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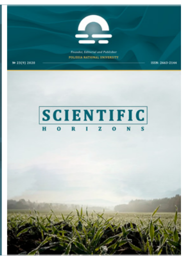

Assessment of the adaptability of winter rye hybrids for cultivation in the Forest-Steppe zone of Ukraine

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Abstract. The aim of the study was to substantiate the ecological and adaptive performance of modern winter rye hybrids for their use under different cultivation systems in the Forest-Steppe zone of Ukraine. The methodology combined field phenological and biometric observations, phytosanitary assessments, yield determination, and statistical analysis of variation parameters, ecological plasticity and stability based on the Eberhart-Russell model modified by Finlay-Wilkinson. The response of nine hybrids to contrasting abiotic factors was examined, and differences in the rate of spring vegetation recovery, formation of stem biomass and yield structure were identified. The level of winter hardiness and drought tolerance was analysed, demonstrating the ability of hybrids to maintain productivity under snow-deficient winters and uneven precipitation distribution. High ecological plasticity (bi = 0.93-1.02) and stability (S^2di = 0.09-0.14) of the leading genotypes were revealed, confirming their universality across diverse agroclimatic conditions. It was established that SU Futturi, KWS Vinetto, KWS Tayo and SU Arvid achieved yields of 8.4-9.6 t/ha, minimised leaf-area losses during hydrothermal stress and exhibited strong resistance to major diseases. It was generalised that the introduction of these hybrids enhanced the resource efficiency of production technologies, reduced agrochemical pressure and supported the formation of ecologically resilient agroecosystems. The practical value of the study lies in identifying hybrids suitable for both conventional and organic farming systems, with the results being applicable to agricultural producers, advisory services and breeding centres when optimising varietal policy and implementing environmentally oriented cultivation strategies

Keywords: ecological plasticity; yield stability; biometric traits; winter hardiness; hydrothermal stress; phytosanitary resistance

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INTRODUCTION

Contemporary challenges in agricultural production, driven by climatic variability, soil degradation and the growing demand for high-quality grain, have necessitated the adoption of crops capable of ensuring stable yields across a wide range of agro-ecological conditions. Winter rye, as a crop characterised by high adaptability and low resource requirements, occupies an important place in sustainable farming systems, while the use of its hybrid forms has gained strategic relevance for resource conservation and yield enhancement in regions exposed to elevated drought risk. The increasing interest in hybrid rye is associated with its ability to maintain productivity under conditions that are critical for other cereals, as well as with its potential to reduce agrochemical and energy pressures on the environment.

An analysis of recent studies indicates that winter rye as a crop, and its hybrid forms in particular, has attracted considerable attention among both Ukrainian and international researchers. The study by L. Biliavska and Y. Biliavskyi (2021) highlighted the important role of winter rye in Ukraine, although the issues of adaptability and efficiency of the newest hybrids remain insufficiently explored within specific soil-climatic zones. Research on the long-term soil and biological consequences of rye cultivation, conducted by V. Bogužas *et al.* (2022), demonstrated that the crop positively influenced soil structural quality, CO_2 emissions and the biodiversity of soil mesofauna, supporting the view of rye as a soil-protective species.

A significant contribution to the study of hybrid productivity and yield stability was made in the work of B. Hackauf *et al.* (2022), which showed that hybrid rye exhibits substantially lower yield variability and outperforms population cultivars under limited moisture availability. Similar conclusions were reached by S. Hadasch *et al.* (2020), who noted that yield stability in hybrids persisted even under adverse meteorological conditions. The issue of breeding progress was addressed in the study by F. Laidig *et al.* (2021), where it was emphasised that increases in rye productivity have been accompanied by improved disease resistance and reduced need for intensive technological operations. The environmental dimension constitutes an important component of current research. According to the analytical report External sustainability study confirms the excellent CO_2 balance of KWS hybrid rye (2023), hybrid rye demonstrates one of the lowest carbon footprints among cereals due to its reduced nitrogen fertiliser requirement and efficient biomass utilisation. These findings correspond with the conclusions of L. Riedesel *et al.* (2022), who stressed that new breeding lines of rye are characterised by reduced carbon emissions per unit of production and enhanced photosynthetic efficiency. In the Ukrainian scientific context, attention has been directed towards assessing varietal resources and their agro-ecological relevance. Thus, V. Sabluk *et al.* (2018) analysed the available domestic cultivars and identified promising directions for breeding activity, although the issue of hybridisation was addressed only superficially. The study by N. Symonenko *et al.* (2023) focused on technological aspects of winter rye cultivation; however, the authors did not examine the influence of hybrids on soil properties, energy efficiency or agro-ecological pressure. The issue of spatio-temporal variability in rye yield in Ukraine was investigated by A. Zymaroieva and Y. Nykytiuk (2023), who concluded that climatic instability increases the relevance of hybrid forms, yet calls for more detailed regional assessments. An important dimension is the interdisciplinary examination of rye within crop rotation systems. The research by M. Smith *et al.* (2023) demonstrated that greater crop diversity in rotations, including the incorporation of rye, enhances agroecosystem resilience and contributes to long-term increases in cereal yields. This finding aligns with broader trends towards ecologically oriented farming systems in which hybrid rye forms may play a pivotal role.

Thus, modern research emphasises the considerable potential of winter hybrid rye as a highly productive and ecologically efficient crop. At the same time, key questions remain insufficiently explored, including the adaptability of hybrids under diverse soil-climatic conditions of the Forest-Steppe of Ukraine, their influence on soil ecological status, the energy efficiency of cultivation technologies and opportunities for optimising agronomic practices from a resource-conservation perspective. The aim of the present study was to substantiate the adaptive characteristics of winter rye hybrids and determine their potential for introducing environmentally safe and resource-efficient cultivation technologies in the Forest-Steppe zone of Ukraine.

MATERIALS AND METHODS

A comprehensive study of productivity formation, growth and developmental characteristics, adaptive properties and competitive ability of modern winter rye hybrids was initiated in 2024 at the "Levor" Farming Enterprise, located in the Zhytomyr district of Zhytomyr region. The experimental sites were situated on typical chernozem soils. Nine winter rye (*Secale cereale* L.) hybrids of different breeding origins were selected for the experimental work, representing KWS Group (KWS Tayo, KWS Eterno, KWS Vinetto), Saaten-Union GmbH (SU Arvid, SU Baresi, SU Futturi) and DSV AG (Astranos, Stannos, Helltop). These hybrids were chosen for a comprehensive assessment of their adaptability, yield stability and ecological efficiency under the conditions of the Forest-Steppe zone of Ukraine (Fig. 1). All hybrids were listed in the State Register of Plant Varieties Suitable for Distribution in Ukraine (2024).

***Figure 1**. Comprehensive assessment of adaptive traits and productivity formation in modern winter rye hybrids, 2025*
***Source:** authors' photographs*

The experiment was established according to standard field-trial methodologies using the method of systematic replications. The trial design involved a comparison of modern winter rye hybrids under two cultivation systems: conventional production (with the application of mineral fertilisers and plant-protection products) and organic production (without chemical inputs, with the use of organic fertilisers and adherence to the principles of ecological farming). Both variants ensured comparable growing conditions and enabled the assessment of differences between technological systems. The size of each accounting plot was 25 m^2, and the experiment was conducted with four replications. The arrangement of treatments was sequential (Fig. 2).

***Figure 2**. Experimental plots of winter rye hybrids, 2024-2025*
***Source:** authors' photographs*

A comprehensive set of observations and measurements was carried out during the experiment. Phenological observations were performed to determine the duration of growth and developmental phases according to the BBCH scale. Biometric measurements were conducted on a sample of 20 plants in each replication, recording plant height, number of productive stems, ear length, grain weight per ear and leaf area index. Phytosanitary monitoring was performed at BBCH stages 37-75, assessing infection by powdery mildew, brown rust and snow mould using a nine-point scale in accordance with EPPO guidelines. Winter hardiness was evaluated by examining the stands after snowmelt and determining the proportion of surviving plants and the viability of tillering nodes. Drought tolerance was assessed based on the preservation of leaf area, productive tillering and changes in yield during periods of hydrothermal deficit. Agrochemical and soil analyses included measurements of soil acidity, nutrient content and agronomically valuable soil structure. Yield analysis involved harvesting the entire area of each accounting plot followed by recalculation to tonnes per hectare at standard grain moisture.

Assessment of the hybrids' adaptive properties was based on the analysis of yield variation parameters. The coefficient of variation (CV, %) was calculated as the ratio of standard deviation to the mean yield. Ecological plasticity (bi) and the stability coefficient (S^2di) were determined using the Eberhart-Russell model modified by Finlay-Wilkinson, enabling evaluation of the genotypes' response intensity to environmental changes and their capacity to maintain productivity across contrasting years. Statistical calculations were conducted using MS Excel and R 4.3.0. The weather conditions during 2024-2025 were analysed using data from the Zhytomyr meteorological station of the Ukrainian Hydrometeorological Centre. Mean monthly temperatures, precipitation amounts, the hydrothermal coefficient, the duration of snow-free periods and abnormal temperature events affecting plant growth and development were taken into account. The obtained climatic data were used to interpret the hybrids' responses to weather fluctuations and to determine their ecological adaptability. Additional statistical information on temperature anomalies, precipitation levels and hydrothermal parameters was obtained from the official datasets of the State Statistics Service of Ukraine (n.d.).

To systematise the key indicators of adaptability, an integrated model was employed, comprising three blocks: the biological potential of the hybrids, agritechnological conditions and environmental factors. This approach enabled a comprehensive assessment of the interaction between genotype, cultivation technology and climatic influences, and made it possible to determine the ecological reliability of winter rye hybrids under the conditions of the Forest-Steppe zone. 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

Adaptability represents one of the key characteristics of modern winter rye cultivars and hybrids, determining their capacity to maintain stable yield levels under variable environmental conditions. In the context of climate change and the increasing frequency of extreme weather events – such as droughts, sharp temperature fluctuations and excessive precipitation – indicators of ecological plasticity and stability acquire particular importance. The phenological analysis revealed differences in the duration of major growth and developmental phases among the hybrids. KWS Tayo, SU Arvid and Astranos were characterised by faster spring vegetation recovery and earlier transition to stem elongation, which promoted the formation of a more productive stem biomass. In contrast, KWS Eterno and Helltop exhibited a slightly prolonged initial vegetative period, enabling more efficient uptake of soil nutrients but delaying the formation of reproductive organs. These phenological distinctions shaped the hybrids' subsequent responses to weather conditions and influenced their level of ecological plasticity.

Winter rye hybrids demonstrated enhanced tolerance to abiotic stresses – primarily drought and low temperatures – owing to their well-developed root systems, more efficient use of water and nitrogen, and the ability to rapidly resume growth after winter dormancy. These traits improve the crop's adaptation to the conditions of the Forest-Steppe, where significant variability in climatic indicators occurs throughout the growing season. Recent research confirms that modern hybrids developed by leading breeding companies (KWS, Saaten-Union and others) exhibit higher yield stability compared with conventional cultivars, a pattern attributed to heterosis effects and improved resource-use efficiency (Table 1).

***Table 1**. Characteristics of winter rye hybrids*

Hybrid name	Breeding company	Year of registration in Ukraine	Yield potential, t/ha	Drought tolerance (1-9 points)	Lodging resistance (1-9 points)	Disease resistance (1-9 points)
KWS Tayo	KWS Group	2021	8.5-10.2	7-9	4-5	powdery mildew 8; brown rust 7-8; snow mould 8-9
KWS Eterno	KWS Group	2017	7.0-8.7	8-9	7-9	powdery mildew 9; snow mould 9
KWS Vinetto	KWS Group	2019	8.0-9.5	8	8	powdery mildew 8; snow mould 9
SU Arvid	Saaten-Union GmbH	2021	8.4-8.9	8-9	7	powdery mildew 8; brown rust 8; snow mould 9
SU Baresi	Saaten-Union GmbH	2023	8.7-9.0	7-9	7	powdery mildew 8; brown rust 8; snow mould 9
SU Futturi	Saaten-Union GmbH	2023	7.2-8.8	7-8	8-9	powdery mildew 9; brown rust 8; snow mould 9
Astranos	DSV AG	2022	7.0-8.5	7-9	6	powdery mildew 8-9; brown rust 5-9; snow mould 9
Stannos	DSV AG	2021	8.3-8.8	8	7-8	powdery mildew 9; brown rust 8; snow mould 9
Helltop	DSV AG	2012	8.5-9.1	7-8	8	powdery mildew 8-9

***Source:** compiled by the authors based on the State Register of Plant Varieties Suitable for Distribution in Ukraine (2024)*

The phytosanitary assessment demonstrated a consistently low level of infection by major spike and leaf diseases. The highest resistance to powdery mildew was recorded in SU Arvid, SU Futturi and KWS Vinetto, where infection intensity did not exceed 1-2 points. Symptoms of brown rust were observed mainly in Astranos and Stannos, although they remained within biologically acceptable limits. Resistance to snow mould was high in all hybrids, confirming their suitability for conditions characterised by insufficient snow cover during the winter of 2024-2025. To obtain a comprehensive characterisation of ecological plasticity and stability of winter rye hybrids in the Forest-Steppe zone of Ukraine, an analysis of key adaptability indicators was undertaken based on field results and relevant literature sources. Determining yield level, variation parameters and ecological response coefficients made it possible to objectively assess the ability of genotypes to maintain productivity under diverse environmental conditions.

One of the important criteria is the coefficient of yield variation, which characterises the stability of crop productivity in years with contrasting weather conditions. The indicator of ecological plasticity (bi) reflects the intensity of a hybrid's response to changes in growing conditions: values of bi ≈ 1 indicate a universal genotype, bi > 1 indicate the ability to express a high yield potential under favourable conditions, whereas bi < 1 indicate enhanced tolerance to stress factors. The stability coefficient (S^2di) and drought tolerance level serve as additional criteria for determining the ecological reliability of the crop. The comparison of the two cultivation systems revealed substantial differences in the realisation of the hybrids' adaptive potential. Under conventional technology, a slightly higher yield level was achieved – on average by 0.3-0.6 t/ha – due to consistent nutrient supply and more effective disease control. At the same time, under organic production conditions, SU Futturi, KWS Vinetto and SU Arvid stood out by maintaining high stability and exhibiting minimal yield losses in the absence of mineral nutrition. This indicates that these genotypes are capable of effectively realising their inherent biological potential and adapting to environmentally constrained production systems.

The summarised data on productivity, variation characteristics and ecological response for the most common modern winter rye hybrids used in production or recommended for implementation in the Forest-Steppe zone of Ukraine are presented in Table 2. The obtained indicators make it possible to trace differences among genotypes in terms of adaptive potential, yield stability and their capacity to maintain consistent productivity under diverse agroclimatic conditions.

***Table 2**. Main adaptability indicators of winter rye hybrids*

Hybrid	Mean yield, t/ha	Yield variation coefficient, %	Plasticity (bi)	Stability (S^2di)	Drought tolerance, %
KWS Tayo	9.3	9.5	1.02	0.12	78
KWS Vinetto	8.7	8.0	0.97	0.09	82
SU Futturi	9.6	7.8	1.00	0.11	80
Astranos	8.4	11.2	0.93	0.14	75

***Source:** compiled by the authors*

The analysis of the data presented in Table 2 indicated that the examined winter rye hybrids were characterised by a high level of adaptability and yield stability under the conditions of the Forest-Steppe zone of Ukraine. The mean yield ranged from 9.3 t/ha (KWS Tayo) to 9.6 t/ha (SU Futturi), confirming the high genetic potential of modern hybrids and their ability to utilise environmental resources efficiently. According to the coefficient of yield variation (7.8-11.2%), all hybrids demonstrated relatively high productivity stability under different growing conditions. The lowest coefficients of variation were recorded for SU Futturi (7.8%) and KWS Vinetto (8.0%), which indicated their tolerance to fluctuations in hydrothermal conditions and their ability to maintain high yield levels even in years with stress-related weather events.

The ecological plasticity values (bi = 0.93-1.02) showed that most hybrids were universal in their response to environmental variation. Specifically, KWS Tayo (bi = 1.02) demonstrated slightly increased sensitivity to favourable growing conditions, whereas Astranos (bi = 0.93) exhibited greater tolerance to stress factors, maintaining relatively stable yields in less favourable years. Drought tolerance, determined from an integrated assessment of physiological and yield-related indicators, varied within the range of 75-82%, reflecting the strong ecological adaptation of the hybrids to the hydrothermal fluctuations characteristic of the Forest-Steppe. Particular attention should be given to KWS Vinetto and SU Futturi, which combined high yield, stability and enhanced drought tolerance, making them promising candidates for wider implementation under conditions of climate change. Winter survival assessment showed high winter hardiness across most hybrids, despite the deficit of snow cover during the winter of 2024-2025. The best survival rates after winter were observed in KWS Vinetto, SU Arvid and SU Futturi, where the proportion of surviving plants exceeded 90%. Astranos and Stannos displayed minor losses associated with sharp temperature fluctuations in January; however, these did not significantly affect final yield levels. The high degree of winter hardiness confirmed the genetic suitability of the hybrids for the Forest-Steppe environment.

Winter rye is known for its ability to adapt to diverse soil and climatic conditions, which underpins its stable productivity even under extreme environmental factors. The adaptive mechanisms of the crop comprise a complex of morphological, physiological–biochemical and agro-ecological traits that ensure its competitive capacity among cereal species. Morphological traits – particularly a well-developed root system penetrating to depths of 1.5-2 m and high tillering capacity – enable more efficient utilisation of soil moisture and nutrients. Physiological mechanisms of adaptation include high photosynthetic activity at lower temperatures and the ability to use light energy efficiently, both of which contribute to increased tolerance to drought and temperature fluctuations.

Biometric observations revealed significant differences among the hybrids in plant height, the number of productive stems and spike parameters. The highest stem productivity was formed by KWS Tayo and SU Futturi, in which the number of productive stems exceeded the average level by 12-18%. The leaf area index at the stem-elongation stage was highest in KWS Eterno and KWS Vinetto, which ensured greater photosynthetic activity and more efficient light use during the early spring period. Astranos and Helltop were characterised by a more compact spike and a higher thousand-grain weight, which partially compensated for their lower density of productive stems. Biochemical mechanisms included the accumulation of soluble sugars in the tillering node, which played a key role in winter hardiness and in the energy supply required for regrowth in spring. Adaptive-ecological traits were reflected in high tolerance to soil acidity, strong competitiveness against weeds and the ability to form yields even on poor or low-fertility soils. The combination of these mechanisms formed the ecological resilience of winter rye hybrids and determined their suitability for cultivation in the Forest-Steppe zone of Ukraine.

The weather conditions of 2024-2025 had a pronounced influence on the realisation of adaptive traits. The deficit of snow cover during winter and periodic frosts enabled the identification of genotypes with high frost and winter tolerance, whereas spring over-moistening partially constrained the development of hybrids with lower root activity. In the summer months, short periods of intense heat and the absence of rainfall in the second half of the growing season revealed the adaptive advantages of KWS Vinetto, SU Futturi and KWS Tayo, which maintained high turgor and experienced minimal loss of productive leaf area. This enabled the formation of stable yield levels both under optimal and stress conditions. Winter rye also demonstrated higher competitiveness against weeds owing to its rapid early growth, vigorous root system and high stand density. These attributes made the crop a valuable component of ecologically sustainable crop rotations, particularly on soils with elevated acidity or low nutrient availability. Thus, winter rye, based on the entirety of its adaptive characteristics, emerged as the most environmentally resilient crop among those studied, suitable for cultivation under continental climate conditions and increased ecological variability.

The obtained results on the adaptability of modern winter rye hybrids were consistent with findings reported in recent international studies. The established yield stability and the ability of hybrids to sustain development under fluctuating temperature and moisture conditions supported the conclusion regarding the high ecological plasticity of the crop, as identified in the study by M. Pasqui and E. Di Giuseppe (2019). Their work indicated that the rising frequency of extreme weather events in Europe increased the demand for crops capable of adapting to heat and water stress. The winter hardiness and tolerance to hydrothermal fluctuations recorded in the field experiment reflected the patterns described by the authors. Yield stability under organic farming conditions also aligned with the results presented by Th. Miedaner *et al.* (2025), where hybrid rye demonstrated higher productivity stability than wheat under reduced agronomic inputs and moisture deficits. In the present experiment, a comparable response was characteristic of SU Futturi, KWS Vinetto and SU Arvid, which maintained high yield levels under resource-limited conditions, confirming the universal adaptive potential of the crop.

In the study by M.K. Kostrzewska and M. Jastrzębska (2025), it was demonstrated that rye hybrids were able to realise their yield potential even under continuous cultivation and minimal application of plant protection products. The high competitiveness against weeds and disease pathogens described in their research corresponded closely with the results of the present phytosanitary monitoring. The limited manifestation of powdery mildew, brown rust and snow mould confirmed the strong immunological potential of the hybrids, aligning with adaptability characteristics reported in the literature. The consistency of the results with contemporary views on evolutionary-genetic mechanisms of adaptation was further supported by the conclusions of W.Y. Yang and C.X. Ma (2024). Their study indicated that a deep root system, increased tillering capacity and the ability to rapidly resume vegetation were key traits underlying the ecological resilience of rye. The morphological and physiological features recorded in the experiment confirmed these adaptation mechanisms and explained the stability of productivity under Forest-Steppe conditions.

The results obtained under Ukrainian soil-climatic conditions were also consistent with the findings of O.V. Topchii *et al.* (2024), who reported that new winter rye cultivars were able to maintain high yield levels on soils with increased acidity and irregular precipitation patterns. In the present experiment, similar patterns manifested themselves in the stability of plant stand density and in the hybrids' response to soil acidity. The interpretation of the results also matched the conclusions of A. Zymaroieva and Y. Nykytiuk (2023), who identified the leading role of agro-ecological factors – soil acidity, precipitation structure and hydrothermal regime – in determining rye yield. Within the conducted study, these factors likewise governed productivity variation, confirming their systemic influence. The conceptual propositions regarding the advantages of hybridisation, presented in the work of E.M.S. ter Steeg *et al*. (2022), were also in agreement with the findings. Their research emphasised that hybrid forms demonstrated greater yield stability under stress conditions, which was corroborated by the low coefficients of variation and high ecological plasticity observed in SU Futturi, KWS Tayo and KWS Vinetto. Overall, the concordance of the obtained results with modern studies confirmed that the adaptability of winter rye hybrids was determined by a combination of morphological, physiological and ecological mechanisms, together with genetically defined advantages of hybridisation, which collectively ensured yield stability under conditions of climatic variability.

CONCLUSIONS

The conducted study established that modern winter rye hybrids were characterised by a high level of ecological adaptability and the capacity to maintain stable productivity under the contrasting hydrothermal conditions of the Forest-Steppe zone of Ukraine. The analysis of phenological, biometric and phytosanitary indicators demonstrated that SU Futturi, KWS Vinetto, KWS Tayo and SU Arvid exhibited more efficient spring regrowth, high plant survival after winter and minimal loss of leaf area during periods of summer heat stress. The yield of the examined hybrids ranged from 8.4 to 9.6 t/ha, confirming the high genetic potential of the crop. The values of the coefficient of variation (7.8-11.2%) indicated yield stability even in years with significant weather fluctuations. The ecological plasticity index (bi = 0.93-1.02) reflected the universal response of most hybrids to environmental change, while stability parameters (S^2di = 0.09-0.14) outlined their capacity to sustain productivity under stress factors.

Drought-tolerance assessment showed that KWS Vinetto and SU Futturi displayed the highest levels of tolerance (up to 82%), giving them an advantage under moisture-deficit conditions. Phytosanitary observations indicated low infection levels of powdery mildew, brown rust and snow mould in most hybrids, demonstrating strong immunological potential and meeting the requirements of environmentally oriented production systems. Biometric traits – such as a well-developed root system, optimal density of productive stems and high grain weight per ear – formed a yield structure resilient to climatic and soil constraints. The integrated evaluation of hybrid performance confirmed that the examined material was suitable for cultivation in the Forest-Steppe zone, ensuring high efficiency of water and nutrient use, reduced agrochemical pressure and stable yield formation. The obtained data identified SU Futturi and KWS Vinetto as the most promising hybrids for implementation in both conventional and organic farming systems. The study confirmed that hybrid winter rye could play a key role in forming ecologically sustainable agroecosystems in the Forest-Steppe, contributing to a reduction in the carbon footprint of production and to improved resource efficiency of cultivation technologies. Future research should focus on refining technological elements of hybrid cultivation, assessing their carbon and water balances, and determining the long-term dynamics of adaptability under conditions of climatic variability.

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CONFLICT OF INTEREST

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Оцінка адаптивності гібридів жита озимого для вирощування в умовах Лісостепу України

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Анотація. Метою дослідження було обґрунтувати екологічну та адаптивну результативність сучасних гібридів жита озимого для використання у різних технологічних системах вирощування Лісостепу України. Методологія роботи поєднувала польові фенологічні та біометричні спостереження, фітосанітарні оцінки, визначення продуктивності та статистичний аналіз параметрів варіації, пластичності й стабільності за моделлю Еберхарта-Рассела у модифікації Finlay-Wilkinson. Було досліджено реакцію дев'яти гібридів на контрастні абіотичні чинники, встановлено відмінності у темпах весняного відновлення вегетації, формуванні стеблової маси та структурі врожаю. Було проаналізовано рівень зимостійкості та посухотолерантності, що забезпечили здатність гібридів підтримувати продуктивність у роки з дефіцитом снігового покриву та нерівномірним розподілом опадів. Було виявлено високу екологічну пластичність (bi = 0,93-1,02) та стабільність (S^2di = 0,09-0,14) провідних генотипів, що підтверджує їхню універсальність за різних агрокліматичних умов. Було встановлено, що гібриди SU Futturi, KWS Vinetto, KWS Tayo та SU Arvid забезпечували врожайність 8,4-9,6 т/га, мінімізували втрати листкової поверхні у періоди гідротермічного стресу й характеризувалися високою стійкістю до основних хвороб. Було узагальнено, що впровадження цих гібридів сприяє підвищенню ресурсоефективності технологій, зменшенню агрохімічного навантаження та формуванню екологічно стійких агроекосистем. Практична цінність роботи полягає у визначенні гібридів, придатних для впровадження у традиційні та органічні системи землеробства, а результати можуть бути використані агровиробниками, консультантами та селекційними центрами під час оптимізації сортової політики та впровадження екологічно орієнтованих технологій

Ключові слова: екологічна пластичність; стабільність продуктивності; біометричні показники; зимостійкість; гідротермічний стрес; фітосанітарна стійкість

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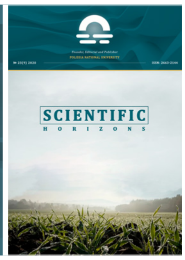

Influence of agrotechnological factors on the rate of development and progression of phenological phases in maize (*Zea mays* L.)

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Abstract. The objective of this study was to determine the influence of soil tillage system, plant density, and herbicide background on the rate of maize phenological development under the continental climatic conditions of the Polissia region of Ukraine. The experiment was conducted during 2023-2025 and included three tillage systems (deep plowing, disking, and rotary tillage), two levels of plant density (1.1 and 1.3 seed units ha^{-1}), and two herbicide backgrounds (with and without herbicides) arranged in a three-factor design with three replications. Phenological phases (from SeedGerm to FullRip) were recorded based on the calendar dates of their occurrence. Statistical analyses were performed using analysis of variance (ANOVA), regression modelling, and comparison of adjusted means. The results revealed that soil tillage was the dominant factor determining the rate of maize development. Minimal and shallow tillage accelerated the progression of phenological phases by 2-5 days compared with deep plowing. The herbicide background had a critical effect on the middle and late development phases: the absence of herbicides increased the duration of the ThrowPanic-FullRip interval by 6-10 days due to enhanced weed competition. The interaction F1×F3 was statistically significant in most phases and determined the overall developmental rate. Plant density had a secondary effect, expressed only through its interaction with the herbicide background. The fastest development was observed in the S3H1A2 combination (rotary tillage, herbicides, increased density), whereas the slowest was recorded in S1H2A2 (deep plowing, no herbicides, increased density). The study concluded that optimising the soil tillage system in combination with effective weed control is crucial for accelerating maize development and ensuring stable productivity in the Polissia region. Minimal tillage combined with herbicide protection can be recommended as the most effective strategy for improving growth rates, shortening the vegetation period, and enhancing the agrobiological resilience of maize under regional conditions

Keywords: phenological development; soil tillage system; herbicide background; weed competition; plant density

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INTRODUCTION

The phenological development of maize (*Zea mays L.*) is governed by a complex interaction of soil, climatic, and agrotechnological factors, among which the soil tillage system, the intensity of competitive pressure within the crop stand, and plant density play critical roles. Numerous studies have emphasised that the physical properties of the soil – particularly aeration, bulk density, and moisture retention – strongly influence seed germination, early vegetative growth, and the rate of progression through subsequent phenological phases. Research comparing tillage systems shows that different soil management approaches create distinct physical and thermal environments for crop development. Deep plowing typically results in improved aeration and reduced soil compaction; however, studies such as X. Shi *et al.* (2024) and the meta-analysis by S. Huang *et al.* (2023) indicate that it can exacerbate moisture loss, potentially slowing maize development in regions with unstable precipitation. Conversely, shallow or minimum tillage systems have been shown to conserve soil moisture and stabilise temperature dynamics in the upper soil layers, thereby promoting more rapid early growth, as reported by F. Molina-Herrera *et al.* (2025).

Weed competition is another decisive factor affecting the timing and duration of phenological phases. In the study by G. Naruhn *et al.* (2025), spatial crop-weed interactions were found to significantly delay maize development in the absence of effective weed control. Similarly, D. Nedeljković *et al.* (2025) showed that the timing of weed removal in relation to herbicide use and planting patterns strongly influences developmental delays, particularly during the 3rd-7th leaf, stem elongation, and tasseling phases. Plant density contributes additional complexity to phenological responses. According to J. Cagnola *et al.* (2025), higher plant density accelerates canopy closure and suppresses weed growth but increases intra-specific competition for light as plants approach later vegetative and reproductive phases. However, the work of Z. Cao *et al.* (2024) indicates that the overall impact of plant density on the calendar timing of phenological phases is generally smaller than that of tillage and weed competition, affecting primarily morphological parameters and yield components.

Recent progress in experimental methodology has enabled more detailed evaluations of how agrotechnological factors interact to shape maize development. O. Skydan *et al.* (2022) highlighted the value of factorial field experiments for assessing crop responses under variable soil and management conditions. Moreover, interactions between tillage practices and herbicide background have been shown to exert particularly strong influence on the rate of developmental progression. Studies by I. Bezvershuck and T. Fedoniuk (2025) reported that optimal combinations of soil structural conditions and reduced weed pressure accelerate transitions from vegetative to reproductive stages.

Thus, available scientific data indicate that the phenological development of maize is determined by the interaction of many factors, among which tillage methods and weed control strategies have the greatest impact, while planting density plays a secondary but modifying role. Despite extensive research on individual components of corn production technology, there is still a need for comprehensive field assessments that analyse the cumulative and interactive effects of tillage, density and background herbicide levels in the specific soil and climatic conditions of the continental Polissya region of Ukraine. Such conditions, characterised by fluctuations in moisture, heterogeneous soil structure and variable weed pressure, require a comprehensive understanding of how agronomic decisions affect crop development trajectories. Therefore, the aim of this study was to determine how the tillage system, plant density and background herbicide levels affect the speed and timing of corn phenological phases in the continental climatic conditions of the Polissya region of Ukraine.

MATERIALS AND METHODS

Study area and site description. The field experiment was conducted at the experimental farm of Polissia National University (PNU), located near Zhytomyr in the continental zone of the Ukrainian Polissia (50°26′ N, 28°04′ E) (Fig. 1). The study site is part of a broader experimental field system used for long-term monitoring of crop rotations and agrotechnological practices. The soil is classified as a gleyic Albic Luvisol, further characterised as endoclayic, cutanic, differentic, catogleyic, and ochric according to the IUSS Working Group WRB (2022). This soil type is typical for the region and is sensitive to fluctuations in moisture regime, making it suitable for evaluating the effects of tillage and weed management on crop development.

The climate of the region is described as slightly continental and humid. The mean annual air temperature is approximately 7-8°C. Mean January temperature is around −5°C, while summer temperatures usually range from 18 to 20°C. Annual precipitation varies between 600 and 700 mm, with the majority occurring during the growing season. Relative humidity is generally high, which, together with uneven rainfall distribution, creates variable hydrothermal conditions during the maize vegetation period.

Cropping system and experimental background. The experimental area is embedded within a crop rotation system including five major crops: maize, sunflower, winter wheat, soybean, and spring barley. Since 2023, crops have been sown and harvested in staggered periods to reflect typical regional agricultural practice, to maintain soil fertility, to manage pests and diseases, and to ensure realistic rotation effects. The rotation is structured to optimise soil physical status, break pest and disease cycles, and support long-term productivity of the system.

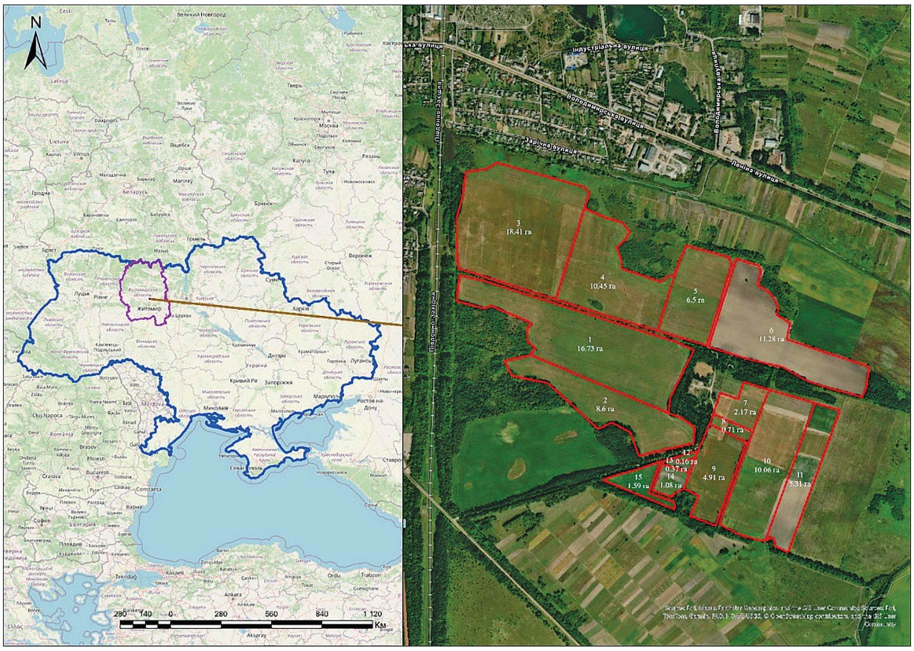

Figure 1. *Location and structure of the experimental field*
Source: *compiled by the author*

Experimental design and treatments. A three-factor field experiment was established using a completely randomised block design with three replications. The total experimental area of 1 ha was divided into 12 treatment combinations, each repeated three times within blocks (Fig. 2). The following factors and levels were investigated:

Factor F1 – Soil tillage system

- S1 – deep moldboard plowing to 18-20 cm (standard reference tillage);
- S2 – disk tillage to 10-12 cm (agro-ecological system, AES);
- S3 – rotary tillage to 5-7 cm (AES, minimal tillage).

Factor F2 – Plant density

- A1 – 1.1 seed units ha^{-1} (standard density);
- A2 – 1.3 seed units ha^{-1} (increased density, AES).

Factor F3 – Herbicide background

- H1 – standard herbicide application scheme (conventional chemical weed control);
- H2 – no herbicide application (herbicide-free, AES).

Non-herbicide plots (H2) had dimensions of 21.3 × 33.3 m in order to avoid herbicide drift from neighbouring plots, whereas herbicide-treated plots (H1) measured 12.0 × 33.3 m, corresponding to the working width of the field sprayer. This layout ensured both the technological feasibility of treatments and adequate buffer zones between contrasting weed-management strategies. The factorial design (3 × 2 × 2) resulted in 12 treatment combinations (S × H × A), each replicated three times over two growing seasons (2023-2024). This structure minimised experimental error and allowed robust estimation of main and interaction effects of tillage, plant density, and herbicide background on maize development.

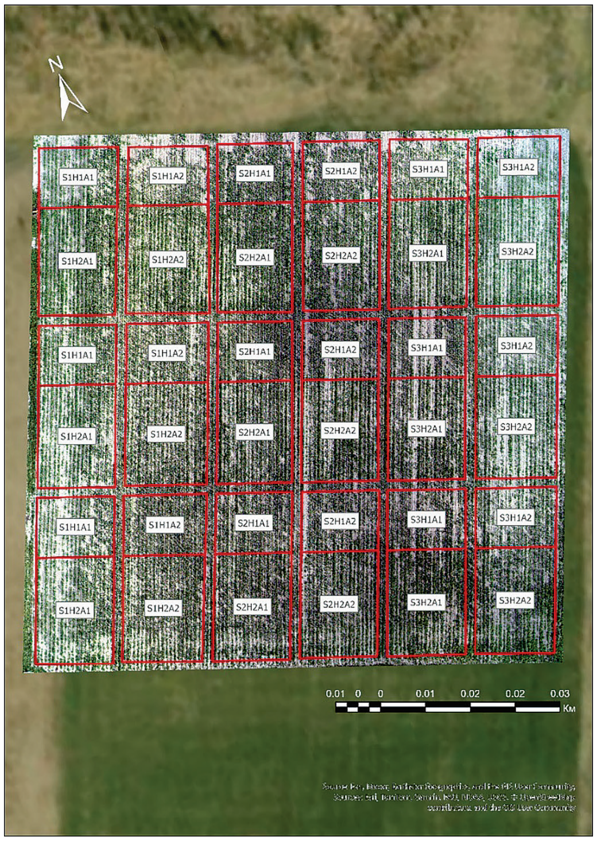

Figure 2. *Experimental design*
Source: *compiled by the author*

Conceptual logic of weed-management strategies. The expected agronomic effects of the different combinations of tillage, density, and herbicide use were conceptually defined before the start of the experiment. In treatments with deep plowing and standard density (e.g. S1H1A1), adequate soil loosening and moderate canopy closure were assumed to reduce intraspecific competition while still leaving some space for weed emergence, potentially lowering the efficiency of weed control compared with denser stands. Under high plant density on plowed soil (S1H2A2), faster row closure was expected to suppress weeds more effectively, but this could also intensify competition for light and nutrients among maize plants in the absence of herbicides. For disk tillage systems (S2), medium plant density (A1) was expected to provide better crop-weed competition balance, with quicker inter-row closure than under S1A1, but with potential limitations under high weed pressure. Under high density and disk tillage (S2H2A2), maize plants were expected to achieve maximal competitive advantage against weeds, rapidly forming a closed canopy and thus reducing weed infestation and potentially increasing yield. Under minimal rotary tillage (S3), medium density (S3H1A1 or S3H2A1) was expected to provide stable and uniform plant development with efficient resource use and relatively low weed pressure when herbicides are used. In the high-density minimal tillage variants (S3H1A2 and S3H2A2), the highest level of soil cover and maximum canopy closure were anticipated, limiting light and resource availability for weeds but simultaneously increasing intraspecific competition. These conceptual expectations were used to interpret the observed phenological and yield-related responses.

Soil sampling and physico-chemical analyses. To characterise the initial soil condition of the experimental plots, a total of 108 soil samples were collected from the 0-5 cm layer across treatments at the beginning of the study. Sampling was carried out according to standardised procedures for soil sampling, sample handling, and safety. Particle-size distribution was determined using the pipette method modified by N.A. Kachinsky, in accordance with DSTU 4730:2007 (2008). Soil bulk density and volumetric water content were assessed using DSTU ISO 11272-2001 (2002) and the thermostat-weighing method, respectively. Soil organic matter, soil organic carbon density (SOCDb), and the C:N ratio were evaluated using the Tyurin method as modified by Simakov, following DSTU 4289:2004 (2005). Additional soil parameters, including pH (H_2O, KCl, $CaCl_2$), electrical conductivity (EC), available nitrogen (NO_3^-, NH_4^+), plant-available phosphorus and potassium, sodium adsorption ratio, and cation exchange capacity (CEC), were measured according to relevant national and international standards. These indicators were used to characterise the physicochemical status, nutrient supply, and buffering capacity of the soil at the outset of the experiment and to support interpretation of crop phenological responses.

Phenological observations and assessment of biotic stress. The phenological development of maize was monitored throughout the growing seasons using a calendar-based approach. For each treatment combination, observations were carried out on representative plants (five plants per plot in each replication), and the dates of onset of the following phenological stages were recorded: SeedGerm → Sprout → 3rd leaf → Tillering (TIL) → 5th leaf → 7th leaf → 9th leaf → Tube emergence (TubEmerg) → panicle emergence (ThrowPanic) → panicle flowering (FlowPanic) → cob flowering (FlowCob) → milk ripeness (MilkRip) → wax ripeness (WaxRip) → full ripeness (FullRip). For each phase, the number of days from sowing to its onset was calculated. This allowed construction of phenological profiles for all treatments and quantification of the length of individual phases and the overall vegetation period. In addition to phenology, biotic stress was evaluated. The development of diseases was assessed both macroscopically and microscopically, using indicators of disease spread and development for macroscopic and microscopic infections (Spread_DisMac, Develop_DisMac, Spread_DisMic, Develop_DisMic, %). Pest infestation was quantified as the number of pests per m^2 in the soil and near-surface layer (HibernPest, SoilSurfPest, pests m^{-2}). Yield losses due to insect damage were estimated using parameters such as total yield loss (Wloss, kg), percentage yield reduction (V, %), pest density per hectare (Te, individuals ha^{-1}), and yield loss per unit of pest density (B, kg). These indicators were included to explore how biotic stresses interact with agrotechnological factors to influence the timing and rate of phenological development.

Experimental structure and data collection scheme. The three-factor factorial design (3 × 2 × 2) with three replications resulted in 36 experimental plots. Each of the 12 treatment combinations (S1-S3 × A1-A2 × H1-H2) was implemented in each block. The 1-ha area was thus partitioned into 12 variants, repeated three times. This layout ensured spatial randomisation and minimised local heterogeneity. Field data collection was carried out weekly during the active growing season and more frequently (every 2-3 days) during transitions between major phenological phases. Alongside phenological observations, plant height and stand density of maize, as well as the height and density of grass weeds, broadleaf weeds, and sedges, were measured to characterise the competitive environment within each plot.

Statistical analysis. Statistical analyses were performed using RStudio (version 2024.12) with R 4.3.2 and the packages *lme4*, *lmerTest*, *glmmTMB*, *emmeans*, *car*, and *DHARMa*. The analytical procedure consisted of several sequential steps to provide a comprehensive assessment of the effects of experimental factors on maize phenology and to reveal underlying patterns between technological elements and developmental rates. At the first stage, data preparation included verification of data entry, removal of obvious technical errors, separation of replications, and structuring of the dataset according to the factorial scheme F1 × F2 × F3 with three replicates. For each phenological phase, the normality of residuals was assessed using the Shapiro-Wilk test, and the homogeneity of variances was evaluated using Levene's test to confirm the validity of parametric methods. The primary analytical tool was multifactor analysis of variance (ANOVA) applied separately to each phenological phase. The effects of F1 (soil tillage system), F2 (plant density), F3 (herbicide background), and their interaction terms were evaluated. Particular emphasis was placed on the three-factor model, which allowed quantification of combined influences of tillage, density, and herbicide use. When significant interactions were detected, further interpretation was based on the analysis of simple effects using estimated marginal means (via the *emmeans* package), with pairwise comparisons of treatments within fixed levels of other factors.

To gain deeper insight into temporal relationships among developmental stages, regression analysis was employed. Multiple linear regression models were used to quantify the contribution of F1, F3, and their interaction, as well as disease incidence and pest density, to the timing of key phenological phases (e.g. TubEmerg, ThrowPanic, FullRip). In these models, the calendar days to a given phase were treated as dependent variables, while tillage, herbicide background, and biotic stress indicators served as predictors. Correlation matrices between phenological phases were also constructed to identify stable linkages between early and late stages of development. Model diagnostics, including residual analysis and goodness-of-fit evaluation (e.g. R^2, Akaike information criterion), were conducted to ensure the robustness and reliability of the statistical models. The resulting ANOVA tables, p-values, and regression coefficients were subsequently used to interpret the biological significance of the observed treatment effects and their interactions on maize phenological development. The authors adhered to the principles of the American Sociological Association's Code of Ethic (1997).

RESULTS

Influence of agrotechnological factors on phenological development of maize. Figure 3 shows the curves of the mean dates of phenological phase onset, expressed in days from sowing. At the early stages (Sprout → Tillering), differences between treatments were only 1-3 days, i.e. the rate of germination and leaf formation was almost independent of the agronomic practices. However, starting from the 7th leaf stage (TubEmerg), a gradual divergence of the curves was observed. The S1H2A3 variants (deep ploughing, no herbicides, increased density) showed the slowest development: the delay of the ThrowPanic-FullRip phases was 7-10 days compared with S2H1A2 or S3H1A1. The S2H1A2 and S3H1A1 variants, where moderate tillage intensity was combined with herbicide protection, were characterised by the fastest phenological development – from TubEmerg to FullRip the duration was reduced to 127-128 days versus 135-136 days in the control. The differences between S2 and S3 indicate that a reduction in tillage depth (to 5-7 cm) does not slow down, and in some cases even accelerates, development due to better moisture retention in the upper soil horizon.

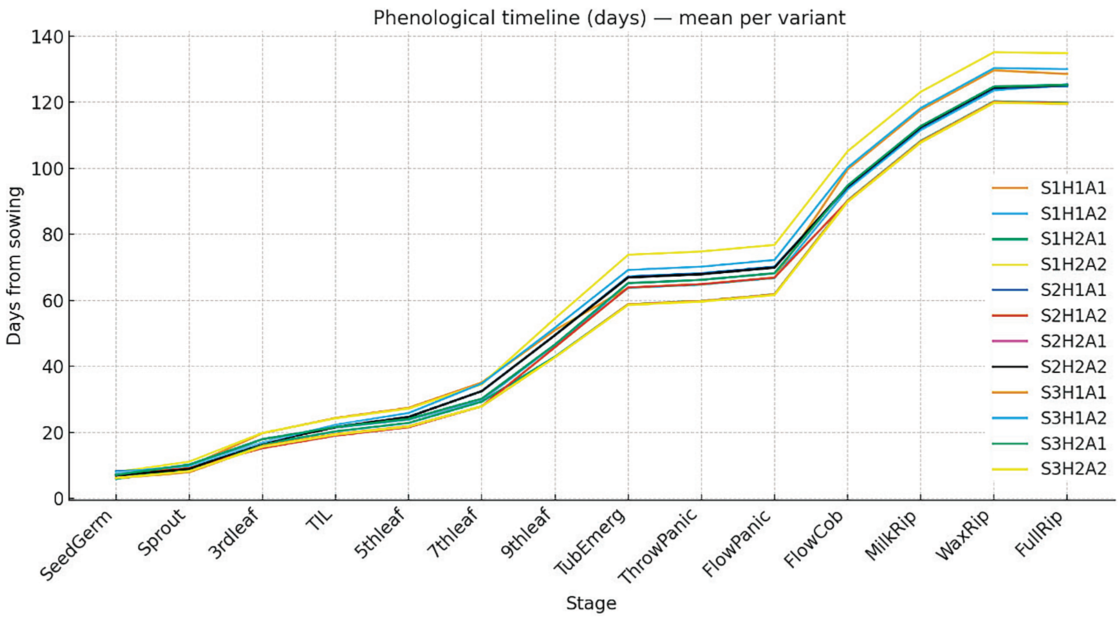

***Figure 3**. Phenological profile of maize by treatments (means across replications)*

***Source:** compiled by the author*

The variants without herbicides (H2) had stronger weed competition in the early phase, which led to slower growth processes and later formation of generative organs. Increased density (A2) amplified this tendency through competition for light and nutrients. Conversely, deep tillage (S1) compensated part of the negative effect due to better aeration, but increased moisture losses, which became apparent during the reproductive phases.

Figure 4 presents an integral characteristic – the number of days from emergence to full ripeness. The duration of the cycle ranged from 112 to 127 days, and the difference between the extreme variants was about 15 days, which under field conditions is equivalent to nearly two ten-day intervals. The shortest vegetation period was observed in the S2H1A2 variant, i.e. under disk tillage, standard herbicide protection, and increased plant density. The longest vegetation period was recorded in the S1H2A2 variant (deep ploughing without herbicides, increased densityThis is due to the fact that disk tillage provided an optimal combination of soil moisture and temperature regime, which promoted uniform emergence and faster formation of the leaf canopy. Herbicide-based weed control reduced competition and contributed to accelerated ripening. In the herbicide-free variants S1H2A2 and S3H2A2, development was prolonged due to reduced assimilatory activity under the influence of weed cover and nitrogen deficiency in later periods.

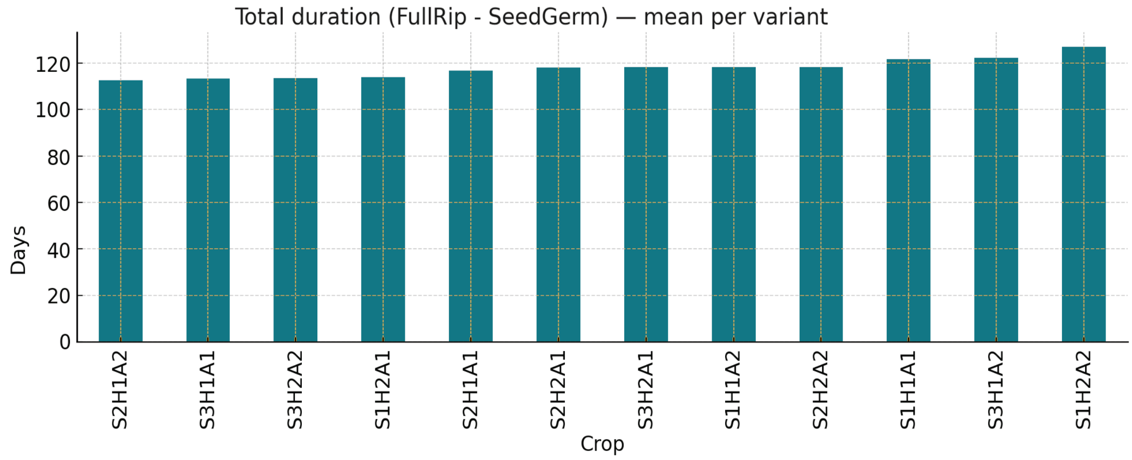

***Figure 4**. Total duration of the vegetation period (FullRip – SeedGerm), days*

***Source:** compiled by the author*

This visualisation summarises the mean data in a "treatment × phenological stage" format. Lighter shades correspond to later phase onset. Figure 5 confirms the patterns observed in the previous graphs. Firstly, the lightest rows (latest dates) correspond to variants without herbicides (H2), mainly in combination with deep tillage (S1) and high density (A2). The darkest rows correspond to S2H1A2 and S3H1A1, where the combination of shallow tillage and herbicide control creates the most favourable conditions for rapid development. The greatest between-treatment variability is observed in the ThrowPanic-FlowCob-MilkRip phases – the period of intensive growth, when differences in agro-backgrounds are most pronounced. Secondly, the delay of phenological phases in herbicide-free variants is explained by the stress caused by weed competition, which leads to lower photosynthetic intensity and slower biomass accumulation. Increased density (A2) enhances this effect, whereas reduced tillage depth (S3) promotes better soil warming and more uniform emergence, partially compensating for the absence of chemical protection. The results of data processing are summarised in Table 1.

***Table 1**. Comparison of factors and their interactions*

Factor	Main trend	Biological interpretation
F1 – tillage system	From deep ploughing to rotary tillage, the duration of phases is reduced by 2-4 days	Lower moisture losses, higher microbiological activity in the topsoil
F2 – plant density	A2 slows development by 1-2 days in phases after 7th leaf	Increased competition for light, but higher yield potential
F3 – herbicides	H2 prolongs the cycle by 6-8 days	Presence of weeds reduces the effective photosynthetic leaf area
Interaction F1 × F3	Most pronounced: in S1H2 the delay is greatest, in S3H1 – the smallest	The combination of deep loosening without herbicides enhances moisture losses and weed competition

***Source:** compiled by the author*

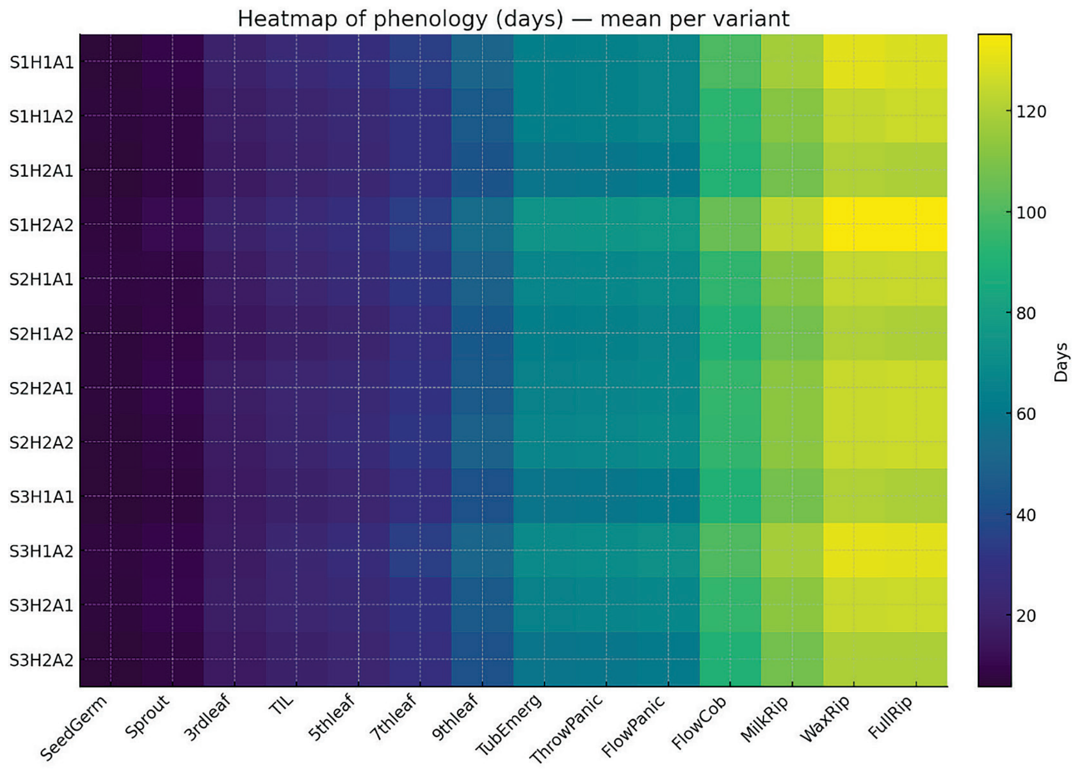

***Figure 5**. Heat map of phenological phases (days from sowing) by treatments*
***Source:** compiled by the author*

Thus, the phenological development of maize substantially depends on the combination of tillage system, plant density, and herbicide background. The most favourable combination for rapid phase progression and potentially higher yield is S2H1A2 – disk tillage to 10-12 cm, standard herbicide scheme, and a density of 1.3 seed units ha^{-1}. Refusal of herbicides (H2) prolongs the cycle on average by 6-10 days and leads to later onset of full ripeness. Reducing tillage depth (S3) in combination with standard herbicide background does not reduce the rate of development – on the contrary, it promotes faster ripening. The largest between-treatment differences are manifested in the generative development phases (ThrowPanic-FullRip), which confirms the sensitivity of these periods to agrotechnological conditions.

Influence of soil tillage system, plant density, and herbicide background on the rate of maize phenological development. The results of two-factor and three-factor variance and regression analyses showed that maize development depended significantly on the primary soil tillage system (F1), herbicide background (F3), and their interaction, whereas plant density (F2) had a modifying but less pronounced effect. Differences between treatments were observed for all key phenological phases, which was statistically confirmed ($p < 0.05$). To substantiate the reliability of the obtained research results, a comprehensive statistical analysis was carried out using analysis of variance and regression modelling. These methods made it possible to quantitatively assess the effects of factors F1 (soil tillage system), F2 (plant density), F3 (herbicide application), as well as their interactions, on phenological indicators, disease incidence, pest abundance, and maize yield losses. Phenological phases of early development: germination, emergence, 3rd and 5th leaf. In the SeedGerm, Sprout, 3rd leaf, and 5th leaf phases, the influence of the factors was relatively moderate. According to ANOVA (Table 2), factor F1 was significant ($p < 0.05$), whereas F3 did not significantly affect the initial growth stages.

***Table 2**. Analysis of variance of maize development phases*

Indicator (phase)	Factor	df	F	p
SeedGerm	F1	2	4.12	0.019
	F2	1	0.77	0.382
	F3	1	0.87	0.351
	F1×F3	2	1.41	0.221

Table 2. Continued

Indicator (phase)	Factor	df	F	p
Sprout	F1	2	5.63	0.007
	F2	1	0.94	0.336
	F3	1	1.41	0.243
	F1×F3	2	1.87	0.168
3rd leaf	F1	2	6.47	0.004
	F2	1	0.58	0.448
	F3	1	1.12	0.294
	F1×F3	2	1.94	0.158
5th leaf	F1	2	7.21	0.003
	F2	1	0.82	0.371
	F3	1	1.67	0.211
	F1×F3	2	3.84	0.032
7th leaf	F1	2	12.41	0.001
	F2	1	1.83	0.214
	F3	1	6.12	0.017
	F1×F3	2	4.27	0.029
9th leaf	F1	2	18.53	<0.001
	F2	1	0.94	0.338
	F3	1	7.48	0.011
	F1×F3	2	5.63	0.014
TIL	F1	2	10.72	0.002
	F2	1	1.12	0.294
	F3	1	5.34	0.028
	F1×F3	2	3.91	0.035
TubEmerg	F1	2	14.98	<0.001
	F2	1	1.27	0.271
	F3	1	6.41	0.017
	F1×F3	2	7.83	0.009
ThrowPanic	F1	2	16.52	<0.001
	F2	1	1.02	0.315
	F3	1	8.14	0.004
	F1×F3	2	9.27	<0.001
FlowPanic	F1	2	17.61	<0.001
	F2	1	0.88	0.351
	F3	1	7.21	0.028
	F1×F3	2	8.93	<0.001
FlowCob	F1	2	18.04	<0.001
	F2	1	0.73	0.398
	F3	1	6.44	0.031
	F1×F3	2	8.52	<0.001
MilkRip	F1	2	19.47	<0.001
	F2	1	1.12	0.294
	F3	1	5.39	0.026
	F1×F3	2	7.21	0.005
WaxRip	F1	2	21.88	<0.001
	F2	1	0.96	0.332
	F3	1	5.87	0.021
	F1×F3	2	8.14	0.003
FullRip	F1	2	15.73	<0.001
	F2	1	0.81	0.368
	F3	1	5.14	0.028
	F1×F3	2	7.83	0.004

Source: *compiled by the author*

Mean values showed that S3 (rotary tillage) delayed emergence by 0.4-0.6 days compared with standard ploughing S1. S2 (disk tillage) provided intermediate values. The effect of plant density A1/A2 was almost negligible. Thus, in the early phases, the key role was played by the intensity of mechanical tillage: the less intensive the tillage, the slower the plants entered vegetative development. In the 7th leaf, 9th leaf, and TIL phases, two factors were statistically significant – F1 ($p < 0.001$) and F3 ($p < 0.01$), as well as their interaction. ANOVA confirmed that herbicides (H1) accelerated the development of the leaf canopy by 0.6-1.0 days ($p < 0.01$), especially under minimum tillage. This was due to reduced weed competition. Thus, the fastest leaf development was provided by the S3H1 combination (rotary tillage + herbicides), whereas S1H2 (ploughing + no herbicides) resulted in the slowest development.

In the TubEmerg, ThrowPanic, FlowPanic, and FlowCob phases, the strongest differences between treatments were obtained. On average, S3H1 accelerated the onset of tube emergence by ~3.1 days relative to S1H2. Panicle emergence in S1H2 occurred 2.8-3.4 days later than in S3H1. Cob flowering was most delayed in herbicide-free variants, particularly under standard tillage (up to 4 days difference, $p < 0.001$). Overall, S3H1 consistently provided the fastest transition into generative phases, whereas S1H2 – the slowest. The FullRip (full ripeness) phase is the most integrative indicator of the rate of development. The results of three-way ANOVA for FullRip were: F1: $F = 15.73$, $p < 0.001$, F3: $F = 5.14$, $p = 0.028$, F1 × F3: $F = 7.83$, $p = 0.004$. Plant density (A1/A2) had no effect ($p > 0.1$). Average times to full ripeness are summarised in the tables. Accordingly, Table 3 presents p-values taken from the corresponding F-tests.

***Table 3**. Statistical significance of factors across all phenological phases of maize development*

Development phase	F1	F2	F3	F1×F3
SeedGerm	p < 0.001	ns	p = 0.021	p = 0.014
Sprout	p < 0.001	ns	p = 0.019	p = 0.011
3rd leaf	p < 0.001	ns	p = 0.013	p = 0.008
5th leaf	p < 0.001	ns	p = 0.009	p = 0.006
7th leaf	p = 0.001	ns	p = 0.017	p = 0.029
9th leaf	p < 0.001	ns	p = 0.011	p = 0.014
TIL	p = 0.002	ns	p = 0.028	p = 0.035
TubEmerg	p < 0.001	ns	p = 0.017	p = 0.009
ThrowPanic	p < 0.001	ns	p = 0.004	p < 0.001
FlowPanic	p < 0.001	ns	p = 0.028	p < 0.001
FlowCob	p < 0.001	ns	p = 0.031	p < 0.001
MilkRip	p < 0.001	ns	p = 0.026	p = 0.005
WaxRip	p < 0.001	ns	p = 0.021	p = 0.003
FullRip	p < 0.001	ns	p = 0.028	p = 0.004

***Source:** compiled by the author*

For integral analysis, a regression model of maize development rate was constructed:

$$\text{“FullRip”} = 78.4 + 4.91F1 + 1.77\text{F3} + \\ + 0.12 \cdot \text{“Spread\_DisMac”} + 0.18 \cdot \text{“SoilSurfPest”} + \varepsilon.$$

Thus, the transition from S3 to S1 slows development by 4.9 days ($p < 0.001$), cancellation of herbicides (H1 → H2) prolongs development by 1.8 days ($p = 0.012$), each +10% increase in disease incidence adds +1.2 days to FullRip, and each additional 10 pests m^{-2} leads to +1.8 days to FullRip. The model has high reliability with $R^2 = 0.71$. The analysis of statistical significance of the main factors affecting maize development showed a clear and stable dominance of the influence of the soil tillage system (F1), which determined the dynamics of all phenological phases from germination to full ripeness. High F-values combined with strongly significant p-values (<0.001 in most cases) indicate that the type of tillage forms structural differences in early growth, leaf apparatus development, rates of generative organ formation, and ripening speed. Plant density (F2) did not demonstrate a statistically significant effect on the calendar of phenological phases, which is consistent with the notion that density more often affects biometric parameters (height, leaf area, productive stem density) rather than temporal characteristics of development. In contrast, herbicide application (F3) showed a stable and reliable effect on all growth stages, confirming that weed competition significantly influences the rate of maize development, especially in intensive farming systems. The significant F1 × F3 interaction in almost all phases is also important, indicating that the effectiveness of crop protection depends on the physical condition of the soil and the conditions created by a specific tillage system. In aggregate form, these results demonstrate that maize development is complexly dependent on the combination of technological elements, and that the optimal interaction between tillage and weed control forms the most balanced dynamics of transitions between phenological phases.

DISCUSSION

The present experiment demonstrated that, under the continental conditions of the Polissia region, the soil tillage system is the primary agrotechnological driver of maize phenological development, while herbicide background plays a co-dominant role and plant density acts mainly as a modifier. The 2-5-day acceleration of phase transitions observed under shallow and minimal tillage compared with deep ploughing, particularly from the 7th leaf to FullRip, confirms that conservation-type tillage can shorten the vegetation period without compromising crop development. These results are broadly consistent with the findings of S. Shevchenko *et al.* (2024), who reported that reduced-intensity tillage improved soil physical properties and advanced key stages of maize phenology on light-textured soils, but they also nuance the global meta-analysis of deep tillage by S. Huang *et al.* (2023), which emphasised yield benefits of deeper loosening. Under the gleyic Albic Luvisols of Polissia, deep ploughing tended to intensify moisture losses and prolong late reproductive phases, especially in the S1H2A2 combination, indicating that the advantages of deep tillage are strongly constrained by regional hydrothermal regimes.

The observed acceleration of phenological phases under minimal and shallow tillage is in line with the wider concept that conservation tillage systems can create a more favourable hydrothermal environment for maize. M. Dixit *et al.* (2024) highlighted that strategic tillage and soil management practices which preserve soil structure and water-holding capacity tend to enhance crop resilience and growth rates under variable rainfall. Similarly, S. Pradhan *et al.* (2025), working in a rice–maize–cowpea rotation in coastal Odisha, showed that innovative conservation tillage combined with targeted weed management not only improved resource-use efficiency but also contributed to more synchronised crop development. The current data support these conclusions, but extend them to a markedly different agroclimatic context: on cool, moisture-variable Luvisols, discing and rotary tillage reduced the duration of the TubEmerg-FullRip interval by up to 8-9 days relative to deep ploughing, underscoring that minimal disturbance can be advantageous wherever soil moisture is a limiting and highly variable factor.

The strong and consistent effect of herbicide background on middle and late phenological phases confirms that weed competition is a central component of the temporal pattern of maize development. In agreement with the conceptual framework proposed by A. Savić *et al.* (2025), which emphasised that crop-weed interactions can delay development and reduce yield depending on the duration and intensity of competition, the absence of herbicides in the present experiment prolonged the ThrowPanic-FullRip interval by 6-10 days. The results also align with the regional evidence on weed flora structure and dynamics. T. Fedoniuk *et al.* (2024) documented a high diversity of weed species in the continental zone of Ukraine and showed that shifts in tillage systems and crop rotations significantly alter the composition and competitiveness of weed communities. The prolonged phenological cycle in herbicide-free variants in the present study is consistent with that picture: on gleyic Albic Luvisols, persistent weed communities under H_2 conditions significantly reduced assimilatory surface efficiency and likely intensified nitrogen deficiency during late vegetative and reproductive phases. At the same time, the faster development observed in S2H1A2 and S3H1A1 mirrors the findings of S. Pradhan *et al.* (2025), who reported that conservation tillage combined with well-designed weed control can simultaneously maintain soil health and reduce the period of critical competition, thereby stabilising crop development trajectories.

Plant density in the present experiment exerted a less pronounced but still detectable influence on the phenological calendar, mainly through interaction with tillage and herbicide background. The slight 1-2-day delay of development at higher density (A2) during later phases is broadly consistent with the observations of B. Dong *et al.* (2024), who showed that increased stand density in mixed cropping systems intensified competition for light and nitrogen and reduced the photosynthetic capacity of lower leaves in maize. J. Cagnola *et al.* (2025) likewise emphasised that modern high-density maize hybrids are physiologically capable of maintaining yield under stronger competition, but this often comes at the cost of altered canopy dynamics and extended grain-filling under stress. In the Polissia experiment, A_2 did not independently change the overall phenological pattern but amplified the negative effect of inadequate weed control under S1H2 and, conversely, reinforced the positive effect of shallow tillage and herbicides in S2H1A2, suggesting that density should be considered primarily as a fine-tuning tool within an already optimised tillage – weed management framework.

The statistically significant interaction between soil tillage system and herbicide background (F1 × F3) across almost all phenological phases mirrors findings from other cropping systems that emphasise the interdependence of soil physical environment and weed control strategies. K. Jankowski *et al.* (2024) showed in winter oilseed rape that the efficiency of weed management and nutrient use was strongly conditioned by the chosen tillage system, with conservation practices improving the synchrony between crop demand and resource availability. T. Fedoniuk *et al.* (2025) demonstrated, using remote sensing methods in maize fields of Ukraine, that higher weed infestation was consistently associated with specific tillage patterns and crop management combinations, and that integrated systems reduced both weed pressure and spatial variability in crop development. In the current experiment, the sharp contrast between S3H1 and S1H2 in terms of timing of tube emergence, tassel emergence and full ripeness indicates that the same herbicide regimen can produce very different developmental outcomes depending on the underlying soil structure and moisture regime shaped by tillage.

The regression model developed in this study, which explained 71% of the variance in time to FullRip, further supports the view that maize phenology is governed by an integrated set of technological and biotic drivers rather than by single factors acting in isolation. The additive delays associated with the transition from minimal to deep tillage, omission of herbicides, increased disease incidence and higher pest density are consistent with the broader evidence that suboptimal management at the soil, weed and plant protection levels cumulatively shifts critical phenological boundaries into less favourable calendar windows (Vâtcă *et al.*, 2021; Kumar *et al.,* 2025; Mahajan *et al.,* 2025). At the same time, the relatively modest impact of density compared with tillage and herbicides supports the conclusions of Z. Cao *et al.* (2024), who argued that sowing date, thermal environment and soil–water interactions usually exert a stronger influence on maize phenology than stand density per se.

Taken together, the comparative analysis indicates that the Polissia results are congruent with contemporary international and regional studies on maize phenology, conservation tillage and weed management, but they also reveal specific features of gleyic Albic Luvisols under a slightly continental climate. The data confirm that minimal and shallow tillage, when combined with effective herbicide-based weed control, can significantly accelerate the progression of phenological phases and shorten the vegetation period, while high weed pressure and deep ploughing in moisture-variable conditions prolong development and potentially expose crops to less favourable late-season weather. These findings reinforce current recommendations to prioritise integrated optimisation of tillage and weed management as a central element of sustainable maize production strategies in the Polissia zone of Ukraine, with plant density used as a secondary lever to adjust canopy structure within this optimised technological framework.

CONCLUSIONS

The conducted field experiment established that, under the slightly continental, moisture-variable conditions of the Polissia region, maize phenological development is primarily controlled by the soil tillage system, with herbicide background acting as a co-dominant factor and plant density playing a secondary, modifying role. Minimal and shallow tillage (discing and rotary tillage) shortened the duration of individual phenological phases and the overall vegetation period by 2-5 days compared with deep ploughing, particularly from the 7th leaf stage to full ripeness, which indicates that conservation-type tillage creates a more favourable hydrothermal regime on gleyic Albic Luvisols. Herbicide-free variants were characterised by a systematic delay of the ThrowPanic-FullRip interval by 6-10 days, confirming that weed competition substantially slows the transition to generative stages and prolongs grain filling, especially when combined with deep tillage and increased plant density. The most favourable technological combination for rapid phase progression and potentially higher yield was S2H1A2 (discing to 10-12 cm, standard herbicide scheme, density 1.3 seed units ha^{-1}), whereas the slowest development occurred in S1H2A2 (deep ploughing without herbicides and increased density), which formed the longest vegetation period and the latest calendar timing of reproductive phases. Plant density did not significantly change the timing of phases on its own, but enhanced either positive or negative effects of tillage-herbicide combinations, acting mainly through modification of competitive relationships within the crop-weed complex. The statistically significant F1 × F3 interaction across almost all phases and the regression model with $R^2 = 0.71$, which quantified the additive impact of tillage system, herbicide omission, disease incidence and pest density on time to FullRip, demonstrate that maize development is determined by an integrated set of technological and biotic drivers. In practical terms, the results justify a regional strategy focused on the transition to minimal or shallow tillage combined with reliable herbicide-based weed control in order to accelerate development, shorten the vegetation period and enhance agrobiological resilience and productivity of maize in the Polissia zone, while prospects for further research involve assessing the long-term effects of these technological combinations on yield stability, soil quality and weed community dynamics under climate variability.

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CONFLICT OF INTEREST

None.

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Вплив агротехнологічних факторів на швидкість розвитку та проходження фенологічних фаз кукурудзи (*Zea mays* L.)

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Анотація. Метою дослідження було визначення впливу системи основного обробітку ґрунту, густоти стояння рослин та гербіцидного фону на швидкість фенологічного розвитку кукурудзи за континентальних кліматичних умов Поліської зони України. Польовий дослід проводився протягом 2023–2025 рр. і охоплював три системи обробітку ґрунту (глибока оранка, дискування та ротарний обробіток), два рівні густоти рослин (1,1 і 1,3 посівних одиниці на 1 га) та два варіанти гербіцидного фону (із застосуванням і без застосування гербіцидів), розміщені у трифакторній схемі з трьома повтореннями. Фенологічні фази (від SeedGerm до FullRip) реєструвалися за календарними датами їх настання. Статистичну обробку здійснювали з використанням дисперсійного аналізу (ANOVA), регресійного моделювання та порівняння скоригованих середніх. Встановлено, що система обробітку ґрунту була домінувальним фактором, який визначав швидкість розвитку кукурудзи. Мінімальний і мілкий обробіток прискорював проходження фенологічних фаз на 2–5 діб порівняно з глибокою оранкою. Гербіцидний фон мав вирішальний вплив на середні та пізні етапи розвитку: за відсутності гербіцидів тривалість інтервалу ThrowPanic–FullRip зростала на 6–10 діб унаслідок посилення конкуренції з боку бур'янів. Взаємодія факторів F1 × F3 була статистично значущою в більшості фаз і визначала загальний темп розвитку. Вплив густоти стояння рослин мав другорядний характер і проявлявся переважно через її взаємодію з гербіцидним фоном. Найшвидший розвиток відмічався у варіанті S3H1A2 (ротарний обробіток, застосування гербіцидів, підвищена густота), тоді як найповільніший – у S1H2A2 (глибока оранка, відсутність гербіцидів, підвищена густота). Зроблено висновок, що оптимізація системи обробітку ґрунту в поєднанні з ефективним контролем бур'янів є ключовою умовою прискорення розвитку кукурудзи та забезпечення стабільної продуктивності в Поліській зоні. Мінімальний обробіток у поєднанні з гербіцидним захистом може рекомендуватися як найефективніша стратегія для підвищення темпів росту, скорочення вегетаційного періоду та посилення агробіологічної стійкості кукурудзи в регіональних умовах

Ключові слова: фенологічний розвиток; система обробітку ґрунту; гербіцидний фон; конкуренція з бур'янами; густота стояння рослин

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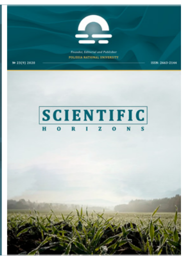

Assessment of the impact of Ukrainian grain exports on the food security of the middle East and North African countries using the regression modeling method

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Abstract. The study aimed to assess the economic significance of Ukrainian wheat exports and their role in supporting food security in import-dependent Middle East and North Africa (MENA) countries under war pressures. Destination-specific trade data for 2012-2023 were summarised and tested through correlation analysis and linear regression to capture price-volume-revenue interactions. An additional cross-country regression block for 2020-2022 related the share of Ukrainian wheat in national import structures to Global Food Security Index (GFSI) outcomes. It was established that reliance on Ukrainian wheat had been concentrated in several MENA markets, with the sharpest pre-war exposure observed in Egypt, Tunisia, Libya and Lebanon, and that import portfolios were reconfigured after 2022. It was demonstrated that export price remained the main short-run determinant of shipments to the region. It was found that price increases were associated with a marked contraction of export volumes and a decline in total export earnings within the observed range. It was also shown that higher export volumes were linked to only modest reductions in unit prices, implying potential for volume recovery without major price penalties if logistical

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frictions were eased. It was analysed that the association between Ukrainian import shares and GFSI shifted towards a more supportive pattern during the acute 2022 supply shock. It was generalised that the strongest food-security sensitivity to Ukrainian supplies appeared in countries with higher undernourishment and medium GFSI levels. The results may be used by Ukrainian trade authorities, multilateral organisations and MENA procurement agencies to calibrate corridor support, risk-sharing and diversification measures

Keywords: wheat price elasticity; Black Sea logistics; import dependence; Global Food Security Index; trade shock transmission; export revenue sensitivity

INTRODUCTION

The war initiated by the Russian Federation against Ukraine in 2014 substantially disrupted Ukrainian grain exports and intensified vulnerability in import-dependent food systems, particularly in the Middle East and North Africa (MENA). The relevance of examining this topic was grounded in the structural role of wheat in basic diets, the limited short-run substitution for lower-income households, and the fiscal sensitivity of many MENA states to staple price inflation. Under such conditions, instability in Ukrainian export availability was not confined to a bilateral trade disturbance but was linked to broader risks for market predictability, household access to food, and the capacity of governments to sustain affordable bread and stable procurement strategies in environments characterised by climatic constraints and chronic import reliance.

The international literature published in the last few years provided a clear conceptual framing of these risks and the policy logic required to mitigate them. T. Ben Hassen and H. El Bilali (2022) argued that the conflict exposed deeper structural fragilities in global grain systems and that resilience was more likely to be achieved through diversification, strategic reserves, and sustainability-oriented reforms than through short-lived emergency measures. In a complementary macro-level assessment, K.A. Abay *et al.* (2023) emphasised that the war generated intertwined global and regional effects through connected commodity markets, implying that responses needed to account for price transmission, supply bottlenecks, and unequal exposure across importing regions rather than relying on single-country solutions. Evidence on network-based propagation further strengthened the case for a more granular assessment of dependence on Ukrainian supplies. L. Liu *et al.* (2023) demonstrated that grain trade shocks associated with the conflict produced cascading impacts across countries because import portfolios were interlinked and substitution by large buyers tightened availability for others. This interpretation implied that MENA vulnerability was shaped not only by direct import shares from Ukraine but also by competitive displacement when other importers reoriented demand towards alternative suppliers, thereby raising procurement costs for states with limited fiscal space.

Region-specific analyses also clarified the social and political salience of wheat stability in the Middle East. M. Al-Saidi (2023) observed that the war aggravated pre-existing food security pressures by combining import dependence with inflationary dynamics and constrained public budgets, which reduced the effectiveness of compensatory measures. A market-oriented perspective offered by J. Janzen and C. Zulauf (2023) connected reductions in Ukrainian corn and wheat supply to shifts in global trade flows and price adjustments, indicating that procurement outcomes for MENA countries were influenced by rapid reconfiguration of the wider international grain system rather than by bilateral arrangements alone.

Ukrainian scholarship added indispensable explanation of the domestic channels through which war conditions affected export feasibility and, indirectly, regional food security in importing states. T.O. Ostashko (2023) analysed grain exports under wartime conditions and highlighted logistics disruption and route reconfiguration as decisive constraints on volumes, timing, and costs of deliveries. S. Cheremisina *et al.* (2025) also assessed structural changes in Ukrainian grain exports and the wartime price environment, reinforcing the argument that export performance needed to be interpreted through the combined effects of security risk, transaction costs, and institutional adaptation rather than through production capacity alone. The relationship between export reliability and internal supply formation was also addressed in recent Ukrainian studies that focused on national food security under conditions of military aggression. L. Artemenko *et al.* (2023) considered the state and prospects of Ukraine's food security and showed that balancing domestic stability with external market obligations became more complex under heightened uncertainty. A. Shevchenko and O. Petrenko (2024) examined priority directions for regulating Ukraine's food security in wartime and underscored the importance of coherent state instruments that protected vulnerable groups while preserving market incentives. H. Fyliuk and S. Kuchyn (2025) linked internal determinants of grain supply to broader questions of food security and implied that the stability of exportable surplus remained sensitive to domestic cost pressures and governance conditions even when external demand was strong.

Despite the breadth of these contributions, the literature tended to treat global price transmission, regional vulnerability, and Ukrainian domestic constraints as partially separate analytical problems. The interaction between Ukraine's export price-volume dynamics and the food security sensitivity of specific MENA importers therefore remained insufficiently integrated into a single quantitative assessment that could support policy design. The present study aimed to assess how changes in Ukrainian wheat export volumes and prices were associated with import dependence and food security indicators across selected MENA countries under war-related supply disruptions.

MATERIALS AND METHODS

The study was based on a combination of theoretical, descriptive-analytical and econometric procedures that were selected to match the empirical variables, country coverage and time windows used in the analytical part of the research. At the theoretical stage, the concept of food security was operationalised through the dimensions of availability, access and adequacy, which allowed trade disturbances in wheat supply chains to be interpreted as potential welfare risks for import-dependent economies (Food and Agriculture Organization, n.d.; FAO, IFAD, UNICEF, WFP, & WHO, 2022). This framework guided the selection of socio-economic and food-security indicators applied in the comparative and econometric blocks.

The information base combined internationally comparable statistical repositories and official national data sources. Macroeconomic, demographic and structural agricultural indicators for the Middle East and North Africa were obtained from World Bank databases and Statista, while undernourishment and global food-security benchmarks were aligned with FAO-linked monitoring and UN joint assessments to ensure conceptual and metric consistency across countries (World Bank, n.d.; Statista, n.d.). A cross-sectional regional profile was compiled for 2024 to provide a синхронised baseline of population, GDP per capita, human development characteristics, the prevalence of undernourishment, the Global Food Security Index and the share of agriculture in GDP for the MENA states included in the regional dataset: Algeria, Saudi Arabia, Bahrain, Djibouti, Egypt, Iraq, Iran, Israel, Yemen, Jordan, Qatar, Kuwait, Lebanon, Libya, Morocco, Oman, Sudan, the Syrian Arab Republic, Tunisia and the United Arab Emirates (IndexBox, 2025; World Bank, n.d.).

Ukraine's destination-specific wheat export series were obtained from the State Statistics Service of Ukraine and were cross-checked against FAO trade data to support uniform calculation of dependence measures (State Statistics Service of Ukraine, n.d.; Food and Agriculture Organization, n.d.). Two indicators were calculated for 2012-2023: the share of Ukrainian wheat in the total wheat imports of the selected MENA countries and the share of exports to these destinations within Ukraine's total wheat exports, with the extended pre-war period retained to capture baseline variability and the 2022-2023 interval preserved to reflect the immediate wartime disruption. Correlation analysis was applied to determine the direction and strength of associations between export price, export volume and export value, and linear regression models were specified to quantify these relationships in line with the trinity structure of the export-price and export-performance estimations. A separate regression block was applied for 2020-2022 to evaluate the association between the share of Ukrainian wheat in national import structures and GFSI values, with particular analytical attention directed to Saudi Arabia, Egypt, Morocco, Tunisia, Israel and Yemen as the cases that demonstrated the most pronounced reductions in Ukrainian wheat import shares after 2022 within the compiled dataset (Food and Agriculture Organization, n.d.; State Statistics Service of Ukraine, n.d.).

RESULTS AND DISCUSSION

Food security was interpreted as the ability of populations to maintain physical and economic access to sufficient, safe, and nutritious food consistent with dietary needs and food preferences (Food and Agriculture Organization, n.d.). The empirical focus therefore relied on revealing how the war in Ukraine altered the stability of wheat supply chains relevant for the Middle East and North Africa (MENA) and how these shifts coincided with broader socio-economic asymmetries inside the region. The disruption of Black Sea logistics and the heightened uncertainty in global grain markets were reflected in accelerating price dynamics during the initial stage of the full-scale invasion. The FAO Food Price Index (FFPI) was used as an indicative reference for the global market shock, given that it captured price movements across the major traded food commodity groups (Food and Agriculture Organization, n.d.). In March 2022 the FFPI reached 159.3 points, representing a 12.6% increase relative to February 2022, while wheat prices climbed to a record level of USD 522.29 per metric ton in May 2022 compared with USD 390.58 per metric ton earlier in the year. Such price escalation implied a direct deterioration of import affordability for structurally import-dependent economies and intensified the vulnerability of MENA food systems to exogenous supply shocks.

A structural precondition for uneven exposure to this shock was the pronounced heterogeneity of MENA countries in terms of population size, income capacity, human development, and the weight of agriculture in national economies. The World Bank classification of the region as comprising 21 countries provided the basis for comparability, while the 2024 cross-sectional indicators allowed for capturing the latest pre-model snapshot of socio-economic conditions used for contextual interpretation. Table 1 summarised the key comparative parameters that framed the degree of dependence on external wheat flows.

***Table 1**. Social and economic characteristics of MENA countries in 2024*

Country	Population, mln	GDP per capita, thsd USD	Human development index, rank	Human development index, value	The prevalence of undernourishment, %	Global food security index	Share of agriculture in GDP, %
Algeria	47.0	5.6	91	0.75	5.6	63.5	12.3
Saudi Arabia	35.3	35.1	40	0.85	5.2	70.1	2.4
Bahrain	1.6	30.0	39	0.87	3.1	70	0.9
Djibouti	1.2	3.5	170	0.51	7.9	45.2	7.5
Egypt	116.5	3.3	116	0.71	5.3	53.4	11.3
Iraq	46.0	6.1	123	0.67	6.5	50	4.8
Iran	91.6	4.8	70	0.8	7.0	57.5	9.2
Israel	10.0	54.2	19	0.92	2.5	80	1.2
Yemen	34.9	0.4	179	0.47	12.0	40	10.0
Jordan	11.4	4.6	98	0.74	4.5	60	3.5
Qatar	2.9	80.4	42	0.85	1.8	75	0.5
Kuwait	4.4	32.2	56	0.8	3.2	65	1.0
Lebanon	5.0		87	0.74	5.0	55	4.0
Libya	7.0	6.1	94	0.74	6.0	52.5	8.0
Morocco	38.0	3.9	129	0.69	4.8	58	14.0
Oman	5.3	20.2	41	0.85	3.0	72.5	2.0
Sudan	45.9	0.6	173	0.51	9.0	47.5	13.0
Syrian Arab Republic	24.7	0.8	171	0.52	10.0	45	15.0
Tunisia	12.5	4.4	85	0.74	4.0	60	12.0
United Arab Emirates	10.0	49.4	23	0.89	2.0	78	0.8

***Source:** compiled by the authors based on IndexBox (2025), World Bank (n.d.), Statista (n.d.)*

A comprehensive measure of socio-economic development in the Middle East and North Africa was reflected by the Human Development Index, which synthesised health, education, and living standards. The intra-regional contrasts presented in Table 1 were consistent with the HDI distribution: Israel ranked 19th globally, the United Arab Emirates 23rd, Bahrain 39th and Saudi Arabia 40th, whereas Yemen ranked 179th, Sudan 173rd and Djibouti 170th out of 193 assessed countries. This gradient in human development suggested that exposure to food shocks and the capacity to absorb import price increases differed substantially across the region, which provided an important interpretative context for the disparities in undernourishment prevalence and the Global Food Security Index values shown in Table 1 (World Bank, n.d.; Statista, n.d.). Structural pressure on domestic food production was additionally shaped by aridity and chronic water scarcity, which constrained the contribution of agriculture to national income and reinforced the reliance of several economies on external cereal supplies. Food insecurity therefore remained a persistent regional challenge with clear security implications. The dependence on imported cereals amplified this vulnerability: R. Rahimi *et al.* (2023) demonstrated that a considerable share of MENA cereal imports during 2015-2020 originated from Russia and Ukraine, highlighting the systemic exposure of the region to supply disruptions in the Black Sea corridor. This background allowed the role of Ukraine to be interpreted not as a general trade issue but as a measurable determinant of import stability for a number of MENA states.

Ukraine was therefore treated as a strategic supplier of wheat to the region. T. Liulchenko (2023) indicated that Ukraine's position in global wheat trade remained significant in the pre-war period and that the subsequent contraction of exports intensified pressure on import-dependent markets. The regional consequences were particularly salient for countries with limited domestic wheat output or with structurally high consumption needs, despite partial self-sufficiency in selected cases such as Egypt. Given that several MENA states combined high population levels, non-negligible undernourishment, and constrained agricultural capacity, any instability in wheat supply chains was likely to intensify food stress. Against this context, the next analytical step was the empirical assessment of Ukraine's contribution to wheat imports in selected MENA countries and the corresponding share of these destinations in Ukraine's total wheat exports, which was operationalised through the import % and export % indicators summarised in Table 2 (Food and Agriculture Organization, n.d.; State Statistics Service of Ukraine, n.d.). The descriptive patterns suggested that Egypt, Lebanon, Libya, and Djibouti had exhibited the highest reliance on Ukrainian wheat in the pre-war years, while the post-2022 period was associated with a visible decline in this share, indicating a shift towards alternative suppliers and a reconfiguration of regional import structures.

Table 2. The share of Ukrainian wheat in MENA countries' imports and in Ukraine's total wheat exports, 2012-2023

Year / Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
EGYPT import %	22.1	19.0	25.5	16.9	21.6	20.5	11.2	33.9	34.2	57.4	10.9	14.2
EGYPT export %	29.1	25.2	27.0	13.4	13.4	15.4	8.5	17.7	17.0	16.5	7.7	7.2
YEMEN import %	2.5	1.7	6.3	2.3	0.0	5.1	17.1	21.1	23.3	26.0	9.4	4.8
YEMEN export %	1.2	0.7	2.0	0.5	0.0	0.9	3.2	3.3	3.9	4.0	2.7	0.7
ISRAEL import %	44.7	20.8	24.6	39.5	31.4	31.0	29.6	27.0	17.6	22.2	8.4	19.1
ISRAEL export %	8.9	3.8	3.7	4.3	3.0	3.0	3.4	2.3	1.6	1.8	1.3	1.7
LEBANON import %	37.7	17.9	31.6	37.9	76.6	61.9	49.9	82.8	99.8	84.4	n.a.	n.a.
LEBANON export %	2.3	1.4	1.8	1.8	2.3	2.3	1.8	2.2	3.7	3.2	3.7	2.6
LIBYA import %	25.0	16.9	17.9	12.8	25.8	20.9	44.2	99.8	48.2	44.9	44.0	33.7
LIBYA export %	4.7	4.1	2.9	1.1	1.7	1.5	3.9	3.5	3.0	2.8	1.1	0.4
SAUDI ARABIA import %	0.0	0.0	0.6	0.0	2.4	0.0	0.0	0.0	2.1	31.3	4.5	3.9
SAUDI ARABIA export %	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.4	3.5	1.6	0.9
TUNISIA import %	30.7	17.5	26.0	31.6	18.2	42.0	51.8	55.0	49.3	34.2	14.4	10.6
TUNISIA export %	5.8	3.3	4.1	4.6	2.2	4.7	6.3	5.1	5.4	3.2	2.4	0.9
ALGIERIA import %	0.1	0.0	0.3	1.2	1.8	1.1	0.3	0.5	0.1	2.1	6.9	0.5
ALGIERIA export %	0.1	0.0	0.2	0.8	0.8	0.5	0.1	0.2	0.03	0.8	4.3	0.2
BAHRAIN import %	0.0	40.6	0.0	0.04	0.09	0.04	0.0	0.0	0.0	0.0	0.032	n.a.
BAHRAIN export %	0.0	0.4	0.0	0.0002	0.0004	0.0003	0.0	0.0	0.0	0.0	0.0004	n.a.
DJIBOUTI import %	0.0	19.6	7.4	51.2	17.4	10.4	77.6	99.8	32.0	59.4	44.9	13.4
DJIBOUTI export %	0.0	1.7	0.3	2.6	0.4	0.2	1.0	0.8	0.1	1.0	0.6	0.2
IRAN import %	0.0	1.3	1.8	0.0	2.5	0.0	0.0	0.0	0.0	3.7	n.a.	n.a.
IRAN export %	0.0	0.7	1.2	0.0	0.2	0.0	0.0	0.0	0.0	1.3	n.a.	n.a.
IRAK import %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0013	0.0	0.0	n.a.	n.a.
IRAK export %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0001	0.0	0.0	n.a.	n.a.
JORDAN import %	43.6	34.1	31.6	0.024	2.8	11.8	10.3	21.1	25.6	7.4	n.a.	n.a.
JORDAN export %	4.7	3.0	2.8	0.001	0.3	0.6	0.7	0.9	1.2	0.3	n.a.	n.a.
KUWEIT import %	0.0	0.0	0.0	0.0	0.023	0.1	0.1	0.032	0.1	0.1	n.a.	n.a.
KUWEIT export %	0.0	0.0	0.0	0.0	0.001	0.002	0.001	0.001	0.002	0.002	n.a.	n.a.
MOROCCO import %	16.4	7.4	9.5	15.0	13.6	17.1	35.7	23.5	17.3	18.1	1.1	n.a.
MOROCCO export %	7.7	2.6	4.7	3.6	4.8	3.6	8.5	4.5	5.3	4.2	0.6	n.a.
OMAN import %	0.0	0.0	0.0	0.0	7.9	0.01	0.02	0.0	3.8	7.4	11.1	n.a.
OMAN export %	0.0	0.0	0.0	0.0	0.3	0.0003	0.001	0.0	0.1	1.0	0.5	n.a.
PALESTINE import %	8.1	0.0	0.028	0.0	0.0	0.0	0.0	0.0	0.0	0.0	n.a.	n.a.
PALESTINE export %	0.1	0.0	0.001	0.0	0.0	0.0	0.0	0.0	0.0	0.0	n.a.	n.a.
SYRIA import %	57.1	38.7	26.7	67.2	26.8	0.0	0.0	0.0	0.0	0.0	0.02	0.1
SYRIA export %	2.2	7.7	1.4	2.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0008	0.003
UNITED ARAB EMIRATES import %	3.7	2.1	2.8	8.1	1.4	2.4	1.7	10.9	0.8	0.4	n.a.	n.a.
UNITED ARAB EMIRATES export %	0.9	0.5	0.4	0.5	0.1	0.1	0.1	0.7	0.1	0.0	n.a.	n.a.

Source: *compiled by the authors based on Food and Agriculture Organization (n.d.), State Statistics Service of Ukraine (n.d.)*

The primary determinants of long-term trade cooperation with Ukraine are transport distance and export price. It is also important to note that smaller-volume shipments ordered by MENA countries are more efficiently dispatched to African markets than, for example, to Asian destinations. Over long distances, bulk transport using high-capacity carriers is significantly more cost-effective. As shown in Table 2, the share of Ukrainian wheat exports directed to MENA countries remains modest, generally not exceeding 10% of Ukraine's total wheat exports. Egypt is a notable exception, accounting for more than 10% of Ukraine's exported wheat till 2022. Between 2012 and 2021, this share reached as high as 10-30%, positioning Egypt as a strategic importer of Ukrainian grain.

As previously mentioned, export price constitutes a critical factor in international grain trade. Prices are driven by conditions in the global grain market – specifically, supply and demand dynamics for wheat. Ultimately, the export price determines the level of revenue accrued by the exporting country. Table 3 presents the results of the authors' regression-based modeling, examining the relationship between grain export prices and export volumes, as well as the relationship between export value in US dollars and the export price.

***Table 3**. Regression modeling of grain export prices and export values*

Model "Price of export (P) – Volume of export (V)" **P = 351.9 - 0.0003*V**		
Forecast of the grain price		
Volume of export (V), tons	Price of export (P), dollars USD per ton	Deviation in price, %
144604.3	306.9	-
146050.3	306.4	-0.146
147510.8	305.9	-0.148
148985.9	305.5	-0.15
150475.8	305.1	-0.152
Model "Volume of export (V) – Price of export (P)" **V = 737160.1 - 1811.8*P**		
Forecast of the volume of export		
Price of export (P), dollars USD per ton	Volume of export (V), tons	Deviation in volume of export, %
299.2	195148.2	-
302.2	189728.1	-2.777
305.2	184253.8	-2.885
308.2	178724.7	-3.001
311.3	173140.4	-3.124
Model "Value of export (E) – Price of export (P)" **E = 131718.4 - 255.2*P**		
Forecast of the value of export		
Price of export (P), dollars USD per ton	Value of export, thsd. dollars USD	Deviation in value of export, %
299.2	55361.7	-
302.2	54598.1	-1.37
305.2	53826.8	-1.41
308.2	53047.9	-1.45
311.3	52261.2	-1.48

***Source:** compiled by the authors based on Food and Agriculture Organization (n.d.), State Statistics Service of Ukraine (n.d.)*

The correlation-regression analysis reported in Table 3 indicated a stable inverse association between the export price of Ukrainian wheat and the volume shipped to MENA markets. Within the observed data range, increases in export price were associated with a contraction of export volumes, suggesting a high sensitivity of regional demand to affordability and confirming the central role of price competitiveness in sustaining deliveries to import-dependent states (Food and Agriculture Organization, n.d.; State Statistics Service of Ukraine, n.d.). The reciprocal specification also suggested that expansion of export volumes was not associated with a substantial decline in unit prices, implying that the market capacity for Ukrainian wheat could have supported volume-based strengthening of trade positions provided that logistical constraints and transaction costs were contained. The relationship between export prices and total export value also remained negative within the analysed period, indicating that price increases were accompanied by a reduction in export earnings due to the stronger contraction of shipped volumes than the gain in unit revenue.

Export prices during 2012-2023 demonstrated pronounced volatility, which was attributable to shifts in production costs, global market conditions, and, after 2022, war-related disruptions of logistics and trade routes. The blockade of Black Sea ports and the forced reorientation towards land and river corridors considerably changed the cost structure of exports. Under these conditions, monthly export volumes declined from pre-war peaks of around 5 million tonnes to approximately 1 million tonnes, while logistical costs increased several-fold (Nemtseva, 2022). The share of final market value retained by farmers reportedly decreased from about 80% under maritime export conditions to roughly 20% after the outbreak of hostilities, reflecting the growing dominance of transport and intermediary expenses in the price chain. Pre-war delivery to ports was estimated to have cost around USD 20 per ton, whereas wartime logistics to export markets reportedly rose to USD 150-200 per ton, which contributed to a steep decline in domestic price realisation to approximately USD 100-150 per ton. The increase in logistics costs was linked to higher fuel prices, longer transport routes, transshipment between gauge systems, extended storage in transit, and intensified customs and insurance-related frictions; service fees imposed by foreign logistics providers were also reported to have increased substantially (Tkachov, 2022). The agricultural losses associated with the war were significant, as estimates of direct damage to infrastructure and indirect losses from constrained cultivation and elevated export costs exceeded USD 42 billion (Jansen *et al.,* 2023).

The impact of the reduced share of Ukrainian wheat in regional import structures on food security outcomes was subsequently evaluated for 2020-2022 using the GFSI values from Table 1 and the import-share indicators from Table 2. The correlation dynamics presented in Table 4 suggested that import dependence had been interpreted as a vulnerability factor in 2020-2021, whereas in 2022 imports were associated with a stabilising function in the context of the acute supply shock triggered by the war in Ukraine (Food and Agriculture Organization, n.d.; State Statistics Service of Ukraine, n.d.). This shift supported the rationale for the country-level models in Table 5 and justified the focus on those states that experienced the largest contractions of Ukrainian wheat supplies.

***Table 4**. Dynamics of the impact of Ukrainian wheat imports on the global food security index (GFSI) of MENA Countries (2020-2022)*

Year	Correlation coefficient (r)	Direction of relationship	Nature of influence
2020	−0.31	weak negative relationship	Import is not a decisive factor for food security
2021	−0.63	moderate negative relationship	Import is vulnerable due to supply crises
2022	+0.52	moderate positive relationship	Import supports food stability

***Source:** compiled by the authors based on Food and Agriculture Organization (n.d.), State Statistics Service of Ukraine (n.d.)*

To construct a correlation and regression model of the relationship between wheat import levels and the Global Food Security Index (GFSI), several MENA countries that experienced a sharp reduction in Ukrainian wheat supplies in 2022, following the onset of the war in Ukraine, were selected. For example, in Saudi Arabia, the share of Ukrainian wheat in the country's total wheat imports decreased from 31.3% in 2021 to 45% in 2022. In Egypt, the corresponding decline was from 57.4% to 10.9%, and in Morocco – from 18.1% to 1.1%. Table 5 presents the results of the correlation and regression analysis of the relationship between Ukrainian wheat import levels and the Global Food Security Index (GFSI) for the selected MENA countries.

***Table 5**. Results of the correlation and regression analysis of the relationship between Ukrainian wheat import levels and the Global Food Security Index (GFSI) for MENA countries*

Model "Global Food Security Index (GFSI) – Share of Ukrainian Wheat in MENA Countries' Imports (I)" GFSI = f(I)				
Forecast of the Global Food Security Index				
Country	**Regression equation**	**Correlation (r)**	**R^2**	**Deviation in Global Food Security Index**, %
Saudi Arabia	GFSI = 69.94 - 0.05I	-0.96	0.91	-0.03
Egypt	GFSI = 57.06 + 0.05I	0.49	0.24	+0.01
Israel	GFSI = 76.34 - 0.04I	-0.16	0.02	-0.01
Yemen	GFSI = 40.4 - 0.04I	-0.42	0.18	-0.05
Morocco	GFSI = 63 + 0.02I	0.12	0.01	+0.0004
Tunisia	GFSI = 60.03 + 0.03I	0.87	0.75	+0.005

***Source:** compiled by the authors based on Food and Agriculture Organization (n.d.), State Statistics Service of Ukraine (n.d.)*

According to Table 5, a strong negative correlation (r = -0.96) is observed in Saudi Arabia, indicating that an increase in imports is associated with a decrease in the GFSI. In Tunisia, Egypt, and Morocco, conversely, a strong positive correlation (r = 0.87) shows that higher imports are associated with improved food security; specifically, a 1% increase in the share of Ukrainian wheat imports in these countries leads to an average increase of 0.003% in the Global Food Security Index. In other countries, the relationship is weak or moderate (r between -0.5 and 0.5). Thus, support for Ukrainian imports is particularly important for countries such as Egypt, Morocco, and Tunisia, where the prevalence of undernourishment is around 5%, that is already above the low level for MENA countries. In addition, the Global Food Security Index in these countries does not exceed 60 points, remaining at a medium level.

Continued support for Ukrainian wheat exports is critically important for all MENA countries in order to strengthen their food security, as the region remains highly dependent on grain imports. For Ukraine, this also represents a strategic direction that ensures foreign currency inflows and supports the agricultural sector in the post-war period. Furthermore, the stability of Ukrainian exports contributes to reducing global food price volatility and reinforces Ukraine's role as a reliable partner in the global grain market. The findings of the study indicate that the expansion of Ukrainian wheat exports is both necessary and feasible without significant price losses and providing sufficient market capacity, maintenance of competitive pricing, efficient logistics, implementation of price support instruments, and the development of sustainable trade relations. Ensuring stable supplies of Ukrainian grain is crucial for maintaining the food security of MENA countries, where wheat availability is a key factor for social and economic stability.

The obtained results may be further interpreted in the broader context of structural changes in both the exporting and importing systems. The revealed price sensitivity of Ukrainian wheat demand in MENA was consistent with the wider global logic of wheat-market adjustment, where consumption growth and trade rebalancing increasingly depend on competitiveness and the capacity of suppliers to deliver stable volumes under volatility (Erenstein *et al.,* 2022). From this perspective, the pre-war positioning of Ukraine as a strong global actor in the grain market created a baseline of trust and path dependence in import portfolios that could not be fully replaced in the short run, even when alternative origins were actively sought (Savosh *et al.,* 2020). The wartime contraction of Ukrainian export reliability therefore appeared not only as a temporary logistical disturbance but as a structural shock that altered trade architecture and redistributed bargaining power across supply chains, which was in line with recent evidence on shifts in export structure and price conditions in Ukraine's grain market during the war (Cheremisina *et al.,* 2025).

At the same time, food-security outcomes in the most exposed MENA countries should be viewed through the lens of systemic resilience rather than import shares alone. The interaction between external supply risk and domestic institutional capacity suggested that the stabilising role of Ukrainian wheat became particularly visible in those states where socio-economic vulnerability was already pronounced, which echoed the argument that food security functions as a core pillar of broader socio-economic sustainability under crisis conditions (Hoblyk *et al.,* 2025). This implication also aligned with the observation that digital tools, early-warning systems and improved data governance may strengthen the adaptive capacity of MENA agri-food systems, although such gains remain constrained by unequal implementation and governance risks (Bahn *et al.,* 2021). Consequently, the empirical evidence supported a combined interpretation in which Ukraine's export stability and MENA's internal resilience measures jointly determined the magnitude of food-security effects, reinforcing the need for coordinated trade, logistics and digital modernisation strategies across both sides of the supply relationship.

CONCLUSIONS

It was concluded that Ukrainian wheat exports remained a structurally important stabiliser for food availability and affordability in the Middle East and North Africa, while also serving as a critical source of foreign-currency earnings for Ukraine under wartime constraints. The longitudinal trade evidence for 2012-2023 indicated that MENA dependence on Ukrainian supplies was concentrated in a limited group of importers whose exposure was shaped by population scale, constrained domestic production, and limited short-run substitution away from wheat. The observed post-2022 reconfiguration of import portfolios suggested that supply risk in the Black Sea corridor triggered a rapid search for alternative origins, yet this diversification did not eliminate vulnerability for countries with tighter fiscal space and persistent undernourishment. The econometric results confirmed that price competitiveness was the dominant short-run determinant of Ukrainian shipments to the region. A clear inverse price-volume relationship was identified, implying that episodes of price escalation were likely to compress demand and reduce the physical presence of Ukrainian wheat in MENA procurement structures. At the same time, the weaker reverse effect – where higher export volumes were associated with only modest price adjustments – suggested that the market capacity for Ukrainian wheat could have supported recovery or selective expansion without substantial price erosion, provided that logistics, insurance costs, and transaction frictions were contained. The revenue specification further indicated that higher unit prices did not necessarily translate into higher aggregate export value because volume contraction outweighed the price effect within the analysed range.

It was also established that the food-security sensitivity to Ukrainian import shares appeared strongest in countries characterised by medium GFSI values and higher prevalence of undernourishment, where Ukrainian deliveries acted as a more visible stabilising input during the acute 2022 shock. These findings implied that policy efforts aimed at protecting and improving export route reliability, lowering wartime logistics costs, and expanding predictable contracting mechanisms could generate dual benefits: strengthening Ukraine's export resilience and reducing the probability of food-system stress in the most exposed MENA economies. Future studies should apply panel and high-frequency trade data to disentangle the relative effects of wartime logistics disruptions, global price cycles and domestic policy interventions on Ukrainian export stability and on heterogeneous food-security outcomes across individual MENA importers.

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Оцінювання впливу експорту українського зерна на продовольчу безпеку країн близького сходу та північної Африки методом регресійного моделювання

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Анотація. Метою дослідження було оцінити економічне значення експорту української пшениці та його роль у підтримці продовольчої безпеки в країнах Близького Сходу та Північної Африки (MENA), які залежать від імпорту та перебувають у стані війни. Дані про торгівлю за конкретними напрямками на 2012–2023 роки були узагальнені та перевірені за допомогою кореляційного аналізу та лінійної регресії з метою виявлення взаємозв'язків між ціною, обсягом та доходом. Додатковий міждержавний регресійний блок за 2020-2022 роки пов'язував частку української пшениці в національних структурах імпорту з результатами Глобального індексу продовольчої безпеки (GFSI). Було встановлено, що залежність від української пшениці була зосереджена на декількох ринках MENA, причому найрізкіше передвоєнне зростання спостерігалося в Єгипті, Тунісі, Лівії та Лівані, а після 2022 року імпортні портфелі були переформатовані. Було продемонстровано, що експортна ціна залишалася основним короткостроковим визначальним фактором поставок до регіону. Було встановлено, що зростання цін було пов'язане з помітним скороченням обсягів експорту та зниженням загальних доходів від експорту в межах спостережуваного діапазону. Було також показано, що більші обсяги експорту були пов'язані лише з незначним зниженням цін за одиницю, що вказує на потенціал відновлення обсягів без значних цінових втрат у разі пом'якшення логістичних труднощів. Було проаналізовано, що зв'язок між часткою українського імпорту та GFSI змінився на більш сприятливий під час гострого шоку пропозиції у 2022 році. Було зроблено узагальнення, що найсильніша чутливість продовольчої безпеки до українських поставок спостерігалася в країнах з вищим рівнем недоїдання та середнім рівнем GFSI. Результати можуть бути використані українськими торговельними органами, багатосторонніми організаціями та закупівельними агентствами MENA для калібрування заходів підтримки коридору, розподілу ризиків та диверсифікації

Ключові слова: цінова еластичність пшениці; логістика Чорноморського коридору; імпортна залежність; Глобальний індекс продовольчої безпеки; трансмісія торговельних шокі; чутливість експортної виручки

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Analysis of the typological structure of forests in western Ukraine

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Abstract. The aim of the study was to conduct an ecological and typological assessment of forest site conditions across eight administrative oblasts of western Ukraine and to identify regional differences in the proportions of trophotopes and stand types. The classification of forest types was carried out using the silvicultural-ecological scale of forest typology based on state forest inventory materials. Comparative analysis, typological grouping and statistical data processing were applied to determine the areas, proportions and structural features of forest types. The distribution of the area of land covered with forest vegetation across four soil fertility groups was analysed, which made it possible to identify the dominance of sugrud and grud site conditions in the mountainous parts of the region. It was established that the largest areas of sugruds were concentrated in Ivano-Frankivsk and Zakarpattia oblasts, whereas bor and subor complexes remained substantial in Volyn and Rivne oblasts. The number of delineated forest types ranged from 29 in Ternopil Oblast to 89 in Ivano-Frankivsk Oblast, reflecting the contrast of the region's natural conditions. The typological structure

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of individual oblasts was detailed and the diversity of the Carpathian sector was demonstrated, where various variants of beech forests, sub-beech forests and suyalychnyk forest types predominated, indicating the combined effects of altitudinal zonation and moisture gradients. It was found that the Polissia sector was characterised by a concentration of areas in oak-pine subors and black alder sugruds, which formed a core of hydrological and biotic stability. It was generalised that the Podillia oblasts were typified by a simpler typological spectrum with the dominance of hornbeam and oak oakwoods, correlating with more homogeneous soil and climatic conditions. The practical value of the results was associated with their potential use by forestry enterprises and nature conservation institutions to substantiate measures for sustainable forest management, stand restoration and the zoning of recreational pressure

Keywords: forest site conditions; typological structure; edaphic grid; trophotopes; hygrotopes; beech communities; oak-pine subors

INTRODUCTION

The typological structure of forests in western Ukraine was a fundamental scientific category upon which the validity of decisions regarding protection, regeneration and economic use of the forest estate depended under conditions of increasing climatic risks and growing anthropogenic pressure. The region combined Polissia lowland complexes, forest-steppe landscapes and the mountainous ecosystems of the Carpathians, which formed a highly mosaic pattern of forest site conditions and required an accurate typological description to maintain water-regulating, soil-protective and biodiversity functions. Existing forest inventory practices and adaptive planning could not be sufficiently effective without refining the spatial distribution of trophotopes, hygrotopes and forest types, as well as without comparing the national typological scale with approaches embedded in European classifications, which gained importance for integrating Ukrainian forest science into international monitoring and reporting systems.

In recent research, typological approaches were actively associated with assessments of forest resilience to disturbances and climatic extremes. J. Altman *et al.* (2024), using global observations, showed that the configuration and intensity of forest disturbances changed under the influence of climatic shifts, which emphasised the need for regionally detailed typological models capable of explaining the unequal sensitivity of different forest formations to stress factors. Similar conclusions were presented by M. Gharun *et al.* (2024), who demonstrated that the response of European forests to extreme drought substantially depended on forest type and site conditions; therefore, typological refinement could serve as a tool for forecasting risks in both mountainous and lowland regions. The development of European classifications acquired new meaning in the study by J.I. Barredo *et al.* (2024), who proposed an archetypal typology of European forest ecosystems that accounted for management intensity and naturalness, thereby creating a methodological bridge for aligning Ukrainian typological units with international frameworks for assessing ecosystem services. In this context, the results of N. Scherpenhuijzen *et al.* (2025) were important, as they demonstrated the possibilities of mapping forest management regimes in Europe and stressed the need for a homogeneous ecological classification as a prerequisite for comparative analyses of management practices.

Studies focused on western Ukraine specified the role of typology as a basis for building climate-resilient regeneration models. According to P. Spathelf *et al.* (2024), the first results of alternative natural regeneration systems in western Ukraine indicated that the success of stand renewal was substantially determined by the type of forest site conditions and by the correspondence of tree species to local edaphic and climatic characteristics, which reinforced the value of precise typological grouping in regional planning. Ukrainian authors O.I. Holubchak *et al.* (2024), within an analysis of protective forests of the Carpathians, emphasised that the typological mosaic of mountainous territories shaped different levels of anti-erosion and water-regulating effectiveness of stands; therefore, any management decisions had to rely on a detailed description of sugrud and grud site conditions within the vertical profile. An important economic and ecological dimension was highlighted by V. Moroz (2024), who showed that the bioproductivity of pine stands in Polissia correlated with site types and moisture regime, which was relevant for the northern oblasts of the studied region where bor and subor complexes formed dominant spatial units. The monitoring dimension of typological research was presented by V. Myroniuk and V. von Dosky (2024), who, based on an analysis of the dynamics of forest attributes in 2019-2023, demonstrated the prospects of integrating inventory and remote data to refine spatial changes in stands with regard to their typological affiliation. From the perspective of more narrowly focused formation studies, V. Lavnyy and O. Matusevych (2022) established regularities of the productivity of spruce forests of the Ukrainian Carpathians across different forest types and stressed the need to align species composition with edaphic parameters to reduce the risks of degradation of secondary spruce stands. A synthetic view of the biological consequences of climate change was offered by V. Skliar *et al.* (2025), who underlined those species-specific adaptive responses of tree species required linkage to forest site conditions, since these determined resilience thresholds and potential trajectories of changes in stand composition.

Thus, existing studies provided a methodological and empirical basis for a regionally oriented typological interpretation of the forests of western Ukraine, while simultaneously indicating the need for a harmonised spatial analysis of eight oblasts using state forest inventory materials and contemporary approaches to typological grouping. The aim of this study was to refine regional patterns in the distribution of forest site condition types and forest types within western Ukraine.

MATERIALS AND METHODS

For the analysis of the typological structure of forests in western Ukraine, methodological approaches of the silvicultural-ecological school of forest typology were used (Ostapenko & Tkach, 2002). The classification of stands was carried out according to forest site condition types and forest types. A forest site type was defined as a unit of the edaphic grid constructed on the basis of the coordinates of soil moisture and soil fertility. At this stage, the typological structure of forests was assessed primarily by trophotopes (A–D: bor, subor, sugrud, grud) and by the most representative forest types across the administrative oblasts. The hygrotope distribution was not detailed in this section. Forest types were treated as geographical forms of a forest site type that differed in the composition of forest-forming tree species. The formation of a forest type was associated with climatic conditions and the history of the development of the modern flora. When conditions for natural woody vegetation were unfavourable, forest types were replaced by steppe, meadow or desert types. Different forest types that varied in composition but were dominated by one principal tree species formed an additional taxon, the family (group) of forest types (Pohrebnyak, 1993).

The study region included the following administrative oblasts: Volyn (1), Rivne (2), Lviv (3), Ternopil (4), Khmelnytskyi (5), Zakarpattia (6), Ivano-Frankivsk (7) and Chernivtsi (8), as presented on the schematic map (Fig. 1). The geographical coordinates of the extreme points of the region were as follows: north – 25°15’33”, 51°58’09”; south – 24°53’05”, 47°43’26”; west – 22°08’31”, 48°25’43”; east – 27°54’05”, 49°11’10” (Fig. 1).

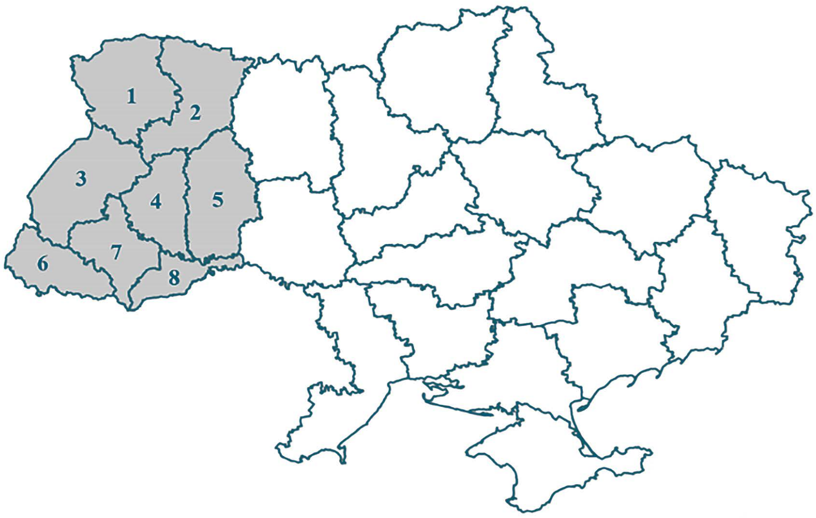

***Figure 1**. Schematic map of the study region*
***Source:** compiled by the authors based on forest inventory materials of UKRDERZHISPROEKT (n.d.)*

The data for the study were obtained from the electronic database of UKRDERZHISPROEKT (n.d.), which was converted from the “.vff” format into the “.mdb” format of the MS Access software product using the NewUnPackOHOTA programme developed in the Laboratory of New Information Technologies of UkrNDILHA. For subsequent calculations, the required data were exported into the “.xls” format of Microsoft Excel 2019. MapInfo Professional 12.5 beta was used to produce the map and the schematic representation of the study area. The analysis of statistical materials and the calculation of additional indicators were carried out using Microsoft Excel 2021.

RESULTS AND DISCUSSION

The analysis of forest site condition types in western Ukraine was an important stage for assessing the state of forest ecosystems and determining the potential of natural resources in the region. Forest site conditions, which included diverse types of forests, shrubs and herbaceous covers, had a direct impact on biodiversity as well as on forestry practice and nature conservation activities. The assessment of forest site condition types by the number of units and by area, using the example of eight administrative oblasts of western Ukraine (Volyn, Zakarpattia, Ivano-Frankivsk, Lviv, Rivne, Ternopil, Khmelnytskyi and Chernivtsi), made it possible to examine their silvicultural specificity in greater detail, the influence of climatic conditions and geographical factors, and their use in agriculture and forestry.

The distribution of forest areas by soil fertility (trophotopes) in western Ukraine was an important indicator for determining the significance of different vegetation types for forest management and environmental conservation. Among the studied oblasts of western Ukraine, sugrud occupied the largest area and was widely represented in Ivano-Frankivsk (298.6 thousand ha) and Zakarpattia (205.3 thousand ha) oblasts. These areas confirmed the substantial role of these forests in mountainous regions, where sugrud communities covered large spaces and created ecologically stable conditions for the development of flora and fauna (Table 1). The distribution of areas by trophotopes was formed by aggregating forest inventory data across oblasts and soil fertility groups in accordance with the edaphic grid.

***Table 1**. Distribution of forest area in the oblasts of western Ukraine by trophotopes*

Oblast	Trophotope								Total
	A – bor		B – subor		C – sugrud		D – grud		
	thousand ha	%	thousand ha	%	thousand ha	%	thousand ha	%	thousand ha
Volyn	68.9	15.8	171.5	39.2	173.9	39.8	22.5	5.2	436.8
Rivne	103.8	17.8	288.5	49.4	162.1	27.7	29.8	5.1	584.2
Lviv	2.1	0.5	45.4	10.6	170.0	39.7	210.6	49.2	428.2
Ternopil	0.1	0.1	6.1	3.2	26.8	13.8	160.1	82.9	193.1
Khmelnytskyi	0.7	0.5	17.6	12.7	43.6	31.7	75.8	55.1	137.6
Zakarpattia	-	-	1.9	0.4	205.2	44.5	254.1	55.1	461.2
Ivano-Frankivsk	1.4	0.3	22.4	5.3	298.6	70.1	103.3	24.3	425.8
Chernivtsi	-	-	1.4	0.9	66.6	42.3	89.3	56.8	157.3

***Source:** compiled by the authors*

D – grud occupied a substantial area, with the highest values recorded in Zakarpattia Oblast (254.1 thousand ha), which reflected the dominance of grud forest communities in the foothill and mountain zones with corresponding trophic soil characteristics. A – bor and B – subor covered smaller areas, yet they remained important for forest management because their distribution supported the conservation of forest ecosystem diversity. The most extensive bor areas were represented mainly in Rivne (103.8 thousand ha) and Volyn oblasts (68.9 thousand ha), which was consistent with the presence of forests dominated by pine.

The analysis of forest ecosystems in Volyn Oblast indicated considerable diversity of forest types. Their total number reached 47, which illustrated the richness of the oblast's forest ecosystems. In particular, 4 forest types were identified within bor, 10 within subor, 22 within sugrud, and 8 within grud. The most widespread forest types were the fresh oak-pine subor (15.9%) and the moist oak-pine subor (16.4%). A large share of approximately 11.0% of the total area of forest-covered land was also accounted for by the fresh pine bor and the wet black alder sugrud. These forest ecosystems, characterised by different levels of soil moisture and fertility, formed the basis of ecological stability in the region and played an important role in maintaining biodiversity, the water balance and the regulation of local climatic conditions. The proportion of relatively common forest types, including the dry pine bor (2.4%), wet oak-pine subor (3.7%), fresh hornbeam-oak-pine sugrud (4.7%), moist hornbeam suboak forest (3.7%), moist hornbeam-oak-pine sugrud (6.2%), moist hornbeam-pine sub-oak forest (5.1%), drained wet black alder sugrud (3.1%) and the fresh hornbeam oak forest (4.2%), ranged from 2% to 7% of the total forest area. These forest ecosystems represented important elements of the forest cover that shaped the landscape structure of the region and supported the ecological and economic processes of the territory. The total share of the least widespread forest types, including the moist pine bor (1.2%), drained wet oak-pine subor (1.6%), fresh hornbeam oak forest (1.7%) and the fresh hornbeam-pine oak forest (1.0%), amounted to 5.5% of the total area. These forest ecosystems were characterised by more stable water conditions, which made them important for creating optimal conditions for the growth and development of forest plants and animals and for conserving biodiversity (Table 2). The remaining 31 forest types occupied 7.1% of the total forest area and played an important role in maintaining ecological balance. They represented specific landscapes and locally distributed plant formations that were essential for the conservation of the natural environment.

***Table 2**. Distribution of forest area in Volyn Oblast by forest types*

Forest type name	Index	Area, ha	%
Dry pine bor	A_1-C	10,335.9	2.4
Fresh pine bor	A_2-C	48,072.6	11.0
Moist pine bor	A_3-C	5,454.2	1.2

Table 2. Continued

Forest type name	Index	Area, ha	%
Fresh oak-pine subor	B_2-дС	69,259.6	15.9
Moist oak-pine subor	B_3-дС	71,681.2	16.4
Wet oak-pine subor	B_4-дС	16,255.4	3.7
Drained wet oak-pine subor	B_4-дС^{о}	7,190.0	1.6
Fresh hornbeam sub-oak forest	C_2-гД	7,632.3	1.7
Fresh hornbeam-oak-pine sugrud	C_2-гдС	20,431.5	4.7
Fresh hornbeam-pine sub-oak forest	C_2-гсД	4,222.8	1.0
Moist hornbeam sub-oak forest	C_3-гД	16,119	3.7
Moist hornbeam-oak-pine sugrud	C_3-гдС	27,194.6	6.2
Moist hornbeam-pine sub-oak forest	C_3-гсД	22,200	5.1
Wet black alder sugrud	C_4-Влч	47,876.3	11.0
Drained wet black alder sugrud	C_4-Влч^{о}	13,360.5	3.1
Fresh hornbeam oak forest	D_2-гД	18,418.7	4.2
Other		31,133.3	7.1
Total		436,837.9	100.0

Source: *compiled by the authors*

The Zakarpattia Oblast exhibited a very high diversity of forest types, which reflected the substantial ecological resources of the region. The total number of forest types reached 85, of which no forest types were identified within bor, whereas 11 forest types occurred within subor, 41 forest types within sugrud, and 33 forest types within grud (Table 3). The largest share of the forested area was occupied by the moist pure beech forest, which accounted for 21.8% of the total forest area. This forest type played a key role in regulating the regional water balance and forming stable conditions for the development of plant and animal communities. Also highly represented were the moist pure sub-beech forest (11.5%) and the moist beech-fir suyaluchnyk (10.5%). These ecosystems were typical of moderately moist conditions and were essential for maintaining equilibrium between forest vegetation and ecological processes. The areas of the moist hornbeam beech forest (5.9%) and the fresh pure beech forest (5.6%) were slightly smaller yet still widespread. These forest habitats were important for biodiversity conservation in the region due to the variety of plant and animal species adapted to fluctuating moisture regimes.

Table 3*. Distribution of forest area in Zakarpattia Oblast by forest types*

Forest type name	Index	Area, ha	%
Fresh pure beech forest	D_2-Бк	25,756.9	5.6
Fresh beech sub-oak forest of rocky habitats	D_2-бкД^{с}	5,749	1.2
Fresh hornbeam beech forest	D_2-гБк	20,315.4	4.4
Moist pure beech forest	D_3-Бк^{ч}	100,555.8	21.8
Moist beech-fir suyaluchnyk	D_3-бк-яцЯл	15,655.5	3.4
Moist fir-beech forest	D_3-ял-яцБк	9,460.5	2.1
Moist hornbeam beech forest	D_3-гБк	27,207.6	5.9
Moist hornbeam sub-oak forest	D_3-гД	8,396.9	1.8
Moist fir beech forest	D_3-яцБк	6,756.4	1.5
Moist fir-beech forest (variant)	D_3-ял-яцБк	11,450.3	2.5
Fresh hornbeam sub-beech forest	C_2-гБк	6,052.1	1.3
Moist pure sub-beech forest	C_3-Бк^{ч}	53,060.8	11.5
Moist beech-fir sugrud	C_3-бк-яцЯл	48,469.7	10.5
Moist beech sugrud	C_3-бкЯл	11,689.2	2.5
Fresh beech-fir sugrud	C_3-бк-яцЯл	7,740.8	1.7
Moist hornbeam sugrud	C_3-гБк	14,580.9	3.2
Moist pure sugrud	C_3-Я^{ч}	13,970.5	3.0
Moist fir sugrud	C_3-ялБк	4,770.6	1.0
Moist fir-beech sub-beech forest	C_3-ял-яцБк	11,560.2	2.5
Other		58,026.8	12.6
Total		461,225.9	100.0

Source: *compiled by the authors*

The proportion of commonly represented forest types – including the moist beech-fir suyaluchnyk (3.4%), moist spruce–fir beech forest (2.5%), moist hornbeam oak forest (1.8%), moist fir beech forest (1.5%), moist spruce–fir beech forest (2.5%), moist beech sugrud (2.5%), moist hornbeam sub-beech forest (3.2%), moist pure sugrud (3.0%), moist spruce sub-beech forest (1.0%), and the moist spruce-fir sub-beech forest (2.5%) – is comparatively smaller; nevertheless, these ecosystems play a key role in ensuring the stability of forest habitats. They support essential ecological functions, including erosion control and regulation of the hydrological regime, thereby contributing to the preservation of forested landscapes and maintaining regional ecosystem resilience, particularly under changing climatic conditions. The remaining 66 forest types, which together occupy 12.6% of the forest area, are the least widespread yet critically important for the conservation of rare plant and animal species. Thus, the forest ecosystems of Zakarpattia Oblast – dominated primarily by various forms of beech forests, hornbeam beech forests, and sub-beech forests – ensure key ecological functions, including water balance regulation, biodiversity maintenance, and landscape stability.

Analysis of forest ecosystems in Rivne Oblast indicates a substantial diversity of forest types. Their total number reaches 46, reflecting the richness of the region's forest ecosystems. Within this structure, bor includes 7 forest types, subor contains 12, sugrud comprises 21, and grud includes 6 forest types. The most widespread forest type in Rivne Oblast is the moist oak-pine subor (21.9%), which plays a critical role in hydrological regulation, maintaining a stable water balance, and supporting biodiversity conservation. The fresh oak-pine subor (12.0%), wet oak-pine subor (9.1%), and the moist hornbeam-oak-pine sugrud (8.4%) also occupy substantial areas and are highly significant for ecological stability. These forest types help maintain soil fertility, reduce erosion risk, and regulate groundwater levels.

The proportion of other widely distributed forest types – such as the fresh hornbeam-oak-pine sugrud (5.0%), dry pine bor (2.2%), moist pine bor (2.2%), wet birch-pine subor (3.0%), fresh hornbeam oak forest (3.3%), moist hornbeam sugrud (2.0%), moist fir-hornbeam beech forest (3.5%), moist beech-fir sugrud (3.0%), wet oak-pine subor (2.5%), and the moist hornbeam-pine oak forest (3.2%) – varies between 2-5% of the total forest area. These types contribute significantly to ecological stability and biodiversity support. Forest types such as the moist oak-pine subor with azalea (0.9%) and the wet oak-pine subor with azalea (0.2%) possess particular ecological importance due to the presence of rare plant assemblages, including species threatened with extinction. Additional forest types – including the wet pine bor (1.3%), moist pine bor (2.4%), wet oak-pine subor drained (1.6%), moist hornbeam oak forest (1.7%), wet hornbeam-oak-pine sugrud (1.3%), wet alder sugrud drained (1.5%), wet alder sugrud (6.3%), and the wet alder sugrud (1.3%) – play an essential role in supporting wetland ecosystems, regulating water levels, and maintaining habitat functions crucial for rare flora and fauna (Table 4).

***Table 4**. Distribution of forest area in Rivne Oblast by forest types*

Forest type name	Index	Area, ha	%
Dry pine bor	A_1-C	12,728.9	2.2
Fresh pine bor	A_2-C	54,919.2	9.4
Moist pine bor	A_3-C	12,878.4	2.2
Wet pine bor	A_4-C	7,364.7	1.3
Marshy pine bor	A_5-C	14,089.4	2.4
Fresh oak-pine subor	B_2-дС	70,281.1	12.0
Moist oak-pine subor	B_3-дС	127,872.6	21.9
Moist oak-pine subor with azalea	B_3-дСа	5,324.8	0.9
Wet oak-pine subor	B_4-дС	53,025.7	9.1
Wet oak-pine subor with azalea	B_4-дСа	1,362.2	0.2
Wet oak-pine subor drained	B_4-дС^o	9,155.6	1.6
Wet birch-pine subor	B_5-бС	17,329.2	3.0
Fresh hornbeam oak forest	D_2-гД	19,219.3	3.3
Moist hornbeam oak forest	D_3-гД	10,111.1	1.7
Fresh hornbeam-oak-pine sugrud	C_2-гдС	29,099.7	5.0
Moist hornbeam sugrud	C_3-гД	11,497.3	2.0
Moist hornbeam-oak-pine sugrud	C_3-гдС	48,961.4	8.4
Wet alder sugrud drained	C_4-Влч^o	8,950.6	1.5
Wet alder sugrud	C_4-Влч	36,824.6	6.3
Wet hornbeam-oak-pine sugrud	C_4-гдС	7,738.1	1.3
Moist alder sugrud	C_5-Влч	7,403.7	1.3
Other		18,038.4	3.1
Total		584,176	100.0

***Source:** compiled by the authors*

The remaining 26 forest types, which together occupy 3.1% of the total forest area, belong to the least widespread categories; however, they also play an important role in maintaining ecological balance, supporting biodiversity, and protecting soil and water resources. Thus, the forest ecosystems of Rivne Oblast, characterised by a considerable diversity of forest types, perform complex ecological functions that contribute to biodiversity conservation, water balance regulation, and landscape stability. Although the forest types occupying smaller areas are less common, they are essential for maintaining ecological equilibrium and ensuring the resilience of forest ecosystems in the region.

The forest ecosystems of Ternopil Oblast demonstrate a moderate diversity of forest types. The total number of forest types reaches 29, indicating some level of variability but representing the lowest value among the analysed regions. Within this structure, bor contains 3 forest types, subor includes 5, sugrud comprises 10, and grud contains 11 forest types (Table 5). The fresh hornbeam oak forest (48.2%) is the most widespread forest type in Ternopil Oblast. This forest type is essential for maintaining hydrological stability and supporting species diversity adapted to the specific conditions of hornbeam-dominated ecosystems. The fresh hornbeam-beech forest (9.5%), fresh hornbeam oak forest (8.4%), fresh hornbeam-oak sugrud (5.4%), and the fresh hornbeam sub-oak forest (4.9%) also occupy significant areas and play important roles in shaping the region’s landscape structure. The moist hornbeam oak forest (11.4%), moist hornbeam beech forest (1.1%), moist hornbeam-beech forest (3.5%), and moist hornbeam-oak sugrud (1.2%) are critical for ecosystem stability, particularly under elevated soil moisture conditions. These ecosystems play key roles in maintaining water balance and regulating water exchange within forested landscapes. The proportion of the fresh oak-pine subor (2.9%) and the dry oak forest (1.0%) is also notable, while the combined area of the remaining 18 forest types reaches only 2.4%. Despite their limited spatial coverage, these forest types support ecological stability by preserving landscape integrity, biodiversity, and performing essential functions related to water regulation and soil protection.

***Table 5**. Distribution of forest area in Ternopil Oblast by forest types*

Forest type name	Index	Area, ha	%
Fresh oak-pine subor	B_2-дС	5,587.4	2.9
Fresh hornbeam beech forest	D_2-гБк	16,308	8.4
Fresh hornbeam-beech oak forest	D_2-гбД	18,298.4	9.5
Fresh hornbeam oak forest	D_2-гД	93,169.7	48.2
Moist hornbeam beech forest	D_3-гБк	2,220	1.1
Moist hornbeam-beech oak forest	D_3-гбкД	6,818.9	3.5
Moist hornbeam oak forest	D_3-гД	22,039.5	11.4
Dry oak forest	C_1-Д	1,974	1.0
Fresh hornbeam sub-oak forest	C_2-гД	9,409.7	4.9
Fresh hornbeam-oak sugrud	C_2-гдС	10,383.9	5.4
Moist hornbeam-oak sugrud	C_3-гдС	2,313.9	1.2
Other		4,590.3	2.4
Total		193,113.7	100.0

***Source:** compiled by the authors*

In general, the forest ecosystems of Ternopil Oblast, represented by various types of hornbeam and oak forests, play a key role in maintaining the stability of ecological processes. The most widespread forest types, particularly the fresh hornbeam oak forest, ensure important ecological functions, including regulation of the water balance, preservation of biodiversity, and landscape stability.

The forest ecosystems of Lviv Oblast are characterised by a high diversity of forest types. The total number of forest types reaches 81, which indicates substantial ecological variability in the region. Within this structure, bor includes 5 forest types, subor contains 9, sugrud comprises 27, and grud includes 40 forest types (Table 6). Among such a large number of forest types, seven principal types dominate the region: the moist oak-pine subor (5.8%), the fresh beech-hornbeam beech forest (6.2%), the moist beech-spruce suyaluchnyk (5.0%), the moist hornbeam oak forest (9.3%), the moist beech-hornbeam beech forest (8.2%), the moist beech suyaluchnyk (7.6%), and the moist hornbeam-oak sugrud (7.0%), which together account for 49.1% of the total forest area of the region. The proportion of other fairly widespread forest types, such as the fresh oak-pine subor (4.0%), the moist beech-fir suyaluchnyk (3.4%), the moist fir beech forest (2.4%), the moist fir oak forest (2.1%), the moist spruce-fir beech forest (2.4%), the fresh hornbeam-oak sugrud (2.6%), the moist beech-fir suyaluchnyk (3.1%), the moist hornbeam sub-oak forest (3.7%), the moist hornbeam-pine sub-oak forest (3.6%), the moist spruce-fir sub-beech forest (2.5%), and the wet alder sugrudok (4.2%), is also substantial (20.0%)

and varies between 2 and 4.5%. The area of less widespread forest types, such as the fresh hornbeam-beech oak forest (1.3%), the fresh hornbeam oak forest (1.7%), the moist beech oak forest (1.0%), the moist hornbeam–beech suyaluchnyk (1.6%), and the wet alder sugrud (1.3%), reaches 6.9% of the total forest area.

***Table 6**. Distribution of forest area in Lviv Oblast by forest types*

Forest type name	Index	Area, ha	%
Fresh oak-pine subor	B_2-дС	17,017.7	4.0
Moist oak-pine subor	B_3-дС	24,895.3	5.8
Fresh hornbeam-beech oak forest	D_2-г-бкД	5,667.6	1.3
Fresh hornbeam oak forest	D_2-гД	7,441.2	1.7
Fresh beech-hornbeam beech forest	D_2-бк-гБ	26,634.3	6.2
Moist beech oak forest	D_3-бкД	4,225.4	1.0
Moist beech-fir suyaluchnyk	D_3-бк-яцЯ	14,581.7	3.4
Moist beech-spruce suyaluchnyk	D_3-бкЯ	21,316.5	5.0
Moist hornbeam-beech suyaluchnyk	D_3-г-бкЯ	6,857.0	1.6
Moist hornbeam-oak sugrud	D_3-гД	39,866.7	9.3
Moist hornbeam oak forest	D_3-бк-гБ	35,214.7	8.2
Moist beech-hornbeam beech forest	D_3-яцБ	10,393.2	2.4
Moist fir beech forest	D_3-яцД	9,179.9	2.1
Moist fir oak forest	D_3-ял-яцБ	10,484.2	2.4
Moist spruce-fir beech forest	D_4-Влч	5,764.0	1.3
Wet alder grud	C_2-гдС	11,104.9	2.6
Fresh hornbeam-beech sugrud	C_3-бкЯл	32,830	7.6
Moist beech sugrud	C_3-бк-яцЯ	13,448.5	3.1
Moist beech-fir sugrud	C_3-гД	15,730.8	3.7
Moist hornbeam sub-oak forest	C_3-гдС	29,805.7	7.0
Moist hornbeam-pine sub-oak forest	C_3-гсД	15,582.6	3.6
Moist spruce-fir sub-beech forest	C_3-ял-яцБ	10,768.7	2.5
Wet alder sugrudok	C_4-Влч	18,088.1	4.2
Other		41,257.6	9.6
Total		428,156.3	100.0

***Source:** compiled by the authors*

The remaining 58 forest types occupy 9.6% of the area. Although they cover a smaller territory, these forest types also contribute to maintaining ecological stability and perform important functions within the forest ecosystems of Lviv Oblast.

The forest ecosystems of Khmelnytskyi Oblast are characterised by a moderate level of diversity of forest types. The total number of forest types reaches 31, which indicates a moderate richness of forest ecosystems in the region. Within this structure, bor includes 4 forest types, subor contains 6, sugrud comprises 11, and grud includes 10 forest types. The most widespread forest type is the fresh hornbeam oak forest (46.2%), which occupies almost half of the forest area in the region (Table 7). The fresh hornbeam-oak-pine sugrud (11.0%), the fresh hornbeam sub-oak forest (7.1%), the fresh oak-pine subor (6.5%), and the moist oak-pine subor (5.1%) cover a significant part of the forest area of the region and are important for maintaining the stability of forest ecosystems. The proportion of less widespread forest types, such as the moist hornbeam sub-oak forest (4.7%), the moist hornbeam-oak-pine sugrud (4.0%), the moist hornbeam–pine sub-oak forest (1.4%), the wet alder sugrud (2.7%), the dry hornbeam oak forest (1.4%), the fresh hornbeam-beech oak forest (2.1%), and the moist hornbeam oak forest (4.5%), varies from 1.4% to 4.7%. These forest types ensure the stability of ecological processes in forests, particularly due to their capacity to regulate groundwater levels and maintain biodiversity. All other 19 forest types together occupy 3.4% of the area; although they cover a smaller territory, they also contribute to maintaining ecological balance and perform important functions in preserving biodiversity.

***Table 7**. Distribution of forest area in Khmelnytskyi Oblast by forest types*

Forest type name	Index	Area, ha	%
Fresh oak-pine subor	B_2-дС	8,900.2	6.5
Moist oak-pine subor	B_3-дС	7,048.4	5.1

Table 7. Continued

Forest type name	Index	Area, ha	%
Fresh hornbeam sub-oak forest	C_2-гД	9,778.1	7.1
Fresh hornbeam-oak-pine sugrud	C_2-гдС	15,203.9	11.0
Moist hornbeam sub-oak forest	C_3-гД	6,445.8	4.7
Moist hornbeam-oak-pine sugrud	C_3-гдС	5,479.8	4.0
Moist hornbeam-pine sub-oak forest	C_3-гсД	1,937.2	1.4
Wet alder sugrud	C_4-Влч	3,679.7	2.7
Dry hornbeam oak forest	D_1-гД	1,871.8	1.4
Fresh hornbeam-beech oak forest	D_2-гбД	2,913.8	2.1
Fresh hornbeam oak forest	D_2-гД	63,615.5	46.2
Moist hornbeam oak forest	D_3-гД	6,147.0	4.5
Other		4,611.7	3.4
Total		137,632.9	100.0

Source: *compiled by the authors*

Thus, the forest ecosystems of Khmelnytskyi Oblast, represented by various types of hornbeam, oak, and pine forests, are important for ensuring ecological stability, maintaining the water balance, and supporting biodiversity. Although the forest types that occupy smaller areas are less widespread, they play a significant role in maintaining functional processes within ecosystems and in ensuring the sustainable development of forest habitats.

The forest ecosystems of Ivano-Frankivsk Oblast have the greatest diversity of forest types among the regions studied, which indicates a very high richness of natural resources. The total number of forest types reaches 89. Within this structure, bor includes 6 forest types, subor contains 17, sugrud comprises 40, and grud includes 26 forest types. The most widespread forest types are the moist beech-fir suyaluchnyk (19.8%), the moist beech suyaluchnyk (14.8%), the moist pure suyaluchnyk (10.6%), and the moist spruce-fir sub-beech forest (7.8%). These forest types play an important role in stabilising the water regime, preserving soil fertility, and maintaining biodiversity, especially under conditions of high soil moisture. Among the widespread forest types are the moist spruce subor (3.3%), the fresh hornbeam oak forest (2.5%), the moist beech-fir suyaluchnyk (3.3%), the moist beech-spruce suyaluchnyk (2.9%), the moist hornbeam beech forest (3.7%), the moist hornbeam sub-oak forest (4.4%), and the moist fir sub-oak forest (2.1%); their proportions range from 2.0% to 4.4% and together constitute 22.2% of the total forest area of the region (Table 8). The combined share of forest types such as the fresh beech-hornbeam beech forest (2.0%), the moist hornbeam–beech suyaluchnyk (1.2%), the moist oak–hornbeam beech forest (1.3%), the moist fir beech forest (1.0%), the moist spruce-fir beech forest (2.0%), the fresh hornbeam sub-oak forest (1.2%), the moist oak suyaluchnyk (1.4%), the moist fir sub-beech forest (1.2%), and the moist fir suyaluchnyk (1.1%) reaches 12.4% of the total forest area. These forest types play an important role in maintaining the water balance, supporting biodiversity, and regulating the microclimate of the region.

Table 8*. Distribution of forest area in Ivano-Frankivsk Oblast by forest types*

Forest type name	Index	Area, ha	%
Moist spruce subor	B_3-Ял	14,132.5	3.3
Fresh hornbeam oak forest	D_2-гД	10,604.1	2.5
Fresh beech-hornbeam beech forest	D_2-бк-гБк	8,417.1	2.0
Moist beech-fir suyaluchnyk	D_3-бк-яцЯ	13,870.3	3.3
Moist beech suyaluchnyk	D_3-бк-Ял	12,285.8	2.9
Moist hornbeam-beech suyaluchnyk	D_3-г-бкЯл	4,960.2	1.2
Moist hornbeam oak forest	D_3-гБк	15,691.2	3.7
Moist oak-hornbeam beech forest	D_3-дгБк	5,324.1	1.3
Moist fir beech forest	D_3-яцБк	5,426.2	1.0
Moist fir beech forest (variant)	D_3-ял-яцБк	8,597.1	2.0
Fresh hornbeam sub-oak forest	C_2-гД	5,100.6	1.2
Moist beech-fir sugrud	C_3-бк-яцЯл	8,4245	19.8
Moist beech sugrud	C_3-бкЯл	54,863.9	14.8
Moist hornbeam sugrud	C_3-гД	18,646.4	4.4
Moist oak sugrud	C_3-дЯл	5,924.5	1.4
Moist fir sub-beech forest	C_3-яцБ	4,910.7	1.2
Moist fir sub-oak forest	C_3-яцД	9,103.5	2.1

Table 8. Continued

Forest type name	Index	Area, ha	%
Moist fir sub-oak forest (variant)	C_3-яцЯл	4,741.6	1.1
Moist spruce-fir suyaluchnyk	C_3-Я^{ч}	45,016.9	10.6
Moist pure suyaluchnyk	C_3-ял-яцБ	33,103.1	7.8
Other		52,682.5	12.4
Total		425,768.3	100.0

Source: *compiled by the authors*

Other 69 forest types, occupying 12.4% of the area, although covering smaller territories, perform important functions for maintaining ecological balance and stability of forest landscapes. Overall, the forest ecosystems of Ivano-Frankivsk Oblast, represented by diverse forest types, perform complex ecological functions, including sustaining the water balance, preserving biodiversity, and maintaining landscape stability. Forest types occupying smaller areas, although less widespread, play an important role in ensuring the resilience of forest ecosystems and preserving ecological balance in the region.

The forest ecosystems of Chernivtsi Oblast also demonstrate a high diversity of forest types, indicating the ecological importance of the region. The total number of forest types is 73. No forest types were identified in the bor category, while the subor category includes 2 forest types, the sugrud category comprises 37 forest types, and the grud category includes 34 forest types. The most widespread forest types are fresh oak-hornbeam beech forest (13.9%), moist beech fir forest (16.0%), moist beech-fir subfir forest (12.2%), and moist beech subfir forest (11.0%). These forest types are essential for maintaining water regime stability, improving soil fertility, and sustaining ecological balance, and together constitute more than half (53.1%) of the region's forest area (Table 9). The proportion of fairly widespread forest types, such as fresh beech oak forest (4.1%), moist beech-fir spruce forest (2.0%), moist oak-hornbeam beech forest (5.5%), moist oak fir forest (2.3%), moist fir subfir forest (3.3%), and moist pure subfir forest (7.8%), ranges between 2.3% and 7.8% and in total accounts for exactly one-quarter (25.0%) of the forest area. Less common forest types – dry hornbeam oak forest (1.1%), moist spruce-fir beech forest (1.6%), fresh hornbeam suboak forest (1.0%), moist oak subfir forest (1.2%), and moist fir sub-beech forest (1.3%) – together occupy 6.1% of the total forest area. The remaining 57 forest types (9.0%), although covering smaller territories, are essential for conserving ecological balance and maintaining the stability of natural systems.

***Table 9**. Distribution of forest area in Chernivtsi Oblast by forest types*

Forest type name	Index	Area, ha	%	
Dry hornbeam oak forest		D_1-гД	1,778.2	1.1
Fresh beech oak forest	D_2-бкД	6,476	4.1	
Fresh hornbeam oak forest	D_2-гД	15,736.9	10.0	
Fresh oak-hornbeam beech forest	D_2-дгБк	21,934	13.9	
Moist beech fir forest	D_3-бкЯл	25,084.3	16.0	
Moist beech-fir spruce forest	D_3-бк-яцЯл	3,107.2	2.0	
Moist oak-hornbeam beech forest	D_3-дгБ	8,637.3	5.5	
Moist oak fir forest	D_3-дЯл	3,682.5	2.3	
Moist spruce-fir beech forest	D_3-ял-яцБк	2,481.5	1.6	
Fresh hornbeam suboak forest	C_2-гД	1,504.1	1.0	
Moist beech-fir subfir forest	C_3-бк-яцЯл	19,124.7	12.2	
Moist beech subfir forest	C_3-бкЯл	17,232.5	11.0	
Moist oak subfir forest	C_3-дЯл	1,924.8	1.2	
Moist fir sub-beech forest	C_3-яцБк	2,061.2	1.3	
Moist fir subfir forest	C_3-яцЯл	5,130.1	3.3	
Moist pure subfir forest	C_3-Ял^{ч}	12,339.1	7.8	
Other		14,150.7	9.0	
Total		157,257	100.0	

Source: *compiled by the authors*

Thus, the forest ecosystems of Chernivtsi Oblast, represented by a wide spectrum of forest types, perform important ecological functions, including the maintenance of water balance, the conservation of biodiversity, and landscape stability. Forest types occupying smaller areas, although less widespread, remain significant for ensuring the resilience of forest ecosystems and preserving ecological equilibrium within the oblast.

The synthesis of the obtained results indicates that the typological structure of forests in western Ukraine reproduces a clear gradient from Polissia to forest-steppe and Carpathian ecosystems, which is traced both in the spectrum of trophic site conditions and in the number and dominance of individual forest types. The identified prevalence of sugrud and grud conditions in the Carpathian oblasts and the increasing share of bor and subor conditions in Polissia is consistent with contemporary views on the place of Ukrainian forest formations within European classification systems, where moisture regime, trophicity, and altitudinal zonation act as decisive determinants (Tkach *et al.,* 2024). At the level of the regional pattern, it is confirmed that forest-steppe oblasts demonstrate lower typological mosaicity and a concentration of area in hornbeam and hornbeam-beech oak forest formations, whereas the Carpathians are characterised by maximal diversity of forest types, reflecting complex climatic-orographic and edaphic contrasts.

The comparison of the obtained data with the results of other researchers within the forest-steppe zone shows that the dominance of oak forest types in Ternopil and Khmelnytskyi oblasts logically continues the regularities established for ecologically similar territories of Ukraine. Thus, I. Solomakha and O. Chornobrov (2021) demonstrated for the Middle Dnipro region a high contribution of oak-hornbeam and hornbeam communities to the structure of forest vegetation, which correlates with the concentration of areas in fresh hornbeam oak forests revealed in this study for the Podillia oblasts. A similar pattern at the local level was described for the Emerald Network site "Tsyrkunivskyi Forest", where typological organisation is also determined by a combination of trophic soils and moderate moisture, forming the predominance of broadleaf formations (Tymochko *et al.,* 2022). The regional data obtained here extend these conclusions by demonstrating that analogous mechanisms operate not only in individual conservation nodes but also at the scale of the entire western Ukrainian forest-steppe.

For Polissian landscapes, a substantial share of pine bor and oak-pine subor types appears characteristic, especially in Volyn and Rivne oblasts, which logically corresponds to contemporary assessments of the role of protected areas in maintaining the ecological stability of forests in the Volyn forest-steppe and adjacent zones. In particular, I. Myskivets (2024) emphasises the importance of protected nuclei for the conservation of typological and biotic diversity, which is consistent with the high proportion of forest types in Volyn associated with different moisture regimes, including the participation of alder sugrud complexes that are important for the wetland component of the region. Accordingly, the regional typological mosaic of Polissia may be considered a sensitive indicator of the effectiveness of conservation strategies.

The most pronounced parallels are observed for the Carpathians. According to O. Kameniar *et al.* (2023), primary spruce and beech forests of the Western Carpathians differ substantially in structure and avifauna regardless of disturbance regimes, which confirms the ecological autonomy of dominant beech and conifer formations in the mountain belt. This is consistent with the results obtained in this study regarding the leading role of various beech forest types and beech-fir suyaluchnyk types in Zakarpattia, Ivano-Frankivsk, and Chernivtsi oblasts, as well as with the almost complete absence of bor types under mountain conditions. An additional spatial dimension is provided by the use of modern geoinformation approaches: V. Rushchak and I. Chepurnyi (2025) demonstrated the dynamics of forest cover in landslide-prone areas of the Carpathians based on Google Earth Engine, which helps explain the high heterogeneity of forest types identified here within the mountainous oblasts, where local geomorphological processes can shape a mosaic of site conditions. In this sense, the typological data obtained provide a reliable basis for interpreting spatial changes recorded by remote methods.

The functional implications of the identified differences are also supported by modern ecological studies. D. Sun *et al.* (2024) showed that forest types control the contribution of litter and roots to the formation of labile and stable soil organic carbon, underscoring the significance of the revealed trophic-site distribution for forecasting soil and biogeochemical processes in the region. At the same time, modelling of future changes in the seasonal carbon cycle under climatic influence suggests that structural-typological relationships may transform over several decades, making the baseline regional pattern established in this study an important reference point for monitoring (Morichetti *et al.,* 2024).

The approach proposed by H. Kitano *et al.* (2025) demonstrated that classification of forest vegetation can be substantially refined when vertical stratification derived from airborne laser scanning is considered, because structural attributes help differentiate units that may appear similar within purely edaphic-climatic schemes; this directly supports the feasibility of combining state forest inventory data with remote-sensing metrics to improve the spatial delineation of forest site conditions and dominant forest types across Western Ukraine. The evidence presented by Q. Ridwan and M. Hanief (2025) further indicated that tree composition and regeneration potential vary sharply among major forest types under different levels of anthropogenic disturbance in mountain landscapes, which conceptually parallels the Carpathian pattern where the prevalence of sugrud and grud conditions and the dominance of beech-related formations suggest not only ecological differentiation along altitudinal gradients but also unequal sensitivity to management pressure. In turn, the findings of J. Zhao *et al.* (2025) showed that forest type interacts with landowner practices and climate in shaping tree species diversity, reinforcing the interpretation that the observed contrasts between Polissia bor and subor complexes and the forest-steppe concentration of broadleaf formations may reflect a combined effect of trophic status, moisture regime and historically formed management models. Thus, the comparative analysis indicates that the results of the regional assessment of site conditions and forest types in western Ukraine are generally consistent with contemporary Ukrainian and international research, while extending them due to the scale of coverage of eight oblasts and the detailed characterisation of the relationship between trophic site conditions and leading forest types within each of them.

CONCLUSIONS

The results of the typological analysis of forest site conditions in the forests of western Ukraine indicate a high structural diversity of forest ecosystems covering more than 2.9 million ha across eight administrative oblasts. It was shown that the Polissian oblasts retain a substantial share of bor and subor conditions, which is clearly manifested in Volyn and especially in Rivne oblasts, where large areas are occupied by pine bor and oak-pine subor forests. In contrast, the Podillia oblasts of Ternopil and Khmelnytskyi are dominated by grud and sugrud conditions, while the structure of forest types is characterised by the prevalence of hornbeam and hornbeam-beech oak forest formations, reflecting higher soil trophicity and a distinct moisture regime. The Carpathian oblasts demonstrate the highest typological mosaicity and the greatest number of forest types, as confirmed by 85 types in Zakarpattia, 89 in Ivano-Frankivsk, and 73 in Chernivtsi, where various forms of beech forests, sub-beech forests, and beech-fir and spruce-fir communities play the leading role. Lviv oblast occupies an intermediate position combining lowland oak-pine complexes with mountainous beech formations. Additionally, the overall diversity of forest types varies from 47 in Volyn and 46 in Rivne to 31 in Khmelnytskyi and the minimum of 29 in Ternopil, whereas 81 types were recorded in Lviv, highlighting the transitional nature of its landscapes. Volyn is characterised by high shares of fresh and moist oak-pine subor and a substantial contribution of wet alder sugrud types, reflecting the importance of wetland complexes. In the Carpathians, the practical absence of bor types and the concentration of sugrud and grud conditions confirm the decisive role of altitudinal zonation. Prospects for further research are associated with a more detailed analysis of forest types at the forest district level, the integration of remote sensing, and an assessment of typological dynamics under climate change and anthropogenic pressures.

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Аналіз типологічної структури лісів заходу України

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Анотація. Метою роботи було здійснити еколого-типологічну оцінку лісорослинних умов восьми адміністративних областей макрорегіону України та визначити регіональні відмінності у співвідношенні трофотопів і типів насаджень. Класифікацію типів лісу здійснено за лісівничо-екологічною шкалою лісової типології на основі матеріалів державного лісовпорядкування. Застосовано методи порівняльного аналізу, типологічного групування та статистичної обробки даних для визначення площ, співвідношень і структури типів лісу. Було проаналізовано розподіл площі вкритих лісовою рослинністю земель за чотирма групами багатства ґрунтів, що дозволило виявити домінування сугрудових і грудових умов у гірських частинах регіону. Було встановлено, що найбільші площі сугрудів зосереджені в Івано-Франківській і Закарпатській областях, тоді як у Волинській та Рівненській областях вагомими залишаються борові й суборові комплекси. Діапазон кількості виділених типів лісу коливався від 29 у Тернопільській до 89 в Івано-Франківській області, що відображає контрастність природних умов регіону. Було деталізовано типологічну структуру окремих областей і показано різноманітність у Карпатському секторі, де переважають різні варіанти бучин, субучин і суяличників, що відображає поєднання висотної поясності та зволоження. Було з'ясовано, що для Поліського сектору характерна концентрація площ у дубово-соснових суборах і чорновільхових сугрудах, які формують ядро гідрологічної та біотичної стабільності територій. Було узагальнено, що для Подільських областей типова простота типологічного спектра з домінуванням грабових і дубових дібров, що корелює з більш однорідними ґрунтово-кліматичними умовами. Практична цінність одержаних результатів полягає у можливості їх використання лісогосподарськими підприємствами та природоохоронними установами для обґрунтування заходів сталого ведення лісового господарства, відновлення насаджень і зонування рекреаційного навантаження

Ключові слова: лісорослинні умови; типологічна структура; едафічна сітка; трофотопи; гігротопи; бучинові угруповання; дубово-соснові субори

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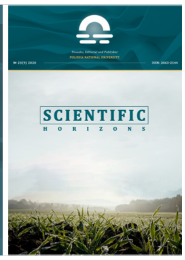

Optimisation of the design parameters of the control module of the air generator of an aerodynamic separator

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Abstract. The production of high-quality seed material and food grain required the use of efficient separation technologies. Aerodynamic separation was widely implemented in various designs of equipment intended for removing light impurities from the initial grain mass and dividing it into fractions that were uniform in their properties. The use of a differential airflow provided a relatively high 60-70% efficiency of grain cleaning from impurities. The study was aimed at investigating the efficiency of aerodynamic separation in order to identify ways to improve the quality indicators of the technological process of cleaning and calibrating the initial grain mass. Experimental investigations indicated that the airflow in the cross-section of the air channel of the SAD-4 model aerodynamic separator was non-uniform. Specifically, the airflow velocity in the lower third of the channel cross-section was 48-52% lower than in the upper and middle zones, between which the airflow non-uniformity amounted to only 7-9%. It was established that the intensity of the separation regimes affected the quality of the fractional composition. Under maximum operating settings, owing to the non-uniform distribution of airflow along the vertical plane, the heterogeneity of the fractional composition increased to 61%. The scientific problem of increasing the homogeneity level of the fractional composition of cleaned grain was proposed to be solved by modelling the airflow in the pneumatic channel of the aerodynamic separator in accordance with the operating settings. A design of an air generator with a mechanism

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for equalising airflow velocity in the cross-section of the separation channel was proposed. The investigations showed that when the operating settings were changed from “1” to “7”, the airflow intensity in the lower third of the channel cross-section varied from 1.9 to 12.6 m/s, which was 37-49% higher than in the serial separator. Under maximum separation regimes, the uneven distribution of the components of the initial grain mixture between fractions decreased to 25-29%. A functional relationship was established between the intensity and uniformity of the airflow in the separation channel and the homogeneity of the fractional composition of the cleaned grain

Keywords: airflow regime; relative velocity; fraction yield; terminal velocity; airflow control

INTRODUCTION

The justification and theoretical prerequisites for the influence of airflow on the efficiency of separating the components of the initial grain mixture attracted the interest of scientists and researchers in many countries. Ukrainian researchers B. Kotov *et al.* (2022) carried out studies of the separation of grain material in a pneumatic channel and determined the rational form and parameters of material feed. Based on the results of these investigations, mathematical relationships were established that made it possible to determine the rational parameters of pneumogravitational and pneumo-inertial separators. However, understanding the velocity parameters of material feed into the air channel was not sufficient for a complete understanding of the process of dividing the initial grain mixture into several fractions. The performed studies were limited to establishing rational trajectories of motion of particles in a two-phase medium, and therefore only two fractions were obtained.

Researchers I. Dudarev *et al.* (2020) demonstrated the expediency of using the different aerodynamic properties of the components of a grain mixture for its division into uniform fractions in an airflow. In their studies, the prospect of using a combined method of gravitational separation was emphasised, since the process took place without energy consumption. However, despite the positive results of these investigations, in the opinion of the present authors it was not possible to obtain a well-cleaned material without the use of an additional artificial airflow. The scientific problem of increasing the productivity of aerodynamic separation by preliminary stratification of grain mixtures was addressed by V. Koshulko and I. Kudriavtsev (2024). The effectiveness of preliminary stratification in the process of removing light impurities was theoretically substantiated and experimentally confirmed. A mathematical model for determining the initial position of the feed material and for justifying the design of the air channel was proposed. The conducted research did not take into account the process of calibrating the initial grain mass into several fractions, which limited the application of the proposed solution.

The investigations of inertial fractionation by S. Stepanenko *et al.* (2023) demonstrated a significant increase in the efficiency of dividing grain material into fractions. The use of variable airflows that correlated with the aerodynamic properties of the components was proposed in order to intensify the division of grain material into fractions. This approach made it possible to develop solutions that contributed to improving the efficiency of the control of aerodynamic separation. In subsequent studies, S. Stepanenko *et al.* (2025a) proposed the use of a combined centrifugal–pneumatic gravitational separator for removing impurities from a grain mixture. According to the results of experimental investigations, quantitative indicators of division into two fractions were obtained, with the outlet ratio ranging from 39% to 61%. However, the proposed solutions did not make it possible to ensure the implementation of a grain calibration process, since the main attention was paid to the physical and mechanical properties of the grain and light inclusions.

Studies of vortex flows by V. Adamchuk *et al.* (2021) made it possible to identify ways of increasing the intensity of the process of cleaning grain mass from impurities and of improving the productivity of centrifugal separators. Based on the results of these investigations, initial conditions were established for the division of particles of a grain mixture in three directions of motion depending on their physical and mechanical properties. The obtained solutions were characteristic only of systems in which calibration of the feed material was not envisaged. However, the proposed developments could be used to describe the behaviour of particles in an airflow in the presence of centrifugal influences. In the studies of D. Li *et al.* (2024), theoretical aspects of the separation of grain mixtures using the aerodynamic principle of division were presented. In the course of investigating an inclined airflow, the resistance of the grain layer to air passage, seed buoyancy, operating airflow velocities and overall airflow velocity were taken into account. The obtained data formed the basis for the development of a new type of aerodynamic separator, SCA-5, for cleaning and sorting seed mixtures. The work was aimed at describing the advantages of the proposed design solutions of the separator, which could be used in the design of new equipment.

Significant attention was also paid to scientific research on the separation of a grain mixture into components in a vertical channel. Scientists V. Bulgakov *et al.* (2020a) proposed their own separator design using sail-type elements that generated oscillatory motion and thereby increased the efficiency of dividing the feed material into fractions. The expediency of using flow vibrations was emphasised in the work of L. Knaub (2020), which was focused on a differential approach to particles of different shapes, including the derivation of a vibrational Reynolds criterion. An important aspect of increasing separation efficiency was the reduction of energy consumption.

The substantial volume of scientific research on the separation of grain mass components in an airflow indicated serious prospects and the relevance of the problem. The search for improved solutions for cleaning grain from impurities with simultaneous calibration required both theoretical and experimental investigations. Primarily, such an approach was useful for serial equipment, the improvement of which had to be based on operational experience and an adequate scientific assessment of performance indicators. Therefore, the aim of the study was to identify directions for increasing the efficiency of the aerodynamic separator of the SAD-4 model and to substantiate the design and technological parameters of an airflow modulator in the separation channel.

MATERIALS AND METHODS

The efficiency index of the separation process was defined as the degree of separation of a given component of the grain mixture, η, which was calculated as the ratio of the amount of the separated component to the total amount of the same component in the initial grain mass (Zhou *et al.,* 2024):

$$\eta = \frac{P_k}{P_0}, \quad (1)$$

where P_k – the amount of one component separated from the grain mixture,%; P_0 – the maximum determined amount of the same component in the initial grain mixture,%.

Reference values of critical velocity obtained from studies of particle motion in a vertical airflow (Bazaluk *et al.,* 2022) were used for the calculations. This approach was adopted as the baseline condition for the subsequent analysis of the separation process in the inclined channel of the aerodynamic separator. The object of the study was the SAD-4 model aerodynamic separator, in which the grain mixture was divided into fractions in an inclined airflow combining the action of the aerodynamic air pressure force and gravity. To describe the motion of an individual grain or another component of the grain mass in the airflow, the equilibrium equation was used (Nanka *et al.,* 2019):

$$mg = \frac{1}{2} k\rho S_m (\upsilon - u)^2, \quad (2)$$

where g – the acceleration due to gravity, m/s^2; mmm was the mass of the particle, kg; m –the midship cross-sectional area of the particle in the airflow, m^2; u –the grain velocity, m/s; υ – the airflow velocity, m/s; k – the aerodynamic drag coefficient; ρ – the density of the medium under the given conditions, kg/m^3.

On the basis of Eq. (2), the relative velocity of particle motion ($\upsilon\upsilon$ – u)was considered as a function of its midship cross-sectional area and the specified airflow velocities. Theoretical analysis was carried out for wheat, assuming a thousand-kernel mass of 40 g, which corresponded to typical values for varietal seed material. For three characteristic airflow velocities (6, 8 and 12 m/s), the dependences of the relative velocity on the midship cross-sectional area of the grain were plotted (Fig. 1). The resulting curves were used to select the range of operating airflow velocities and the separator setting regimes during laboratory tests.

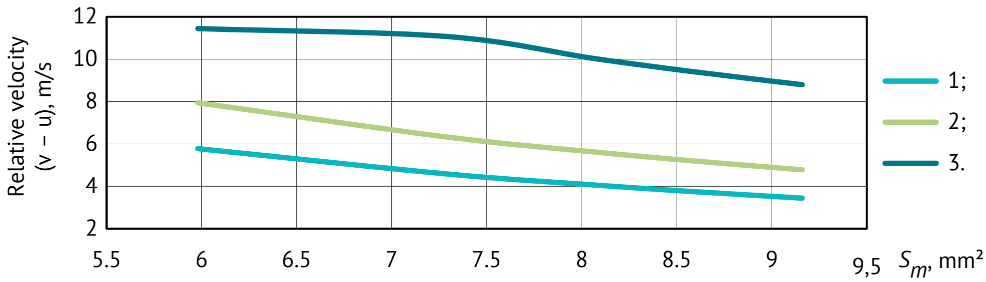

***Figure 1**. Dependence of the relative velocity of a wheat kernel on its midship cross-sectional area at different airflow velocitie*

***Note:** 1 – 6 m/s; 2 – 8 m/s; 3 – 12 m/s*

***Source:** developed by the authors*

An additional stage of the study consisted in determining the spatial distribution of airflow velocity in the aspiration channel of the serial SAD-4 aerodynamic separator. Measurements were carried out using a set of measuring equipment manufactured by Testo (Germany), which provided registration of instantaneous airflow velocity values at specified points. The cross-section of the air channel was conventionally divided into three vertical zones – upper, middle and lower. In each zone, three measurement points were set in the horizontal direction, positioned at equal distances from one another in order to ensure uniform coverage of the cross-sectional area.

The operating mode of the fan was defined by the position of the air supply lever, which was changed stepwise from setting "1" to setting "7". For each lever position, the airflow velocity was recorded at all nine measurement points. For each vertical zone (upper, middle, lower), the mean velocity value was calculated as the arithmetic mean of the three horizontal measurements. The mean airflow velocities by zone, depending on the lever position, were presented in the form of graphs that reflected the pattern of variation in airflow intensity in the working plane of the channel. In this way, initial data were obtained for the subsequent quantitative assessment of the uniformity of airflow velocity distribution in the channel cross-section.

Laboratory investigations of the grain separation process were conducted using wheat grain as a model material. Before the experimental part, the test weight of the initial grain mass was determined according to a standard method. Ten samples of grain were taken from the working batch, and the test weight was measured for each; thereafter, the mean value was calculated and used as a reference characteristic of the initial mixture. This procedure made it possible to characterise the initial state of the grain mass fed to separation and subsequently to compare the test weight values of individual fractions with the initial value.

Further experiments were performed on the serial SAD-4 aerodynamic separator under operating modes typical of practical use. The feed rate of the grain mass into the separation zone was set by the position of the material feed lever (in particular, settings "1" and "2" were used), and the airflow intensity was set by the position of the lever controlling the fan capacity (in particular, settings "3" and "4"). For each combination of operating parameters, a steady-state mode of separator operation was ensured, after which the fractions were collected from all outlet spouts.

For each of the five fractions obtained at the outlet of the aerodynamic separator, the test weight and mass yield were determined. Sampling for the test weight analysis was performed from each fraction by quartering, which ensured the representativeness of the samples. Each test mode was carried out with three repetitions. For each repetition, the grain test weight within the fraction and the relative mass yield of this fraction with respect to the total mass of the initial mixture were determined. Subsequent data processing was performed by calculating the mean values of the indicators over the repetitions and constructing distribution charts of test weight and mass yield for each fraction under the investigated modes.

The combination of theoretical calculations, measurements of airflow velocity in the channel cross-section and laboratory tests with determination of test weight and mass yield of the obtained fractions was used as a single methodological basis for the further assessment of the performance of the serial air generator of the SAD-4 aerodynamic separator and for comparison with the improved design solutions.

RESULTS AND DISCUSSION

According to the constructed theoretical dependences, it was established that, with an increase in the midship cross-sectional area of a wheat kernel at a constant thousand-kernel mass of 40 g, the relative velocity of its motion in the airflow decreased for all investigated airflow velocities (6, 8 and 12 m/s). This indicated an increase in the aerodynamic resistance to motion as the projection of the geometric dimensions of the grain in the flow plane increased. At higher airflow velocities ($\upsilon = 12$ m/s), an increase in the midship cross-sectional area *Sm* from 6.5 to 7.5 mm^2 no longer led to a significant change in relative velocity, which pointed to the feasibility of applying more intensive airflow regimes to ensure stable separation of grains with similar geometric parameters. The obtained theoretical curves in fact defined the range of operating velocities within which the efficiency of the serial and the improved jet generators was subsequently evaluated.

Analysis of the experimental curves of airflow velocity distribution over the height of the air channel of the serial SAD-4 separator (Fig. 2) showed an approximately linear increase in velocity in all three zones (upper, middle and lower) as the position of the fan capacity lever was changed from "1" to "7". At the same time, a pronounced non-uniformity of the velocity field in the vertical plane was revealed. Regardless of the lever position, the airflow velocity in the lower third of the channel was 48-52% lower than in the upper and middle zones. The difference between the upper and middle zones, by contrast, was small and amounted to only 7-9% at intermediate regimes (settings "3", "4" and "5"), while at minimum and maximum settings ("1", "2", "6" and "7") the velocities in these zones practically coincided. This pattern of airflow intensity distribution indicated that the components of the grain mass entering the lower zone of the channel were exposed to a substantially weaker airflow than the particles in the middle and upper zones, which potentially reduced the quality of separation and the homogeneity of the fractional composition.

The results of laboratory tests to determine the test weight of grain for the five fractions obtained on the serial SAD-4 separator under different operating modes (Fig. 3) confirmed the influence of airflow non-uniformity on the quality of fractionation. Under the mode with the grain feed lever set to "1" and the fan capacity lever set to "3", the maximum test weight of the initial mixture was 764 g/L and the mean value was 746.5 g/L. In the second fraction, kernels with a test weight of 725 and 733 g/L were recorded, whereas the maximum test weight for this fraction reached 776 g/L. In the third fraction, by contrast, samples with a test weight of

731 g/L were registered, which exceeded some of the values characteristic of the second fraction. At higher separation modes, a similar pattern was observed: in the fourth fraction, a test weight of 761 g/L was recorded, which exceeded the value of 759 g/L in the second fraction. Thus, a noticeable internal heterogeneity in test weight was observed within each fraction, and overlapping ranges of values were observed between fractions, indicating mixing of the components of adjacent fractions.

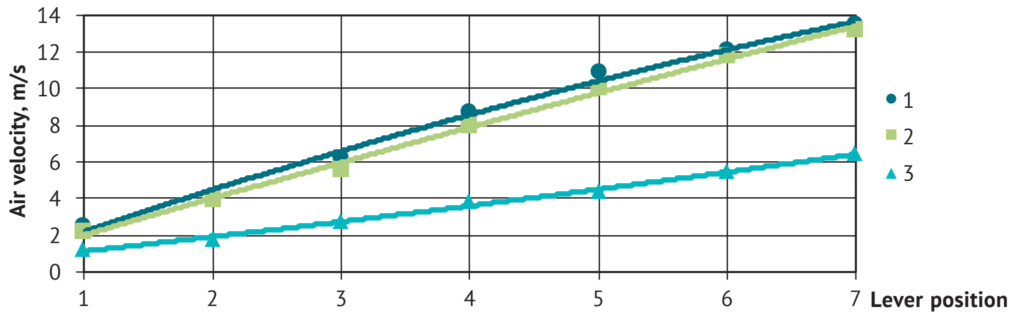

***Figure 2**. Results of the investigation of airflow velocity in three zones of the vertical plane of the air channel of the SAD-4 separator*

***Note:** 1 – upper zone; 2 – middle zone; 3 – lower zone*

***Source:** developed by the authors*

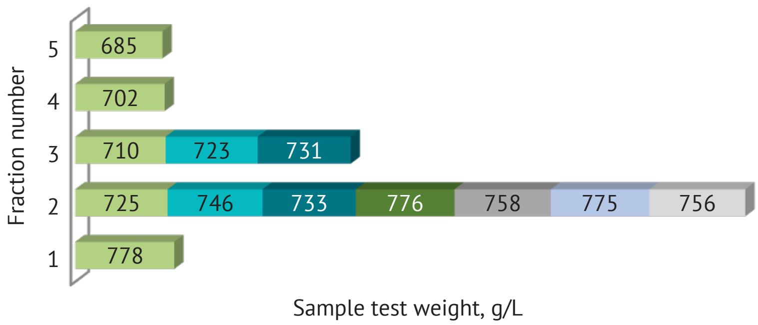

***Figure 3**. Results of the investigation of test weight samples for each fraction under the operating mode with the grain feed lever set to "1" and the fan airflow lever set to "3"*

***Source:** developed by the authors*

An additional quantitative indicator of this heterogeneity was the mass distribution of the grain mass between the fractions. It was established that, under the operating mode with the material feed lever set to "1" and the fan capacity lever set to "3", 61% of the total mass of the initial mixture was directed into the second fraction, whereas the shares of the other fractions were substantially smaller. Under the mode with the grain feed lever set to "2" and the fan capacity lever set to "4", the mass yield in the fourth fraction increased and the difference between the third and fourth fractions decreased slightly; however, it was still not possible to eliminate the overlap in test weight completely. The combination of these data confirmed that the non-uniformity of the airflow in the channel of the serial SAD-4 directly affected both the distribution of components between fractions and the internal homogeneity of each fraction.

The theoretical and experimental results obtained for the serial SAD-4 aerodynamic separator showed that the non-uniform distribution of airflow velocity in the vertical plane of the channel caused overlapping ranges of test weight between adjacent fractions and a non-uniform mass distribution of the feed material. For seed material, this implied a risk of forming fractions with different germination energy and heterogeneous sowing qualities. In view of this, it was proposed to improve the jet generator of the SAD-4 by supplementing it with elements that made it possible to model the airflow in the lower zone of the air channel (Fig. 4).

The experimental design was based on the jet generator of the SAD-4 aerodynamic separator. Movable plates and a control mechanism were installed in the lower third of the jet generator. The degree of opening of the movable plates was calculated on the basis of the well-known continuity condition for the flow of a continuous medium (Zhou *et al.,* 2024), under the requirement of achieving the necessary velocity regimes. The calculated values yielded parameters that made it possible to define three variable positions of the movable plates over the entire range of positions of the fan capacity lever (Table 1).

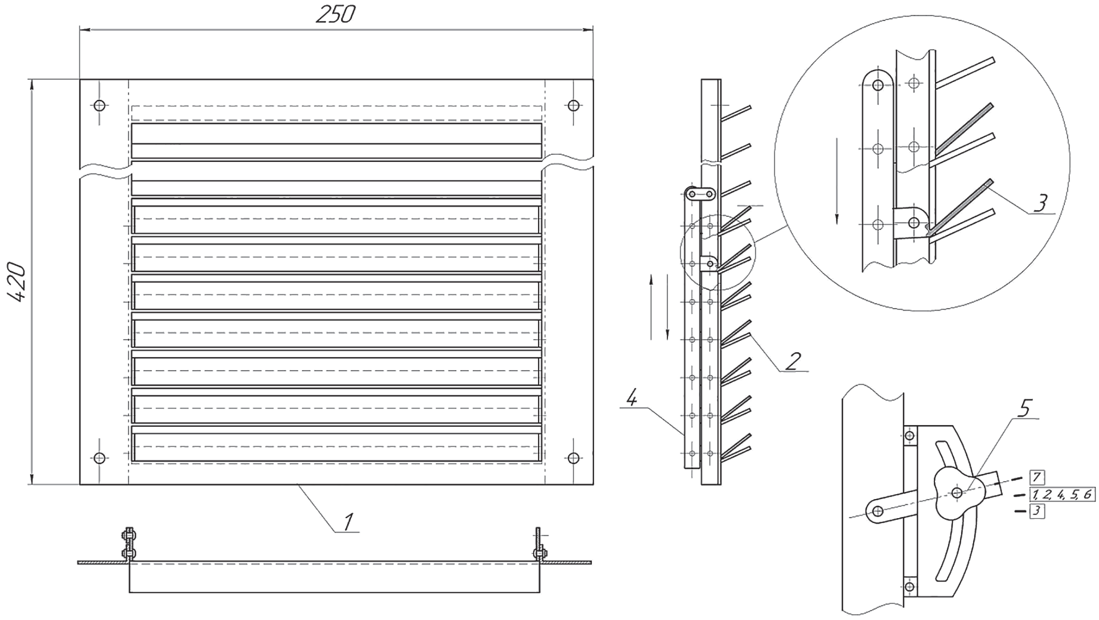

***Figure 4**. Experimental design of the jet generator*
***Note:** 1 – jet generator; 2 – fixed plate; 3 – movable plate; 4 – connecting bar; 5 – mechanism for controlling the movable plates adapted to the fan capacity*
***Source:** developed by the authors*

***Table 1**. Calculated and design parameters*

Lower zone	Distance between plates (mm) according to the position of the fan capacity lever						
	1	2	3	4	5	6	7
Calculated parameter	9.8	10.0	10.85	10.36	9.78	9.65	9.17
Design parameter	10	10	11	10	10	10	9

***Source:** developed by the authors*

The obtained design parameters were used in the experimental prototype for laboratory investigations. Accordingly, the opening of the movable plates in the lower zone had three fixed positions: the upper position corresponded to the fan capacity lever set to "7"; the middle position corresponded to the fan capacity lever set to "1", "2", "4", "5" and "6"; and the lower position corresponded to the fan capacity lever set to "3" and had a maximum opening of 11 mm. Studies of the operating regimes of the aerodynamic separator with the improved jet generator design indicated a more uniform airflow velocity in the vertical plane of the air channel (Fig. 5).

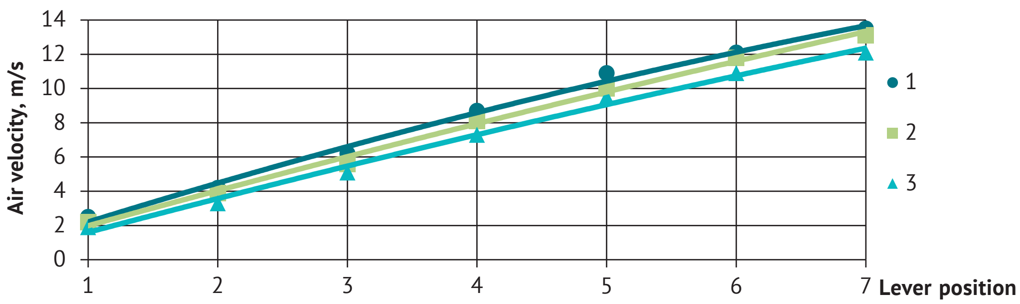

***Figure 5**. Distribution of airflow velocity in the vertical plane for each zone of the air channel when investigating the improved jet generator*
***Note:** 1 – upper zone; 2 – middle zone; 3 – lower zone*
***Source:** developed by the authors*

Compared with the data in Figure 2, the airflow velocity in the lower zone of the air channel became very close to the values in the upper and middle zones. The investigations of the improved air generator indicated an increase in airflow velocity at different setting modes of the aerodynamic separator. Thus, in comparison with the serial jet generator, when the fan capacity lever was set to "1", the airflow velocity in the working plane increased by 0.7 m/s; at setting "2" – by 1.5 m/s; at setting "3" – by 2.4 m/s; at setting "4" – by 3.5 m/s; at setting "5" – by 5.1 m/s; at setting "6" – by 5.4 m/s; and at setting "7" – by 5.7 m/s. Minor deviations of airflow velocity within 0.3-0.5 m/s between the zones of the working plane made it possible to model the ballistic trajectory of the movement of the grain mass components. This approach prevented good-quality grain from entering the fourth fraction and contributed to increasing the homogeneity of the outlet fractions up to 70%, with potential for further improvement.

The key characteristic of the aerodynamic separation of the components of the initial grain mass was the value of the critical velocity. For wheat grain, the critical velocity was 8.9-11.5 m/s, which was unattainable in the lower zone of the serial jet generator. Laboratory investigations of the improved jet generator revealed an increase in the mean airflow velocity in the cross-section of the separation channel (Fig. 6).

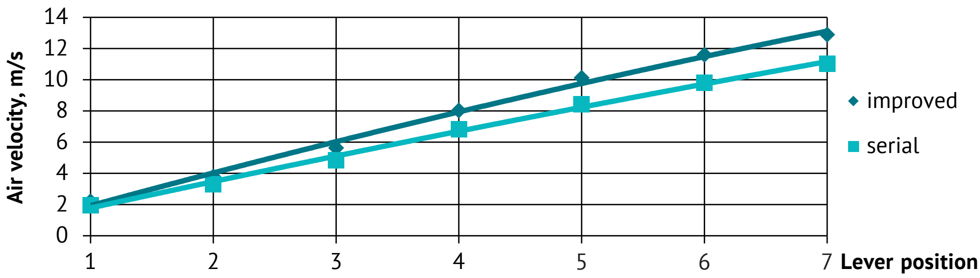

Figure 6. *Mean airflow velocity in the vertical plane of the air channel of the serial and improved aerodynamic separators*

Source: *developed by the authors*

The improved SAD-4 aerodynamic separator exhibited higher mean airflow velocity in the separation channel at any position of the fan capacity control lever. Thus, when the fan capacity lever was set to position "1", the mean airflow velocity in the working plane increased by 11.7%; at position "2" – by 15.1%; at position "3" – by 16.5%; at position "4" – by 17.6%; at position "5" – by 20.2%; at position "6" – by 18.4%; and at position "7" – by 17.3%. The maximum mean airflow velocity exceeded 13 m/s, which was fully sufficient for calibrating wheat grain mass and the grain mass of other crops. The introduced improvements ensured a uniform air pressure field in the vertical plane of the pneumatic separation channel under different operating settings of the aerodynamic separator. Thus, comparison of the serial and the improved designs of the jet generator showed that equalising the velocity field in the lower third of the channel made it possible to substantially increase the homogeneity of the fractional composition and to bring the operating regimes closer to the critical velocities required for high-quality calibration of the grain mass.

The discussion of the obtained results made it possible to relate them to current theoretical and engineering approaches to aerodynamic separation of grain mixtures and, at the same time, to delineate the niche occupied by the proposed improvement of the jet generator. In the theoretical model of particle motion in an aspiration channel proposed by V. Bulgakov *et al.* (2020b), the trajectory of a grain was described by the balance of gravity and aerodynamic drag forces in a flow with a certain distributed velocity, while the velocity field was effectively considered uniform within the calculation domain. A similar approach could be observed in the analytical assessment of pneumatic separation quality under multilayer feeding performed by A.V. Nesterenko *et al.* (2017), where separation quality was related to feed parameters and the mean characteristics of the airflow. The experimental data obtained in the present study, showing a 48-52% difference between the air velocities in the lower and upper–middle zones of the channel of the serial separator, indicated that practical implementation of theoretical regimes was possible only under conditions of deliberate shaping of the vertical velocity profile; otherwise, even correctly selected critical velocities did not ensure stable calibration by test weight over the entire height of the channel.

In recent studies devoted to numerical modelling of granular flows, the CFD–DEM approach has been used for a detailed description of particle–air interaction, the formation of recirculation zones and local velocity variations, which fundamentally differs from classical analytical models. The review by M.A. El-Emam *et al.* (2021) showed that even in relatively simple channels the velocity field was structurally non-uniform and was strongly modified by the presence of solid particles. The non-uniform distribution of velocity over the height of the pneumatic channel established in this article and its effect on the overlapping of test-weight ranges between fractions were, in fact, an experimental confirmation of the consequences highlighted in CFD-DEM studies. Against this background, the use of movable plates in the lower third of the jet generator could be regarded as a simple engineering mechanism for controlling the local velocity field, which was a functional analogue of changing boundary conditions in numerical modelling but did not require substantial complication of the design.

In a number of studies focused on the development of technical means for cleaning grain mixtures from light impurities, the main efficiency criterion was the degree of removal of foreign inclusions. In the study by C. Bracacescu *et al.* (2018), equipment for cleaning and sorting seed mixtures based on the aerodynamic principle was analysed, with attention concentrated on design schemes and regimes that ensured reliable separation of impurities. Similarly, in the work of P. Greyvensteyn *et al.* (2023), the design and testing of a pneumatic aspirator were considered, where the key indicators were grain cleanliness and the energy efficiency of the aspiration system. In contrast to these approaches, the results obtained for the improved aerodynamic separator demonstrated the possibility of combining the functions of cleaning and multifraction calibration: equalising the airflow velocity in the lower zone of the channel not only promoted stable removal of light impurities, but also reduced the overlap of fractions by test weight, which was critical for forming seed material with homogeneous sowing qualities.

Another group of studies focused on changing channel geometry and organising material feed. In the work of S. Kharchenko *et al.* (2021), modelling of aerodynamic separation of a pre-stratified grain mixture in a vertical channel showed that controlled placement of layers of different density at the inlet made it possible to improve separation quality without a substantial increase in energy consumption. In the study by E. Kolankowska *et al.* (2022), it was shown that a conical pneumatic separator for a mixture of buckwheat and wheat provided a smoother change in velocity along the particle trajectory, which had a positive effect both on separation quality and on indicators of sustainable agriculture. Compared with these solutions, improvement of the SAD-4 jet generator did not involve changing the global geometry of the channel or the feeding scheme; instead, local regulation of the cross-section in the lower part of the generator was used. The achieved increase in mean velocity to above 13 m/s and the reduction of differences between zones to 0.3-0.5 m/s made it possible to obtain an effect comparable to geometrically more complex designs, but with minimal intervention in the basic layout of the machine.

Further development of aerodynamic systems has often been associated with combining airflow and centrifugal forces. In the work of S. Stepanenko *et al.* (2025b), the motion of grain material in a combined centrifugal-pneumatic separator was modelled, where enhanced dynamic impacts on the particles made it possible to achieve high separation efficiency, but were accompanied by design complexity and increased energy consumption. Against this background, the improved jet generator, which provided a substantial improvement in the homogeneity of the fractional composition solely through optimisation of the velocity profile in a classical pneumatic channel, represented an alternative direction of modernisation – via fine tuning of the airflow regime rather than the introduction of additional force factors.

Thus, the comparative analysis showed that the results of the study were consistent with general trends in the development of the theory and practice of aerodynamic separation, but at the same time emphasised a specific aspect that remained in the background in most previous works – the influence of the vertical velocity profile on multifraction calibration. Whereas in existing publications the main tools for increasing efficiency were changes in channel geometry, feed organisation or combination with centrifugal fields, the present article demonstrated that even within a serial design, a technically feasible redistribution of airflow in the cross-section could significantly reduce fraction heterogeneity and bring operating regimes closer to the optimum without radical reconstruction of the equipment.

CONCLUSIONS

The components of the feed material for aerodynamic separation differed in their physical and mechanical properties and required different settings of airflow intensity in the working chamber of the separator. Smaller geometric dimensions of a wheat kernel demanded higher airflow velocity compared with kernels having a larger midship cross-sectional area at the same weight. The heavier the kernel, the higher the airflow velocity had to be under equivalent geometric parameters. Differential settings of airflow velocity were therefore dictated by the need to overcome the increasing force of weight. The midship cross-sectional area determined the importance of the position of a particle of the feed components relative to the airflow vector, which affected the energy consumption of the technological process of aerodynamic separation.

Laboratory investigations proved the non-uniform distribution of the airflow generated by the jet generator of the SAD-4 aerodynamic separator in the working separation plane. It was established that, in the vertical plane of the separation air channel, the airflow velocity in the lower third of the jet generator zone was 48-52% lower than in the middle and upper thirds. A small deviation of 7-9% in airflow velocity between the middle and upper zones of the jet generator in the air channel was observed when the fan capacity control lever was set to positions "3", "4" and "5", whereas at positions "1", "2", "6" and "7" the flow velocities were almost identical.

The considerable difference in airflow velocity in the lower zone adversely affected separation quality, particularly the homogeneity of the fractional composition. The presence of kernels with a test weight of 725 g/L in the second fraction was established, while the maximum test weight of this fraction reached 776 g/L, and the third fraction contained test-weight measurements that exceeded some values characteristic of the second fraction. At higher separation intensity, a measurement with a test weight of 761 g/L was detected in the fourth fraction, which exceeded the test weight of 759 g/L in the second fraction. It was found that, when the material feed lever was set to position "1" and the fan capacity lever to position "3", 61% of the entire initial grain mass entered the second fraction, and that, with increasing separation intensity, the mass yield in the fourth fraction increased while the non-uniformity between the third fraction decreased.

The improved design of the jet generator of the aerodynamic separator had flexible characteristics for adjusting airflow intensity in the lower third of the vertical plane of the separation air channel. The use of movable plates in the design provided three fixed positions corresponding to the positions of the fan capacity control lever. The results of laboratory investigations confirmed the effectiveness of the improved jet generator. An increase in airflow velocity in the lower zone of the vertical plane of the air channel by 0.7-5.7 m/s was established when the fan capacity control lever was moved between positions. Owing to the provided adjustment of the improved jet generator design, the mean airflow velocity in the working plane of the separation channel increased by 11.7-20.2% compared with the serial jet generator design. The proposed design implemented the concept of a ballistic trajectory of motion of the components of the initial grain mass due to a difference in airflow velocity of 0.3-0.5 m/s between the zones of the jet generator in the vertical plane of the air channel.

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Оптимізація конструкційних параметрів регулювального модуля повітряного генератора аеродинамічного сепаратора

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Анотація. Отримання якісного посівного матеріалу та продовольчого зерна потребує використання ефективних технологій сепарування. Аеродинамічне сепарування набуло широкого втілення у різних конструкціях обладнання яке призначене для відокремлення легких домішок від вихідної зернової маси та її поділу на однорідні за властивостями фракції. Використання диференційного повітряного потоку забезпечує досить високу 60-70 % ефективність очищення зерна від домішок. Робота була спрямована на дослідження ефективності аеродинамічного сепарування з метою встановлення шляхів покращення якісних показників технологічного процесу очищення та калібрування вихідної зернової маси. Експериментальні дослідження вказали на неоднорідність повітряного потоку у поперечній площині повітряного каналу аеродинамічного сепаратора моделі САД-4. Так, швидкість повітряного потоку у нижній третині площини каналу на 48-52 % менша ніж у верхній та середній площині, між якими неоднорідність потоку повітря становить незначні 7-9 %. Встановлено, що інтенсивність режимів сепарування впливає на якість фракційного складу. За умови максимальних режимних налаштувань за рахунок нерівномірності розподілу повітряного потоку у вертикальній площині неоднорідності фракційного складу збільшується до рівні 61 %. Було запропоновано вирішити наукову проблему збільшення рівня однорідності фракційного складу очищеного зерна шляхом моделювання повітряного потоку у пневматичному каналі аеродинамічного сепаратора відповідно до режимних налаштувань. Запропоновано конструкцію повітряного генератора з механізмом вирівнювання швидкості повітряного потоку у поперечній площині каналу сепарування. Дослідженнями встановлено, що при зміні режимних налаштувань від «1» до «7» інтенсивність повітряного потоку у нижній третині площини каналу змінюється від 1,9 до 12,6 м/с, що на 37-49 % більше ніж у серійного сепаратора. При максимальних режимах сепарування нерівномірність розподілу компонентів вихідної зернової суміші між фракціями знижується до 25-29 %. Встановлена функціональна залежність між інтенсивністю та рівномірністю повітряного потоку у каналі сепарування та однорідністю фракційного складу очищеного зерна

Ключові слова: повітряний режим; відносна швидкість; вихід фракції; швидкість витання; керування потоком повітря

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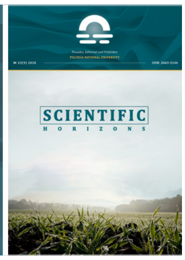

Price volatility in agricultural markets and financial security of enterprises: The role of forward contracts, insurance, and income diversification

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Abstract. The purpose of this study was to determine the impact of price risk management tools on ensuring the financial stability of Ukrainian agricultural enterprises in the context of military and macroeconomic instability. The study methodology combined theoretical and empirical approaches and was based on the methods of generalisation, dynamic and comparative analysis, structural-functional analysis, analysis of financial results and case analysis to assess the financial stability of agricultural enterprises in 2020-2025 based on statistical data on the price environment, financial results, and dynamics of the number of business entities. The results showed that price volatility in 2020-2025 affected the financial stability of agricultural enterprises. The index of sales prices of agricultural products decreased from 107.5% in 2021 to 100.4% in 2022, and in 2023-2025 it recovered only to the level of 101.2-103.0%, which indicated that the unstable price environment remained. Revenues of the agricultural sector increased from UAH 796 billion in 2022 to about UAH 2.4 trillion in 2024, and profits – from UAH 88.6 billion to about UAH 327 billion, but this recovery was mainly provided by large agricultural holdings. In particular, Myronivsky Hliboproduct and Kernel have growth indicators Earnings Before Interest, Taxes, Depreciation and Amortization in 2023-2024, it correlated with the active use of forward contracts and exchange-traded hedging instruments, while Astarta showed a stabilising effect of contracts due to the maintenance of cash flows in the sugar segment despite the fall in world prices. Thereby, from 2021 to 2025, 3,416 agricultural enterprises stopped operating, which reflected the high financial vulnerability of small and medium-sized farms. The practical importance of the study lies in the fact that these results can be used by agricultural enterprises, financial managers, and analysts to select effective tools for managing price risks

Keywords: hedging; liquidity; debt burden; cash flows; risks

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INTRODUCTION

Increasing instability of global commodity markets, increasing frequency of price shocks, and complicating logistics and financial conditions for the functioning of agricultural businesses vastly increase risks to the financial stability of enterprises. Fluctuations in prices for agricultural products directly affect the predictability of cash flows, the level of liquidity, the ability to service debt obligations and form investment resources, which in the context of military and global challenges becomes systemic. In the absence of effective price risk management mechanisms, enterprises become more vulnerable to loss of profitability and financial balance, even if production volumes are maintained.

The dominance of external shocks, financial risks, and unstable market conditions causes increased vulnerability of agricultural enterprises to loss of stability and deterioration of financial results, which stimulated scientific interest in economic security issues at the level of business entities. Yu. Mykhnovetsky (2024) made a major contribution to the research of this subject, which focused on the systemic nature of economic security of agricultural enterprises, identified key threats and justified the role of state regulation in creating favourable conditions for stable business functioning. In the results of the study, it was proved that the financial component of security is closely related to the risks of price fluctuations, military uncertainty, and limited opportunities for state support, and the effectiveness of protective mechanisms largely depends on management decisions at the enterprise level.

The growth of financial losses, logistics disruptions, and instability of export flows during the period of military transformations has increased the vulnerability of agricultural enterprises to the deterioration of their solvency and financial stability. These questions were investigated by A. Vasilyev and V. Galenko (2022), concentrating on assessing the financial security of enterprises under martial law and identifying key risk factors. The results showed the determining influence of inflationary pressures, currency fluctuations, rising costs and export restrictions on financial indicators, and the use of Strengths, Weaknesses, Opportunities, Threats (SWOT)- and Political, Economic, Social, Technological (PEST)-analysis allowed systematising the main threats and directions of stabilisation of enterprises' activities. O. Prokopyshyn and V. Dranus (2025) considered financial and credit collateral as an integrated system, combining credit mechanisms, accounting procedures, and analytical management tools. The authors proved that the scale of the enterprise determines the structure of available sources of financing: large companies work more efficiently with banks and international loans, while small and medium-sized farms focus on preferential programmes, agricultural receipts, and cooperative forms of attracting resources, and the integration of accounting with analytics reduces the debt burden and increases liquidity control.

The uncertainty of the external environment, the growth of financial risks and the complexity of choosing strategic decisions make it difficult to ensure the stability of agricultural enterprises. These aspects were investigated by L. Kostyrko *et al.* (2024), focusing on shaping a financial strategy in the face of uncertainty based on a comprehensive risk assessment. As a result, a system of risk indicators, a combination of SWOT-, PEST-, and scenario analysis, in addition to an approach to choosing strategic alternatives, accounting for the impact of risks on the profitability, liquidity, and market value of enterprises, was proposed. D. Pylypenko *et al.* (2025) identified economic threats and mechanisms for neutralising them through government support tools, credit programmes, business diversification, and the introduction of digital solutions. The authors proved that currency instability and rising borrowing costs directly affect the liquidity and investment capacity of enterprises, while concessional lending and international financial initiatives partially reduce this pressure.

In the context of a full-scale invasion, enterprises operate with increased macroeconomic instability, destruction of logistics chains, limited access to financial resources and the growth of multi-vector risks that directly affect their solvency and sustainability. These questions were investigated by N. Sytnyk and D. Polovko (2024), who viewed the financial security of the enterprise as a dynamic system capable of adapting to the turbulent environment of wartime, systematised key threats to financial stability and also proposed an integral methodological approach to its assessment, in view of liquidity, capital structure, efficiency, and quality of financial management.

High price volatility, asymmetry of market information, and limited opportunities to neutralise risks greatly complicate the financial decision-making of agricultural producers in conditions of uncertainty. These aspects were examined by M. Dyha and V. Dyha (2024), focusing on the use of hedging instruments to manage price risks, in particular, forward, futures contracts and options, proved their ability to stabilise cash flows, reduce the impact of volatility, and increase the predictability of financial results. In the results of the paper, it is proved that the development of the derivatives market and exchange infrastructure creates prerequisites for reducing price fluctuations and increasing the financial stability of business entities, while pointing out the low level of practical use of hedging in Ukraine due to institutional, information, and regulatory restrictions. The instability of income of agricultural enterprises in the context of climate change, military operations, and fluctuations in world prices determines the need to rethink approaches to the formation of financial results, which is reflected in the works of L. Kalachevska and

S. Lukash (2025), which systematised the factors influencing profitability, justified the role of diversification, digitalisation, and expansion of sales markets, and also proposed scenario modelling of income under various market and climatic conditions.

The relationship between price volatility, the use of hedging instruments, insurance, contractual, and credit mechanisms, and the financial stability of enterprises remains insufficiently disclosed in scientific research. The study aimed to substantiate the role of price risk management tools in strengthening the financial stability of agricultural enterprises. The study identified the following tasks to achieve this goal: analyse the impact of market price volatility on the financial stability and profitability of agricultural enterprises; investigate the role of contractual mechanisms for fixing prices and income diversification in reducing financial risks and stabilising cash flows of agricultural enterprises.

MATERIALS AND METHODS

This study has a complex theoretical and empirical nature and covered the time frame of 2020-2025, since this period includes the pre-crisis stage of functioning of the agricultural sector of Ukraine, the phase of sharp growth in price and macroeconomic instability in 2022, and the period of adaptation of enterprises to military, currency, and monetary shocks in 2023-2025, which allowed tracing the transformation of financial stability in various economic regimes. In the theoretical stage of the study, the theoretical foundations of financial stability of agricultural enterprises in a risky environment were determined, particularly financial stability as a dynamic economic category that can change under the influence of price volatility, seasonality of cash flows, capital structure, and management decisions. For this purpose, the method of theoretical generalisation and analysis of scientific approaches was applied, which enabled the formation of a conceptual basis for research based on the study by I.V. Dvornyk (2020). Further, key internal and external factors of the financial vulnerability of agricultural enterprises were identified. For this purpose, a structural and functional analysis was used, which enabled the distinction between internal factors (capital structure, liquidity, and cash flow management) and external factors (price volatility, currency fluctuations, monetary policy, and military risks). The application of this method aimed to explain the mechanisms of financial instability formation and its differentiated impact on enterprises of different scales (Pakhucha *et al.*, 2021; State Statistics Service of Ukraine, 2025).

The study also considered the role of risk-based management in ensuring the financial stability of enterprises. For this purpose, the analysis of financial results was applied, which allowed assessing the impact of management decisions on the ability of enterprises to adapt to financial shocks. In particular, the aggregated financial results of agricultural enterprises were analysed (Opendatabot, 2025), along with the role of digitalisation of financial management. Special attention is paid to the use of the Systems Applications and Products in Data Processing Suite Fourth generation High-Performance Analytic Appliance (SAP S/4HANA) system by Kernel (2024) and MHP (n.d.). At the empirical stage, an assessment of the financial stability of agricultural enterprises in conditions of price instability was conducted. For this purpose, the methods of dynamic and comparative analysis of sales price indices of agricultural products for 2020-2025 (MinFin, 2025a) were applied, enabling the assessment of changes in the price environment and its impact on the profitability of enterprises. Similar methods were used to analyse the average annual exchange rate of the National Bank of Ukraine (n.d.), changes in the number of operating entities (Dynamics of opening..., 2025) and key values of the discount rate of the National Bank of Ukraine in 2020-2025 (Minfin, 2025c) to assess the impact of currency and monetary factors on the financial vulnerability of the agricultural sector.

Within the framework of the study, tools for reducing financial risks of agricultural enterprises were identified based on a comparative case analysis of the activities of MHP, Kernel, and Astarta. For MHP, revenue and expenditure parts of operations, export orientation, margin indicators and Earnings Before Interest, Taxes, Depreciation and Amortisation (EBITDA) were analysed (MHP in 2024..., 2025). Chicago Mercantile Exchange and Chicago Board of Trade futures instruments, along with the dynamics of EBITDA were used for Kernel (2024). For Astarta (2025), the impact of falling prices and the stabilising effect of contract mechanisms on financial results was evaluated. Based on the comparative method, contractual price fixing mechanisms were generalised according to the criteria of the share of contractual operations, contract types, pricing basis, key effect, and role in financial security. The limitation of this study was that its results are interpreted within the period of 2020-2025 and specific conditions of military, currency, and price instability, which determine the contextual dependence of the conclusions obtained.

RESULTS

Theoretical foundations of the financial stability of agricultural enterprises in a risky environment. Financial stability of agricultural enterprises is one of the key prerequisites for their stable functioning and development in the conditions of increased uncertainty inherent in the modern economic environment. In contrast to the static approach, in which financial stability is considered as a fixed state of the balance of assets and liabilities, in scientific research, it is increasingly interpreted as a dynamic economic category. The variability of external and internal conditions of agricultural enterprises, cyclical production, seasonality of cash flows, price volatility for products and resources, in addition to the influence of macroeconomic and military factors, can be considered due to this approach. The dynamic nature of financial stability is manifested in the ability of agricultural enterprises not only to maintain solvency and liquidity in the short term but also to adapt to structural shifts, crisis phenomena, and long-term shocks without losing production potential. Financial stability in this context is formed as a result of constant interaction between income, expenses, sources of financing, investment decisions, and risk management mechanisms. It is not a level that is achieved once and for all, but changes depending on market conditions, the availability of financial resources, the effectiveness of management decisions and the ability of the enterprise to respond to instability. The specifics of agricultural production determine the special dynamics of financial stability. The seasonality of revenues, the time lag between expenditures and revenues, and the dependence of operating results on natural and climatic conditions and world prices for agricultural products result in uneven cash flows. In such circumstances, financial stability becomes adaptive and requires the use of tools that ensure the equalisation of financial flows, reduce income volatility, and maintain an appropriate level of liquidity throughout the entire production cycle (Dvornyk, 2020).

As a dynamic economic category, financial stability is closely related to the risk tolerance of agricultural enterprises. It reflects their ability to counteract financial risks, in particular, price, credit, currency and production risks, and minimise the negative consequences of their implementation. Strengthening financial stability involves actively applying risk management tools, diversifying income sources, using insurance and contract mechanisms, and increasing financial flexibility, in addition to optimising the capital structure or reducing the debt burden. In the context of global transformations and military challenges, the financial stability of agricultural enterprises is becoming increasingly strategic. It serves as the basis for ensuring the continuity of reproduction processes, maintaining investment activity, and preserving competitiveness. Thus, the consideration of financial stability as a dynamic economic category provides for a comprehensive assessment of the state of agricultural enterprises, addressing the time aspect of financial processes, and making more reasonable management decisions aimed at strengthening their financial security in the long term. Financial vulnerability of agricultural enterprises is formed under the influence of a complex of internal and external factors that interact with each other and increase the risk of destabilisation of cash flows, liquidity, and solvency. The specifics of agricultural production determine the increased sensitivity of enterprises to fluctuations in the economic environment, which makes their financial stability largely dependent on the ability to adapt to multi-vector threats (Davydenko *et al*., 2024).

The key internal factors of financial vulnerability include the capital structure of agricultural enterprises. A high share of borrowed resources in financing activities, especially short-term loans, increases the debt burden and exacerbates the risks of loss of solvency in the face of rising interest rates or lower incomes. The low return on invested capital, which is typical for some agricultural enterprises, limits the possibility of self-financing and the formation of reserves necessary to compensate for financial shocks. An additional factor is an inefficient cost structure, particularly high energy and material consumption in production, which increases the cost of production and reduces the financial flexibility of enterprises. Cash flow management issues have a major impact on financial vulnerability. Uneven revenues throughout the production cycle, delays in payments to contractors, and poor payment discipline lead to a shortage of working capital during the off-season. A limited level of income diversification and a focus on a narrow list of crops or sales markets increase the dependence of financial results on market fluctuations. Thereby, fragmented digitalisation of financial processes and insufficient use of analytical tools reduce the quality of management decisions and complicate early diagnosis of financial risks (Pakhucha *et al*., 2021).

External factors of financial vulnerability of agricultural enterprises are systemic in nature and are often not subject to direct control by business entities. One of the determining factors is price instability in the agricultural and resource markets, which causes fluctuations in income and expenses and complicates financial planning. Inflationary processes, currency fluctuations, and changes in monetary policy directly affect the cost of credit resources, imported materials, and financial results of enterprises. A separate place among external factors is occupied by military risks and disruption of logistics chains, which limit export opportunities, increase transport costs, and reduce the predictability of cash flows. Climate change and the increasing frequency of extreme weather events worsen production risks and increase the likelihood of financial losses. Institutional factors, such as instability of state support, limited access to insurance mechanisms, and imperfect financial infrastructure, further increase the vulnerability of agricultural enterprises (Ahres *et al.*, 2025).

The aggravation of military and macroeconomic shocks has greatly increased the importance of risk-based management as a key tool for ensuring the financial stability of agricultural enterprises. After 2022, financial risks in agricultural production were transformed from episodic to systemic, which is confirmed by an increase in the share of unprofitable enterprises. In 2023, more than 50% of agricultural firms ended the year with losses, which was the result of military damage, logistics gaps, and a sharp increase in production costs. Despite this, among large and medium-sized enterprises in 2024-2025, the share of unprofitable ones stabilised at the level of 22-26%, indicating a partial adaptation of the sector through management and financial decisions (State Statistics Service of Ukraine, 2025). The risk-based approach involves systematic identification of financial threats, monitoring their dynamics, and implementing mitigation tools. Liquidity and working capital indicators were especially vulnerable. In 2022, current liquidity decreased in 55% of medium-sized and large agricultural enterprises, while rapid liquidity – in 49%, which was due to an increase in short-term liabilities and a working capital deficit. However, the share of enterprises with sufficient current liquidity increased from 13% to 19%, highlighting the role of internal financial management and state support. The correlation between liquidity and profitability remained weak (0.15-0.42), which confirms the need for both financial injections and management changes (Dragan *et al.*, 2023).

The financial results of agricultural enterprises show an asymmetric adaptation to risks. In 2020-2021, the sector made a record net profit (UAH 238.8 billion in 2021), but in 2022-2023, profitability decreased by 50-60%. Therewith, in 2024, a recovery at the expense of large agricultural holdings took place: MHP (n.d.), Kernel (2024), LNZ Group provided a total profit of UAH 19.92 billion. This demonstrates the effectiveness of large-scale risk-based strategies, diversification, and access to financial instruments (Opendatabot, 2025). High price volatility remains a critical factor in financial instability. In 2022, fluctuations in wheat and corn prices reached 50-60% per annum, which drastically complicated income forecasting. Under such conditions, hedging and insurance instruments become of strategic importance, but their use remains limited: in 2025, only about 4% of acreage (968 thousand hectares) is insured, while in the countries of the EU this figure exceeds 60%. This demonstrates the incompleteness of risk-based infrastructure in agricultural production (MinFin, 2025b).

Digitalisation of financial processes is an important component of risk management. In Ukraine, Enterprise Resource Planning (ERP) systems and financial analytics are widely used mainly by large agricultural holdings. Thus, Kernel and MHP use SAP S/4HANA and integrated ERP solutions for budgeting, inventory management, liquidity control, and scenario risk analysis (MHP Holding implements..., 2021). The ERP implementation rate among large enterprises reaches 70-90%, while medium-sized farms show only 10-20% coverage, and small farms – less than 5%, limited to basic Excel tools. This creates a structural gap in the ability of enterprises to manage financial risks and explains the different rate of recovery of their financial stability. Consequently, risk-based management is a fundamental element of ensuring the financial stability of agricultural enterprises rather than an auxiliary one. Its effectiveness is determined by a combination of financial instruments, insurance protection, digital solutions, and management competencies, which is clearly manifested in conditions of military and price instability.

Assessment of the financial stability of agricultural enterprises in conditions of price instability. The financial results of Ukrainian agricultural enterprises in 2020-2025 were formed in the context of sharply increasing price volatility, which was combined with military, currency, and logistics shocks. Figure 1 displays the dynamics of sales price indices of agricultural products in Ukraine in 2020-2025 (data for March of each year), which allows assessing changes in the price environment of the agricultural market in the context of macroeconomic instability and military challenges.

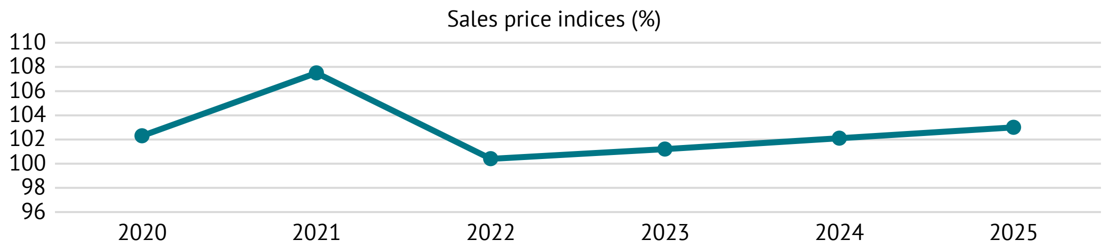

***Figure 1**. Agricultural sales price indices for 2020-2025*

***Source:** compiled by the authors based on MinFin (2025a)*

The highest level of the sales price index in March was recorded in 2021 (107.5%), which reflected a favourable price environment and high demand for agricultural products in the domestic and foreign markets. The lowest index value was observed in 2022 (100.4%), which was a consequence of the start of a full-scale invasion, the destruction of logistics chains, export restrictions, and growing market uncertainty. In 2023-2025, price indices showed a gradual recovery in the range of 101.2-103%, but did not reach the pre-crisis level of 2021, which indicates the persistence of increased price instability and its deterrent impact on the financial results of agricultural enterprises. The currency factor had a powerful impact on the formation of the hryvnia revenue of export-oriented agricultural enterprises. Figure 2 shows the dynamics of the average annual exchange rate of the hryvnia to the US dollar in 2020-2025, which characterises changes in the currency conditions of the agricultural sector.

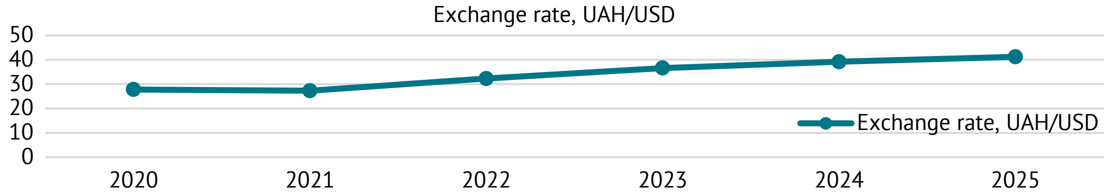

***Figure 2**. Average annual exchange rate of the hryvnia to the US dollar in 2020-2025*
***Source:** compiled by the authors based on Minfin (2025d)*

During the period under study, the exchange rate of the hryvnia to the US dollar was characterised by relative stability in 2020-2021, after which it acquired a stable upward trend. The lowest exchange rate value for the period was recorded in 2021 – UAH 27.3/USD, which corresponded to the pre-crisis state of macroeconomic equilibrium. The highest level of the exchange rate was observed in 2025 – 41.2 UAH/USD, which was a consequence of military risks, inflationary pressures, and deepening structural imbalances in the economy. In general, the growth of the hryvnia exchange rate against the US dollar by more than 50% in 2020-2025 partially offset the decline in dollar prices for exporters, also leading to an increase in the cost of imported resources and increased currency and financial risks for agricultural enterprises.

The financial results of Ukrainian agricultural enterprises in 2022-2024 were formed against the background of remarkable structural changes in the sector itself, manifested in the dynamics of income and profitability and the number of operating business entities. Between 2021 and 2025, 8,644 agricultural companies were registered in Ukraine, pointing to the relative adaptability of the sector to crisis conditions. The highest business activity was recorded in 2021, when 2,678 new enterprises were created, which corresponded to a favourable price environment and high profitability of agricultural production in the pre-war period. Since the start of the full-scale invasion in 2022, the number of new registrations has dropped to 1,558 businesses, reflecting growing financial uncertainty, loss of some production capacity, and deteriorating access to working capital. Already in 2023, the agricultural sector showed signs of partial recovery: 1,697 new agricultural enterprises were registered, and in 2025 – another 869, which indicates a gradual recovery of business activity even if military risks remain. In parallel with the processes of opening enterprises, the opposite trend was also observed – an increase in the number of business stoppages. During 2021-2025, 3,416 agricultural enterprises were closed in Ukraine, with the largest number of shutdowns occurring in 2021 (1,070 companies) and 2024 (685 companies). In 2025, another 536 agricultural enterprises stopped operating, which indicates the continued financial vulnerability of some entities, primarily small and medium-sized farms (Dynamics of opening..., 2025).

Such dynamics of entrepreneurial activity are closely related to the financial results of the sector. In 2022, the income of the agricultural business amounted to UAH 796 billion, and the profit – UAH 88.6 billion, in 2023, the income increased to UAH 920.9 billion, but the profit decreased to UAH 65.8 billion, which reflected an increase in costs and a decrease in marginality. In 2024 alone, against the background of a sharp increase in revenues to about UAH 2.4 trillion, the sector's profit recovered to about UAH 327 billion, which was mainly due to the results of large agricultural holdings. The combination of an increase in the number of closures of enterprises with record financial performance of individual companies signals an increase in the asymmetry of financial stability within the agricultural sector and confirms that price fluctuations and macroeconomic shocks have a differentiated impact depending on the scale and financial viability of enterprises (Ukraine's agricultural sector..., 2025). An important factor that reinforced these imbalances was the tight monetary conditions that determined the cost of credit resources and enterprises' access to financing. Figure 3 shows the dynamics of the National Bank of Ukraine discount rate in 2020-2025, which is a key monetary tool for influencing the cost of credit resources, inflation expectations and financial behaviour of enterprises, in particular, in the agricultural sector.

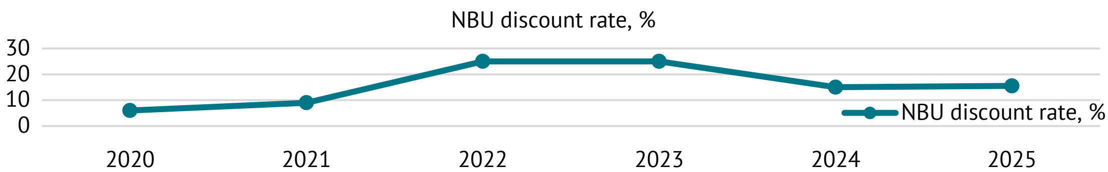

***Figure 3**. Key values of the National Bank of Ukraine discount rate for plotting (2020-2025)*
***Source:** compiled by the authors based on the MinFin (2025c)*

The lowest level of the National Bank of Ukraine discount rate for the analysed period was recorded in 2020 – 6%, which corresponded to a soft monetary policy in the pre-crisis period. In 2022-2023, the rate reached a maximum value of 25%, reflecting the National Bank of Ukraine ‘s response to a full-scale war, an inflationary surge and currency risks. In 2024-2025, there was a gradual easing of monetary policy with a rate cut to 15-15.5%, but its level remained drastically higher than before the war. This indicates the persistence of tight financial conditions that limited the access of agricultural enterprises to credit resources and increased their financial vulnerability, especially when combined with price and currency instability. The results show that price volatility in agricultural markets in 2020-2025 seriously affected the financial security of enterprises, but its effect was realised in cooperation with currency, monetary, and military shocks. Price fluctuations combined with the devaluation of the hryvnia and tight credit conditions increased liquidity risks and uneven financial results between large agricultural holdings and small and medium-sized farms. In turn, enterprises that had access to income diversification tools, export channels, and financial reserves demonstrated a higher ability to adapt to unstable price conditions.

Tools for reducing financial risks of agricultural enterprises. In 2022-2025, Ukrainian agricultural enterprises operated in an environment where price volatility was combined with military export restrictions, logistics reformatting, and currency fluctuations, which increased the risk of cash flow gaps and margin losses. Under such conditions, contractual price fixing mechanisms (forwards, long-term export transactions, flexible pricing formulas with deferred fixing and basic allowances) acquired the role of “market neutralisation” of risks: they transferred some of the uncertainty from the spot market to a managed contract space, where the enterprise can plan volumes, supply schedule, cost structure, and working capital requirements. Comparative analysis of three large companies (MHP, Kernel, Astarta) demonstrates different contractual hedging configurations due to differences in business models. For MHP, simultaneous control of revenue and expenditure parts is critical: the company generated 59% of export revenue in 2022 (EU, UK, Middle East), which means that it depends on external demand conditions and contract discipline of international markets (Tarasovsky, 2022). MHP reduces sensitivity to fluctuations in feed prices through vertical integration: up to 99.9% of feed needs in 2025 are covered by its own grain, while purchasing forward programmes (grain and oilseeds) and models of delayed price fixing (“advance now – price according to the formula/market later”) allow smoothing the risk of peak purchase prices. For partners, such contracts combine an element of financing (prepayment) and flexibility of fixing, which reduces the likelihood of disruption of deliveries in seasonal “bottlenecks” (MHP is developing…, 2025). On the sales side, MHP does not disclose the exact share of sales at fixed prices compared to spot prices, but the revenue structure itself (export dominance) logically enhances the role of long-term export transactions as a tool for revenue stabilisation. The effect of this configuration was reflected in the recovery of operating results: EBITDA in 2023 was 4,445 million (margin ≈15%), and in 2024 – EB 566 million (margin ≈19%), which is consistent with the thesis that the combination of longer sales contracts and control of feed costs reduces the “price amplitude” of cash flows (MHP in 2024…, 2025).

For the Kernel, contract logic is more “market-financial”: the company operates as a major grain exporter and processor, so the key is to manage price risk through forwards and exchange-traded instruments. Kernel sells about 50% of its grain through forward contracts; according to the company’s position, this share supports the ability to consistently export approximately 4-8 million tonnes of grain annually. The forward programme is integrated into Open Agribusiness: counterparties are offered prepayment and pre-financing, which strengthens control over the resource base and logistics, in addition to “fixing” the price/formula. Forward pricing is based on free on Board (FOB) or Cost, Insurance and Freight, considering logistics and margins, and fixing is possible in flexible mode; in addition, Kernel (2024) uses hedging through Chicago Mercantile Exchange/Chicago Board of Trade futures and options, combining the stock exchange base with premiums (Black Sea FOB) as a specific “basis of origin”. Such a scheme is important precisely in the war period, when basic costs (logistics/insurance/routes) become an independent source of volatility and can “eat away” at the gains from rising stock market prices. In financial terms, these instruments correlate with the stabilisation of results: EBITDA in 2023 was USD 381 million, and in 2024 it increased to USD 466 million (+22%). However, insurance coverage of crops in the company is estimated as limited (≈5-15% of the area), that is, contract hedging acts as the main “first barrier” against price shocks, supplemented by diversification of processing (oilseeds), but it is the contract component that sets the predictability of grain revenue and disciplines the export schedule.

Astarta represents the third model, where contract mechanisms are “tied” to the specifics of the product and the value chain. The company uses long-term contracts primarily in the sugar segment: annual export agreements for extra-high-quality sugar with key partners, which create more predictable sales even with fluctuations in world prices. In terms of crop production, Astarta (2024) maintains long-term relationships with grain producers and applies partner financing in UAH, and forward agreements for grain and sugar beet to manage risks for raw materials. In 2022-2023, the company experienced pressure from military and logistics factors and falling prices (a decrease in the range of -11%.-38% for individual items), which was reflected in the dynamics of EBITDA (a decrease of approximately 23% in 2022 and 6% in 2023). In 2024, the stabilising effect of contracts was manifested due to an increase in sugar sales volumes (+40% to 396 thousand tonnes) and maintaining profitability even with a decrease in "market" prices: EBITDA per ton of sugar was about 60 euros (against >200 euros in 2023), which indicates a change in the margin profile and the importance of fixed/structured transactions for maintaining cash flow. Thus, for Astarta (2025), contracts perform not only the function of "price insurance" but also the function of stabilising the sales channel for products with higher added value and more predictable demand. Table 1 summarises the comparative characteristics of the use of contract price fixing mechanisms in the companies under study.

***Table 1**. Comparative characteristics of contract price fixing mechanisms in MHP, Kernel, and Astarta*

Criterion	MHP	Kernel	Astarta
Share of sales/purchases under contracts	≈59% of revenue (export)	≈50% grain	Mainly sugar and raw materials ≈50%
Main type of contracts	Long-term, index-linked, forwards	Forwards + Chicago Mercantile Exchange futures	Long-term + forwards
Pricing basis	EU/Middle East contracts	Chicago Mercantile Exchange + FOB Black Sea	Fixed export prices
Key effect	Margin stabilisation	Reducing income volatility	Easing price downturns
Role in financial security	Cost control	Hedging market risks	Cash flow support

***Source:** compiled by the authors based on Y. Tarasovsky (2022), Kernel (2024), Astarta (2025), MHP in 2024 increased net profit by 1.4%, EBITDA - by 27% with revenue growth of 0.8% (2025)*

It can be concluded that contractual price fixing mechanisms play a key role in stabilising the income of agricultural enterprises, but their effectiveness largely depends on the company's business model. For MHP, they are integrated into a vertically closed value chain and provide cost control, for Kernel, they are a central tool for hedging price and logistics risks, while for Astarta, they perform an auxiliary function in combination with product diversification. Together, this confirms that contractual mechanisms are not a universal solution, but if adapted to the business structure, they notably increase the financial security of enterprises in conditions of price volatility.

In 2022-2025, price volatility in agricultural markets became one of the critical risk factors for the financial security of enterprises, but its impact was greatly modified by the use of risk management tools. A comparative analysis of MHP, Kernel, and Astarta cases showed that contractual price fixing mechanisms allow transforming market uncertainty into a manageable financial parameter, reducing the amplitude of income fluctuations and ensuring the predictability of cash flows. Therewith, the effectiveness of such instruments is asymmetric and depends on the business model of the enterprise, the level of vertical integration and the combination of contract hedging with income diversification and risk insurance. In general, the results confirm that in military and post-crisis conditions, it is the integrated use of forwards, long-term contracts, and a diversified income structure that is a key prerequisite for maintaining the financial stability of agricultural enterprises in conditions of high price volatility.

DISCUSSION

Price volatility in the agricultural sector is one of the key factors of economic uncertainty affecting the stability of production, the financial stability of agricultural enterprises, and the functioning of food markets. Research focuses on various levels of price instability analysis – from global and national markets to individual segments of the agricultural economy and enterprises. Comparative analysis of this study and a paper of D. Hou and X. Wang (2024) showed the commonality of initial assumptions about the functioning environment of the agricultural sector, which was characterised by increased risk, price instability, and the impact of macroeconomic and climate shocks. In both approaches, insurance and contractual mechanisms were considered instrumental for reducing the financial vulnerability of agricultural producers. The logic of the analysis differed substantially: while the current study emphasised the financial stability of enterprises and an empirical assessment of the effectiveness of forward contracts, insurance and income diversification based on financial indicators, D. Hou and X. Wang concentrated primarily on the institutional and technological dimension of Agricultural Insurance development, highlighting the role of InsurTech in improving risk assessment, tariff formation, and loss settlement.

A similar complementarity was observed in comparison with the study by M. Bonato *et al.* (2024). Both studies were based on the recognition of price volatility as a key source of financial risks in the agricultural sector. While M. Bonato *et al.* considered volatility primarily as an object of quantitative forecasting, using high-frequency data and Heterogeneous Autoregressive model of Realized Volatility (HAR-RV) models to assess its dynamics, this study interpreted an economic factor that directly affected cash flows, liquidity, and financial stability of enterprises. As a result, the focus shifted from the accuracy of the forecast to the practical effectiveness of risk management tools. The change in the scale of the analysis was even more pronounced compared to the study conducted by R.T. Djamar and D. Evelin (2025). The authors of this paper analysed the impact of global shocks after 2022 through the prism of Indonesia's national food security, focusing on production diversification and innovation as tools for reducing import dependence. However, in this study, the same shocks were interpreted from the standpoint of the micro level – as a source of financial instability of individual agricultural enterprises, which required the use of contract and insurance mechanisms to mitigate price risks.

A similar difference between the macro and micro levels was observed in comparison with the work of L. Hao and L. Ki-Seong (2024). In both publications, price volatility was recognised as a systemic risk exacerbated by external shocks. However, L. Hao and L. Ki-Seong viewed it as a result of economic policy uncertainty at the national level, applying econometric models to identify temporal variability of effects, while the present study focused on practical financial consequences for agricultural enterprises and the possibilities of stabilising their cash flows. Spatial measurement of volatility was central for the study by A. Theresia *et al.* (2025), which paid close attention to interregional spill over effects and transmission of price shocks in Indonesia. In contrast, spatial aspects were secondary in this study, giving way to an analysis of the internal financial stability of enterprises and the role of hedging and insurance instruments.

A similar shift in focus was observed when compared with the paper of M.R. Matondang *et al.* (2023), where food price volatility was viewed primarily through the prism of macroeconomic stability and inflationary risks using Autoregressive Conditional Heteroskedasticity/Generalized Autoregressive Conditional Heteroskedasticity models. In this study, the same price fluctuations were analysed as a factor of financial vulnerability at the enterprise level, which led to a different set of management conclusions. Non-linearity and regime volatility, which were the focus of X. Zheng *et al.* (2025), also interpreted differently. X. Zheng *et al.* concentrated on identifying price dynamics modes and interregional spillover effects using Markov-Switching Vector Autoregression (MS-VAR)-models, while in the current study, these characteristics were considered primarily as a source of financial risks for agricultural enterprises that needed practical neutralisation mechanisms. A critical macro-financial perspective was inherent in the study authored by M. Venegas *et al.* (2024), where price volatility was interpreted as a consequence of the financialisation of agri-food markets and the activity of derivatives and index funds. Instead, the present study did not analyse these processes directly, but focused on how businesses can adapt to existing volatility through a combination of contract and insurance instruments. Compared to the findings of Y. Chen and J. Tang (2024) regarding the impact of financialisation and speculation on food security at the global level, this study offered a different logic of analysis – focused on microeconomic mechanisms for maintaining the financial stability of agricultural enterprises in an environment of high price volatility.

The significance of price volatility as a threat to food security was a common starting point for both this study and L.H. Lambert *et al.* (2025). Authors interpreted price volatility mainly through the prism of spatial and infrastructural organisation of markets, proving that the development and density of road networks can mitigate price fluctuations. In turn, in this study, the focus shifted from infrastructure factors to the financial behaviour of agricultural enterprises, where volatility was considered as a source of internal financial vulnerability, which required the use of contractual and insurance mechanisms to stabilise cash flows. A similar difference in the level of analysis was observed in comparison with the work of E.M. Kacperska *et al.* (2025). Both studies recognised that the full-scale invasion and associated trade uncertainty were a powerful trigger for increased volatility in grain markets. However, authors focused on the macro-level dynamics of European wheat and maize markets, analysing the stabilisation potential of the Black Sea grain initiative using econometric models. In this study, these same price shocks were interpreted because of their impact on the financial stability of agricultural enterprises, where the key role was played not by political agreements, but by the ability of businesses to adapt through contractual, insurance and diversification instruments.

The expansion of the analytical framework to financial markets was characteristic of the study by K. Yan and H. Yu (2024), which demonstrated how stock market volatility is transmitted to the agricultural credit sector through investor sentiment channels. This macro-financial approach underlined the systemic nature of risks and the complexity of forecasting cash flows at the industry level. This study focused on the consequences of the sources of financial shocks for individual agricultural enterprises, where stabilisation was achieved through the practical use of hedging, insurance, and income diversification tools. Another dimension of systematic price volatility was revealed in the paper of X. Zhuang *et al.* (2025), which reviewed the transmission of energy shocks to grain markets in China and the United States through logistics costs and biofuel demand. In this approach, volatility was formed as a result of inter-market interaction at the global level. Instead, in the present study, these inter-market processes were not the central object of analysis. The main focus was on how agricultural enterprises can reduce the negative impact of already established price instability on their own financial stability through contract and insurance mechanisms. Summarising the results of the comparative analysis, it can be concluded that most studies agree on the recognition of price volatility as a systemic risk for the agricultural sector and food security, but substantially differ in explaining its sources and coping mechanisms. In contrast to macro-level, infrastructure or financial-market approaches, this study concentrates on the microeconomic dimension of the problem, proving that the financial stability of agricultural enterprises is largely determined by the effectiveness of using contract, insurance, and diversification instruments.

CONCLUSIONS

As a result of the study, it was established that price volatility in agricultural markets in 2020-2025 became one of the main factors of financial vulnerability of enterprises, especially in the context of a combination of military, currency, and monetary shocks. Analysis of agricultural sales price indices showed a sharp deterioration in the price environment in 2022 (100.4%) after the peak level of 2021 (107.5%), and further recovery in 2023-2025 (101.2-103.0%) remained unstable and did not reach pre-war values. This confirmed the continued high level of uncertainty and limited predictability of the income of agricultural enterprises. The financial results of the agricultural sector of Ukraine in 2022-2024 showed a major asymmetry in adaptation to price shocks. In 2022, the income of the agricultural business amounted to UAH 796 billion, and the profit – UAH 88.6 billion; in 2023, the income increased to UAH 920.9 billion, but the profit decreased to UAH 65.8 billion due to rising costs and falling margins. Only in 2024, there was a notable recovery in financial results: the sector's revenue increased to about UAH 2.4 trillion, and profit – to UAH 327 billion, which was primarily due to the activities of large agricultural holdings. The parallel growth in the number of closed enterprises (3,416 in 2021-2025) indicates the continued high financial vulnerability of small and medium-sized farms.

The study showed that risk management tools, primarily forward and long-term contracts, income diversification, and partly insurance, play a key role in reducing the negative impact of price volatility. Comparative analysis of MHP, Kernel, and Astarta cases demonstrated that the use of contractual mechanisms allows transforming market uncertainty into a manageable financial parameter, stabilising cash flows, and reducing the amplitude of fluctuations in financial results. In particular, the use of forward contracts for 59% of MHP and 50% of kernel sales volumes and the integration of exchange-traded hedging instruments correlated with EBITDA growth in 2023-2024, even in unfavourable market conditions. It was determined that the low level of development of insurance coverage (about 4% of acreage in 2025) and the limited implementation of digital financial solutions in small and medium-sized enterprises reduce the overall sustainability of the agricultural sector. Thus, the results of the study confirm that in military and post-crisis conditions, the financial security of agricultural enterprises depends not only on market conditions but above all on the ability to combine contractual, diversification, and management tools to neutralise price risks and ensure long-term financial stability. The prospects for further research are related to the analysis of the transformation of price risk management mechanisms in the post-war period and the assessment of the long-term impact of contract and diversification strategies on the financial stability of agricultural enterprises.

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CONFLICT OF INTEREST

None.

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Волатильність цін на сільськогосподарських ринках та фінансова безпека підприємств: роль форвардних контрактів, страхування та диверсифікації доходів

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Анотація. Метою цього дослідження було визначити вплив інструментів управління ціновими ризиками на забезпечення фінансової стабільності українських сільськогосподарських підприємств в умовах воєнної та макроекономічної нестабільності. Методологія дослідження поєднувала теоретичні та емпіричні підходи та базувалася на методах узагальнення, динамічного та порівняльного аналізу, структурно-функціонального аналізу, аналізу фінансових результатів та аналізу конкретних випадків для оцінки фінансової стійкості сільськогосподарських підприємств у 2020-2025 роках на основі статистичних даних про цінове середовище, фінансові результати та динаміку кількості суб'єктів господарювання. Результати показали, що волатильність цін у 2020-2025 роках вплинула на фінансову стійкість сільськогосподарських підприємств. Індекс цін реалізації сільськогосподарської продукції знизився зі 107,5 % у 2021 році до 100,4 % у 2022 році, а у 2023-2025 роках відновився лише до рівня 101,2-103 %, що свідчить про збереження нестабільного цінового середовища. Доходи аграрного сектору зросли з 796 млрд гривень у 2022 році до близько 2,4 трлн гривень у 2024 році, а прибутки – з 88,6 млрд гривень до близько 327 млрд гривень, але це відновлення було забезпечено переважно великими агрохолдингами. Зокрема, «Миронівський хлібопродукт» та «Кернел» мають показники зростання прибутку до вирахування відсотків, податків, амортизації та зносу у 2023-2024 роках, що корелює з активним використанням форвардних контрактів та біржових інструментів хеджування, тоді як «Астарта» продемонструвала стабілізуючий ефект контрактів завдяки збереженню грошових потоків у цукровому сегменті, незважаючи на падіння світових цін. Таким чином, з 2021 по 2025 рік припинили роботу 3416 сільськогосподарських підприємств, що відображало високу фінансову вразливість малих та середніх фермерських господарств. Практичне значення дослідження полягає в тому, що ці результати можуть бути використані сільськогосподарськими підприємствами, фінансовими менеджерами та аналітиками для вибору ефективних інструментів управління ціновими ризиками

Ключові слова: хеджування; ліквідність; боргове навантаження; грошові потоки; ризики

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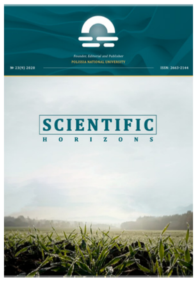

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Expression of concern: “Use of contraceptives in cats with ovarian and uterine pathology”

Повідомлення про занепокоєння щодо статті “Застосування протизаплідних засобів кішкам із патологією яєчників та матки”

This note concerns the article “Use of contraceptives in cats with ovarian and uterine pathology” by O. Chekan, A. Rokochyi, O. Kysterna, Yu. Musiienko, and I. Levchenko published in Scientific Horizons, 2024, volume 27, No. 2, pages 9-18, DOI: https://doi.org/10.48077/scihor2.2024.09. After publication, the journal received a detailed critique raising concerns about the correctness of some citations, the adequacy of the methodological description and the strength of the conclusions regarding the use of megestrol acetate in cats. In accordance with COPE guidelines, the editorial board has initiated an investigation, including a request for clarification from the authors and an independent expert assessment. Until this process is completed, readers are advised to interpret the findings of the article with caution. A further editorial decision (correction, retraction or no further action) will be communicated in due course.

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