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Productivity, ecological plasticity and stability of winter bread wheat (*Triticum aestivum* L.) cultivars across different agroecological zones of Ukraine

Abstract. Winter bread wheat (*Triticum aestivum* L.) is the principal cereal crop in Ukraine and plays a crucial role in national food security and grain production. As climate change intensifies, evaluating the adaptability of newly developed cultivars under contrasting agroecological conditions has become increasingly important. The present study aimed to assess the productivity, ecological plasticity, and stability of winter bread wheat cultivars grown in the Steppe, Forest-Steppe, and Polissia zones of Ukraine. Thirty cultivars listed in the State Register of Plant Varieties Suitable for Dissemination in Ukraine were evaluated during the 2023/24 and 2024/25 growing seasons within the network of experimental sites of the Ukrainian Institute for Plant Variety Examination. Grain yield, thousand-grain weight, plant height, protein content, and wet gluten content were determined, while ecological plasticity and stability were evaluated using the Eberhart-Russell method. The Forest-Steppe provided the most favourable conditions for crop productivity, with an average grain yield of 8.45 t/ha, whereas the lowest mean yield (6.34 t/ha) was recorded in the Steppe. Among the cultivars studied, 'LG TOMYOL' produced the highest average grain yield (8.28 t/ha). Intensive-response cultivars included 'LG TOMYOL', 'Rozumnytsia Odeska', 'Ratatui', and 'Vira Odeska' ($b_i > 1.20$), whereas 'Avatar Kharkivskyi', 'Gravis', 'Polova Krasunia', and 'Nahoroda' combined broad adaptability with high stability ($b_i \approx 1.0$). Grain yield showed a moderate positive correlation with thousand-grain weight ($r = 0.48$) but was negatively correlated with protein content ($r = -0.55$). In most cultivars, the highest protein and wet gluten contents were obtained under Steppe conditions. Overall, the results emphasise the importance of genotype × environment interaction in determining both grain productivity

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and quality and identify cultivars with high adaptive potential for cultivation across the major agroecological zones of Ukraine

Keywords: grain yield; adaptability; "genotype × environment" interaction; ecological plasticity; regression coefficient; grain quality

INTRODUCTION

Winter bread wheat (*Triticum aestivum* L.) is among the most important cereal crops worldwide and remains a strategic component of agricultural production in Ukraine. It provides high-quality grain, contributes significantly to the country's export capacity, and plays a key role in maintaining national food security. Ongoing climate change, characterised by increasing air temperatures, irregular precipitation patterns, more frequent droughts, and other extreme weather events, has intensified the need for cultivars capable of maintaining stable productivity across contrasting soil and climatic environments. Under these conditions, evaluating the productivity, ecological plasticity, and stability of modern cultivars has become a major objective of contemporary wheat breeding, cultivar assessment, and the official plant variety testing system.

The adaptation of wheat to changing climatic conditions has attracted considerable attention from both Ukrainian and international researchers. According to R. Abramoff *et al*. (2023), integrating adaptive cultivars with improved crop management practices can substantially mitigate the negative impact of climate change on cereal production. Likewise, S. Mousavi *et al*. (2024) reported that agroclimatic modelling combined with machine learning techniques enables reliable prediction of wheat yield potential, although the accuracy of such predictions depends largely on incorporating genotype-specific responses. Alongside predictive approaches, considerable effort has been devoted to understanding the physiological basis of yield formation. X. Huang *et al*. (2020) demonstrated that wheat productivity is closely associated with the coordinated accumulation of carbon and nitrogen throughout the growing season, whereas S. Impa *et al*. (2020) showed that elevated night-time temperatures interfere with grain development and adversely affect grain quality. Collectively, these studies indicate that the response of modern cultivars to abiotic stress is strongly influenced by their genetic background. Considerable emphasis has also been placed on analysing the interaction between genotype and environment. V. Popovic *et al*. (2020) showed that the Additive Main Effects and Multiplicative Interaction (AMMI) model together with the Genotype and Genotype × Environment interaction biplot (GGE-biplot) provides a more reliable assessment of cultivar adaptability than comparisons based solely on mean grain yield. Similar conclusions have been reached in Ukrainian studies. N. Kononiuk & O. Prysiazhniuk (2025) reported that cultivars with superior productivity do not necessarily exhibit the highest level of stability across environments, while L. Holyk *et al*. (2026) demonstrated that combining ecological plasticity and stability parameters offers a more comprehensive evaluation of modern winter cereal cultivars.

A separate area of current research is devoted to studying the impact of agronomic factors on the realisation of crop cultivar potential. O. Bahatchenko & L. Tsentylo (2026) reported that the effectiveness of modern cultivation technologies is determined by the interaction between cultivar characteristics, weather conditions, and agronomic practices. Similar conclusions were reached by J. Liu *et al*. (2023), O. Barabolia & R. Yanovskyi (2025), and S. Vlasenko & S. Zaiets (2026), who demonstrated that optimisation of sowing date is one of the key factors in achieving high and stable yields of modern cultivars. The comprehensive evaluation of modern cultivars has become particularly important in view of the rapid renewal of the varietal composition of wheat in Ukraine. H. Dutova *et al*. (2026) reported that growing conditions significantly affect both grain yield and the quality characteristics of newly developed cultivars, confirming the necessity of their ecological evaluation.

Despite the considerable number of recent studies, most have focused on individual aspects of climatic or agronomic effects or on grain productivity and quality separately, whereas comprehensive studies of modern winter bread wheat cultivars in terms of grain yield, ecological plasticity, and stability within the framework of the official plant variety testing system of Ukraine remain limited. The aim of this study was to conduct a comprehensive evaluation of modern winter bread wheat cultivars in terms of grain yield, ecological plasticity, and stability across the principal agroecological zones of Ukraine in order to determine their adaptive potential and to provide recommendations for their effective cultivation under different growing conditions.

LITERATURE REVIEW

One of the major challenges facing modern agriculture is the increasing variability of climatic conditions, which has a significant impact on the yield potential of cereal crops. For winter bread wheat, temperature conditions, moisture availability and their interaction during specific phases of organogenesis are particularly important. It is precisely these factors that determine the intensity of growth processes, the efficiency of photosynthesis, the accumulation of plastic substances and the formation of yield components. In this regard, a significant number of studies in recent years have been devoted to predicting the impact of climate change on crop productivity and identifying ways to adapt the current range of varieties. Based on the results of a global analysis, R. Abramoff *et al.* (2023) found that, without the implementation of adaptation measures, climate change will lead to a significant reduction in the yields of major agricultural crops in most regions of the world. At the same time, the authors demonstrated that the use of adapted varieties, optimisation of sowing dates and improvements in cultivation techniques can significantly reduce the negative impact of climatic factors. The researchers place particular emphasis on the need to combine breeding and agronomic solutions, as it is precisely this integrated approach that yields the greatest adaptive effect.

Unlike global forecasting models, S. Mousavi *et al.* (2024) applied modern methods of machine learning and agroclimatic modelling to spatially forecast wheat yield shortfalls. The authors found that combining climatic indicators with soil characteristics allows crop productivity in specific regions to be predicted with high accuracy. At the same time, they emphasised that the accuracy of forecasts depends to a large extent on taking into account varietal characteristics, as different genotypes respond differently to the same environmental conditions. Similar conclusions were reached by M. Solodushko *et al.* (2024), who investigated the patterns of productive moisture accumulation during the autumn growing season of winter wheat in the Northern Steppe of Ukraine. The researchers demonstrated that soil moisture reserves in autumn determine the intensity of plant growth prior to the onset of winter and significantly influence subsequent yield formation. This confirms that, even within a single climatic region, weather conditions in individual years can substantially alter the extent to which the potential of modern cultivars is realised.

Alongside research into climatic factors, considerable attention is being paid to the physiological mechanisms of yield formation. X. Huang *et al.* (2020) demonstrated that wheat yield is directly dependent on the coordination of carbon and nitrogen accumulation processes throughout the growing season. The authors showed that a disruption of this balance leads to a reduction in grain weight, lower yield and a deterioration in the grain's processing properties. Thus, the impact of adverse weather factors manifests itself through changes in the physiological processes that determine the intensity of yield formation. A more detailed analysis of the effects of temperature stress was presented by S. Impa *et al.* (2020). In their study, they found that an increase in night-time temperatures alters the synthesis of starch, proteins and lipids in the grain, resulting in a reduction in grain weight and a deterioration in its quality parameters. At the same time, the researchers noted that the response of different varieties varied, indicating significant genotypic differences in resistance to high temperatures. Overall, the available evidence indicates that the productivity of winter bread wheat is governed by the combined influence of climatic, soil, and physiological factors. Furthermore, recent studies increasingly emphasise the interactions among these factors rather than their individual effects, providing a stronger scientific basis for assessing the adaptability of new cultivars across contrasting environmental conditions.

Increased ecological variability has led to a change in the criteria for evaluating modern wheat cultivars. Whilst maximum yield has traditionally been the primary criterion, the ability of a cultivar to maintain a stable yield across a wide range of growing conditions is becoming increasingly important. This is precisely why the "genotype × environment" interaction has become one of the central areas of contemporary breeding and cultivar research. Of fundamental importance to the development of this field are the studies by V. Popovic *et al.* (2020), who used AMMI and GGE-biplot models to analyse the response of wheat varieties to changes in growing conditions. The authors found that cultivars with the same average yield can differ significantly in terms of their adaptation to the environment. Some genotypes are characterised by broad ecological plasticity and are able to make effective use of favourable conditions, whilst others demonstrate relatively stable performance regardless of the ecological background. Consequently, assessing average yield alone does not allow for an objective determination of a cultivar's production value. Further development of this concept is reflected in the work of N. Kononiuk & O. Prysiazhniuk (2025), who investigated the ecological plasticity and stability of wheat cultivars under the conditions of the Forest-Steppe region of Ukraine. The authors demonstrated that high plasticity ensures the maximum realisation of productive potential under favourable conditions, but is accompanied by greater sensitivity to abiotic stresses. In contrast, stable cultivars are characterised by lower inter-annual yield variability, although their maximum potential may be slightly lower. These findings highlight the importance of the combined use of plasticity and stability parameters in the evaluation of modern cultivars. Similar conclusions were reached by L. Holyk *et al.* (2026), who applied plasticity and stability indices to evaluate cultivars of winter cereals. The researchers found that the most promising genotypes for production are those that combine high yield with low variability in performance under different growing conditions. The authors also emphasised that a reliable assessment of adaptability is only possible based on the results of multi-ecological trials covering a wide range of natural and climatic conditions.

Of particular interest are the results of the study by H. Dutova *et al.* (2026), which assessed the impact of environmental factors on the yield and grain quality of new winter bread wheat cultivars. The authors found that growing conditions significantly influence both yield levels and the development of key grain quality parameters. Moreover, the contribution of environmental factors often exceeded that of the genotype, which once again confirms the need for multi-ecological testing of cultivars prior to their widespread introduction into production. Overall, analysis of contemporary research indicates that the effectiveness of modern cultivars is determined primarily by the nature of their interaction with environmental conditions. Consequently, comprehensive assessment of productivity, ecological plasticity, and stability within multi-environment testing systems has become a priority in modern cultivar evaluation, providing the most reliable basis for assessing the adaptive potential of new cultivars.

Alongside the genetic characteristics of cultivars and environmental conditions, crop management practices are an important factor influencing the productivity of winter bread wheat. Contemporary research indicates that the effectiveness of agronomic practices depends not only on their intensity but, above all, on their compatibility with the biological characteristics of a particular cultivar and the prevailing growing conditions. Consequently, the concept of adaptive crop management, which integrates the genetic potential of a cultivar with an appropriate system of agronomic practices, has gained increasing attention. O. Bahatchenko & L. Tsentylo (2025) found that both grain yield and seed quality characteristics of modern cultivars are significantly influenced by a combination of agronomic factors. The authors demonstrated that optimising crop management practices promotes a more complete realisation of the productive potential of different genotypes and improves yield stability. In subsequent research, O. Bahatchenko & L. Tsentylo (2026) showed that seed productivity results from the complex interaction between weather conditions, the biological characteristics of the cultivar, and crop management practices. According to the authors, the application of standardised management systems without considering cultivar-specific characteristics considerably restricts the potential productivity of modern cultivars.

An important element of cultivation technology is the sowing date, which determines the conditions for autumn plant development, overwintering and the formation of the yield structure. O. Barabolia & R. Yanovskyi (2025) found that changes in sowing dates and sowing rates significantly affect both yield and grain quality indicators in the Northern Steppe of Ukraine. Similar results were obtained by S. Vlasenko & S. Zaiets (2026), who demonstrated that optimal sowing dates ensure the formation of a more productive agrophytocenosis and facilitate the full realisation of the potential of promising cultivars in the southern regions of Ukraine. Summarising the results of long-term international research, J. Liu *et al.* (2023) concluded that optimising sowing dates is one of the most effective tools for increasing not only yield but also its stability under various weather conditions. Consequently, the response of cultivars to sowing dates is strongly genotype-dependent and must be taken into account during their practical application.

Equally important are the issues of fertilisation systems and preceding crops. G. Hospodarenko *et al.* (2020) demonstrated that balanced nitrogen nutrition ensures both an increase in yield and an improvement in the bread-making properties of the grain. However, S. Burykina *et al.* (2026) showed that the effectiveness of fertilisation varies significantly depending on the preceding crop, the weather conditions of the year and the plants' moisture supply. Similar patterns were noted by A. Siroshtan *et al.* (2021), who established a significant influence of preceding crops and sowing dates on the yield and sowing quality of the seed quality of winter wheat. In turn, V. Polovyi *et al.* (2025) demonstrated that even within a single natural and climatic zone, different farming systems have varying effects on yield formation, and their effectiveness depends to a large extent on varietal characteristics. Thus, recent research confirms that cultivation techniques cannot be considered in isolation from the biological properties of the cultivar. The full expression of a cultivar's productive potential depends on the adjustment of agronomic practices to both its genetic characteristics and the environmental conditions in which it is grown.

In addition to increasing grain yield, maintaining consistently high grain quality has become a major objective, as grain quality determines both its nutritional significance and its technological suitability for processing. Numerous studies have shown that quality traits are governed by the combined effects of genotype, environmental conditions, and crop management practices. I. Pravdziva *et al.* (2023) established significant correlations between yield and key grain quality indicators for cultivars and breeding lines of *Triticum aestivum* L. The authors concluded that promising cultivars must be evaluated based on a complex of interrelated traits, as selection based solely on yield does not guarantee the production of high-quality grain. A study by K. Kostecka *et al.* (2024) showed that cultivars differ significantly in terms of the milling properties of their grain, and that varietal characteristics largely determine the efficiency of its technological utilisation. At the same time, N. Vasylenko *et al.* (2026) demonstrated that the expression of key grain quality indicators varies significantly under the influence of phenotypic components of productivity and nitrogen nutrition. This highlights the need to assess grain quality across a wide range of growing conditions, rather than solely on the basis of average indicators.

A comprehensive approach to the evaluation of modern cultivars is implemented within Ukraine's state variety testing system. In accordance with the current regulations of the Ukrainian Institute for Plant Variety Examination (2023), the evaluation of new cultivars is carried out across a network of testing stations located in various agroecological zones of the country, which ensures the objective determination of their agronomic value. At the same time, the Ministry of Economy, Environment and Agriculture of Ukraine (2026) reports the continuous expansion and renewal of the winter bread wheat cultivar portfolio, creating an ongoing need for the systematic assessment of newly developed genotypes before their widespread adoption. However, an analysis of the current scientific literature shows that most published studies focus on individual aspects of productivity, grain quality or the influence of agronomic and climatic factors. Far fewer studies provide a comprehensive assessment of modern cultivars in terms of yield, ecological plasticity and stability, based on the results of multi-ecological trials. Furthermore, most Ukrainian studies have been conducted within specific natural and climatic zones, which limits the possibility of an objective comparison of the adaptive potential of cultivars across the whole territory of Ukraine. Consequently, despite significant progress in studying the adaptability of modern winter bread wheat cultivar, there remains a need for a comprehensive assessment of their productivity, ecological plasticity and stability within the state cultivar testing system, using a unified research methodology across different agroecological zones of Ukraine. It is precisely this approach that makes it possible to objectively assess the "genotype × environment" interaction, determine the adaptive potential of new cultivars and formulate scientifically sound recommendations regarding their dissemination and effective use under modern farming conditions.

MATERIALS AND METHODS

The study involved 30 winter bread wheat (*Triticum aestivum* L.) cultivars: 'Ivanna Poliska', 'Katrusia Poliska', 'Hazda', 'Volodarka Nosivshchyny', 'Aziia plius', 'Valkiriia', 'Gravis', 'Avatar Kharkivskyi', 'Flahman', 'Furiia', 'Ratatui', 'Kollana', 'Blackwit', 'LG TOMYOL', 'Sandman', 'Vinsent', 'Yednannia', 'Polova Krasunia', 'Stelian', 'Lippert', 'Mriia Odeska', 'Vira Odeska', 'Nezlamna', 'Nadiia Odeska', 'Nahoroda', 'Rozumnytsia Odeska', 'Hrafynia Odeska', 'TR Shafranova', 'TR Zelenasta', and 'TR Lazurova', included in the State Register of Plant Varieties Suitable for Dissemination in Ukraine. The study was conducted during the 2023/24 and 2024/25 growing seasons at the network of experimental facilities of the Ukrainian Institute for Plant Variety Examination across three agroecological zones of Ukraine: the Steppe (Dnipropetrovsk, Kirovohrad, and Odesa branches), the Forest-Steppe (Vinnytsia, Sumy, Ternopil, Kharkiv, Cherkasy, Chernivtsi, and Kyiv Specialised branches), and Polissia (Volyn, Zakarpattia, Ivano-Frankivsk, Lviv, Rivne, Chernihiv, and Khmelnytskyi branches). The traits evaluated included grain yield (t/ha), thousand-grain weight (g), plant height (cm), protein content (%), and wet gluten content (%). The soils of the experimental plots were representative of their respective cultivation zones. The accounting plot area was 25 m^2, with a randomised experimental design and four replications. Field experiments were conducted in accordance with the methodological recommendations for the qualification examination of plant varieties for suitability for dissemination in Ukraine, specifically those of the Ukrainian Institute for Plant Variety Examination (2016). Laboratory analyses were performed following the methodology of the Ukrainian Institute for Plant Variety Examination (2023). The study complied with the ethical principles of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (1973).

Statistical analysis of the results was performed using Statistica 10.0 software. To assess the variability of traits, the arithmetic mean (M), standard deviation (SD) and coefficient of variation (CV, %) were determined. Correlations were assessed using Pearson's correlation coefficient. Differences were considered statistically significant at a p-level of ≤0.05. Correlation analysis – to establish relationships between traits; the method of S. Eberhart & W. Russell (1966) – to assess stability: regression coefficient (b_i), variance of deviations (S^2d_i). The growing seasons of 2023/24-2024/25 were characterised by elevated temperatures and an uneven distribution of precipitation. The most unfavourable conditions occurred in the Steppe zone, where a moisture deficit and high air temperatures were observed throughout the spring and summer. In the Forest-Steppe, conditions were relatively favourable for the varieties to realise their productive potential, whilst the Polissia region was characterised by better moisture supply and moderate temperatures. The observed weather conditions had a significant impact on the formation of yield and grain quality indicators for the varieties under study.

A detailed analysis of agrometeorological conditions by growth stage showed that the most critical periods for yield formation were "stem elongation-heading" and "grain filling". In the Steppe zone, a moisture deficit was observed during these very phases in both years (hydrothermal coefficient (HTC) 0.60-0.85), which limited the realisation of the varieties' yield potential. In the Forest-Steppe zone, weather conditions during the heading phase were close to optimal (HTC 1.05-1.25), which ensured the highest yield levels were achieved. At the same time, in the 2024/25 season, a trend towards lower moisture levels was observed during the grain-filling phase, which may have partially limited the yield potential of certain varieties. The Polissia zone was characterised by sufficient and excessive moisture, particularly during the "stem elongation-heading" phase (HTC up to 1.50), which created favourable conditions for plant growth but, at the same time, may have increased the risk of disease development.

RESULTS AND DISCUSSION

Analysis of the study results confirmed the significant influence of soil and climatic conditions on the yield potential of modern winter bread wheat varieties. The most favourable conditions for realising the productive potential of the varieties were found in the Forest-Steppe zone, where the average yield was 8.45 t/ha, whilst in the Polissia and Steppe zones it was lower, at 7.52 and 6.34 t/ha respectively. The results obtained demonstrate the decisive importance of the combination of temperature regime, moisture supply and soil fertility in determining the productivity of the varieties (Fig. 1). The patterns identified are consistent with the findings of R. Abramoff *et al.* (2023), who demonstrated that adapting varieties and cultivation techniques to climate change can significantly reduce yield losses. Similar conclusions were reached by S. Mousavi *et al.* (2024), who showed that the spatial variability in winter wheat yield is largely determined by a complex of agroclimatic factors, whilst A. Krivenko & S. Pochkolina (2021) noted a significant influence of abiotic conditions on the productivity of cereal crops.

The highest mean grain yield was recorded for the cultivar 'LG TOMYOL' (8.28 t/ha), which exceeded the overall trial mean. High productivity was also observed in the cultivars 'Hazda', 'Katrusia Poliska', 'Rozumnytsia Odeska', 'Ratatui', and 'Vinsent'. These findings demonstrate that modern cultivars are capable of effectively expressing their genetic yield potential under favourable agroecological conditions. Similar trends in the productivity of modern winter wheat cultivars were reported by O. Bahatchenko & L. Tsentylo (2025; 2026), who identified agronomic factors as playing a decisive role in the realisation of cultivar yield potential. However, the results of the present study extend these findings by demonstrating that the high productivity of 'LG TOMYOL' was maintained under the contrasting soil and climatic conditions of the three major natural zones of Ukraine. This indicates that, in addition to agronomic practices, the genetically determined ability of a cultivar to realise its yield potential across a wide range of environments is of considerable importance. Thus, the present findings broaden current knowledge of the adaptive potential of newly developed winter bread wheat cultivars and confirm the importance of evaluating them in multi-environment field trials.

The analysis of ecological plasticity and stability demonstrated clear differences in the adaptive behaviour of the evaluated cultivars. Cultivars such as 'LG TOMYOL', 'Rozumnytsia Odeska', 'Ratatui', and 'Vira Odeska' were classified as intensive types because their regression coefficients (b_i) exceeded 1.20, indicating a strong response to favourable growing conditions. By contrast, 'Avatar Kharkivskyi', 'Gravis', 'Polova Krasunia', and 'Nahoroda' combined regression coefficients close to 1.0 with low deviation variance values, reflecting broad ecological adaptability and stable performance across environments. Ecological plasticity and stability were assessed according to the method proposed by S. Eberhart & W. Russell (1966), which remains one of the standard approaches for evaluating cultivar adaptability. The regression coefficient (b_i) varied from 0.643 to 1.284, highlighting the considerable diversity in cultivar responses to environmental variation. The highest values were observed for 'TR Shafranova' (1.284), followed by 'LG TOMYOL' (1.274), 'Vira Odeska' (1.241), and 'Volodarka Nosivshchyny' (1.205), indicating greater responsiveness to improved environmental conditions. In contrast, the lowest regression coefficients were recorded for 'Ivanna Poliska' (0.643), 'Katrusia Poliska' (0.695), 'Nezlamna' (0.720), and 'Hazda' (0.756), suggesting comparatively lower environmental responsiveness. The variance of deviations from regression (S^2d_i) ranged between 0.020 and 0.527, indicating differences among cultivars in the consistency of their responses relative to the linear regression model (Table 1).

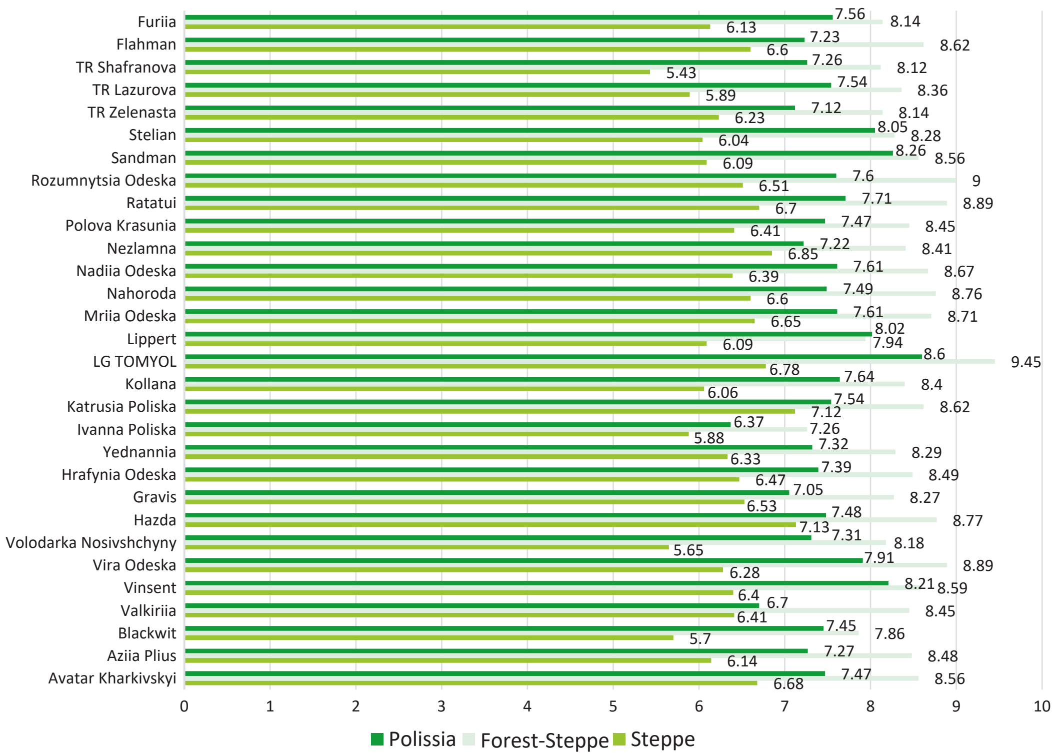

Figure 1. Grain yield of winter bread wheat cultivars according to agroecological zone (mean for the 2023/24 and 2024/25 growing seasons)

Note: $LSD_{0.05}$: Steppe = 0.41; Forest-steppe = 0.40; Polissia = 0.44
Source: compiled by the authors

Table 1. Ecological plasticity and stability parameters of winter bread wheat cultivars

Cultivar	Mean grain yield, t/ha	SD	CV, %	b_i (plasticity)	S^2d_i (stability)
'Avatar Kharkivskyi'	7.57	0.95	12.5	1.02	0.043
'Aziia plius'	7.30	1.19	16.3	1.10	0.020
'Blackwit'	7.00	1.14	16.3	0.80	0.200
'Valkiriia'	7.19	1.05	14.6	1.05	0.474
'Vinsent'	7.73	1.00	12.9	1.18	0.233
'Vira Odeska'	7.69	1.06	13.8	1.25	0.021
'Volodarka Nosivshchyny'	7.05	1.27	18.0	0.72	0.042
'Hazda'	7.79	0.84	10.8	1.18	0.210
'Gravis'	7.28	0.87	12.0	0.98	0.133
'Hrafynia Odeska'	7.45	1.01	13.6	1.08	0.145

Table 1, Continued

Cultivar	Mean grain yield, t/ha	SD	CV, %	b_i (plasticity)	S^2d_i (stability)
‘Yednannia’	7.31	0.98	13.4	1.00	0.100
‘Ivanna Poliska’	6.50	0.70	10.8	0.85	0.051
‘Katrusia Poliska’	7.76	0.77	9.9	1.15	0.114
‘Kollana’	7.37	1.00	13.6	1.12	0.061
‘LG TOMYOL’	8.28	1.37	16.5	1.42	0.074
‘Lippert’	7.35	1.10	15.0	1.15	0.527
‘Mriia Odeska’	7.66	0.85	11.1	1.12	0.037
‘Nahoroda’	7.62	0.89	11.7	1.05	0.099
‘Nadiia Odeska’	7.56	0.94	12.4	1.10	0.059
‘Nezlamna’	7.49	0.82	10.9	1.05	0.165
‘Polova Krasunia’	7.44	1.02	13.7	1.01	0.070
‘Ratatui’	7.77	0.90	11.6	1.28	0.073
‘Rozumnytsia Odeska’	7.70	1.02	13.2	1.31	0.164
‘Sandman’	7.64	1.09	14.3	1.20	0.421
‘Stelian’	7.46	1.12	15.0	1.22	0.456
‘TR Zelenasta’	7.16	0.96	13.4	0.95	0.123
‘TR Lazurova’	7.26	1.08	14.9	1.02	0.173
‘TR Shafranova’	6.94	1.39	20.0	0.68	0.074
‘Flahman’	7.48	1.01	13.5	1.08	0.277
‘Furiia’	7.28	1.05	14.4	1.07	0.133

Source: compiled by the authors

Highly plastic cultivars included ‘LG TOMYOL’ ($b_i = 1.42$), ‘Rozumnytsia Odeska’ ($b_i = 1.31$), ‘Ratatui’ ($b_i = 1.28$), and ‘Vira Odeska’ ($b_i = 1.25$), which expressed their yield potential most effectively under the favourable conditions of the Forest-Steppe. In contrast, the cultivars ‘Avatar Kharkivskyi’, ‘Gravis’, ‘Polova Krasunia’, and ‘Nahoroda’ exhibited b_i values close to unity, indicating broad adaptability. Meanwhile, ‘Volodarka Nosivshchyny’, ‘TR Shafranova’, ‘Blackwit’, and ‘Ivanna Poliska’ were characterised by b_i values below unity, suggesting relatively greater tolerance to unfavourable environmental conditions.

These findings are fully consistent with those of L. Holyk *et al.* (2026), who demonstrated that the combination of high grain yield and stability is one of the principal criteria for the selection of modern cultivars. Similar conclusions were reported by N. Kononiuk & O. Prysiazhniuk (2025), who emphasised the importance of evaluating ecological plasticity to support cultivar zoning recommendations. At the same time, the present study provides a clearer differentiation of cultivars according to their adaptive response under the conditions of the Steppe, Forest-Steppe, and Polissia. In particular, it was shown that high grain yield is not always accompanied by high ecological stability, whereas some genotypes with a slightly lower yield potential exhibit a more predictable response to changes in growing conditions. These findings highlight the importance of the combined use of grain yield, the regression coefficient (b_i), and the deviation variance (S^2d_i) when selecting cultivars.

Thousand-grain weight was strongly influenced by growing conditions. Overall, the trait tended to increase from the Steppe to the Forest-Steppe, followed by stabilisation or a slight decline in Polissia. The most favourable conditions for the formation of large grains were observed in the Forest-Steppe (Fig. 2). The study revealed a clear increase in thousand-grain weight from the Steppe to the Forest-Steppe. The mean values were 39.07 g in the Steppe, 45.40 g in the Forest-Steppe, and 43.72 g in Polissia. The highest thousand-grain weights across all agroecological zones were recorded for the cultivars ‘Volodarka Nosivshchyny’, ‘Gravis’, ‘Katrusia Poliska’, and ‘Yednannia’, whereas ‘LG TOMYOL’, ‘Lippert’, and ‘Ivanna Poliska’ were characterised by lower thousand-grain weights.

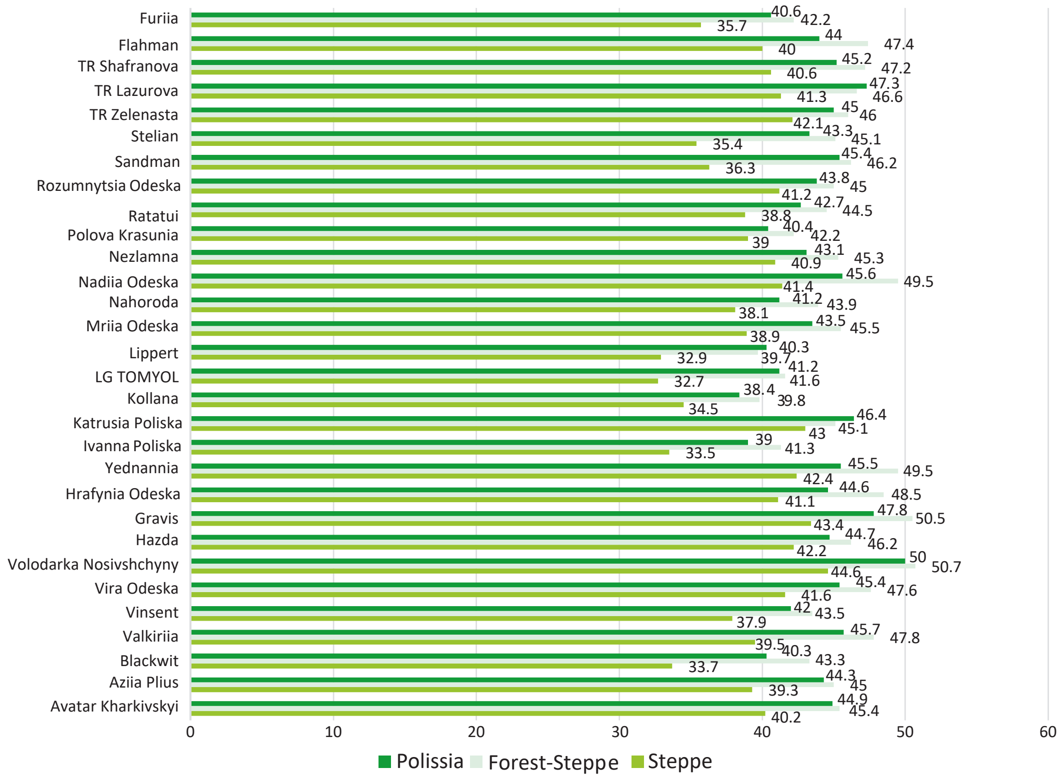

Figure 2. Weight of 1,000 grains of winter bread wheat cultivars by growing region (average for 2023/24-2024/25)

Note: $LSD_{0.05}$: Steppe = 1.25; Forest-Steppe = 1.09; Polissia = 1.01

Source: compiled by the authors

The obtained results indicate a substantial influence of agroecological conditions on the expression of grain size potential and confirm the suitability of using thousand-grain weight as one of the criteria for cultivar selection. These findings are consistent with those reported by O. Bahatchenko & L. Tsentylo (2025), who demonstrated that this trait largely depends on the availability of soil moisture and nutrients during the grain-filling period. Plant height increased progressively from the Steppe to Polissia, where the mean value reached 94.14 cm compared with 88.37 cm in the Steppe. The tallest plants across all agroecological zones were recorded for the cultivars 'TR Zelenasta', 'TR Shafranova', and 'TR Lazurova' (Fig. 3). A similar relationship between moisture availability and plant height was reported by M. Solodushko *et al.* (2024). These authors demonstrated that adequate moisture supply promotes more vigorous stem elongation, whereas moisture deficit under Steppe conditions restricts the linear growth of plants. The present findings confirm the important role of hydrothermal conditions in determining the morphological characteristics of winter bread wheat. Protein and wet gluten contents were also strongly influenced by growing conditions. For most cultivars, the highest grain quality parameters were recorded under Steppe conditions, whereas lower values were observed in the Forest-Steppe and Polissia. This pattern is associated with increased grain yield and the well-known protein dilution effect (Table 2).

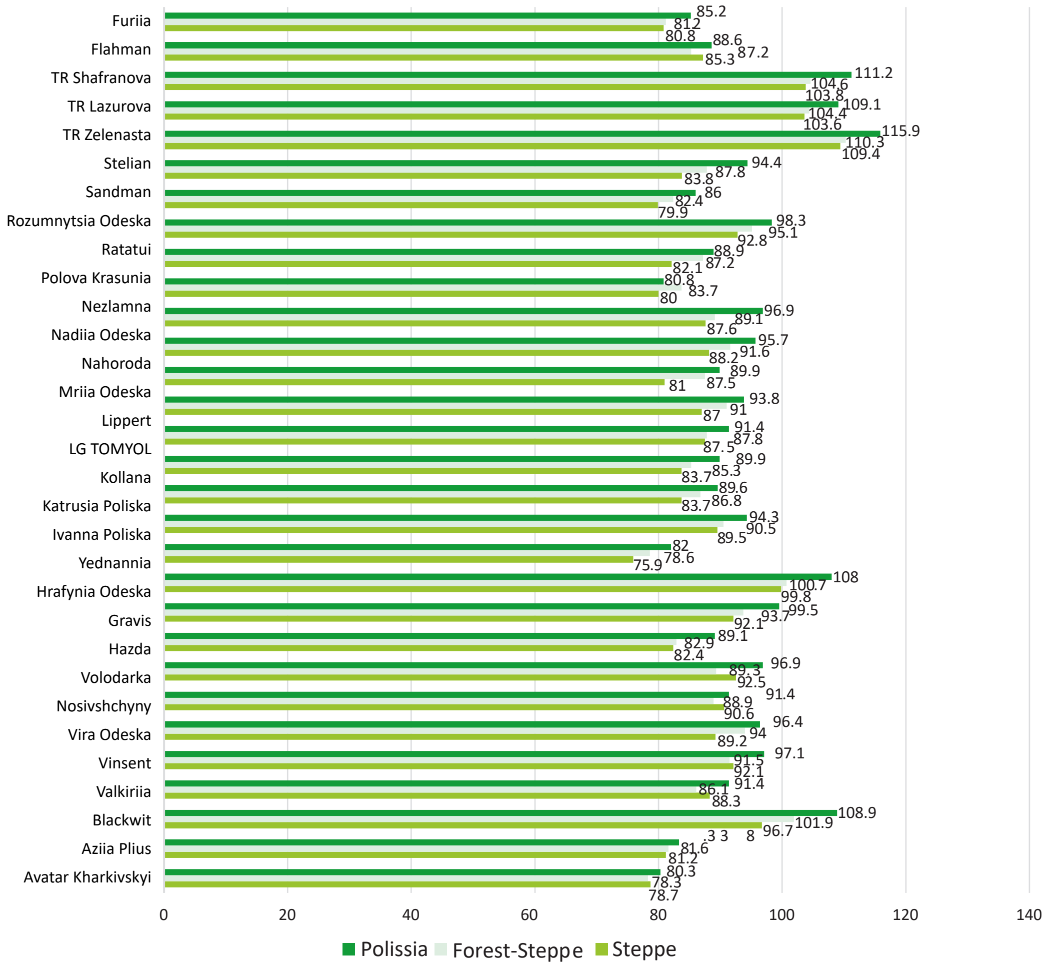

Figure 3. Plant height of winter bread wheat cultivars by growing zone (average for 2023/24-2024/25)

Note: $LSD_{0.05}$: Steppe = 3.01; Forest-Steppe = 2.95; Polissia = 3.41

Source: compiled by the authors

Table 2. Protein and wet gluten contents of winter bread wheat cultivars according to the growing zone (mean for the 2023/24 and 2024/25 growing seasons)

Cultivar	Protein content, %			Wet gluten content, %		
	Steppe	Forest-Steppe	Polissia	Steppe	Forest-Steppe	Polissia
‘Ivanna Poliska’	13.6	13.7	13.4	27.5	27.2	26.6
‘Katrusia Poliska’	13.9	13.3	12.9	29.2	26.7	25.0
‘Hazda’	14.1	12.9	12.7	29.5	24.9	25.0
‘Volodarka Nosivshchyny’	13.5	13.4	13.5	27.8	26.1	26.2
‘Aziia plius’	13.3	12.5	12.7	25.6	24.8	24.5
‘Valkiriia’	14.0	13.0	14.3	28.4	25.6	28.4
‘Gravis’	13.5	12.3	12.6	27.2	23.9	24.7
‘Avatar Kharkivskyi’	13.5	12.8	12.7	26.9	26.6	25.0
‘Flahman’	13.9	12.9	14.0	28.2	25.4	27.5

Table 2, Continued

Cultivar	Protein content, %			Wet gluten content, %		
	Steppe	Forest-Steppe	Polissia	Steppe	Forest-Steppe	Polissia
‘Furiia’	14.3	13.4	13.2	27.7	26.5	26.1
‘Ratatui’	14.5	13.0	12.8	30.0	25.2	24.8
‘Kollana’	13.5	13.0	12.6	27.4	25.7	24.4
‘Blackwit’	13.8	13.4	13.5	28.5	26.8	25.7
‘LG TOMYOL’	13.5	13.1	13.4	26.8	25.8	26.1
‘Sandman’	14.3	12.9	12.8	28.8	25.4	25.1
‘Vinsent’	13.2	12.9	12.7	25.7	25.6	24.5
‘Yednannia’	14.1	13.0	13.1	29.1	25.8	25.8
‘Polova Krasunia’	13.7	13.3	13.1	27.3	26.2	26.3
‘Stelian’	13.8	13.1	12.7	28.5	25.4	24.2
‘Lippert’	13.7	13.2	12.7	27.0	25.9	24.5
‘Mriia Odeska’	14.2	13.1	13.0	28.6	26.1	25.1
‘Vira Odeska’	13.5	12.9	13.2	26.8	26.2	25.7
‘Nezlamna’	13.7	13.2	13.8	27.4	26.7	27.3
‘Nadiia Odeska’	13.5	13.3	13.2	27.1	26.8	26.1
‘Nahoroda’	14.0	13.2	13.0	28.9	26.1	25.0
‘Rozumnytsia Odeska’	14.1	13.1	13.2	28.1	25.3	25.0
‘Hrafynia Odeska’	14.2	13.4	13.8	28.8	26.7	25.9
‘TR Shafranova’	13.5	13.2	13.0	27.3	26.1	25.2
‘TR Zelenasta’	14.5	13.2	13.2	29.1	26.3	26.1
‘TR Lazurova’	13.4	13.4	13.4	27.0	26.5	26.0
Average	13.8	13.1	13.1	27.9	25.9	25.6
Minimum	13.2	12.3	12.6	25.6	23.9	24.2
Maximum	14.5	13.7	14.3	30.0	27.2	28.4
$LSD_{0.05}$	0.36	0.28	0.44	1.07	0.72	0.99

Source: compiled by the authors

For most cultivars, the highest grain quality parameters were recorded under Steppe conditions. The mean protein content reached 13.81%, while the mean wet gluten content was 27.87%, exceeding the corresponding values observed in the Forest-Steppe and Polissia. The cultivars ‘Valkiriia’, ‘Flahman’, ‘Nezlamna’, and ‘Hrafynia Odeska’ consistently exhibited elevated protein and wet gluten contents irrespective of the growing zone. Grain quality characteristics are determined not only by the genetic background of a cultivar but also by growing conditions and agronomic management practices. This is supported by the findings of G. Hospodarenko *et al.* (2020), who demonstrated the decisive influence of nitrogen fertilisation systems on grain yield and bread-making quality. Similar conclusions were reported by S. Burykina *et al.* (2026), who established the significant effects of preceding crops, weather conditions, and fertilisation on grain quality. Furthermore, N. Vasylenko *et al.* (2026) identified relationships between the phenotypic components of productivity and protein and wet gluten contents.

To determine the relationships among the principal agronomically important traits of winter bread wheat cultivars, correlation analysis was performed using Pearson’s correlation coefficient based on the mean values obtained during the 2023/24 and 2024/25 growing seasons across the three agroecological zones of Ukraine (Steppe, Forest-Steppe, and Polissia) (Table 3). The study found that the nature and strength of the relationships between traits depend to a large extent on growing conditions, confirming the important role of the “genotype × environment” interaction.

Table 3. Correlation coefficients among traits of winter bread wheat cultivars across different agroecological zones of Ukraine (2023/24 and 2024/25 growing seasons)

Trait	Grain yield	Thousand-grain weight	Plant height	Protein content	Wet gluten content
Steppe					
Grain yield	1.00	0.41	0.28	-0.52	-0.50
Thousand-grain weight	0.41	1.00	0.32	-0.25	-0.27
Plant height	0.28	0.32	1.00	0.06	0.10
Protein content	-0.52	-0.25	0.06	1.00	0.92
Wet gluten content	-0.50	-0.27	0.10	0.92	1.00
Forest-Steppe					
Grain yield	1.00	0.58	0.34	-0.63	-0.60
Thousand-grain weight	0.58	1.00	0.38	-0.30	-0.33
Plant height	0.34	0.38	1.00	0.04	0.07
Protein content	-0.63	-0.30	0.04	1.00	0.94
Wet gluten content	-0.60	-0.33	0.07	0.94	1.00
Polissia					
Grain yield	1.00	0.47	0.29	-0.44	-0.46
Thousand-grain weight	0.47	1.00	0.36	-0.26	-0.29
Plant height	0.29	0.36	1.00	0.08	0.12
Protein content	-0.44	-0.26	0.08	1.00	0.90
Wet gluten content	-0.46	-0.29	0.12	0.90	1.00

Source: compiled by the authors

Correlation analysis revealed a moderate positive relationship between yield and the weight of 1,000 grains (r = 0.41-0.58), indicating the important role of grain fullness in determining yield. Similar results are reported in the study by I. Pravdziva *et al.* (2023), which established a positive effect of the 1,000-grain weight on the yield of modern wheat cultivars. A negative correlation of moderate strength was found between yield and protein content (r = -0.44...-0.63), as well as between yield and wet gluten contents (r = -0.46...-0.60). A similar pattern is noted by X. Huang *et al.* (2020), who explain it by the "protein dilution" effect, whereby the proportion of protein in the grain decreases as yield increases. The strongest positive correlation was found between protein content and wet gluten contents (r = 0.90-0.94), which is fully consistent with the data from I. Pravdziva *et al.* and confirms the common physiological and biochemical mechanisms underlying the formation of the grain protein-gluten complex.

The results also confirm the importance of optimising cultivation practices. According to O. Barabolia & R. Yanovskyi (2025), sowing dates and seed rates significantly influence both yield and grain quality. Similar results were obtained by S. Vlasenko & S. Zaiets (2026), who demonstrated that the response of modern cultivars to sowing dates depends on their biological characteristics. At the same time, J. Liu *et al.* (2023) demonstrated the importance of selecting optimal sowing dates as one of the key factors in ensuring stable yields under conditions of climate change. The results of these studies confirm the value of a comprehensive assessment of modern winter bread wheat cultivars in terms of yield, grain quality indicators, ecological plasticity and stability. This approach ensures an objective assessment of the cultivar adaptive potential and provides a scientific basis for their effective regionalisation, the improvement of breeding programmes and the enhancement of grain production efficiency under current climate change conditions.

CONCLUSIONS

The study demonstrated a significant influence of soil and climatic conditions on the productivity of modern winter bread wheat cultivars. The most favourable conditions for the expression of their genetic potential were observed in the Forest-Steppe zone, where the mean grain yield reached 8.45 t/ha, whereas the lowest yield (6.34 t/ha) was recorded in the Steppe, confirming the decisive role of agroecological factors in yield formation. Based on the comprehensive evaluation, the cultivar 'LG TOMYOL' produced the highest mean grain yield (8.28 t/ha), exceeding the overall trial mean and demonstrating high productivity with considerable potential for expression under favourable growing conditions. According to the ecological plasticity assessment, 'LG TOMYOL', 'Rozumnytsia Odeska', 'Ratatui', and 'Vira Odeska' were classified as intensive-type cultivars ($b_i > 1.20$), exhibiting the greatest capacity to express their yield potential under improved growing conditions. In contrast, 'Avatar Kharkivskyi', 'Gravis', 'Polova Krasunia', and 'Nahoroda' demonstrated high ecological adaptability and yield stability, indicating their suitability for cultivation across diverse soil and climatic zones of Ukraine.

Correlation analysis revealed a moderate positive association between grain yield and thousand-grain weight (r = 0.41-0.58), indicating that grain size contributes substantially to overall productivity. Conversely, grain yield showed a moderate negative correlation with both protein content (r = -0.44 to -0.63) and wet gluten content, suggesting the well-known trade-off between high productivity and grain quality. These relationships support the need to consider both yield and quality traits simultaneously during breeding and cultivar evaluation rather than focusing on a single characteristic. Taking into account grain yield, ecological plasticity, stability, and the overall performance for agronomically valuable traits, the cultivars 'LG TOMYOL', 'Rozumnytsia Odeska', 'Avatar Kharkivskyi', and 'Gravis' can be regarded as the most promising for practical cultivation and for use in breeding programmes. Their consistently high productivity, combined with favourable adaptive characteristics, indicates a strong capacity to perform reliably across contrasting agroecological conditions in Ukraine. Further research should concentrate on expanding multi-year and multi-location testing of modern winter bread wheat cultivars to provide a more comprehensive assessment of their adaptive performance. The application of advanced statistical approaches for analysing genotype × environment interactions, including AMMI and GGE biplot analyses, would improve the interpretation of cultivar responses under contrasting environments. Additional attention should also be given to evaluating the adaptability of newly developed cultivars under increasingly variable climatic conditions, examining the stability of grain quality traits across different agroecological zones of Ukraine, and integrating multiple agronomic characteristics into a comprehensive assessment of breeding material. Such studies would strengthen the scientific basis for cultivar zoning, support the development of improved breeding programmes, and contribute to more efficient and sustainable cereal production under future climate conditions.

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CONFLICT OF INTEREST

None.

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Продуктивність, екологічна пластичність та стабільність сортів пшениці м’якої озимої (*Triticum aestivum* L.) у різних агроекологічних зонах України

Анотація. Пшениця м’яка озима (*Triticum aestivum* L.) є провідною зерновою культурою України, продуктивність якої значною мірою залежить від взаємодії генотипу з умовами середовища. У зв’язку зі змінами клімату особливого значення набуває оцінювання адаптивності нових сортів у різних агроекологічних умовах. Метою дослідження було оцінити продуктивність, екологічну пластичність і стабільність сортів пшениці м’якої озимої в умовах Степу, Лісостепу та Полісся України. Об’єктом дослідження були 30 сортів пшениці м’якої озимої, занесених до Державного реєстру сортів рослин, придатних до поширення в Україні. Польові дослідження проводили у 2023/24-2024/25 роках на мережі дослідних пунктів Українського інституту експертизи сортів рослин. Оцінювали врожайність, масу 1000 зерен, висоту рослин, вміст білка та сирої клейковини. Екологічну пластичність і стабільність визначали за методом Ебергарта-Рассела. Установлено, що найвищу середню врожайність сформовано в умовах Лісостепу (8,45 т/га), найнижчу – у Степу (6,34 т/га). Найбільш продуктивним сортом був ‘ЛГ ТОМЙОЛЬ’ із середньою врожайністю 8,28 т/га. До сортів інтенсивного типу належали ‘ЛГ ТОМЙОЛЬ’, ‘Розумниця Одеська’, ‘Рататуй’ і ‘Віра Одеська’ (b_i > 1,20), тоді як найбільш стабільними та широкоадаптивними виявилися ‘Аватар Харківський’, ‘Гравіс’, ‘Польова красуня’ та ‘Нагорода’ ($b_i \approx 1,0$). Виявлено позитивний кореляційний зв’язок між урожайністю та масою 1000 зерен (r = 0,48) і негативний – між урожайністю та вмістом білка (r = -0,55). Найвищі показники білка та сирої клейковини формувалися переважно в умовах Степу. Результати дослідження підтвердили значну роль взаємодії «генотип × середовище» у формуванні продуктивності та якості зерна й дали змогу виділити сорти з високим адаптивним потенціалом для вирощування в різних агроекологічних зонах України

Ключові слова: урожайність; адаптивність; взаємодія «генотип × середовище»; коефіцієнт регресії; селекційна цінність; якість зерна