
Control (hand weeding)	Biloba CLP	4.53	4.25	2.50	3.76	-	-
	NK Neoma	4.10	5.10	2.90	4.03	-	-
	Suvex	4.07	5.05	2.07	3.73	-	-
	Average	4.23	4.80	2.49	3.84	-	-
Soil-applied herbicide (Primextra TZ Gold 4.5 L ha ⁻¹ + Yastryb 2.0 L ha ⁻¹)	Biloba CLP	4.13	3.80	1.97	3.30	-0.46	-12
	NK Neoma	3.93	4.70	2.33	3.66	-0.38	-9
	Suvex	4.03	4.60	1.93	3.52	-0.21	-6
	Average	4.03	4.37	2.08	3.49	-0.35	-9
Soil-applied herbicide: Eclipse 2.0 L ha ⁻¹ + Filder 2.0 L ha ⁻¹	Biloba CLP	3.73	3.50	2.27	3.17	-0.59	-16
	NK Neoma	3.77	4.65	3.07	3.83	-0.21	-5
	Suvex	3.73	4.90	2.20	3.61	-0.12	-3
	Average	3.74	4.35	2.51	3.54	-0.31	-8
Post-emergence herbicide: Helianthex 45 g ha ⁻¹	Biloba CLP	3.00	3.05	1.30	2.45	-1.31	-35
	NK Neoma	3.17	4.20	2.07	3.14	-0.89	-22
	Suvex	3.07	4.00	1.53	2.87	-0.86	-23
	Average	3.08	3.75	1.63	2.82	-1.02	-27
Post-emergence herbicide: Stels 350 mL ha ⁻¹	Biloba CLP	3.60	3.05	2.33	2.99	-0.77	-20
	NK Neoma	3.37	4.45	2.20	3.34	-0.69	-17
	Suvex	3.53	4.65	2.17	3.45	-0.28	-7
	Average	3.50	4.05	2.23	3.26	-0.58	-15
Post-emergence herbicide: Challenge 0.4 L ha ⁻¹ .	Biloba CLP	3.40	3.75	1.63	2.93	-0.83	-22
	NK Neoma	3.23	4.45	2.03	3.24	-0.79	-20
	Suvex	3.23	4.25	1.70	3.06	-0.67	-18
	Average	3.29	4.15	1.79	3.08	-0.76	-20
Average	Biloba CLP	3.73	3.57	2.00	3.10	-	-
	NK Neoma	3.60	4.59	2.43	3.54	-	-
	Suvex	3.61	4.58	1.93	3.37	-	-
	Average	3.65	4.24	2.12	3.34	-	-
Post-emergence herbicide: Pulsar Flex 1.6 L ha ⁻¹	Biloba CLP	3.47	3.75	1.87	3.03	-0.73	-19
	NK Neoma	3.20	4.55	2.43	3.39	-0.64	-16
	Suvex	-	-	-	-	-	-
	Average	-	-	-	-	-	-
Post-emergence herbicide: Granstar 40 g ha ⁻¹	Biloba CLP	-	-	-	-	-	-
	NK Neoma	-	-	-	-	-	-
	Suvex	3.60	4.55	1.72	3.29	-0.44	-12
	Average	-	-	-	-	-	-
LSD ₀₅		A – 0.15; B – 0.10; C – 0.21; AB – 0.29; AC – 0.40; BC – 0.38; ABC – 0.51					

Source: developed by the author

The moderate yield reduction under soil-applied herbicides indicates that these treatments primarily

affected early vegetative development rather than reproductive success. The relatively higher yield under

Eclipse + Filder compared with Primextra TZ Gold + Yastryb is consistent with its shorter residual activity and partial selectivity for broadleaf weeds. Because soil-applied herbicides are incorporated before sowing, they interact less with floral organs and pollinator behavior, explaining the weaker correlation between bee visitation and yield reduction. In contrast, the post-emergence herbicides act directly on the green tissue during active growth stages (V8-R1), potentially disrupting photosynthesis and assimilate transport at critical periods of head and seed formation. Helianthex (ALS inhibitor) and Pulsar Flex (imidazolinone group) can transiently slow chlorophyll biosynthesis and carbon fixation, leading to smaller heads and fewer filled achenes. Challenge (aclonifen) and Stels (a PPO inhibitor) caused less physiological stress because of their contact-type mode of action and limited translocation within the plant. However, repeated exposure to such herbicides may still lower pollen viability and nectar secretion, indirectly reducing pollination efficiency and seed fill.

Overall, yield responses followed the same trend as pollinator activity: treatments that least disturbed plant physiology (Primextra + Yastryb, Stels, Challenge) maintained both higher bee visitation and higher yield. This suggests that maintaining floral integrity and minimising post-emergence stress is critical for balancing weed control efficiency with pollination-dependent productivity in sunflower cultivation. Differences in bee visitation and yield among herbicide programs demonstrate how weed-control chemistry can mediate sunflower-pollinator interactions through both plant-physiological and environmental pathways. The pattern observed – highest bee activity under mechanical weeding and progressively lower visitation under chemical treatments – parallels the conclusions of L. Russo *et al.* (2023), who found that common herbicide and fertilizer inputs altered floral rewards and reduced visitation in multiple crops. The moderate reduction under the soil-applied mix Primextra TZ Gold + Yastryb corresponds with reports that pre-emergence chloroacetamide-based programs exert limited short-term stress on floral tissues, while the sharper decline under Eclipse + Filder is consistent with the higher volatility and residual action of clomazone, which can transiently bleach petals and alter nectar secretion. Such plant-mediated effects likely explain why differences in bee activity persisted even under standardised hive density. Post-emergence herbicides showed the steepest visitation losses, a result comparable with those of M. Saleem *et al.* (2023), who documented reduced pollinator activity and seed production under intensive pesticide regimes in sunflower. The pronounced decline under Helianthex (ALS inhibitor) matches the mechanism-based expectation that interference with amino-acid biosynthesis and photosynthetic metabolism suppresses nectar and pollen formation. Challenge (aclonifen) and Stels (a PPO inhibitor) caused smaller

penalties, reflecting their limited systemic mobility. These chemical-specific outcomes reinforce the view that physiological selectivity and timing relative to reproductive stages are decisive for pollinator safety.

The outcomes of the present research closely aligned with recent advances in pollinator-pesticide interaction studies. According to P. Basu *et al.* (2024), the impact of pesticide use on pollinators depended not only on active ingredients but also on application timing, mobility and the sensitivity of floral tissues. This concept supported the clear distinction observed between soil-applied programmes and post-emergence chemistries: the former exerted limited physiological stress, whereas the latter strongly interfered with nectar and pollen formation. The multiscale perspective proposed by O. Catrice *et al.* (2023) further reinforced the need to assess sunflower-pollinator interactions across physiological, agronomic and landscape levels. Their findings mirrored the current results by indicating that pollination outcomes could not be explained solely by floral traits but must integrate management regimes and environmental stressors. Physiological mechanisms underlying bee-herbicide interactions were also evident. W.M. Farina *et al.* (2019) demonstrated that glyphosate exposure impaired sensory perception and cognitive performance of *Apis mellifera*, even in the absence of lethal doses. This observation corresponded with the steeper reduction in bee visitation recorded under post-emergence ALS inhibitors, where disruption of amino acid synthesis and photosynthetic metabolism likely suppressed nectar secretion. Comparable trends were reflected in the current study, where lower systemic mobility of Stels and Challenge resulted in smaller penalties, supporting earlier claims regarding the role of herbicide selectivity in pollinator safety.

The influence of pollinator density had previously been examined by M. Reyes *et al.* (2024), who showed that increased hive numbers significantly shaped sunflower yield components. Their findings implied that physiological stress from chemical treatments may alter pollination efficiency even under equal hive distribution, which corresponded with the observed differentiation in visitation among herbicide programmes despite standardised stocking rates. This highlighted the sensitivity of sunflower-*bee* systems to both chemical and ecological contexts. Climatic variability further moderated treatment effects. The precision-agronomy framework developed by M. Zalai *et al.* (2025) demonstrated that sowing accuracy, water availability and microenvironment regulation were decisive for reproductive stability in sunflower. These conclusions corresponded with the narrowing differences between treatments under the drought conditions of 2024, suggesting that hydrothermal stress could override management-based effects. The current findings therefore indicated that herbicide

compatibility must be interpreted in relation to seasonal variability and agronomic environment, rather than solely through crop protection objectives.

Seasonal patterns underline the sensitivity of bee-sunflower systems to hydrothermal stress. The drought year 2024 produced a decline in visits, aligning with the results of Q. Ali *et al.* (2024), who showed that water shortage curtails floral reward production and modifies pollination efficiency. The narrowing of treatment differences during this season suggests that climatic stress can override management effects – an increasingly relevant factor under continental climate variability. The yield data broadly followed visitation trends yet did not coincide perfectly, an outcome typical of pollination-limited crops. L. Mota *et al.* (2022) emphasised that final yield integrates both pollinator supply and crop physiological status; where herbicides induced only mild stress, assimilating flow during grain filling buffered yield losses. The relatively small reductions observed with Eclipse + Filder and Primextra + Yastryb confirm that soil-applied programs primarily affect early growth rather than reproductive success. Conversely, foliar ALS and imidazolinone treatments act during active photosynthesis, disturbing carbon allocation and head development – hence the larger penalties under Helianthex and Pulsar Flex. Such partial decoupling between bee visitation and yield has been noted previously in hybrid trials where reproductive compensation mitigated the effects of reduced pollination. The magnitude of pollination benefit implied by control versus herbicide contrasts fits well within the empirical range reported for sunflower in Europe and Ukraine. I. Kulynych and T. Soloviova (2021) observed yield increase of 20-47 % with managed bees, while P. Herasymiuk *et al.* (2025) reported yield losses up to 57 % when pollinators were excluded. Three-year average differentials between the control and chemical variants fall squarely within this range, confirming the robustness of the pollination effect across climatic zones. Treatment-specific insights, however, extend earlier Ukrainian work by identifying which herbicide groups exert the smallest interference with bee activity, thereby bridging agronomic weed management and ecological outcomes. Landscape and habitat conditions may further modulate these relationships. S. Boinot *et al.* (2024) and C. Siopa *et al.* (2024) demonstrated that herbicide intensity and habitat simplification reduce overall pollinator abundance. Even though the present study equalised hive distance, the simplified vegetation of the Steppe region likely accentuated the influence of floral stress from foliar treatments. Incorporating habitat buffers, as recommended by L. Mota *et al.* (2024), could mitigate these effects and sustain visitation in chemically managed fields.

The collective evidence from this and other studies points toward an integrative management framework.

Herbicide programs differ markedly in their compatibility with pollination processes: pre-emergence mixtures with moderate persistence (e.g., Primextra + Yastryb) and low-mobility post-emergence products (Challenge, Stels) appear most pollinator-safe. Programs relying on high-systemicity ALS inhibitors near anthesis pose greater risks to bee visitation and potentially to colony activity. Such distinctions are crucial for balancing weed control efficacy with the ecosystem services that underpin sunflower productivity. Climatic variability remains a dominant constraint. Under drought and high temperatures, even the most bee-friendly programs cannot fully maintain pollination rates, underscoring the need for adaptive scheduling of herbicide applications, supplemental irrigation where feasible, and hybrid selection with stronger floral resilience. Long-term sustainability will depend on integrating chemical choice with ecological infrastructure – flower strips, staggered bloom resources, and colony management – to stabilise both pollinator activity and yield in sunflower agroecosystems of the Eastern Steppe.

CONCLUSIONS

Across three-year field experiment (2022-2024) was demonstrated that the interaction between herbicide program, hybrid genotype, and seasonal weather strongly determines both bee visitation and sunflower yield. Across all treatments, the hand-weeded control remained the most favorable for pollinators, recording an average of 6.11 bee visits per head per 10 minutes and the highest yields (3.84 t ha⁻¹). Among the studied hybrids – Biloba CLP, NK Neoma, and Suvex – clear differences in pollinator attractiveness and productivity were observed. NK Neoma maintained the highest mean yield (4.03 t ha⁻¹ in control plots) and relatively stable bee visitation across herbicide programs, confirming its better tolerance to both chemical and drought stress. Biloba CLP achieved slightly lower yields (3.76 t ha⁻¹) and showed moderate sensitivity to herbicide application, whereas Suvex proved the most susceptible, with average yields declining from 3.73 t ha⁻¹ in the control to 2.87 t ha⁻¹ under post-emergence treatments. A distinct pattern emerged between herbicide categories. Soil-applied herbicides caused moderate decreases in bee visitation (-29 to -56%) and yield (-8 to -9%) relative to the control. Within this group, the combination Primextra TZ Gold + Yastryb produced the smallest reduction in pollinator activity (average 4.33 visits head⁻¹ 10 min⁻¹) and yield (-0.35 t ha⁻¹). Eclipse + Filder showed slightly stronger effects, especially under low moisture, but remained less detrimental than any post-emergence treatment.

Post-emergence herbicides, by contrast, exerted a greater negative impact, reducing bee visitation by 33-86 % and yields by 15-27 %. Among them, Challenge (0.4 L ha⁻¹) and Stels (0.35 L ha⁻¹) were the least harmful, maintaining bee visitation around 3.1-4.1 visits

head⁻¹ 10 min⁻¹ and yields close to 3.1-3.3 t ha⁻¹, while *Helianthus* (45 g ha⁻¹) caused the sharpest decline in both metrics (-82% bee activity; -27 % yield). These results indicate that pre-emergence programs are inherently safer for pollinators because they act before flowering and do not directly affect floral physiology, whereas foliar ALS-inhibiting or imidazolinone herbicides applied near anthesis impose greater physiological stress on plants and reduce nectar secretion. The drought year 2024 amplified yield losses and reduced bee activity to 1.28 visits head⁻¹ 10 min⁻¹ on average, confirming that climatic stress can override chemical effects. Still, the relative ranking of treatments remained consistent, supporting the robustness of these trends. Overall, the findings show that soil-applied herbicides are significantly less risky for pollinators than post-emergence ones, and that hybrid selection can mitigate or exacerbate chemical stress effects. For sustainable sunflower production in Ukraine's Eastern Steppe, integrating pre-emergence programs with pollinator-friendly, low-mobility post-emergence products (such as Challenge or Stels) and drought-resilient hybrids like NK Neoma will provide the best compromise between weed control efficiency, pollination safety, and yield stability.

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CONFLICT OF INTEREST

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Вплив гербіцидів на запилення бджолами та взаємозв'язок із урожайністю у виробництві соняшнику

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Анотація. Метою дослідження було кількісно оцінено та порівняно вплив ґрунтових і післясходових гербіцидних програм на відвідуваність соняшника бджолами та урожайність різних гібридів за контрастних сезонних умов у Східному Степу України. Польові експерименти проводилися у 2022–2024 рр. в селі Василівка (Дніпропетровська область) із використанням трьох гібридів (Biloba CLP, NK Neoma, Suvex), ручного прополювання як контролю, двох ґрунтових програм (Primextra TZ Gold + Yastryb; Eclipse + Filder) та кількох післясходових варіантів (Helianthex, Stels, Challenge, Pulsar Flex, Granstar), застосованих згідно з етикетковими нормами. Кількість бджолосімей становила 5 вуликів на гектар з вирівнюванням дистанції льоту. Активність бджіл у період цвітіння фіксувалася за допомогою 24 камер GoPro (10:00–12:00; чотири дні; три повторення) та виражалася як кількість візитів на кошик⁻¹ за 10 хв⁻¹, тоді як урожайність (т га⁻¹ при 7 % вологості) визначалася після збирання. Погодні умови істотно різнилися, зокрема 2024 рік характеризувався вираженою посухою. У контролі зафіксовано найвищу відвідуваність бджолами (у середньому 6,11 візитів кошик⁻¹ за 10 хв⁻¹). Ґрунтові програми знижували відвідуваність на 29–56 %, причому найменше зниження спостерігалось за Primextra TZ Gold + Yastryb (-29 %), а найбільше – за Eclipse + Filder (-56 %). Післясходові програми зумовили зниження на 33–86 %: Challenge (0,4 л га⁻¹) спричинив найменший вплив (-33 %), тоді як Helianthex (45 г га⁻¹) – найбільший (-82 %). Відвідуваність бджолами була виражено залежною від року проведення експерименту (≈4,5–5,0 у 2022–2023 рр. проти 1,28 у 2024 р.). Урожайність демонструвала часткове розходження з динамікою візитів: серед ґрунтових варіантів найменше зниження зафіксовано для Eclipse + Filder (-0,31 т га⁻¹; -8 %), за ним слідував Primextra TZ Gold + Yastryb (-0,35 т га⁻¹; -9 %); серед післясходових програм найкраще проявив себе Stels (-0,58 т га⁻¹; -15 %), перевищивши Challenge (-0,76 т га⁻¹; -20 %) та Helianthex (-27 %). Загалом ґрунтові гербіциди продемонстрували нижчий ризик для активності запилювачів та урожайності порівняно з післясходовими ALS/імідазоліновими сполуками, тоді як посуха залишалася домінуючим обмежувальним чинником обох процесів. Інтеграція гербіцидного вибору з урахуванням запилювачів та сезонних ризиків розглядається як шлях до підтримання екосистемних послуг і продуктивності агроценозу

Ключові слова: соняшник; відвідуваність бджолами; гербіцидні програми; привабливість для запилювачів; урожайність



Development of a drone-based sowing technology for oilseed radish as a green manure crop

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Abstract. The aim of the study was to experimentally justify a drone-based surface sowing technology for oilseed radish as a green manure crop under the conditions of the Polissia region of Ukraine. The methodology included laboratory testing of seed quality, NDVI field monitoring, a field experiment with variable flight height, sowing rate and soil preparation type, as well as statistical assessment of variability and survival using ANOVA ($p \leq 0.05$). High physiological quality of the Raiduha seeds was confirmed (94.0% germination energy; 99.0% laboratory germination rate), which ensured stability of the initial plant stand. Spatial unevenness of sowing caused by aerodynamic seed drift was investigated; the coefficient of variation reached 68.3%, indicating pronounced asymmetry of the agrophytocenosis. The influence of two

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sowing rates (320 and 560 plants/m²) and two flight heights (3 and 5 m) was analysed, establishing that the optimal combination consisted of a rate of 320 plants/m², a 5 m flight height and glyphosate-based soil preparation, which resulted in 13.4% viable plants. Herbicide application accelerated phenological development and reduced inter-species competition. A technological solution was analytically proposed in the form of drone-based cross-seeding to compensate for aerodynamic seed displacement and stabilise plant stand density. The practical value of the research lies in its applicability for developing a UAV-based sowing standard for green manure crops within precision farming and post-war agricultural rehabilitation programmes

Keywords: aerodynamic seed drift; agrophytocenosis density; phenological monitoring; precision agriculture; sowing variability; post-war agricultural recovery

INTRODUCTION

The intensification of digital technologies within agricultural production fundamentally transformed the principles of crop cultivation and field management, particularly in regions with complex terrain and degraded soils. The Polissia area of Ukraine remained one of the most challenging agroecological zones, characterised by excessive soil moisture, acidity, and geomorphological heterogeneity, which substantially limited the use of conventional sowing machinery. Under such conditions, the development of autonomous drone-based sowing technologies for green manure crops acquired strategic value for resource conservation, soil restoration, and post-war agricultural reconstruction. Oilseed radish has been identified in previous agronomic investigations as a biologically adaptive and technologically promising species for biomass accumulation and structural soil recovery, yet the problem of achieving its uniform distribution during drone-assisted sowing has remained insufficiently resolved at the scientific level.

The current global tendency towards precision agriculture stimulated an increased interest in using unmanned aerial vehicles for direct sowing, although the technological performance of spreading mechanisms and airflow stability did not always meet agronomic standards. Researchers noted that sowing efficiency significantly depended on the interaction between seed weight and aerodynamic turbulence generated by the drone, which resulted in asymmetric distribution and formation of sparsely vegetated areas (Qi *et al.*, 2022). Similar conclusions were reached by X. Wang *et al.* (2024), who established that large-seeded crops demonstrated greater adaptability to aerial broadcasting; however, seed displacement increased exponentially with rising flight altitude and wind variability. Experimental work performed by M.N. Nordin *et al.* (2022) confirmed that airflow generated during drone trajectory shifts caused lateral drift of seeds even under moderate wind conditions, which reduced the accuracy of seed placement and complicated the prediction of final plant density.

Aerial seeding was also analysed from the perspective of seeding mechanism design. Field simulations conducted by W. Zhijun *et al.* (2023) demonstrated that auger-type spreading systems could ensure higher stability

than centrifugal distribution, although their efficiency markedly declined when seeds demonstrated low thousand-seed weight. According to H. Li (2023), the technological reliability of sowing systems required precise calibration before each flight, while the absence of post-sowing incorporation into the soil remained the primary limiting factor for uniform germination. Other studies proposed the modification of existing drone seeders to counteract airflow distortion and improve the dispersion radius (Adithya *et al.*, 2024). However, the integration of these improvements into an agronomically viable sowing standard remained underdeveloped.

The question of seed germination and subsequent resilience under surface broadcasting was examined in several studies. It was found that independently of sowing uniformity, high seed physiological quality, particularly germination energy, had a decisive influence on the early stages of organogenesis (Tsytsiura, 2024a). Laboratory investigations into oilseed radish germination under surface conditions demonstrated that rapid water absorption and metabolic activation were essential for successful emergence without conventional soil embedding. Nonetheless, uneven seed distribution and intensified intra-species competition, especially at high sowing rates, remained a limiting factor for green manure efficiency (Stroud *et al.*, 2017). These observations raised the need to adapt seeding algorithms to crop-specific biological features rather than relying solely on standardised rates used in conventional agriculture.

An increasingly relevant research direction concerned the interaction between drone-assisted sowing and soil preparation technologies. The combined application of green manure sowing and herbicide-based treatment was reported to improve weed suppression and enhance plant survival during early development stages (Helander *et al.*, 2019). According to Y. Tsytsiura (2024b), oilseed radish contributed to the restoration of organic matter content and improved phosphorus mobilisation, which increased its agronomic value for organic crop rotations. Ukrainian research also confirmed the suitability of this species for restoring structural integrity in light loam soils of Polissia, although sowing outcomes depended heavily on climatic stability and moisture retention capacity.

UAV-based monitoring methods provided further advancement of this technological approach. Remote sensing and NDVI mapping were increasingly used to evaluate sowing uniformity and assess the effectiveness of alternative sowing strategies (Vavlas *et al.*, 2024). D.Reddy *et al.* (2025) demonstrated that UAV-based multispectral imaging enabled precise detection of vegetation gaps and facilitated corrective assessment of sowing efficiency. Such methods were considered to be particularly valuable in unstable climatic conditions and agronomic zones with spatially heterogeneous soil cover.

The reviewed literature indicated that drone-assisted sowing could be successfully applied for green manure crops, provided that aerodynamic constraints, sowing rates, and crop biological characteristics were appropriately synchronised. However, the absence of an experimentally validated technological standard for oilseed radish sowing from UAVs remained a critical research gap that limited large-scale implementation in post-war agricultural recovery programmes. The aim of the study was to determine technological parameters that ensured uniform surface sowing of oilseed radish from drones in unprepared soil conditions of the Polissia region of Ukraine, with a view to developing an agronomically justified framework for its practical application in green manure farming.

MATERIALS AND METHODS

The study aimed at developing a drone-based technology for sowing green manure crops was conducted over a two-year period at the research field of Polissia National University, located near the village of Velyka Horbasha, Cherniakhiv Territorial Community, Zhytomyr

District, Zhytomyr Region (50°26'17" N, 28°41'38" E). The soil cover of the experimental site is represented by grey forest light loam soils, characterised by low humus content, insufficient levels of essential nutrients, and increased acidity. Prior to the establishment of the experiment, a soil agrochemical survey was conducted, with samples taken from depths of 0-10 cm, 10-20 cm, and 20-30 cm to determine pH, humus content, and available forms of nitrogen, phosphorus, and potassium. These measurements were necessary to establish the initial agrochemical background that could influence the germination, growth, and development of oilseed radish.

The object of the study was the oilseed radish variety Raiduha, developed by the V.Ya. Yuriev Institute of Plant Production of the National Academy of Agrarian Sciences of Ukraine. This annual, cold-season crop is characterised by rapid accumulation of green biomass and a well-developed root system that contributes to improving the structural and physical properties of the soil. Its seeds contain 40-46% oil, rich in omega-3 fatty acids and antioxidants. In conventional agriculture, the recommended seeding rate ranges from 16 to 22 kg/ha. However, in this study, increased seeding rates were applied due to the specific requirements of drone-based sowing. The research was conducted in three stages. At the preparatory stage, laboratory assessment of the seed material was performed (germination rate and germination energy testing), an experimental design was developed, and the study plot was selected and delineated. The main stage involved testing two field preparation approaches: glyphosate-based and glyphosate-free technologies (Fig. 1).

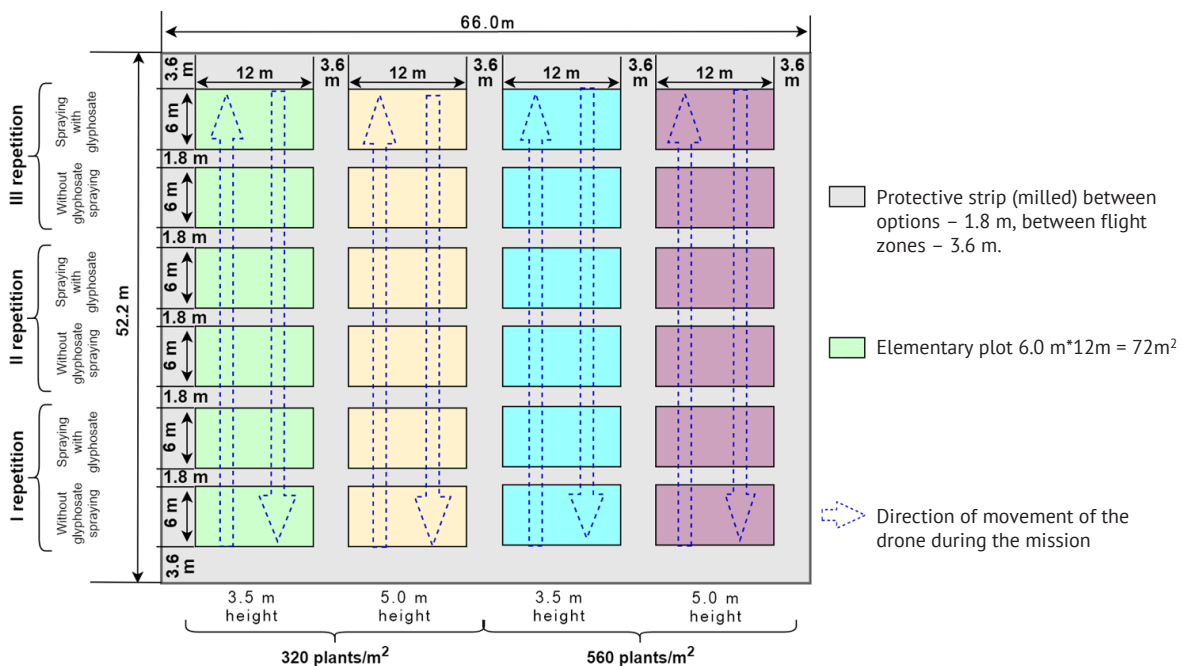


Figure 1. Experimental scheme

Source: developed by the authors

Herbicide application was carried out using an MC A22 (Multicopter LLC, Ukraine) drone at a rate of 2 l/ha, with a working solution rate of 7.5 l/ha, a flight altitude of 4 m, and a flight speed of 8 m/s under wind conditions of 2 m/s and a wind direction of A338°. Spraying was conducted in two passes in mission mode, with drone flight directions of A73° and A253°. Moderate lateral drift of the herbicide was recorded; however, it did not affect the geometric layout of the experimental plots.

Sowing of oilseed radish was performed with an XAG P100 Pro drone in three replications using two seeding rates: 320 plants/m² (62 kg/ha) and 560 plants/m² (76 kg/ha). Prior to each flight, calibration of the seeding mechanism was carried out. Sowing took place under favorable weather conditions: air temperature +22.6°C, relative humidity 60%, and wind speed 1.1 m/s, which ensured uniform seed distribution. Each experimental plot was sown in two passes in mission mode with flight directions of A295° and A115°, under a wind direction of A163°. Only minimal lateral seed drift was observed, and it did not affect the geometric accuracy of the sowing pattern. For spatial referencing of the results, preliminary NDVI mapping of the study area was conducted using Sentinel-2 satellite imagery in the ArcGIS Pro environment (ESRI), confirming the homogeneity of the site in terms of soil productivity. During monitoring, the proportion of areas with NDVI < 0.35 was determined as an indicator of insufficient seedling density, which made it possible to identify potential areas of uneven development of the agrophytocenosis. Ground control points were established using a Hi-Target V30Plus RTK GNSS receiver to synchronise field observations with aerial imagery.

Phenological observations included the assessment of field emergence, plant stand density, and plant development at the cotyledon stage; the first and second true leaf stages; the 3-4 leaf stage; bud formation; flowering; and green biomass accumulation. Weed infestation levels and pest damage were also recorded. The final stage of the study involved mathematical and statistical processing of the collected data, comparative analysis of the experimental treatments, and formulation of conclusions. The duration of each phenological phase was recorded in days after sowing, followed by a comparison between the variants with herbicide

treatment and the control plots for quantitative assessment of plant growth rates. To compare survival rates and variability, it was used the ANOVA criterion with a significance threshold of $p \leq 0.05$, which ensured the reliability of the calculated differences between the experimental variants. During the analysis of sowing variability, an additional technological approach was formulated – cross-seeding, which was not included in the initial experimental scheme but was proposed as an empirically justified recommendation. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

As part of the preparatory stage, a laboratory assessment of the seed quality of the oilseed radish variety Raiduha was conducted, as this parameter is critical for the implementation of drone-based sowing technology. Unlike conventional mechanical seed drills, drone sowing does not incorporate seeds into the soil; instead, they remain on the soil surface, where they are exposed to fluctuations in temperature and moisture, biodegradation processes, and the risk of bird predation. Consequently, the success of germination under such conditions largely depends on the intrinsic physiological potential of the seeds, particularly their germination energy and laboratory germination rate. For this reason, the evaluation of seed quality served as one of the fundamental tasks of the study.

The laboratory experiment ($n = 3$) demonstrated that the oilseed radish seeds possessed high biometric quality (Table 1). The mean germination energy was 94.0%, while laboratory germination rate reached 99.0%. These values exceed the minimum standard requirements for green manure crop seed material (at least 85% germination rate), which justifies the use of calculated seeding rates without adjusting for potential losses. The high germination energy indicates rapid water uptake by the germ and active development of the sprout. These factors are particularly important when seeds are deposited on the soil surface during UAV-based sowing. High laboratory germination rate, in turn, ensures stability of the initial plant stand, which is a key determinant of productivity in green manure farming.

Table 1. Seed quality indicators of the oilseed radish variety Raiduha according to laboratory testing ($n = 3$), %

Indicator	Replication			Mean
	I	II	III	
Germination energy	94	96	92	94.0
Germination rate	98	100	98	99.0

Source: developed by the authors

The high physiological quality of the seeds made it possible to avoid artificially increasing the seeding

rate, which is commonly practiced in direct surface broadcasting. This allowed to evaluate the influence of

strictly technological factors (drone flight altitude, number of passes, and seeding rate) without confounding them with biological losses of the seed material. The next stage of the study involved assessing the uniformity of seed distribution on the soil surface, as this parameter is considered crucial for establishing a homogeneous agro-phytocenosis. Within the experiment, the distribution of seeds dropped from the drone was analysed at two flight altitudes (3 and 5 m) and under different seeding rates, which made it possible to determine the impact of aerodynamic factors on sowing accuracy. Uniformity was evaluated by establishing 1 m² control plots where the actual number of seeds per unit area was counted; the coefficient of variation was then calculated as a measure of distribution stability. Thus, the laboratory results confirmed the suitability of the selected oilseed radish variety for this type of experiment and substantiated the feasibility of proceeding to the field stage using drone-based sowing technology. This provided scientific validity for the subsequent field observations in terms of the crop's physiological potential.

The results of the field experiments (Table 2) revealed substantial unevenness in the distribution of oilseed radish seeds during drone-based sowing. This unevenness was reflected not only in variations in plant density within the seeded strip but also in a considerable drift of seeds beyond the boundaries of the control plots. In particular, lateral displacement of seeds was observed in the direction corresponding to the drone's flight path. Such an effect is typical for surface broadcasting of lightweight seeds, even under minor airflow conditions. Spatial analysis of plant density showed that at a drone flight altitude of 3 m and a seeding rate of 320 plants/m², the actual emergence averaged 283 plants/m² (88.5% of the intended rate). When the flight altitude was increased to 5 m, this value decreased to 279 plants/m² (87.1%), indicating a loss of distribution accuracy with increasing sowing height. A similar trend was recorded at the higher seeding rate of 560 plants/m²: the actual density ranged from 440 to 458 plants/m² (78.6-81.7%), indicating a substantial deviation from the target plant density.

Table 2. Distribution of winter rape and oilseed radish seeds across the plot depending on the drone's flight trajectory (average values)

Projected plant density, plants/m ²	Seed sowing height, m	Distance from the drone's flight line, m			Weighted mean number of sown seeds, pcs/m ²	% of the planned seeding rate
		0	1.5	3		
Number of seeds, pcs/m ²						
320	3	304	404	142	283	88.5
	5	316	352	168	279	87.1
560	3	522	680	118	440	78.6
	5	557	554	262	458	81.7

Source: developed by the authors

These deviations can be explained by the aerodynamic behavior of the seeds, as oilseed radish has a lower thousand-seed weight compared with traditional cereal or legume crops. This increases its susceptibility to horizontal displacement under the influence of airflow, particularly within the vertical vortex zones that form behind the drone. These findings support the hypothesis that drone-based sowing of crops with low seed weight is associated with an elevated risk of sowing asymmetry and the formation of both densely populated and sparsely populated zones within a single technological pass. Analysis of the obtained results indicates that cross-seeding, where the drone performs two perpendicular passes using half of the standard seeding rate each time, may be a practical solution for improving sowing uniformity. This approach helps equalise plant density across the field, reduces localised competition for nutrients and moisture, and enhances the overall quality of the agro-phytocenosis. Additionally, cross-seeding has the potential to minimise lateral seed drift by offsetting sowing asymmetry from opposite flight directions. From the perspective of green manure farming, uniformity of sowing is of critical

importance, as the homogeneity of plant cover directly determines the crop's capacity to accumulate green biomass, its phytosanitary effectiveness, and its ability to suppress weed growth. Thus, the results confirm the need for technological adaptation of agricultural drones for sowing small-seeded crops through improvements to seed-dispersion algorithms and modifications to flight-pattern design. Such advancements would ensure more stable biometric parameters and enable the formation of an agronomically justified plant density for green manure cover in the context of organic production.

The next stage of the research involved field monitoring of the growth and development of oilseed radish throughout the entire vegetation period in order to determine the influence of soil-preparation technology, seeding rate, and drone flight altitude on the formation of a stable plant stand density. The duration of each phenological phase was recorded in days after sowing, allowing quantitative comparison between herbicide-treated plots and control variants to assess the tempo of organogenesis. The emergence of the first true leaf pair occurred on average after 11.3 days in herbicide-treated plots and after 14.8 days in control

variants, confirming different developmental dynamics depending on soil preparation. Post-emergence plant survival is one of the key indicators of sowing effectiveness, as the actual plant density determines the crop's ability to realise its green-manure potential through biomass accumulation and weed suppression.

As shown by the results presented in Table 3, the highest field germination and seedling survival rates were recorded in the cases that included pre-application of glyphosate and a projected density of 320 plants/m².

In this case, sowing from a height of 5 m resulted in an average of 42.9 plants/m², which corresponds to 13.4% of the sown seeds. When sowing was carried out from a height of 3 m, the survival rate was slightly lower – 37.7 plants/m², or 11.8%; yet it remained substantially higher than in the plots without herbicide application. The use of glyphosate reduced competitive pressure from the weed component, thereby creating more favorable conditions for oilseed radish growth during emergence and early development.

Table 3. Effect of soil preparation technology, seeding rate, and drone sowing height on the residual number of oilseed radish plants, pcs/m²

Case (cultivation technology)	Projected plant density, plants/m ²	Seed sowing height, m	Mean across replications, pcs/m ²			Case mean	Coefficient of variation, %	Plant survival per 1 m ² , %
			0	1.5	3			
Without glyphosate	320	3	30	33	49	37.15 ± 9.79	26.34	11.61
		5	28	32	31	30.21 ± 10.27	34.01	9.44
	560	3	10	11	15	12.15 ± 8.3	68.30	2.17
		5	17	12	17	15.16 ± 5.05	33.32	2.71
Glyphosate treatment	320	3	35	36	42	37.73 ± 6.85	18.14	11.79
		5	40	42	46	42.94 ± 14.94	34.79	13.42
	560	3	39	53	56	49.42 ± 10.98	22.21	8.83
		5	36	30	35	33.8 ± 7.88	23.33	6.04

Source: developed by the authors

The cases with an increased seeding rate (560 plants/m²) exhibited notably lower plant survival – only 2.2-9.4%. This outcome is due not so much to the biological characteristics of the crop as to intensified competition among seedlings and their uneven distribution on the soil surface. The high coefficient of variation (up to 68.3%) in this case further confirms that excessive stand density combined with surface seed placement led to the loss of a portion of the plants during the early stages of organogenesis. The presented data indicate that the most technologically justified approach is the combination of glyphosate-based soil preparation with a drone-applied seeding rate of 320 plants/m², as this provides an optimal balance between biological productivity and the uniformity of the green manure cover. Achieving an optimal plant stand density is a critical factor for successful green manuring, since the quantitative stability of the plant population determines the effectiveness of biomass accumulation, soil enrichment with organic matter, and the phytosanitary improvement of the agroecosystem.

The discussion required a comparison of the obtained experimental results with current research trends in UAV-based sowing of green manure and cover crops. It was found that the detected spatial variability of sowing corresponded to similar patterns reported in earlier studies, although distinct differences were associated with the biological properties of oilseed radish and the agroclimatic conditions of Polissia. According to B. Berner (2020), effective drone-assisted sowing was achievable only under minimal wind influence, whereas

in this experiment the coefficient of variation reached 68.3%, exceeding the author's findings due to the lower thousand-seed weight of the Raiduha cultivar. Comparable aerodynamics-related constraints were reported by H. Liu *et al.* (2023), who demonstrated that flight stability and seed displacement were strongly dependent on UAV construction and airflow.

Cross-seeding emerged as a solution to compensate for airflow-induced drift and intraspecific competition. This aligned with the findings of S. Zhang *et al.* (2022), who achieved reductions in seed losses by adjusting speed and drop parameters during sowing. In contrast, H. Zhou *et al.* (2024) emphasised the potential of centrifugal distribution systems to ensure more stable seed trajectories, suggesting possible engineering modifications for green manure crops. Similar adaptive approaches were observed in forestry regeneration, where UAV-assisted sowing relied on topography-sensitive algorithms (Mohan *et al.*, 2021), reinforcing the relevance of spatial variability monitoring found in this study. Survival dynamics were consistent with agronomic research on cover crops. J.S. Cavadini and E.J. Klavivko (2025) confirmed that excessive sowing density induced strong intraspecific competition, closely matching the observed reduction to 2.2-9.4% survival under higher seeding rates. The adaptive potential of oilseed radish was further supported by H. Hereshko *et al.* (2021), who classified it as a biologically resilient crop with high suitability for sustainable farming.

A prominent direction in modern research involved digital assessment and post-sowing density estimation.

A deep learning approach using RGB imagery was developed by T. Luu *et al.* (2025), providing methodological opportunities to automate evaluation of agrophytocenosis structure. Comparable principles were applied in reforestation activities, where UAVs were controlled via observer-based algorithms for optimal placement accuracy (Istiak *et al.*, 2023; Muñoz *et al.*, 2025). Moreover, NDVI-based monitoring was validated as an effective post-seeding assessment tool, aligning with recommendations made by Y. Han (2024), which mirrored the approach implemented in this experiment.

A recent review by R. Guebsi *et al.* (2024) outlined major challenges in precision agriculture using UAVs, particularly regarding uneven distribution on irregular terrain. In comparison, the results of this study demonstrated that seed mass rather than topography was the primary limiting factor, indicating the necessity of biological adaptation in UAV-sowing protocols. Consequently, cross-seeding was analytically proposed as a potential baseline strategy for managing spatial variability. The comparison with international studies demonstrated that UAV-based sowing of oilseed radish was consistent with broader scientific trends yet revealed species-specific constraints shaped by seed mass and airflow dynamics. Existing research confirmed both the agronomic potential of the crop and the feasibility of drone-assisted sowing; however, it underscored the need for technological refinement and spatial correction strategies. The analytical justification of cross-seeding indicated a promising direction for optimising agrophytocenosis structure and integrating oilseed radish into precision farming systems.

CONCLUSIONS

The findings demonstrated that the high physiological quality of the Raiduha oilseed radish seeds, confirmed by laboratory indicators of 94.0% germination energy and 99.0% laboratory germination rate, provided a reliable biological foundation for testing surface drone-based sowing. The field experiment indicated

that the principal limitation of this technology was the uneven spatial distribution of seeds, caused by the low thousand-seed weight and the influence of the drone's aerodynamic airflow. The coefficient of variation reached 68.3%, confirming the formation of asymmetric zones of seed accumulation and depletion within a single technological pass, which intensified intraspecific competition and reduced plant survival during early ontogenesis.

The combination of glyphosate-based soil preparation and a seeding rate of 320 plants/m² yielded the most stable agrophytocenosis, resulting in an average of 42.9 surviving plants/m² at a 5 m flight height, equivalent to 13.4% of the sown seeds. In control plots without herbicide treatment, survival remained comparatively high at 11.6%, which indicated a strong adaptive potential of the crop under surface sowing conditions. However, an increased seeding rate of 560 plants/m² led to a marked reduction in survival to 2.2-9.4%, confirming the negative effect of excessive stand density when uniformity was not ensured. A technologically grounded solution was analytically proposed in the form of cross-seeding, based on spatial variability analysis, with the aim of counteracting airflow-induced seed displacement and levelling intra-row competition. This approach was considered promising for enhancing sowing uniformity and strengthening the agroecological value of green manure crops within precision farming systems. Further research should focus on experimental validation of cross-seeding efficiency under varied flight parameters and climatic risk scenarios.

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Розробка технології посіву олійної редьки з дрону як сидеральної культури

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Анотація. Метою дослідження було експериментальне обґрунтування технології поверхневого посіву редьки олійної дроном як сидеральної культури в умовах Полісся України. Методологія включала лабораторний аналіз посівних якостей насіння, NDVI-моніторинг ділянки, польовий експеримент із варіюванням висоти польоту, норми висіву та типу підготовки ґрунту, а також статистичну оцінку варіабельності та виживання рослин за критерієм ANOVA ($p \leq 0,05$). Було встановлено, що насіння сорту Raiduha мало високі біометричні показники (94,0 % енергії проростання; 99,0 % лабораторної схожості), що забезпечувало стабільність початкового агрофітоценозу. Було досліджено просторову нерівномірність посіву, спричинену аеродинамічним зносом дрібного насіння; коефіцієнт варіації сягав 68,3 %, що зумовлювало утворення асиметричних зон загушення та прорідження. Було проаналізовано вплив двох висот польоту (3 і 5 м) та двох норм висіву (320 і 560 рослин/м²) на виживання рослин, було встановлено, що оптимальна комбінація включала норму 320 рослин/м², висоту польоту 5 м та гербіцидну підготовку, де формувалося 13,4 % життєздатних рослин. Було узагальнено, що гербіцидна обробка прискорювала проходження фенологічних фаз і знижувала міжвидову конкуренцію. Було аналітично запропоновано технологічне рішення – перехресний (cross-seeding) посів дроном як спосіб компенсації аеродинамічного зносу та вирівнювання густоти агрофітоценозу. Практична цінність дослідження полягає у можливості використання отриманих результатів під час формування стандарту посіву сидеральних культур з БПЛА в системах точного землеробства та післявоєнного агровідновлення

Ключові слова: аеродинамічний знос насіння; густина агрофітоценозу; фенологічний моніторинг; точне землеробство; варіабельність посіву; післявоєнне агровідновлення

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