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Evaluation of new winter wheat varieties in diverse environments

M. Nazarenko, V. Horshchar, O. Izhboldin

Dnipro State Agrarian and Economic University, Dnipro, Ukraine

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Dnipro State Agrarian and Economic University,
Serhii Efremov st., 25,
Dnipro, 49600, Ukraine.
Tel.: +38-095-848-53-86.
E-mail:
nik_nazarenko@ukr.net

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Yield stability is largely determined by the ability of varieties and hybrids to withstand unfavorable environmental factors. Multi-environment variety testing is one of the most important approaches for assessing the adaptability, ecological plasticity, and stability of genotypes under contrasting growing conditions. In the present study, the grain yield of 15 winter wheat varieties was analyzed across 17 environments representing the three main natural and climatic zones of Ukraine: the Steppe, Forest-Steppe and Polissia. The aim of the study was to determine the extent to which yield is influenced by genotype, environment, and their interaction, and to identify the most stable and productive forms. Analysis of variance of the yield data showed that 29.0% of the total variability of the trait was attributable to environmental conditions, 44.6% to genotypic differences and 15.2% to genotype × environment interaction. These proportions confirm the determining role of hereditary characteristics of the varietal material, while at the same time demonstrating the substantial contribution of environmental factors and the unequal response of individual genotypes under different growing conditions. The AMMI analysis showed that in the overall structure of yield variability, the leading role belonged to the genotypic component, whose share exceeded both the environmental effect and the contribution of genotype × environment interaction. This distribution of sources of variation indicates a pronounced change in varietal response depending on growing conditions and confirms that, when preparing recommendations for production, it is necessary to consider not only mean yield level but also adaptability parameters. In terms of mean yield, the best-performing varieties among those studied were Pamiati Horlacha, ZU Willem, BHV20GV0009, ZU Shamal and Slava Unavy. Particular attention should also be paid to the variety STK21G, which occupied leading positions in many environments and showed a broad adaptive potential. The highest stability of response was demonstrated by the variety HIATSYNT, which was characterized by minimal sensitivity to changes in environmental conditions, indicating its considerable ecological plasticity. The group of genotypes with relatively high stability also included Zoloto Stepu, Epos, Pamiati Horlacha and Slava Unavy. When both productivity and stability of trait expression are considered simultaneously, the most promising varieties for broad agricultural use are Pamiati Horlacha, Zoloto Stepu, Slava Unavy, HIATSYNT and BHV20GV0009. The zonal analysis made it possible to reveal certain features of varietal adaptation. Under Steppe conditions, represented by Dnipropetrovsk, Kirovohrad and Odesa regions, the best productivity was most often demonstrated by HIMALAYA, Slava Unavy and ZU Shamal. In addition, the variety DARYNA showed pronounced specific adaptation to the drier conditions of this zone. In the Forest-Steppe environments, the most frequent leaders were STK21G, Zoloto Stepu, Atrybut, and ZU Willem, which makes it possible to regard them as valuable genotypes for conditions of moderate moisture availability. In the Polissia zone, a high repeatability among the best-performing varieties was characteristic of Pamiati Horlacha, STK21G, Atrybut, Dnistrianka Odeska and ZU Willem. Kvitoslava and Dnistrianka Odeska should also be considered promising for this zone. In further studies, it would be advisable to focus not only on yield, but also on grain quality and yield structure components in order to more deeply assess the influence of environments and varietal material on the formation of economically valuable traits.

Keywords: cereals; wheat; genotype; environment; AMMI-analysis; grain productivity; adaptability.

Introduction

Stable grain yield formation and the economic efficiency of crop production remain among the key objectives of modern breeding and practical agriculture. For winter wheat cultivars, it is no longer sufficient to demonstrate high productivity potential only under optimal conditions. They are expected to express agronomically valuable traits consistently across environments differing in moisture availability, temperature regime, soil fertility, and overall agronomic background (Abdelghany et al., 2024). Such reliability of performance determines not only the breeding value of a genotype but also the effectiveness of applying modern cultivation technologies (Nazarenko et al., 2023). At the same time, the same variety may perform differently depending on yearly weather conditions, the characteristics of a particular location, and the cropping system used, which makes a deeper analysis of genotype adaptive response necessary (Nazarenko et al., 2022).

One of the main reasons for such inconsistent varietal performance is genotype × environment interaction (GEI). Its essence lies in the fact that the superiority of a given genotype is not constant across all conditions: a variety that performs best in one environment may be inferior in another. For this reason, evaluation based only on mean yield often does not provide a complete picture of the actual breeding and production value of the material, especially in regions with pronounced environmental heterogeneity and increasing climatic instability. Therefore, systematic assessment of breeding and source material across a wide range of environments is a necessary prerequisite for selecting cultivars suitable for practical use in different agroecological niches (Saeidnia et al., 2023). A detailed analysis of GEI helps reduce the likelihood of losing valuable genotypes with specific adaptation and improves the reliability of recommendations for varietal deployment (Gupta et al., 2023).

Various statistical approaches are used in breeding practice to quantitatively describe genotype × environment interaction and to evaluate yield stability. These include regression models, nonparametric procedures, and multivariate analytical methods. Regression-based approaches make it possible to assess the nature of genotype response to changing conditions through the slope of the regression line and the magnitude of deviations from it. Nonparametric methods are useful when the classical statistical assumptions of normality or homogeneity of variance are not met. At the same time, multivariate methods have the advantage of revealing complex patterns that cannot be adequately described by a single parameter, especially when many environments are involved in the analysis (Yan, 2024; Güngör et al., 2024). Among these approaches, the AMMI and GGE biplot models occupy a special place, as they are based on the use of principal components to decompose the structure of GEI (Nirmalaruban et al., 2026). Traditional analysis of variance makes it possible to estimate the overall effects of genotype, environment, and their interaction, but it does not reveal the internal structure of the interaction itself. In contrast, principal component analysis effectively summarizes complex patterns of variability, but it does not directly reflect the main additive effects. It is precisely the combination of these two approaches that forms the basis of the AMMI model, which integrates the advantages of ANOVA and PCA into a single analytical framework (Yue et al., 2025). Within AMMI, the main effects of genotype and environment are evaluated by analysis of variance, while the interaction component is decomposed using the interaction principal component axes (IPCA). This makes it possible to separate stable, reproducible interaction patterns from random noise, thereby substantially increasing the interpretability of the results (Mullualem et al., 2024).

From the standpoint of applied breeding, the results of AMMI analysis are especially important because they allow not only comparison of genotypes by mean yield level, but also determination of the nature of their adaptation. Using this approach, it is possible to identify broadly adapted cultivars that maintain relatively stable positions across environments, as well as specifically adapted forms capable of realizing their full potential only under certain conditions. In addition, AMMI allows the environments themselves to be evaluated in terms of representativeness, contrast, and ability to differentiate genotypes. This creates an opportunity to design the testing network more rationally by selecting the most informative locations and years for breeding evaluation. In regions where contrasting moisture regimes, temperature fluctuations, differences in soil fertility, and specific overwintering conditions are combined, such analytical capability is particularly valuable (Brković et al., 2025; Khoroshun & Nazarenko, 2025).

The relevance of such studies is increasing against the background of current climate change. For winter wheat, short-term but intense heat stress, uneven distribution of precipitation, and disruptions of normal overwintering are becoming increasingly important (Iwańska et al., 2025). In the Steppe and Forest-Steppe zones, these factors often occur in combination: after winter thaws followed by freezing events, tillering nodes may be damaged and shoots weakened; later, plants may face spring moisture deficits that restrict root system functioning, reduce nutrient uptake, and suppress the early stages of stem elongation. This is further complicated by increased susceptibility to diseases, because weakened tissues and uneven crop development create additional risks, especially during warm and humid periods, the frequency of which is rising along with weather variability (Pour-Aboughadareh et al., 2025).

Under such conditions, breeding should be oriented not only toward maximizing yield potential, but also toward reducing the risk of sharp yield fluctuations. Of practical importance is the ability of a genotype to maintain productivity under unstable conditions, when weather scenarios may change abruptly within a single season. Thus, breeding programs should focus on developing cultivars that combine adequate yield potential with resistance to stress factors and with a lower risk of substantial losses in unfavorable years (Mohammadi & Amri, 2022; Nazarenko et al., 2023).

The aim of the present study was to determine to what extent winter wheat grain yield is controlled by the effects of genotype, environment, and their interaction, and to identify forms capable of combining high productivity with stability under contrasting growing conditions. Achieving this goal required not only a quantitative assessment of the contribution of individual sources of variation to yield formation, but also an analysis of how consistently varietal differences were maintained across years and locations, or conversely, whether genotype rankings changed substantially depending on the agroecological background (Urbanaviciute et al., 2024).

Within the framework of this work, primary attention was given to characterizing genotype responses in a multi-environment trial, where each environment represented a specific combination of local soil properties, weather characteristics, and management conditions. This experimental design made it possible to evaluate not only the overall productivity of the varieties, but also the structure of their interaction with the environment. This is especially important because different genotypes may realize their potential in different ways: some perform better under optimal conditions, whereas others remain more even and reliable under stress conditions (Abdelghany et al., 2024).

Accordingly, the study was aimed at identifying two key categories of breeding-valuable material. The first includes broadly adapted genotypes, characterized by relatively stable yields across environments and, consequently, lower production risk. The second includes genotypes with specific adaptation, capable of outperforming other forms under particular conditions and therefore especially valuable for targeted use in specific zones or production systems (Mullualem et al., 2024). Combining the assessment of mean yield level with evaluation of yield stability was necessary in order to improve the scientific validity of breeding selection and the accuracy of regional recommendations for cultivar deployment under conditions of increasing climatic variability.

Materials and methods

The study was carried out on the basis of a multi-environment trial involving 15 winter wheat varieties: DARYNA (Ukraine), BHV20GV0009 (Germany), Zoloto Stepu (Ukraine), HIATSYNT (Germany), Slava Unavy (Ukraine), HIMALAYA (Germany), Trembita (Ukraine), ZU Shamal (Germany), Pamiati Horlacha (Ukraine), ZU Willem (Germany), Kvitoslava (Ukraine), Atrybut (Germany), Epos (Ukraine), STK21G (France) and Dnistrianka Odeska (Ukraine).

The accounting plot area was 20 m², and the experiment was conducted with three replications. The study was performed during 2023–2025. In all cases, black fallow was used as the preceding crop, and agronomic practices were those generally accepted for the respective soil and climatic conditions of the growing zones. The varieties were selected so as to represent, as fully as possible, the main directions in the development of breeding material suitable for introduction under the conditions of Ukraine. The environments were chosen according to the principle of maximum representativeness, taking into account the soil and climatic variability of the country. Grain yield obtained in field trials according to the standard methodology of the State variety testing system was used as the trait under analysis. To evaluate the genotype × environment interaction, the AMMI model (Additive Main Effects and Multiplicative Interaction) was applied, combining analysis of variance for the main effects with principal component analysis of the interaction matrix.

The Steppe zone included Dnipropetrovsk region (E01; 48°51′06.55″ N, 35°25′23.08″ E), Kirovohrad region (E02; 48°18′33.18″ N, 30°16′48.40″ E), and Odesa region (E03; 46°27′21.08″ N, 30°40′06.78″ E). The Forest-Steppe zone was represented by Vinnytsia region (E04; 48°33′14.95″ N, 28°41′34.22″ E), Kyiv region (E05; 49°46′18.96″ N, 30°06′39.92″ E), Sumy region (E06; 50°59′42.38″ N, 34°31′31.33″ E), Ternopil region (E07; 49°27′55.58″ N, 25°32′09.68″ E), Kharkiv region (E08; 49°53′10.15″ N, 36°24′55.17″ E), Cherkasy region (E09; 49°24′17.19″ N, 31°58′48.49″ E), and Chernivtsi region (E10; 48°25′21.34″ N, 25°43′25.96″ E). The Polissia zone comprised Volyn region (E11; 50°30′23.11″ N, 24°56′06.32″ E), Zakarpattia region (E12; 48°32′48.53″ N, 22°25′16.08″ E), Ivano-Frankivsk region (E13; 48°51′28.73″ N, 25°00′57.99″ E), Lviv region (E14; 49°52′50.77″ N, 24°07′04.11″ E), Rivne region (E15; 50°38′02.22″ N, 26°19′51.70″ E), Khmelnytskyi region (E16; 49°26′18.79″ N, 27°02′12.09″ E), and Chernihiv region (E17; 51°35′37.18″ N, 31°17′20.24″ E).

The AMMI model is described by the following equation:

$$Y_{ij} = \mu + G_i + E_j + \Sigma\, \lambda_k\, \alpha_{ik}\, \gamma_{jk} + \varepsilon_{ij},$$

where μ is the overall mean of the trait; G_i is the effect of the i-th genotype; E_j is the effect of the j-th environment; λ_k is the singular value for the k-th principal component; α_{ik} and γ_{jk} are the genotype and environment scores for the corresponding principal component; and ε_{ij} is the random error. For interpretation of the results, the AMMI1 biplot (mean yield vs. IPC1), the AMMI2 biplot (IPC1 vs. IPC2), as well as stability and adaptability parameters were used. Calculations were performed on the basis of the matrix of mean yield values obtained from the three replications.

The yield stability index (YSI) was calculated according to the formula:

$$YSI = RASV + RY,$$

where RASV is the genotype rank according to ASV, and RY is the rank according to mean yield (Y).

All statistical analyses were conducted using Statistica 12.0 (Tibco, Palo Alto, USA). The effects of genotype (variety), active substance, concentration, and their interactions were evaluated by factorial analysis of variance (ANOVA). Differences were considered statistically significant at $P < 0.05$. The assumption of normality was assessed using the Shapiro–Wilk W test. When necessary, the data were transformed or analyzed using methods appropriate for the underlying distribution. Descriptive statistics, including means and standard deviations, were calculated for all studied traits. Graphical presentation of the results was used to facilitate interpretation and to visualize environmental-related patterns.

Results

The AMMI analysis showed that the key factor underlying yield variability was genotype × environment interaction. In the structure of the total sum of squares, the share of genotype was 44.6%, environments accounted for 29.0% and G×E interaction contributed 15.2%. This pattern indicates that varietal productivity is determined not only by genetic potential and not solely by the general agroecological background, but also to a considerable extent by how each specific genotype responds to particular growing conditions. Thus, changes in the ranking of varieties across environments have a regular pattern: the advantage of certain genotypes may either increase or decrease depending on location and year. For this reason, evaluating varieties exclusively on the basis of mean yield does not provide a complete picture of their actual value in production, since a high average yield may be accompanied by substantial fluctuations across environments, whereas genotypes with a lower average productivity may sometimes ensure a much more stable performance.

Under such conditions, the use of the AMMI approach is fully justified from both methodological and practical points of view, because it allows simultaneous evaluation of yield level and cultivar stability/adaptability. Unlike simple ranking by mean yield, AMMI makes it possible to determine how strongly the yield of a particular variety depends on environmental change, and also to distinguish broadly adapted genotypes from specifically adapted ones. Therefore, within a multi-environment testing system, it is advisable to identify, on the one hand, universal varieties capable of producing relatively stable yields across a wide range of conditions and, on the other hand, genotypes that realize their potential to the maximum only in particular agroecological niches.

The first two IPC components proved to be the most informative, explaining 49.1% and 35.1% of the G×E interaction variance, respectively, or 84.2% in total. This means that the main part of the reproducible interaction patterns is concentrated precisely in the IPC1–IPC2 plane, and therefore this plane is sufficient for meaningful interpretation of the results. In practical terms, this confirms that AMMI1 (Mean vs IPC1) and AMMI2 (IPC1 vs IPC2) allow the most complete identification of broadly adapted genotypes with low IPC values, varieties with specific responses to individual environments characterized by large absolute IPC values, as well as environments that most strongly differentiate genotypes and generate contrasting responses (Table 1).

Table 1
Part of explained genotype-environment interaction
by IPC components

Component	SS (GE)	Part of interaction, %	Cumulative, %
IPC1	46 197.55	49.10	49.10
IPC2	38 463.32	35.10	84.20
IPC3	12 309.49	4.11	88.31
IPC4	7 923.94	2.14	90.45
IPC5	4 649.69	1.79	92.24
IPC6	3 257.10	1.51	93.75
IPC7	3 202.14	1.45	95.20
IPC8	2 480.68	1.30	96.50
IPC9	1 750.64	1.12	97.62
IPC10	1 546.90	1.09	98.71
IPC1	46 197.55	49.10	49.10
IPC2	38 463.32	35.10	84.20
IPC3	12 309.49	4.11	88.31
IPC4	7 923.94	2.14	90.45
IPC5	4 649.69	1.79	92.24
IPC6	3 257.10	1.51	93.75
IPC7	3 202.14	1.45	95.20

Thus, interpretation of AMMI results based on the first two IPC components is fully sufficient to explain the main patterns of genotype × environment interaction and to support practical decisions regarding cultivar selection and recommendation. Subsequent components (IPC3 and beyond) usually contribute much less useful information, as they more often reflect secondary, less stable, or random fluctuations. For this reason, focusing on IPC1 and IPC2 may be regarded as the optimal compromise between completeness of G×E description and convenience of practical interpretation in breeding and varietal testing.

Table 2
Evaluation of main components

N	Variety	Origin	Yield 2023–2025, t/ha	IPC1	IPC2	ASV	YSI	Range YSI
G01	DARYNA	UA	7.23 ± 0.24	–26.34	–53.41	62.08	15	8
G02	BHV20GV0009	GE	7.54 ± 0.27	73.49	47.06	100.03	14	5
G03	Zoloto Stepu	UA	7.44 ± 0.36	–22.71	–28.86	39.70	8	2
G04	HIATSYNT	GE	7.17 ± 0.30	3.05	–12.35	12.88	12	4
G05	Slava Unavy	UA	7.45 ± 0.25	46.89	–11.35	57.45	10	3
G06	HIMALAYA	GE	7.41 ± 0.17	31.84	–122.73	128.55	22	13
G07	Trembita	UA	6.24 ± 0.20	31.02	71.08	80.26	24	14
G08	ZU Shamal	GE	7.46 ± 0.29	73.69	–23.40	91.55	14	6
G09	Pamiati Horlacha	UA	7.56 ± 0.14	–41.94	–26.57	56.95	5	1
G10	ZU Willem	GE	7.56 ± 0.25	68.20	64.29	104.13	14	7
G11	Kvitoslava	UA	6.70 ± 0.31	–58.91	–19.90	73.50	21	11
G12	Atrybut	GE	7.20 ± 0.21	–29.55	58.56	68.48	17	9
G13	Epos	UA	6.35 ± 0.19	38.38	–10.80	47.35	17	10
G14	STK21G	FR	7.01 ± 0.14	–104.53	18.39	126.89	26	15
G15	Dnistrianka Odeska	UA	7.28 ± 0.29	–82.58	49.98	111.07	21	12

Note: UA – Ukraine, GE – Germany, FR – France.

The analysis of mean yield and stability indicators showed that the structure of varietal superiority depends substantially on which criterion is used as the basis for evaluation. If only mean yield is considered, the leading group includes Pamiati Horlacha (7.56), ZU Willem (7.56), BHV20GV0009 (7.54), ZU Shamal (7.46) and Slava Unavy (7.45). This pattern indicates that the studied set includes genotypes with very high productivity potential, capable of producing maximum yields in favorable environments or under an optimal combination of agroecological factors. However, a high mean value alone does not necessarily mean that a variety is the best choice for broad deployment, because mean yield does not reflect the degree of variation in performance across environments.

It is noteworthy that the group of productivity leaders includes varieties of different origin, which indicates that the study represents a sufficiently broad ecological and genetic diversity. Among them, German (3) and Ukrainian (2) varieties predominate, whereas the only

French variety did not enter the cluster of highly productive genotypes. In this context, the ASV index is of particular importance, since it is used to assess genotype stability on the basis of its position in the AMMI space. Within this approach, stability is reflected by the coordinates of the IPC components: the lower the ASV value, the more stable the variety is considered to be. In our case, ASV was calculated on the basis of the relationship between IPC1 and IPC2, taking into account the proportions of explained interaction, which makes it possible to correctly weight the contribution of the first and second components to the overall level of instability. Thus, the ASV index makes it possible to move beyond a simple description of mean yield toward a deeper understanding of how reliably a genotype realizes its potential across different environments.

The lowest ASV value was recorded for HIATSYNT (12.88), which makes it possible to identify it as the most stable genotype among all those studied. It was followed in terms of stability by Zoloto Stepu (39.70), Epos (47.35), Pamiati Horlacha (56.95), and Slava Unavy (57.45). This list differs substantially from the ranking based on mean yield, indicating that some high-yielding varieties achieve their results through marked positive deviations only in part of the environments. By contrast, genotypes with a somewhat lower but more even level of yield may be much more valuable for production, especially under conditions of variable weather and strong contrasts between testing years.

The case of Pamiati Horlacha is particularly illustrative. It belongs simultaneously to the group of absolute leaders in terms of mean yield and also occupies a high position in terms of stability, with an ASV of 56.95. It is precisely this combination that makes it one of the most promising genotypes in the studied set. In contrast, ZU Willem and ZU Shamal, despite their very high mean values, did not enter the group of the most stable genotypes, which indicates a greater dependence of their productivity on specific environments. This does not diminish their breeding value, but it points to potential risks in broad commercial use without additional zonal specification.

No less important is the analysis of the integrated YSI index, which combines yield rank and stability rank (yield rank + stability rank; lower values are better). This criterion makes it possible to avoid one-sided evaluation, when selection is based either only on productivity potential or only on predictability of response. According to YSI, the best “yield + stability” combination was demonstrated by Pamiati Horlacha, Zoloto Stepu, Slava Unavy, HIATSYNT, and BHV20GV0009. In practical terms, this means that these varieties should be regarded as priority candidates for further deployment.

Pamiati Horlacha is the most balanced genotype in the set, since it combines the highest mean yield (7.56) with a high position for stability and the best YSI rank. Such a combination indicates broad adaptation and a good ability to maintain a competitive level of productivity across different environments. Zoloto Stepu occupies a special place in the analysis, because in terms of mean yield it is only slightly inferior to the absolute leaders, yet in terms of stability it clearly surpasses them. An ASV of 39.70 indicates a relatively weak specific interaction with the environment; therefore, this variety may be regarded as a broadly adapted genotype with high practical potential. Its second position according to YSI is entirely logical: it is not the highest-yielding variety in peak performance, but it is one of the most reliable within the multi-environment trial system. Genotypes of this type often prove to be the most suitable for large-scale deployment, because they provide more predictable results across a wider range of agroecological conditions.

Slava Unavy also demonstrates a very convincing combination of high yield and satisfactory stability. With a mean yield of 7.45 and an ASV of 57.45, this variety ranks among the best according to YSI, indicating good ecological plasticity. From the standpoint of practical breeding, this means that the variety can be considered not only high-yielding but also relatively reliable. Its advantage may be expressed primarily in environments with a moderate level of stress, where a combination of intensive yield formation and relatively stable response is required.

HIATSYNT deserves special attention. This means that its performance depended least on changes in environmental conditions and, consequently, it was characterized by minimal specific response. Such genotypes are especially important in both breeding and production as a stabilizing component of the varietal set. In years or regions with unstable conditions, a variety of this type may not provide the maximum yield, but it can offer the most predictable performance, which is often more valuable than a peak but unstable result.

BHV20GV0009 occupies an interesting intermediate position. On the one hand, it belongs to the highest-yielding varieties in the entire set; on the other hand, its ASV is rather high (100.03), indicating a much stronger dependence on specific environments. However, due to its high rank for yield, it still belongs to the group of the best genotypes according to YSI. This is a typical example of a genotype with very high productivity potential that nevertheless requires more careful zonal targeting and technological support. For breeding, it may serve as a valuable source of high productivity, whereas for commercial use it requires a clear understanding of the conditions under which its advantage is expressed most fully.

A more detailed examination of the IPCA1 and IPCA2 coordinates shows that genotypes with large absolute values of these indicators are characterized by more pronounced specific adaptation. For example, STK21G has an IPCA1 value of -104.53 and a very high ASV of 126.89, which indicates a sharp response to changes in environments and, accordingly, low suitability for universal use. In a similar way, Dnistrianka Odeska (ASV 111.07), ZU Willem (ASV 104.13), BHV20GV0009 (ASV 100.03), and ZU Shamal (ASV 91.55) belong to the group of varieties with more contrasting responses. This does not mean that they are weak; on the contrary, such varieties may be very strong in specific environments, but their value lies primarily in local rather than general adaptation.

Particular interest is also associated with genotypes that have relatively modest mean yield but pronounced stability or specificity. Epos has a mean yield of 63.45 but an ASV of 47.35, which makes it one of the most stable varieties in the trial. This is a typical example of a genotype that cannot be classified among the leaders in productivity, yet it has substantial value as a source of adaptability. Varieties of this type may be useful in breeding programs aimed at creating combinations in which stability of trait expression is as important as its absolute level.

Based on the presented results, the varieties can be divided into several functional groups. The universal and most balanced genotypes include Pamiati Horlacha, Zoloto Stepu, Slava Unavy and HIATSYNT. Varieties with high productivity potential but greater dependence on environmental conditions include BHV20GV0009, ZU Willem and ZU Shamal. Genotypes with a pronounced specific response and therefore greater suitability for local use include STK21G, Dnistrianka Odeska, HIMALAYA and Trembita.

The most stable genotypes according to ASV were HIATSYNT (ASV 12.88), Zoloto Stepu (ASV 39.70), Epos (ASV 47.35), Pamiati Horlacha (ASV 56.95) and Slava Unavy (ASV 57.45). According to the integrated YSI criterion, the best “yield + stability” combination was demonstrated by Pamiati Horlacha, Zoloto Stepu, Slava Unavy, HIATSYNT and BHV20GV0009.

Figure 1, presented in the AMMI biplot format, is one of the most informative ways to interpret genotype × environment interaction, because it simultaneously reflects not only the strength of the interaction, but also the spatial arrangement of genotypes relative to one another and to the set of environments. In such a graph, the vertices of the polygon are formed by those genotypes that have the largest absolute IPC1 and IPC2 coordinates, that is, those that respond most strongly to changes in growing conditions. It is precisely these genotypes that define the boundaries of the multidimensional response space and therefore may potentially be winners in individual environmental sectors, although they are less often universally stable. In the presented graph, such extreme genotypes, located farthest from the origin of coordinates, include HIMALAYA, STK21G, Dnistrianka Odeska, ZU Willem, BHV20GV0009, and ZU Shamal.

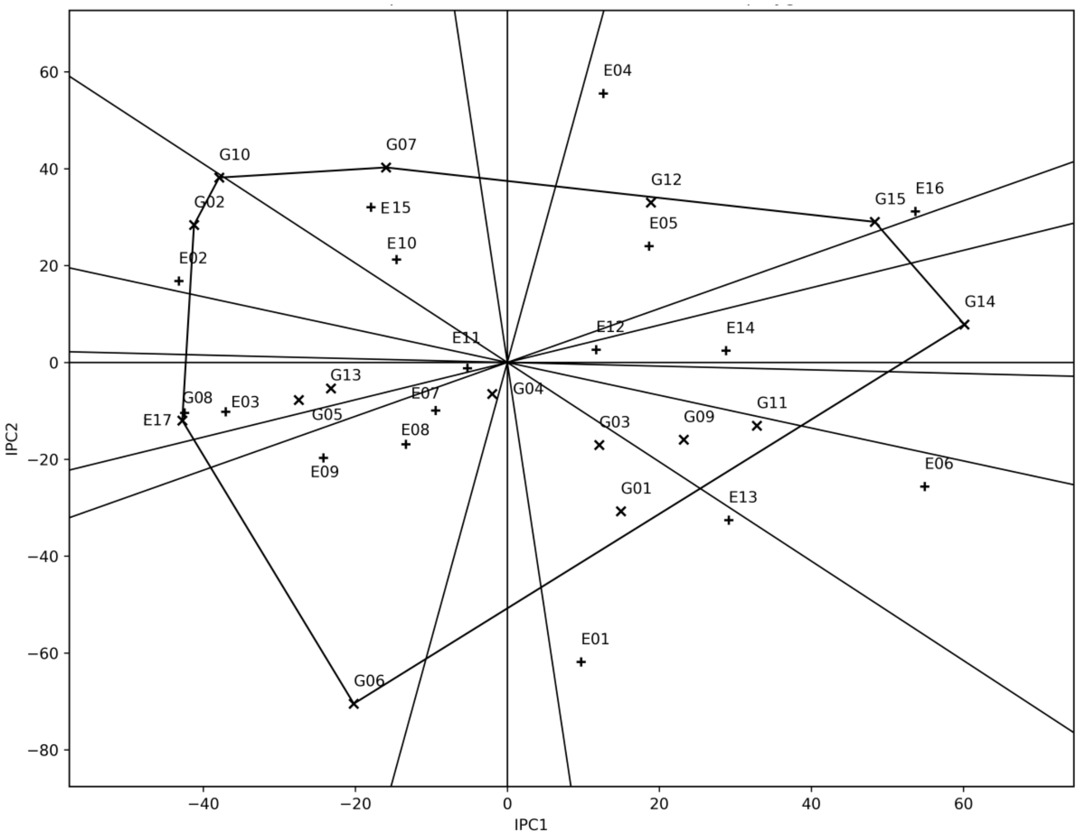

Fig. 1. AMMI biplot (IPC1×IPC2) — which-won-where

From a practical point of view, a large distance from the origin means that the yield performance of the corresponding variety depends substantially on the particular combination of soil and climatic, technological, and weather conditions under which it is grown. Such genotypes may produce very high results in those environments where their reaction norms are best matched to local conditions; however, in less favorable or more contrasting environments, they often lose their advantage. HIMALAYA is one of the most distinctly peripheral genotypes, which is fully consistent with its pronounced specificity of response. The position of this variety in the lower part of the graph, at a considerable distance from the origin, indicates a strong contribution to the interaction and a high dependence on a specific environmental profile. STK21G also occupies an extreme position and its distance from the center is combined with a clearly one-sided pattern of response. This means that the variety belongs to the group of genotypes with a strong environmental response. Dnistrianka Odeska, ZU Willem, BHV20GV0009 and ZU Shamal form another part of the peripheral group. The peculiarity of this group is that it likely represents genotypes with different types of specialization: some may be more sensitive to moisture availability, others to temperature regime and still others to soil fertility level or cultivation intensity.

It is important to emphasize that the polygon vertices should not automatically be interpreted as the best genotypes in an absolute sense. Rather, they should be viewed as varieties with the most strongly expressed reaction norms. It is precisely these genotypes that create the contrast among environmental sectors and exert the strongest influence on changes in varietal ranking.

Special attention should also be paid to the group of genotypes located closer to the origin. In the present description, these include HIATSYNT, Zoloto Stepu and Epos. Their position indicates a more moderate interaction with environments, that is, a lower dependence on sharp fluctuations in the agroecological background. Such varieties usually do not show extreme productivity peaks in individual environments, but they provide greater predictability of performance across the entire testing network. In this context, HIATSYNT may be regarded as a standard of stable response. From a breeding perspective, this is highly valuable material as a source of ecological plasticity.

Zoloto Stepu occupies a position close to the center, though not completely neutral. This may be interpreted as a combination of relatively good stability with a certain degree of adaptation to specific environments. Epos, although it does not belong to the group of absolute leaders in productivity, occupies an important place among genotypes with a moderate interaction pattern. In practical terms, this means that the variety may not have the highest yield peak, but at the same time it may ensure a more even performance. The polygon is sufficiently elongated in several directions, and its vertices are located in different quadrants. This means that the testing system covers contrasting environments capable of differentiating genotypes in different ways. Accordingly, the presence of several clearly expressed vertices indicates that the network contains not one, but several ecological niches in which different varieties may show an advantage. Special importance also belongs to the position of genotypes located in the immediate vicinity of the origin, such as Vinnytsia and, to some extent, Kyiv, Kharkiv and Ivano-Frankivsk. These are characterized by a minimal contribution to specific interaction.

Thus, Figure 1 makes it possible to distinguish at least two major functional groups of genotypes. The first group consists of genotypes with pronounced specific adaptation, which form the vertices of the polygon and may be the best only in part of the environments. These include HIMALAYA, STK21G, Dnistrianka Odeska, ZU Willem, BHV20GV0009 and ZU Shamal. The second group includes genotypes with a more moderate response, located closer to the center, which are characterized by better stability and greater predictability of performance; among these, HIATSYNT, Zoloto Stepu and Epos should be noted first.

Figure 2 presents an AMMI biplot in which interpretation is based not only on the absolute position of genotypes in the IPC1 × IPC2 space, but also on their position relative to the axis of the average environmental response. In the presented graph, the genotypes located closest to the positive direction of the average response axis include STK21G, Dnistrianka Odeska, Kvitoslava and Pamiati Horlacha. Such a position provides grounds to conclude that they combine features of a relatively favorable average response with acceptable or moderate stability relative to the dominant ecological gradient.

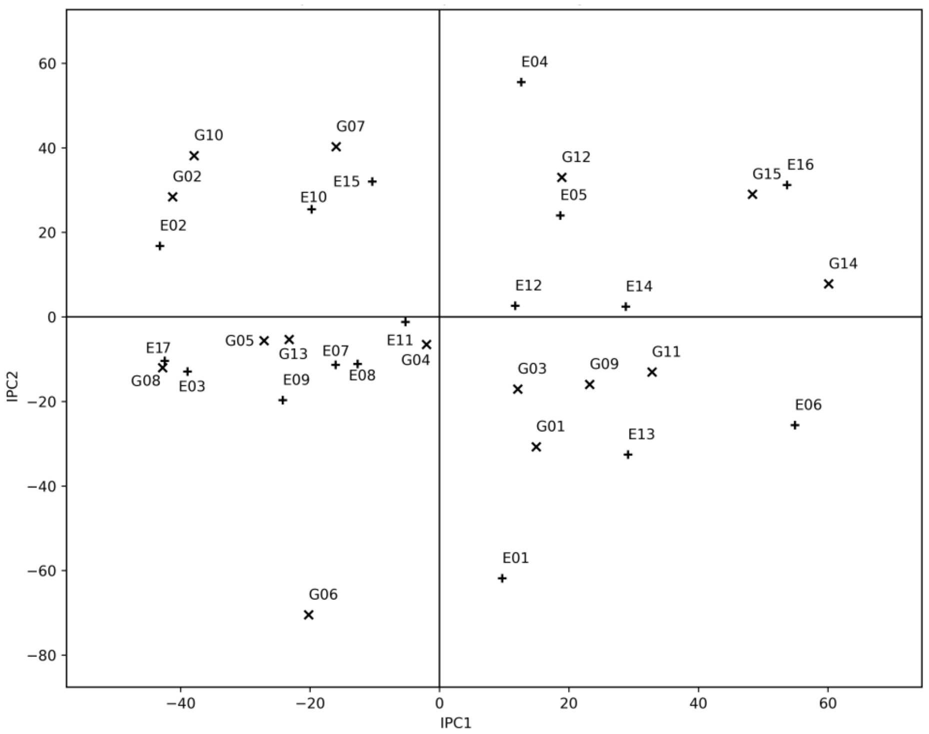

Fig. 2. AMMI biplot – mean response & stability (environment axis)

STK21G is positioned far to the right and at the same time relatively close to the axis of the average response. This indicates that the variety has considerable potential for a productive response in the more favorable direction of the ecological gradient, while at the same time not showing excessive deviation toward a highly specific response. Dnistrianka Odeska occupies a position that is similar in logic, although somewhat different in expression. Compared with STK21G, this variety may show a somewhat greater dependence on individual environmental factors. The position of Kvitoslava provides grounds to interpret it as a genotype with good potential for universal use in environments where excessive stress pressure is not expected. Pamiati Horlacha is also located in a favorable part of the graph, which is fully consistent with its high ranking according to the integrated indicators of yield and stability.

All genotypes can be divided into at least several functional groups. The first group includes genotypes with a large positive projection onto the mean response axis and only a small or moderate deviation from it. The second group consists of genotypes that, although showing a substantial projection on the x-axis, deviate strongly from it. These may be highly productive, but they are also more specialized. The third group includes genotypes located far from the positive direction or even in the opposite sector, which indicates lower correspondence to the average productive response and greater specificity.

Figure 3 presents one of the more practically oriented variants of AMMI interpretation, namely the comparison of genotypes with a theoretical ideal type. The concentric circles around the hypothetical center serve as a scale of distance from the ideal genotype: the closer a variety is to the center of the circles, the better the combination of the desired direction of response and stability in the IPC1–IPC2 space is considered to be. In the presented graph, the shortest distance to the theoretical "ideal" genotype is shown by STK21G, Kvitoslava, Dnistrianka Odeska, and Pamiati Horlacha. This means that these genotypes combine most successfully the desired environmental response direction with relative stability. Among this group, STK21G is located closest to the center of the concentric circles, which gives grounds to interpret it as the genotype with the best balance between two key characteristics: the ability to respond to favorable conditions and a moderate magnitude of specific interaction.

In this configuration, STK21G may be regarded as one of the most promising genotypes for further use. Its position close to the center of the concentric circles indicates that the variety corresponds well to the hypothetical favorable direction of environmental response and at the same time exhibits only a moderate degree of destabilizing interaction. For production, this may indicate potential suitability for broader use, while for breeding it suggests particular value as a reference form against which other genotypes may be compared or as a parent in crosses aimed at combining a strong response to improved conditions with a more stable expression of the trait. Kvitoslava also occupies a very favorable position in close proximity to the inner concentric circles. This indicates that the variety shows a high level of correspondence to the hypothetical ideal genotype and may therefore be regarded as one of the most balanced forms in the studied set. Such genotypes are especially important for zones where the aim is not to obtain a record maximum in isolated cases, but rather a stable and sufficiently high realization of yield potential across a wide range of conditions. According to Figure 3, Dnistrianka Odeska also belongs to the group of genotypes approaching the theoretical ideal. Its position shows that the variety combines a favorable orientation toward the positive ecological gradient with acceptable stability. Pamiati Horlacha is likewise among the genotypes located closest to the ideal type. For farms seeking to reduce risk without sacrificing yield potential, such varieties may serve as the basis of varietal structure.

Genotypes located at greater distances from the center of the circles should be interpreted as less close to the breeding-desirable type. As a rule, these include either strongly specifically adapted forms or genotypes for which the combination of mean response and stability is less favorable. This does not mean that such varieties lack value. On the contrary, they may possess substantial potential in particular environmental sectors or serve as sources of important adaptive traits. However, they are more appropriately regarded as material for local use or targeted breeding rather than as universal forms for broad deployment. This refers not to an absolute biological ideal, but to the best available combination of traits within the studied set of material. This is a very important methodological clarification. A variety located closest to the center in one population of genotypes will not necessarily retain that position in a broader set or in another testing network. Nevertheless, within the framework of the present experiment, STK21G, Kvitoslava, Dnistrianka Odeska, and Pamiati Horlacha should be interpreted as the main candidates for the status of the most balanced forms.

The presented results indicate that the testing network covered a broad spectrum of agroecological conditions, within which differences were simultaneously expressed both in terms of mean yield background and in the ability of environments to differentiate genotypes. It is precisely the combination of these two characteristics that is fundamentally important for correct varietal evaluation, because high productivity of a location does not necessarily imply high breeding value, just as strong discriminating ability is not always accompanied by representativeness. In this context, it is particularly noteworthy that the most productive environments included Chernivtsi, Ternopil, Lviv, Rivne and Vinnytsia regions. This list is composed mainly of Forest-Steppe and Polissia locations, indicating a more favorable combination of moisture availability, temperature regime, and duration of active vegetation for the realization of the potential of the studied varieties.

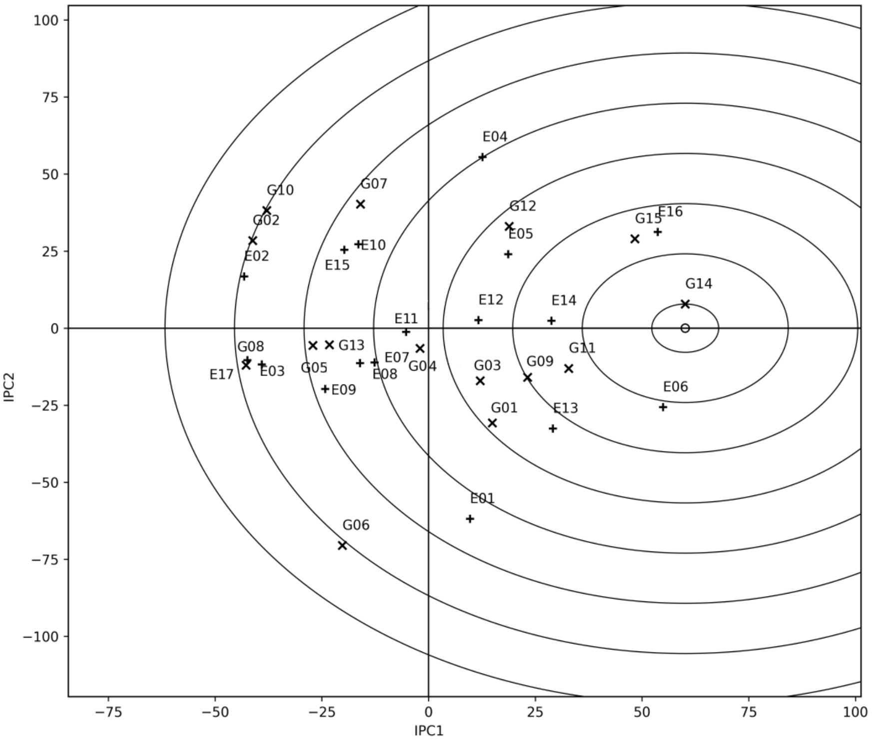

Fig. 3. AMMI biplot – comparison with the "ideal" genotype

At the same time, the most representative environments, that is, those with the shortest vector in the IPC1–IPC2 space and therefore those that better reflected the average response of the set of genotypes, were Volyn, Zakarpattia, Ternopil, Kharkiv, and Lviv regions. This means that the results obtained at these sites were less likely to be determined by specific interactions between individual varieties and local factors and more accurately reflected their general adaptive suitability. From a practical point of view, such locations are especially valuable for primary breeding evaluation, for drawing generalized conclusions about plasticity, and for making decisions about broad regional suitability of varieties.

A different function was performed by the most discriminating environments, namely Dnipropetrovsk, Khmelnytskyi, Sumy, Vinnytsia and Kirovohrad regions. The large length of their vectors in the AMMI principal component space indicates an increased ability to reveal intervarietal differences and to capture specific genotype responses. Such locations are not necessarily the most convenient for generalization, but they are indispensable for selecting contrasting genotype pairs, identifying narrowly specialized adaptation, and establishing the limits of varietal stability.

Additional analytical value is provided by the table of relative varietal ranking in specific regions (Table 3). It makes it possible to move from a general characterization of environments to a more applied interpretation. In total, ten varieties appear as TOP-1 across different regions, which in itself indicates the absence of a single universal dominant for the entire network. However, an analysis of the frequency of inclusion in the top three reveals varieties with a broader adaptive profile. The variety ZU Willem entered the TOP-3 most often, in six cases, whereas Slava Unavy, BHV20GV0009, Atrybut and Pamiati Horlacha appeared five times each. Such genotypes should be regarded as material with increased ecological plasticity or, at the very least, as varieties capable of maintaining competitiveness across a wide spectrum of agroecological backgrounds.

Among the Steppe locations, no complete unification of the leading varieties was observed, which is a very important result. In Dnipropetrovsk region, DARYNA ranked first; in Kirovohrad region, ZU Shamal was the TOP-1 variety; and in Odesa region, HIMALAYA occupied the leading position. Thus, across the three Steppe testing sites, three different winners were identified. This directly indicates the high contrast among environments even within the same natural zone.

At the same time, even within this highly heterogeneous Steppe block, it is possible to identify varieties showing signs of relatively broad adaptation. In particular, HIMALAYA, Slava Unavy and ZU Shamal entered the TOP-3 twice, which indicates their competitiveness under different variants of the Steppe agroecological background. DARYNA, although ranked first in only one environment, showed the ability to realize its potential under a specific combination of conditions, which provides grounds for considering it a variety with specific but valuable adaptation.

The Forest-Steppe zone appeared intermediate between the heterogeneous Steppe and the more consistent Polissia. Here, the varieties STK21G, Zoloto Stepu, Atrybut, and ZU Willem were repeated more frequently among the leaders, although the rankings still varied among regions. STK21G ranked first twice, and Zoloto Stepu also led the ranking twice, whereas Dnistrianka Odeska, Epos, and ZU Willem became the best-performing variety only in individual locations. At the same time, Atrybut, ZU Willem, and BHV20GV0009 entered the TOP-3 three times each, which emphasizes their good balance between productivity and adaptability specifically for the Forest-Steppe complex of conditions.

It is particularly noteworthy that Vinnytsia, Ternopil and Chernivtsi regions belonged to the group of the most productive environments, while Ternopil was simultaneously among the most representative. This means that the Forest-Steppe environments not only provided a high yield background, but in some cases also allowed a rather reliable integrated evaluation of genotypes. However, the fact that Vinnytsia and Sumy regions were among the most discriminating environments indicates that both relatively reference-like and contrasting conditions coexist within this zone. Therefore, a multi-location approach is especially appropriate for the Forest-Steppe: some sites can be used for generalization, whereas others are useful for testing varietal responses to stressful or specific environmental factors.

A higher repeatability of leaders was characteristic of the Polissia locations, which makes it possible to speak of relatively better predictability of varietal response. The variety Pamiati Horlacha ranked first four times, specifically in Volyn, Zakarpattia, Ivano-Frankivsk, and Lviv regions. Such repeatability is one of the clearest indicators of the broad adaptation of this genotype specifically to Polissia-type conditions. In addition, ZU Willem, Atrybut, Kvitoslava, STK21G, Slava Unavy, and Dnistrianka Odeska repeatedly entered the top three in Polissia. Thus, the zone is not absolutely homogeneous; however, against its background, a group of consistently competitive varieties is distinguished much more clearly than in the Steppe.

It is also noteworthy that Lviv and Rivne regions belonged to the group of the highest-yielding environments, while Volyn, Zakarpattia, and Lviv were among the most representative environments. This reinforces the conclusion about the high analytical value of the Polissia block, since some of its locations not only created a favorable background for the realization of varietal potential, but also adequately reflected the average response of the genotypes. At the same time, Khmelnytskyi region was classified among the most discriminating environments; therefore, even within this relatively more consistent zone, contrasting sites remain that are important for breeding analysis.

Table 3
Ranking of varieties by the environment

No.	Region	Zone	TOP-1	TOP -2	TOP -3
E01	Dnipropetrovsk	Steppe	DARYNA	HIMALAYA	Slava Unavy
E02	Kirovohrad	Steppe	ZU Shamal	BHV20GV0009	Slava Unavy
E03	Odesa	Steppe	HIMALAYA	ZU Willem	ZU Shamal
E04	Vinnytsia	Forest-Steppe	STK21G	Atrybut	ZU Willem
E05	Kyiv	Forest-Steppe	Dnistrianka Odeska	Atrybut	ZU Willem
E06	Sumy	Forest-Steppe	STK21G	Kvitoslava	Pamiati Horlacha
E07	Ternopil	Forest-Steppe	Epos	BHV20GV0009	HIATSYNT
E08	Kharkiv	Forest-Steppe	Zoloto Stepu	Dnistrianka Odeska	BHV20GV0009
E09	Cherkasy	Forest-Steppe	Zoloto Stepu	HIATSYNT	Atrybut
E10	Chernivtsi	Forest-Steppe	ZU Willem	BHV20GV0009	Slava Unavy
E11	Volyn	Polissia	Pamiati Horlacha	ZU Willem	HIATSYNT
E12	Zakarpattia	Polissia	Pamiati Horlacha	Atrybut	Kvitoslava
E13	Ivano-Frankivsk	Polissia	Pamiati Horlacha	STK21G	ZU Shamal
E14	Lviv	Polissia	Pamiati Horlacha	Kvitoslava	Slava Unavy
E15	Rivne	Polissia	DARYNA	BHV20GV0009	Dnistrianka Odeska
E16	Khmelnytskyi	Polissia	STK21G	Dnistrianka Odeska	Atrybut
E17	Chernihiv	Polissia	Slava Unavy	HIMALAYA	ZU Willem

Discussion

In terms of the mean yield background, the most favourable environments were Chernivtsi, Ternopil, Lviv, Rivne and Vinnytsia. The most representative environments, defined by the shortest vector in the IPC1–IPC2 space (Al-Ashkar et al., 2022), were Volyn, Zakarpattia, Ternopil, Kharkiv and Lviv, whereas the most discriminating environments were Dnipropetrovsk, Khmelnytskyi, Sumy, Vinnytsia and Kirovohrad. This confirms the value of combining both reference and contrast environments within the varieties testing network (Kassie et al., 2025).

Among the Steppe locations, no complete unification of leaders was observed: in Dnipropetrovsk region, DARYNA ranked first; in Kirovohrad region, ZU Shamal was the top-ranked genotype; and in Odesa region, HIMALAYA occupied the first position. Such heterogeneity confirms the high contrast of environmental conditions within this zone and the need for localized recommendations. In the Forest-Steppe environments, STK21G, Zoloto Stepu, Atrybut, and ZU Willem appeared more frequently among the leading genotypes; however, their ranking varied considerably among regions. This indicates the high internal heterogeneity of the Forest-Steppe zone and the importance of considering the specific agroecological background of each location (Gupta et al., 2022; Menzir et al., 2025). In the Polissia locations, a higher repeatability of leaders was observed, Pamiati Horlacha ranked first four times, while STK21G, Atrybut, Dnistrianka Odeska and ZU Willem were frequently included among the top three. This suggests a relatively greater homogeneity of the zone and better predictability of genotype responses (Eskezia et al., 2025).

Summarizing these results, it can be stated that the structure of genotype × environment interaction had a clearly zonal, though not simplistically deterministic, character (Kebede et al., 2023; Korpetis et al., 2026). The Steppe was characterized by the greatest differentiation among leading genotypes and, accordingly, by the strongest need for local recommendations. The Forest-Steppe combined features of high productivity, the presence of partially recurring leaders, and substantial internal heterogeneity. Polissia was distinguished by a greater recurrence of the best-performing varieties and, therefore, by a more predictable genotype response, although some contrasting locations were also present there.

For breeding practice, these findings have several important implications. First, no single location can fully replace a network-based trial, because different test sites perform different analytical functions (El Baouchi et al., 2024). Second, varieties that repeatedly enter the top three across different zones should be regarded as material with broad adaptation potential and as a source of valuable genetic components of stability (Roostaei et al., 2024). Third, varieties that show local leadership but less frequent superiority in other environments are of no less breeding value, because they may carry specific adaptation to particular agroecological backgrounds (Tanin et al., 2022). Therefore, the optimal breeding strategy does not consist in identifying one best variety for all conditions, but rather in forming a differentiated set of genotypes for different zones and production situations (Ejaz et al., 2023; Mohammadi et al., 2025).

The observed structure of variation confirms that, in this set of material, genotype × environment interaction accounts for the main share of the differences among varieties. This means that reliance on mean yield alone, without considering stability, may be misleading, especially when recommendations are intended for different climatic zones (Darwish et al., 2023).

In terms of mean productivity, the best-performing varieties were Pamiati Horlacha, ZU Willem, BHV20GV0009, ZU Shamal and Slava Unavy, whereas in terms of stability the unquestionable leader was HIATSYNT. Thus, universal selection should not rely on a single indicator, but rather on the combination of mean yield, ASV, YSI, and visual interpretation through the AMMI biplot (Dang et al., 2024).

Their proximity to the ideal genotype and their high positions according to YSI allow STK21G, Kvitoslava and Dnistrianka Odeska to be regarded as the most balanced forms. At the same time, HIMALAYA, STK21G, Dnistrianka Odeska and ZU Willem showed pronounced specific adaptation and are therefore more suitable for targeted zonal use. In other words, STK21G is able both to realize its potential fully in specific environments and to maintain only minimal yield variation across changing environments, which makes it the most universal genotype (Bhandari et al., 2026; Khare et al., 2026).

The practical value of this analysis lies in its ability to simultaneously identify universal varieties for broad use, define genotypes suitable for local technological niches and determine environments that are most appropriate either for primary ranking or, conversely, for stress-testing breeding material (Taherian et al., 2024).

Thus, the results of the ranking analysis, combined with the evaluation of productivity, representativeness and discriminating ability of environments, provide a comprehensive view of the adaptive potential of the studied varietal set. They clearly demonstrate that an effective variety testing system should be based on a combination of highly productive, representative, and contrasting locations, while varietal recommendations should account not only for mean yield level, but also for the nature of genotype interaction with specific ecological conditions (Yan, 2024).

Conclusion

At the multi-environment trial, the main component of yield variation was the genotype variation, which confirms the necessity of applying the AMMI approach to assess variety adaptability and stability. In terms of mean grain yield, the leading varieties were Pamiati Horlacha, ZU Willem, BHV20GV0009, ZU Shamal and Slava Unavy; HIATSYNT was the most stable according to ASV, while the best integrated performance according to YSI was shown by Pamiati Horlacha, Zoloto Stepu and Slava Unavy. The genotypes showing the strongest specific adaptation according to the AMMI2 configuration were HIMALAYA, STK21G, Dnistrianka Odeska, ZU Willem, BHV20GV0009, and ZU Shamal, whereas the genotypes located closest to the theoretical ideal genotype were STK21G, Kvitoslava, Dnistrianka Odeska and Pamiati Horlacha. Thus, Pamiati Horlacha may be regarded as a relatively universal variety, whereas STK21G appears capable both of expressing its potential most effectively under favorable environmental conditions and of maintaining a consistently good average level of performance. Therefore, the combined cultivation of these two varieties appears to be the most promising option. Kvitoslava and Dnistrianka Odeska may also be considered valuable additional components in such a varietal combination. The environments of Volyn, Zakarpattia and Ternopil may be used as reference sites for primary genotype ranking, whereas Dnipropetrovsk, Khmelnytskyi and Sumy can be regarded as the most discriminating locations for identifying specific adaptation. Among the Steppe locations, no complete unification of the leading varieties was observed; however, these environments were the most contrasting and therefore the most limiting for the use of individual varieties. The obtained results can be directly applied to the development of recommendations for winter wheat cultivation, optimization of the varietal testing network, and selection of source material for breeding programs.

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