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Evaluation of new winter wheat varieties under different environmental conditions of Ukraine

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Abstract. Yield stability depends largely on the resistance of varieties and hybrids to environmental stress factors. Assessing the extent of genotype × environment interaction (GEI) helps breeders select the best genotypes for submission to the State Variety Testing system. Multienvironment trials are a key tool for evaluating the adaptability of genotypes to contrasting soil and climatic conditions. In this study, the grain yield of 20 winter wheat varieties was analyzed across 17 environments represented by branches of the UIESR, covering the three major agroecological zones of Ukraine: the Steppe, Forest-Steppe, and Polissia. The AMMI analysis showed that the largest share of the total variance was attributable to the genotype × environment interaction, which exceeded the contributions of genotype and environment considered separately. This variance structure indicates substantial changes in cultivar ranking depending on the location of cultivation and confirms the need to account for adaptability when selecting varieties. Among the evaluated genotypes, the highest mean yield was recorded for LG Orlice, CHIKO, Bosporus, Khvylia Dnipra, and LG Quadrant. Special attention should be given to LG Orlice, which ranked among the leaders in most environments and demonstrated the broadest adaptability. The most stable genotype was MIP Roksolana, characterized by minimal interaction with the environment and high ecological plasticity. The group of relatively stable varieties also included LG Quadrant, CHIKO, and LG Orlice. Considering the combination of high yield and stability, the most promising candidates for broad adoption are LG Orlice, CHIKO, and LG Quadrant. In the Steppe zone (Dnipropetrovsk, Kirovohrad, and Odesa environments), the highest productivity was shown by CHIKO and LG Orlice, whereas in the Kirovohrad branch Khvylia Dnipra and Bosporus dominated, indicating specific adaptation to drier conditions. In the Forest-Steppe zone, the most frequent leaders were Bosporus, Khvylia Dnipra, LG Orlice, and CHIKO, which characterizes them as high-yielding genotypes for moderately moist conditions. In Polissia, LG Orlice and CHIKO dominated in virtually all environments, demonstrating consistently high yields under sufficient moisture supply. Bosporus and LG Quadrant are also considered promising for this zone. The obtained results confirm the necessity of a zonal approach to the deployment of winter wheat varieties and demonstrate the feasibility of using universally adapted genotypes as a foundation for large-scale production. The objective of the research was to determine the degree of influence of genotype, environment, and their interaction on yield and to identify stable and productive genotypes. The experiment was established in a randomized design with three replications. Analysis of variance of yield data quantified the contributions of environmental effects (37.7%), genotype (14.3%), and genotype × environment interaction (48.0%) to overall yield variability.

Keywords: cereals; winter wheat; variety; environment; AMMI-analyse; yield; adaptability.

Introduction

Stable grain yield and economic profitability remain among the most critical challenges for both plant breeders and farmers. Modern winter wheat cultivars are expected not only to produce high yields under favorable conditions, but also to maintain reliable performance across a broad range of environments, ensuring consistent realization of genetic potential and efficient use of cultivation technologies (Nazarenko et al., 2023). However, varieties often respond differently to shifts under soil and climatic conditions, agronomic backgrounds, and seasonal weather patterns (Nazarenko et al., 2022). These differences are largely driven by genotype × environment interaction (GEI), which reflects the fact that the relative ranking of genotypes can change from one environment to another (Al-Ghumaiz et al., 2025).

Genotype × environment interaction complicates the identification of the best genotypes because superiority observed in one location or season may not be consistent elsewhere. As a result, selection decisions based solely on average yield can be misleading, particularly in regions with strong environmental heterogeneity and increasing climatic instability. Therefore, breeders must continuously screen germplasm and breeding material to identify and introduce cultivars that are well adapted to diverse environments and management systems (Saeidnia et al., 2023). In this context, detailed information on GEI for promising breeding lines is of primary importance: It supports more accurate selection, reduces the risk of discarding valuable materials with specific adaptation, and strengthens the scientific justification for regional variety recommendations (Gupta et al., 2023).

To address these challenges, a range of statistical approaches has been developed to quantify the magnitude of GEI and to identify genotypes with minimal interaction effects, i.e., genotypes whose phenotypic response to environmental change is more predictable. Commonly used methods include linear regression techniques, nonlinear regression models, multivariate procedures, and nonparametric statistics (Yan, 2024). Regression-based stability models typically interpret adaptability through the slope of genotype response across environments and the deviation from regression, enabling differentiation between broadly adapted and specifically adapted materials. Nonparametric methods, in turn, can be useful when assumptions of normality or homogeneity are breached, or when breeders need robust rankings under heterogeneous variance structures. Multivariate methods provide additional advantages by capturing patterns in the data that are not easily represented by single-parameter models, particularly when many environments are considered simultaneously (Tshikunde et al., 2019).

Among the most effective tools for GEI quantification and yield stability assessment are the AMMI and GGE biplot models, which are grounded in principal component methodology (Ye et al., 2019). Classical analysis of variance (ANOVA) is an additive framework in which GEI appears as a source of variation, but the internal structure of that interaction is not explicitly decomposed or interpreted. By contrast, principal component analysis (PCA) is a multiplicative approach: It can effectively summarize complex interaction patterns, yet it does not directly represent the additive main effects of genotype and environment (Yue et al., 2025). This methodological contrast is important because breeders usually need both types of information: how genotypes differ on average (main effects) and how their performance changes across environments (interaction) (Abdolshahi et al., 2015).

The AMMI model (Additive Main effects and Multiplicative Interaction) integrates the strengths of ANOVA and PCA within a unified analytical framework and is widely applied for evaluating genotype adaptability and stability (Yue et al., 2025). In AMMI, ANOVA is used to test and estimate the main effects of genotype and environment, while PCA is applied to the residual (multiplicative) portion of the GEI term. This decomposition allows the GEI sum of squares to be represented using a minimal number of degrees of freedom through interaction principal component axes (IPCAs). Practically, this enables researchers to separate signal (repeatable interaction patterns) from noise (random variation), improving interpretability and supporting more confident selection decisions. Because both ANOVA and PCA are integral parts of the AMMI methodology, AMMI is often considered particularly effective for describing and visualizing GEI in multienvironment trials (Ye et al., 2019).

From an applied breeding perspective, AMMI outputs can be used to identify genotypes with broad adaptation (small interaction scores and stable ranking), detect genotypes with specific adaptation (large interaction scores associated with distinct environmental groups), characterize environments in terms of their discriminating ability and representativeness, rationalize the design of testing networks by selecting informative locations and years. In regions where environmental contrasts are strong, due to differences in moisture supply, temperature regime, soil fertility, or overwintering conditions, such analytical capability is especially valuable (Brković et al., 2025). Moreover, under current trends of climate variability, GEI-driven instability may intensify, increasing the need for robust stability models and evidence-based variety deployment strategies. Thus, AMMI and GGE biplot analyses are not merely statistical tools, but practical decision-support methods that help align breeding objectives with real-world production risks and environmental diversity (Saeidnia et al., 2022).

Under global warming, winter wheat is increasingly challenged by short, intense heat spikes, irregular precipitation patterns, and more frequent disruptions of normal overwintering. In the Steppe and Forest-Steppe zones, these pressures often occur in combination, and crops may endure freeze–thaw cycles that damage crowns and weaken tillers, followed by spring moisture deficits that constrain root activity, nutrient uptake and early stem elongation. Such stress sequences rarely act in isolation. They can also predispose plants to disease, because weakened tissues and uneven canopy development create windows of vulnerability, especially during warm, humid intervals that have become more common as weather variability intensifies (Pour-Aboughadareh et al., 2025).

Under these conditions, breeding programs can help stabilize yield formation by supporting stress physiology while simultaneously limiting disease pressure that often escalates under warmer and intermittently wetter seasons. The objective is not always to push for maximum yield in every year, but to reduce yield volatility, owering the probability of severe losses and increasing the likelihood of reaching target productivity when weather patterns swing unpredictably (Nazarenko et al., 2023).

The objective of the study was to quantify how strongly genotype (G), environment (E), and their genotype × environment interaction (G×E) influence winter wheat grain yield and, on this basis, to identify the genotypes that combine high productivity with yield stability across contrasting growing conditions. In practical terms, this objective involved not only estimating the overall contribution of each source of variation to yield formation, but also clarifying whether yield differences among genotypes remain consistent from site to site and year to year, or whether rankings change substantially under different agroecological backgrounds.

To achieve this objective, the research focused on characterizing the response of a set of genotypes in a multi-environment trial framework, where environments represented diverse combinations of location- and season-specific factors (soil properties, weather patterns, and management conditions). Particular attention was given to determining the magnitude and structure of G×E, because this component directly reflects differences in genotype sensitivity and adaptation: Some genotypes may express their yield potential only in favorable environments, whereas others maintain more stable performance under variable or stressful conditions (Omrani et al., 2022).

Accordingly, the study sought to distinguish two complementary groups of varieties, widely adapted genotypes, which deliver comparatively stable yields with minimal fluctuations across environments and thus reduce production risk; and high-potential genotypes with specific adaptation, which may outperform others in particular environments and can be recommended for targeted zones or agrotechnical systems (Sallam et al., 2019). By integrating the evaluation of mean yield and stability, the work was designed to support evidence-based genotype selection for breeding programs and to improve the accuracy of cultivar recommendations for regional deployment under conditions of increasing climatic variability.

Materials and methods

The study was conducted within a multienvironment trial involving 20 winter wheat varieties: Perlyna (Ukraine), Pozytsiia Odeska (Ukraine), Tika Taka (Romania), Tenor (Ukraine), MIP Nika (Ukraine), MIP Roksolana (Ukraine), MIP Feieriia (Ukraine), MV Mente (Hungary), MV Nador (Hungary), MV Menrot (Hungary), Bosporus (Germany), Vezha (Ukraine), Vitalina (Ukraine), Setar (Ukraine), Khvylia Dnipra (Ukraine), CHIKO (Germany), LG Orlice (France), LG Quadrant (France), LG Magirus (France), and LG Litopys (France). The varieties were evaluated across 17 environments located in three major agroecological zones of Ukraine: the Steppe, Forest-Steppe, and Polissia.

The net plot area was 10 m², with three replications, and the study covered three growing seasons (2022–2024). In all cases, the preceding crop was bare fallow, and zonal agronomic practices were applied. The varieties were selected to represent, as comprehensively as possible, the major breeding directions for developing source material intended for deployment under the conditions of Ukraine. The test environments were chosen to be maximally representative, taking into account the broad variability in soil and climatic conditions across regions. The trait analyzed was grain yield, obtained from field experiments following the standard methodology of the State Variety Testing system.

To evaluate genotype × environment interaction, the AMMI model (Additive Main Effects and Multiplicative Interaction) was applied, combining analysis of variance for main effects with principal component analysis of the interaction matrix.

The trial network included the following environments: Dnipropetrovsk Oblast (48°51'07" N, 35°25'23" E), Kirovohrad Oblast (48°18'33" N, 30°16'49" E), Odesa Oblast (46°27'21" N, 30°40'07" E) (Steppe zone), Forest-Steppe zone, Vinnytsia Oblast (48°33'15" N, 28°41'34" E), Kyiv Oblast (49°46'19" N, 30°06'40" E), Sumy Oblast (50°59'42" N, 34°31'31" E), Ternopil Oblast (49°27'56" N, 25°32'10" E), Kharkiv Oblast (49°53'10" N, 36°24'55" E), Cherkasy Oblast (49°24'17" N, 31°58'49" E), Chernivtsi Oblast (48°25'21" N, 25°43'26" E), Polissia zone, Volyn Oblast (50°30'23" N, 24°56'06" E), Zakarpattia Oblast (48°32'49" N, 22°25'16" E), Ivano-Frankivsk Oblast (48°51'29" N, 25°00'58" E), Lviv Oblast (49°52'51" N, 24°07'04" E), Rivne Oblast (50°38'02" N, 26°19'52" E), Khmelnytskyi Oblast (49°26'19" N, 27°02'12" E), Chernihiv Oblast (51°35'37" N, 31°17'20" E).

The model is expressed as:

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

where μ is the overall mean; G_i is the effect of the *i*-th genotype; E_j is the effect of the *j*-th environment; λ_k are the singular values; α_{ik} and γ_{jk} are the scores (coordinates) of genotypes and environments for the *k*-th interaction principal component axis; and ε_{ij} is the random error term.

For interpretation, the following were used: the AMMI1 biplot (mean yield vs. IPC1), the AMMI2 biplot (IPC1 vs. IPC2), and indices of stability and adaptability. Calculations were performed using the matrix of mean yield values across environments, based on replicated observations.

The Yield Stability Index (YSI) was calculated as: YSI = RASV + RY, where RASV is the genotype rank according to the ASV value, and RY is the rank based on grain yield (Y).

All statistical analyses were conducted using Statistica 10.0 (TIBCO, Palo Alto, USA). The factorial analysis of variance (ANOVA) was applied to test the main effects and interactions of genotype (variety), active compound, and concentration. Effects were considered significant at $P < 0.05$. Data normality was assessed with the Shapiro–Wilk test; when assumptions were not met, datasets were transformed or analyzed using methods appropriate for the underlying distribution. For each trait, descriptive statistics (means and standard deviations) were calculated, and graphical summaries were prepared to support interpretation and to visualize the treatment-related trends.

Results

The variability structure indicates that the AMMI analysis of variance for grain yield across the environments and varieties revealed the dominance of the genotype × environment (G×E) interaction, as the main source of variation. Specifically, the genotypes (G) accounted for 14.3% of the total sum of squares, environments (E) for 37.7%, whereas the G×E interaction contributed 48.0%. This distribution implies that variety performance is determined not only by genetic potential and not so much by general soil and climatic conditions, but primarily by the specific response of each genotype to particular growing conditions. In other words, the same variety may change its ranking across environments, and the advantages of certain genotypes may be reduced or, conversely, amplified depending on the environment. Therefore, evaluating genotypes only by mean yield, without considering the stability of trait expression, may lead to misleading conclusions: Cultivation of a genotype with a high mean yield can be risky due to strong fluctuations, whereas genotypes with more moderate yield levels may provide more predictable performance in plant production.

Under such circumstances, applying AMMI analysis is methodologically justified and practically meaningful, because it enables simultaneous assessment of productivity (yield level) and stability/adaptability of the studied genotypes. Unlike simple ranking based on the overall mean, AMMI helps clarify to what extent the yield of a given genotype depends on environmental variation and whether this dependence is directional (specific adaptation) or minimal (broad adaptation). Therefore, within multienvironment trials it is reasonable to classify varieties into universal (widely adapted) genotypes that show relatively stable performance across a wide range of conditions, and specifically adapted genotypes that express their maximum potential only in particular zones or under a defined set of agroecological factors. This approach has direct practical value because it reduces production risks and improves the efficiency of region-specific cultivar deployment.

Regarding the contribution of interaction principal components (IPC; PCA of the interaction), the first two components were found to explain the major share of structured G×E variability. In particular, IPC1 accounted for 40.63% of the interaction variance and IPC2 for 18.1%, providing IPC1 + IPC2 = 58.8%. This indicates that most reproducible G×E patterns are concentrated in the first two interaction dimensions; consequently, their use provides sufficiently informative interpretation both in the AMMI1 biplot (Mean vs. IPC1) and the AMMI2 biplot (IPC1 vs. IPC2). In practical terms, these components are especially useful to: identify broadly adapted genotypes (small IPC scores), distinguish genotypes with specific responses to particular environments (large absolute IPC scores), and determine environments that discriminate genotypes most strongly and generate contrasting responses (Table 1).

Thus, interpreting AMMI using the first two IPC components is sufficient to explain most meaningful G×E regularities and to support breeding and applied decisions for cultivar selection and recommendation. Inclusion of subsequent components (IPC3 and beyond) usually adds relatively little useful information for identifying superior varieties, because they more often capture minor, less stable, or random interaction fluctuations. For this reason, focusing on IPC1 and IPC2 represents an optimal compromise between completeness of G×E description and interpretability for breeding and practical variety testing.

If varieties are evaluated only by their multi-year mean yield across environments, without considering the specifics of their response to growing conditions (i.e., without analyzing stability and the pattern of trait expression), then the leaders for this trait (mean across 17 environments) are: LG Orlice (82.41), Bosporus (82.09), CHIKO (81.83), Khvylia Dnipra (79.93), LG Quadrant (78.72), MV Nador (78.59), and Pozytsiia Odeska (77.30) (Table 2). This approach is the simplest and most commonly used in practice, because at first glance it allows rapid identification of the highest-yielding genotypes. However, it essentially ignores the fact that the same high mean can arise through different pathways: either due to consistently good performance in most environments, or due to very high peaks in some environments accompanied by noticeable declines in other.

Table 1

Part of explained G×E interaction by IPC components

Component	Singular value	Share of interaction, %	Cumulative, %
IPC1	174.8935	40.6304	40.6304
IPC2	116.8408	18.1340	58.7645
IPC3	100.5391	13.4269	72.1914
IPC4	69.5984	6.4343	78.6257
IPC5	66.7492	5.9183	84.5440
IPC6	56.5005	4.2404	88.7844
IPC7	50.4919	3.3865	92.1709
IPC8	45.5121	2.7514	94.9223
IPC9	36.2825	1.7486	96.6709
IPC10	30.2607	1.2164	97.8873
IPC11	26.3842	0.9247	98.8120
IPC12	17.5352	0.4084	99.2204
IPC13	16.3030	0.3531	99.5734
IPC14	14.9226	0.2958	99.8692
IPC15	7.9695	0.0844	99.9536
IPC16	5.7199	0.0435	99.9971
IPC17	1.4867	0.0029	100.0000

Notably, the group of yield leaders includes cultivars of diverse origin, reflecting a broad ecogenetic diversity represented in the study: French (2), German (1), Hungarian (1), and Ukrainian (2) varieties. This makes it difficult to argue for the dominance of any single breeding direction or an unequivocal advantage of a particular breeding center. On the contrary, the observed pattern suggests that competitive genotypes can be developed within different scientific and breeding systems, and their success largely depends on how effectively they combine yield potential with adaptability to growing conditions. As a preliminary generalization, it can be stated that modern breeding overall meets production demands, as it is capable of generating materials with high yield potential for different agroecological zones and technology levels.

At the same time, focusing exclusively on mean yield may lead to undesirable destabilization of grain production, because some mean-yield leaders may exhibit strong specific responses to particular environments and to the conditions of individual years. In practice, this corresponds to situations where a cultivar performs exceptionally well under favorable conditions, but loses its ability to deliver stable yields when the weather scenario changes or when grown at another location. At the farm or regional scale, such behavior manifests as large fluctuations in total grain output: some seasons are peak years, while others are poor. From an economic perspective, this is highly undesirable because it increases risk, complicates planning, reduces predictability of profitability, and heightens sensitivity to both price and weather variability. Therefore, for production systems, the most valuable trait is often not maximum mean yield per se, but the ability of a cultivar to provide a reliable, predictable yield level across a wide range of conditions.

As practical experience and multienvironment trial results show, a more informative approach is to analyze genotypes in terms of stability, i.e., the extent to which productivity is minimally affected by specific genotype × environment interaction and is less mediated by external conditions. Within the AMMI framework, this is reflected in the IPC scores, and an integrated stability metric is ASV: The smaller the ASV value, the more stable the cultivar. In our case, ASV was calculated based on the IPC1/IPC2 relationship, weighted by the shares of explained interaction, which allows an appropriate weighting of the first and second interaction components in the overall stability assessment.

When moving from ranking by mean yield to ranking by ASV, the overall picture changes markedly. Some cultivars that were leaders by mean yield retain high positions, indicating a combination of high potential and relative stability. By contrast, other cultivars that appear highly productive on average may drop in the stability-based ranking if their high mean was achieved mainly through environment-specific peaks accompanied by strong fluctuations elsewhere. Conversely, cultivars that were not absolute leaders in mean yield may emerge as more stable and therefore more suitable for broad production deployment, especially under high weather variability. Thus, combining productivity and stability assessments (via ASV and integrated criteria such as YSI) is methodologically and practically more justified than relying solely on mean yield values.

A particularly convincing outcome of the stability assessment is that the best variety according to ASV was MIP Roksolana (ASV = 14.44), the most stable genotype in the entire set. Notably, this variety was not included in the top group based on mean yield, although its productivity is not critically lower than that of the leaders and it shows a clearly competitive average performance. This is a typical situation in multienvironment data: Genotypes that do not always rank at the very top by mean yield may prove most valuable from the standpoint of stability, because they exhibit minimal yield fluctuations across environments and years.

Table 2
Assessment of the principal components of variability and ranking of varieties by grain yield

No.	Variety	Yield 2022–2024, t/ha	Origin	IPC1	IPC2	ASV	YSI
1	Perlyna	67.88 ± 1.37	UA	-19.47	19.80	21.63	36
2	Pozytsiia Odeska	77.30 ± 1.20	UA	-26.54	14.32	18.59	15
3	Tika Taka	73.54 ± 1.04	RO	-25.63	-66.64	67.62	40
4	Tenor	73.54 ± 1.31	UA	62.43	-44.53	52.54	40
5	MIP Nika	74.21 ± 1.24	UA	47.67	-0.31	21.28	27
6	MIP Roksolana	76.09 ± 1.27	UA	-15.24	-12.73	14.44	15
7	MIP Feieriia	72.71 ± 1.16	UA	36.47	29.07	33.32	37
8	MV Mente	76.91 ± 1.22	HU	-34.66	36.87	39.99	29
9	MV Nador	78.59 ± 1.31	HU	-22.05	-36.57	37.88	25
10	MV Menrot	74.66 ± 1.17	HU	-22.54	26.72	28.55	29
11	Bosporus	82.09 ± 1.33	GE	57.14	13.10	28.67	18
12	Vezha	70.90 ± 1.35	UA	0.97	-19.81	19.82	32
13	Vitalina	74.14 ± 1.19	UA	-22.23	15.97	18.81	26
14	Setar	76.67 ± 1.09	UA	-23.38	14.39	17.78	16
15	Khvylia Dnipra	79.93 ± 1.14	UA	80.69	16.69	39.69	24
16	CHIKO	81.83 ± 1.35	GE	-37.70	8.159	18.70	12
17	LG Orlice	82.41 ± 1.32	FR	-33.51	8.24	17.08	7
18	LG Quadrant	78.72 ± 1.24	FR	-36.18	0.65	16.16	10
19	LG Magirus	71.52 ± 1.26	FR	-21.87	-27.30	28.99	37
20	LG Litopys	69.45 ± 1.18	FR	61.09	4.78	27.68	36

Note: UA – Ukraine, RO – Romania, HU – Hungary, GE – Germany, FR - France.

Next, the group of the most stable varieties (in ascending order of ASV) includes: LG Quadrant (ASV = 16.16) – a cultivar that was already present among the leaders by mean yield; LG Orlice (ASV = 17.08), also among the mean-yield leaders, proving to be highly stable; Setar (ASV = 17.78), a new entry among stable genotypes; Pozytsiia Odeska (ASV = 18.59), present in the previous mean-yield group; and CHIKO (ASV = 18.70), one of the high-yielding cultivars under the initial (mean-based) evaluation, which also demonstrates a good level of stability. Thus, the transition from simple mean-yield ranking to stability assessment (ASV) shifts the emphasis: some leaders retain their positions, but new important genotypes emerge that may be less focused on peak-yield yet are more predictable.

Importantly, when ranking by stability, the overall positions of the varieties of Ukrainian breeding strengthened: Two new Ukrainian varieties appeared in the upper part of the list, whereas representatives of Hungarian and German breeding disappeared (in the context of stability). At the same time, the cultivars of French breeding remained in the updated set, for which greater universality and more uniform grain productivity across environments and years were confirmed. This pattern may be interpreted as evidence that some foreign genotypes show substantial potential but do not always ensure equally predictable realization of that potential across all testing environments. By contrast, Ukrainian varieties appear better adapted to the diversity of local environments represented within the studied network.

To obtain an integrated assessment of the yield–stability compromise, the YSI approach was applied (yield rank + stability rank; lower is better). This criterion is particularly convenient in practical breeding because it helps avoid selecting either a very high-yielding but unstable cultivar or a very stable but only moderately productive one. According to YSI, the most promising widely adapted universal varieties are LG Orlice, with the highest mean yield (82.41) combined with high stability (ASV 17.08); LG Quadrant, with high yield (78.72) and very good stability (ASV 16.16); CHIKO, with high yield (81.83) and good stability (ASV 18.70); and MIP Roksolana, with record-high stability (ASV 14.44) a good mean yield level (76.09). If broadly adapted varieties are required for a wide range of conditions, then based on YSI ranks the primary recommendations are LG Orlice, LG Quadrant, and CHIKO, while MIP Roksolana should be considered a stability optimum and a risk-buffering component of the variety set.

Thus, the most universal genotypes combining a high mean yield with relative stability in this dataset are: LG Orlice (mean-yield leader and simultaneously one of the most stable), CHIKO, LG Quadrant, and MIP Roksolana (absolute leader in stability under sufficiently high yield). In production terms, this means these cultivars can provide not only high potential but also greater predictability of outcomes. From a geographical (ecotype) perspective, they can be regarded as well aligned with the zonal conditions of the Forest-Steppe–Polissia transition (based on the nature of the testing environments) and therefore can serve as the core of the cultivar structure for broad deployment. If a reliable cultivar set for multiple zones is needed, the first candidates to consider are LG Orlice, CHIKOб and LG Quadrant, complemented by MIP Roksolana as a stabilizing component that reduces the risk of yield failures in unfavorable years.

A concise characterization of these universal cultivars may be summarized as follows: LG Orlice was the best combination of maximum mean yield and high stability, i.e., a first-choice variety; CHIKO produced consistently high yield across zones, making it suitable for large-scale adoption; LG Quadrant was strong, productive, and at the same time fairly stable, effectively a benchmark of balance; MIP Roksolana was the most stable according to AMMI coordinates (minimal specific interaction), with a good mean yield level, which makes it especially valuable where predictability is critical. Practically, combinations involving the third and fourth cultivars (LG Quadrant + MIP Roksolana) may provide the most reliable outcome, whereas the first and second (LG Orlice + CHIKO) offer greater opportunity to maximize yield under favorable conditions.

Separately, a group of specifically adapted varieties should be highlighted. These genotypes exhibit strong G×E interaction (large deviations in the AMMI2 space), meaning they can achieve peak yields in certain environments but are less predictable on average across the testing network. This group includes Khvylia Dnipra, Tika Taka, Tenor, LG Litopys, Bosporus, and MIP Nika. They should not be interpreted as inferior; rather, they are candidates for local recommendations, when it is known that a farm operates under a specific type of conditions where these cultivars have an advantage. Among them are three varieties of Ukrainian breeding from different breeding centers (Forest-Steppe and Steppe ecotypes) and one variety each of Romanian, French, and German breeding. The overall tendency suggests that specifically adapted cultivars are predominantly of an intensive type, better suited to conditions of moderate (rather than insufficient) moisture supply and relatively mild winters (five out of six). Therefore, based on AMMI2 patterns, these genotypes should be considered tools for precise zonation: They may be more promising in particular environments, but they require more careful matching of location and management to avoid undesirable yield declines under less suitable conditions (Figure 1; variety numbering in the figure follows Table 2).

These varieties are mainly characterized by large IPC scores and, consequently, are located far from the origin in the AMMI2 biplot (IPC1 × IPC2). This spatial pattern is not accidental: A greater distance from zero indicates a strong environment-specific response, i.e., a pronounced genotype × environment (G×E) interaction. In practical terms, such genotypes may achieve very high (peak) yield levels in certain environments where their response pattern matches the prevailing combination of soil–climatic and management conditions. At the same time, their performance may decline substantially in other environments, making these varieties less predictable and generally less stable both across the entire testing network and when transferred to new or contrasting conditions.

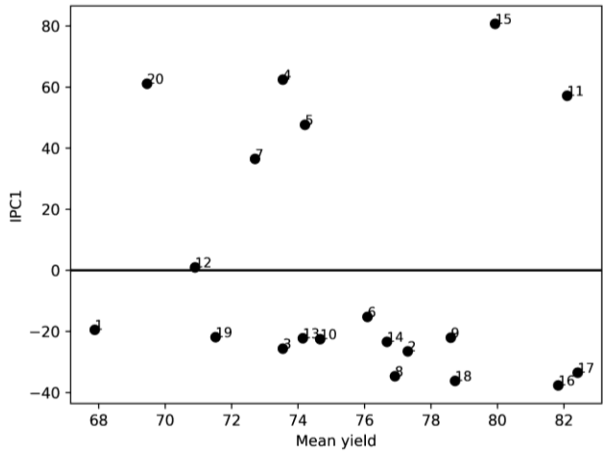

Fig. 1. Variety classification plot based on vectors AMMI1

The analysis showed that the listed genotypes differ in the dominance of particular interaction components. For example, Khvylia Dnipra has a very large IPC1 score, indicating a strong response to the primary environmental gradient that accounts for the largest part of G×E (e.g., differences in moisture supply, temperature regime, or mineral nutrition level). By contrast, Tika Taka is characterized by a large IPC2 score, meaning that its adaptability is associated with the second independent interaction direction, which often reflects another complex of limiting factors (for instance, overwintering conditions, contrasts in spring regrowth, differences among soil types, or specific agronomic practices). The varieties Tenor, LG Litopys, Bosporus, and MIP Nika are also clearly displaced in the AMMI2 space, i.e., they have substantial values for IPC1 and/or IPC2. This indicates pronounced specific adaptation: They perform best not universally, but in particular combinations of conditions where their reaction norms coincide with the environmental profile of a given agroecosystem.

Therefore, these varieties should be viewed not as universal options but as tools for targeted, zone-specific deployment. They are recommended for use only under those agroecological conditions where their advantage has been confirmed, preferably on a limited share of the sown area (15–20%) to combine yield maximization with risk control. From a production standpoint, this corresponds to a diversification strategy: Most of the area is planted with universal and stable cultivars, while a smaller proportion is allocated to high-potential but more demanding genotypes capable of delivering record yields under favorable scenarios (Figure 2; variety numbering in the figure follows Table 2). Such an approach allows farms to increase overall production efficiency while minimizing the probability of undesirable yield losses in years or locations where conditions fall outside the optimum for these specifically adapted cultivars.

An additional aspect of strong practical relevance is the assessment of environment representativeness and discriminating ability with respect to the evaluated variety set, especially when considered across the major geographical zones (Steppe, Polissia, and Forest-Steppe) and their regional specificities. In multienvironment trials, an environment plays a dual role: On the one hand, it determines the overall productivity background (i.e., how high the general yield level can be expressed across the tested genotypes), and on the other hand, it determines how strongly it differentiates genotypes, that is, whether it can clearly classify varieties by productivity or, conversely, smooths differences and makes rankings less contrasting. Therefore, environmental evaluation is important not only for interpreting results, but also for optimizing the testing network and substantiating zone-specific recommendations.

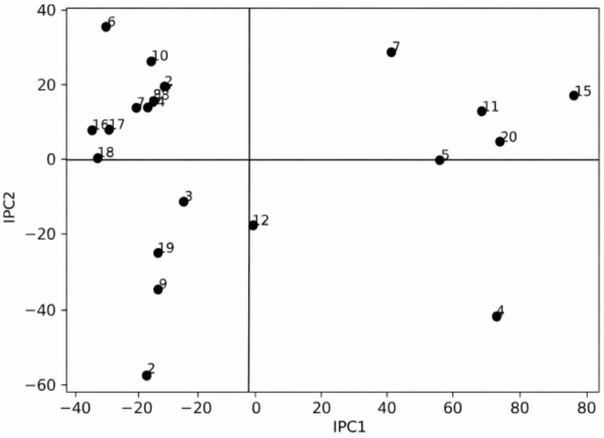

Fig. 2. Variety classification plot based on vectors AMMI2

The results showed that the most productive environments (i.e., those providing a high mean yield background across the entire cultivar set) are distributed in a zonally consistent pattern. In the Steppe, the highest mean background was recorded in Odesa Oblasts, whereas in the Forest-Steppe it was observed in the Sumy, Cherkasy, Kharkiv, and Vinnytsia regions. Overall, this aligns with the established knowledge of the optimal soil and climatic conditions for winter wheat in Ukraine: These regions typically combine favorable moisture availability during critical developmental stages, relatively high soil fertility, and a comparatively stable temperature regime. Consequently, such environments often allow varieties to express their maximum yield potential, making them important for demonstrating the upper yield ceiling within the trial system (Fig. 3).

At the same time, it is essential to emphasize that high environmental productivity does not necessarily imply representativeness or stability in terms of G×E. An environment may be highly productive on average while still reshaping cultivar rankings if it is strongly contrasting or includes specific limiting factors that affect genotypes differently. Therefore, to evaluate representativeness and proximity to an average or theoretically optimal environment, it is appropriate to use the environment vector length in the AMMI2 space, calculated as $\sqrt{(IPC1^2 + IPC2^2)}$. The shorter this vector (i.e., the closer the environment point is to the origin), the smaller the contribution of this environment to specific interaction effects, and the more neutral or representative it can be considered (Fig. 4).

Based on vector length (and thus proximity to the theoretically optimal or average environment), the most representative environments were: Chernihiv (Polissia), Khmelnytskyi (Polissia), Lviv (Polissia), Chernivtsi (Forest-Steppe), and Volyn (Polissia). Practically, this means that these locations provide a background in which cultivar differences are expressed in a more averaged manner, without an excessive influence of environmental extremes. In other words, they shift rankings less and allow a more objective assessment of the baseline productivity of cultivars. Among them, the environment of Chernihiv Oblast had the shortest vector, making it particularly convenient as a reference (anchor) environment for initial cultivar comparisons (environment numbering in the plots corresponds to Table 3).

From a practical perspective, environments with short vectors are extremely useful as benchmark sites for primary yield-based ranking, because genotype × environment interaction exerts a smaller influence there; consequently, the resulting ranking is more stable and less accidental with respect to the specifics of a given location. Such environments can serve as baseline points for developing general recommendations, verifying the potential of new breeding lines, and evaluating productivity without strong distortion by location-specific factors. By contrast, environments with long vectors (far from the origin) are best used as discriminating environments, i.e., those that better reveal differences among genotypes and help identify cultivars with specific adaptation. Taken together, these findings confirm that an optimal testing network should include high-productivity environments, representative/benchmark environments, and contrasting (highly discriminating) environments to provide a comprehensive characterization of cultivar resources.

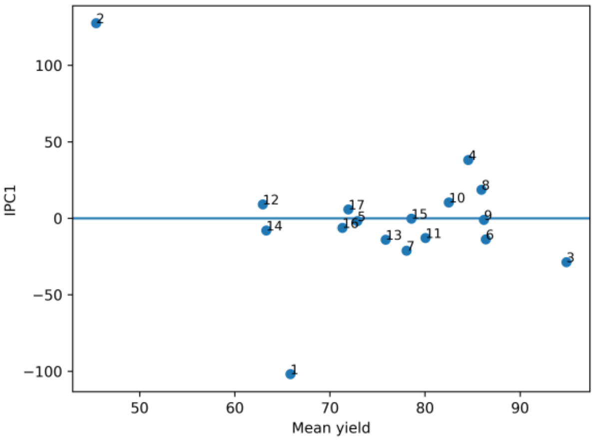

Fig. 3. Environmental classification plot based on vectors AMMI1

The most discriminating environments (i.e., those that best separate varieties by the expression level of the trait, provide clear differentiation among genotypes, yet at the same time generate highly specific responses) were observed to be the following. Kirovohrad (Steppe) was the strongest classifying environment in terms of genotype × environment interaction, followed by Dnipropetrovsk (Steppe), Kharkiv (Forest-Steppe), Cherkasy (Forest-Steppe) and Kyiv (Forest-Steppe). Their key characteristic is the largest vector length in the AMMI2 space, reflecting a strong contribution of G×E (high values of $\sqrt{(IPC1^2 + IPC2^2)}$). Practically, this means that under these conditions varieties respond most differently: Differences among genotypes become more contrasted, and variety ranking becomes more sensitive to the specific factors of a given environment.

For this reason, such environments are extremely useful for breeding and applied tasks related to identifying specific adaptation and performing a kind of stress test of genotypes. They make it easier to determine what varieties gain an advantage under a particular complex of limiting factors (drought, temperature fluctuations, contrasting overwintering conditions, unstable spring regrowth), as well as what genotypes lose productivity sharply in response to these stresses. In other words, discriminating environments help reveal differences that may be smoothed out under more representative conditions. Moreover, these locations are especially suitable for testing ecological plasticity and identifying genotypes capable of maintaining productivity when conditions deviate strongly from the optimum.

At the same time, the reverse side of their value should also be emphasized: Environments with the largest vector length can substantially change the overall cultivar ranking, because they create specific advantages for some genotypes and penalties for others. This implies that relying only on results from such locations, without considering representative environments, may bias recommendations. In an applied sense, these environments should be treated as targeted sites: Rather than reproducing the average background, they amplify the expression of particular adaptive mechanisms and allow more precise selection of genotypes for specific agroecological niches.

This is especially important because several varieties in the study exhibited pronounced specific adaptation (notably Khvylia Dnipra, Tika Taka, Tenor, LG Litopys, Bosporus, and MIP Nika). For such genotypes, discriminating environments have the highest diagnostic value: They help capture the locations and condition profiles where these cultivars can deliver peak yield levels, while also identifying situations in which their performance becomes less stable. Accordingly, for zonation and the formulation of targeted recommendations, it is advisable to rely specifically on results from these environments in order to match each cultivar as accurately as possible to the agroecological profile where its advantage is realized most effectively (Fig. 4). Thus, the Kirovohrad, Dnipropetrovsk, Kharkiv, Cherkasy, and Kyiv environments can be regarded as key indicator locations within the testing network, they simultaneously function as strong cultivar classifiers and as effective platforms for assessing adaptability, yet they require cautious interpretation in overall rankings. The optimal strategy for using such environments is to combine them with more representative locations: The former are used to detect specific responses and select for adaptability, whereas the latter are used to validate universality and stability of cultivars under average plant production conditions.

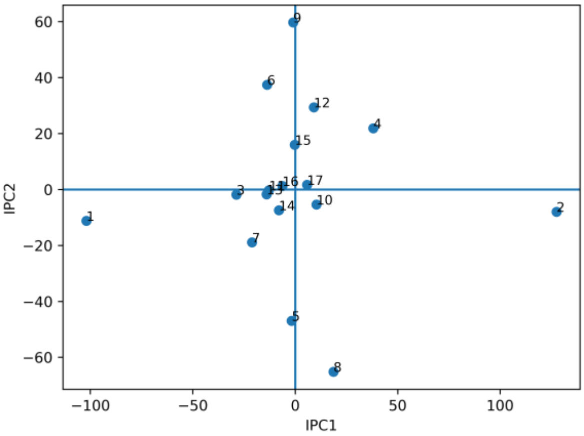

Fig. 4. Environmental classification plot based on vectors AMMI2

The results of the AMMI analysis of the multienvironment trial clearly demonstrated a pronounced dependence of variety yield on climatic conditions, confirming the dominance of the genotype × environment (G×E) interaction in shaping productivity. This means that the superiority of a given cultivar is not constant and can change substantially depending on the specific combination of seasonal meteorological conditions, soil properties and regional characteristics of the agronomic background. Under such circumstances, the AMMI approach is especially useful because it allows not only ranking cultivars by mean yield, but also interpreting adaptability and specificity of response across zones, thereby directly increasing the practical value of the results for zonal variety testing and production recommendations. A clear zonal differentiation of cultivar adaptability was observed (Table 3), with different genotypes showing advantages in different agroclimatic zones and rankings within zones.

Among the Steppe environments (Dnipropetrovsk, Kirovohrad, and Odesa branches), the varieties CHIKO and LG Orlice showed the highest and, at the same time, relatively stable performance, ranking among the leaders in two of the three environments. Such repeated leadership indicates that these genotypes possess a set of traits particularly important for the Steppe conditions, namely the ability to maintain productivity under limited moisture supply, tolerate temperature stresses, and realize yield potential more efficiently in environments characterized by high variability throughout the growing season. Therefore, CHIKO and LG Orlice should be considered primary candidates for broad deployment in the dry and contrasting conditions of the Steppe zone, especially in farming systems where not only maximum yield levels, but also yield predictability at the seasonal and regional scales, are critical.

At the same time, the analysis showed that the Kirovohrad environment is the most discriminating one, i.e., a site where the expression of G×E is maximally contrasting and cultivar rankings undergo the strongest reshuffling. In this environment, Khvylia Dnipra gained the advantage, while Bosporus and Tenor also displayed high potential. This outcome is important because it points not merely to a random productivity spike, but to signs of a specific adaptation of these genotypes to conditions typical of the central Steppe, where sharp temperature fluctuations, uneven precipitation distribution, and elevated risks of spring-summer stress events often co-occur. In practical terms, this implies that Khvylia Dnipra, as well as Bosporus and Tenor, may be particularly effective under targeted (local) conditions where their advantages are realized most fully; however, they should be recommended with consideration of their higher response specificity and the potential variability of performance in other Steppe environments.

Thus, within the Steppe zone, two logical variety groups can be distinguished: more universal and stable cultivars suitable for broad deployment, primarily CHIKO and LG Orlice, which demonstrate repeatable superiority across most Steppe locations; and specifically adapted varieties suited to the most contrasting conditions (notably those represented by the Kirovohrad environment), such as Khvylia Dnipra, Bosporus, and Tenor, which are best used as tools for targeted zonal placement or on a portion of the sown area to maximize yield under the appropriate agroecological environment profile.

Table 3

Relative ranking of varieties depending on the environment

No.	Region	Zone	TOP-1	TOP-2	TOP-3
1	Dnipropetrovsk	Steppe	CHIKO	LG Orlice	LG Quadrant
2	Kirovohrad	Steppe	Khvylia Dnipra	Bosporus	Tenor
3	Odesa	Steppe	CHIKO	LG Orlice	LG Quadrant
4	Vinnytsia	Forest-Steppe	Khvylia Dnipra	Bosporus	MIP Feieria
5	Kyiv	Forest-Steppe	Tika Taka	MV Nador	Tenor
6	Sumy	Forest-Steppe	Bosporus	Khvylia Dnipra	LG Orlice
7	Ternopil	Forest-Steppe	Bosporus	LG Orlice	CHIKO
8	Kharkiv	Forest-Steppe	Bosporus	Khvylia Dnipra	CHIKO
9	Cherkasy	Forest-Steppe	Bosporus	Khvylia Dnipra	LG Orlice
10	Chernivtsi	Forest-Steppe	LG Orlice	CHIKO	Bosporus
11	Volyn	Polissia	LG Orlice	CHIKO	Bosporus
12	Zakarpattia	Polissia	LG Orlice	CHIKO	MV Mente
13	Ivano-Frankivsk	Polissia	LG Orlice	CHIKO	Bosporus
14	Lviv	Polissia	LG Orlice	CHIKO	LG Quadrant
15	Rivne	Polissia	LG Orlice	CHIKO	Bosporus
16	Khmelnytskyi	Polissia	LG Orlice	CHIKO	Pozytsiia Odeska
17	Chernihiv	Polissia	LG Orlice	CHIKO	Bosporus

In the Forest-Steppe environments, a pronounced differentiation in genotype responses was observed, which is typical for a zone with high internal heterogeneity. This zone combines differences in soil types, moisture availability during critical growth stages, contrasts in temperature regimes, and varying levels of agronomic intensification among regions. As a result, variety ranking can change substantially from one environment to another, and the advantage of particular genotypes is expressed unevenly. Nevertheless, despite this variability, the cultivars most frequently appearing among the leaders in Forest-Steppe environments were Bosporus, Khvylia Dnipra, LG Orlice and CHIKO. Therefore, they can be considered high-yielding cultivars with good adaptability to conditions of moderate moisture supply and relatively fertile soils. Their frequent inclusion among the top performers indicates an ability to realize high yield potential under favorable conditions while remaining competitive in years with moderate stress (intermittent droughts, temperature fluctuations, and uneven precipitation).

At the same time, clear environment-specific patterns were evident within the Forest-Steppe, some locations had their own favorites that gained an advantage due to a unique combination of local factors. For instance, in the Kyiv environment, the best results were shown by Tika Taka, MV Nador, and Tenor. This may indicate that in this particular agronomic background, considering soil parameters, water regime, sowing dates, nutrient supply, or the seasonal weather pattern, these genotypes express their adaptive properties most fully. This means that, alongside universal leaders, there are grounds in the Forest-Steppe for targeted cultivar selection tailored to specific farm conditions: If a producer operates under similar agroecological parameters, such locally superior genotypes should be taken into account. However, for zone-wide recommendations, priority should be given to varieties that demonstrate consistently high productivity across most Forest-Steppe environments, primarily Bosporus, Khvylia Dnipra, LG Orlice, and CHIKO.

A different pattern is characteristic of Polissia environments greater uniformity of rankings and less variation in leaders among locations. In virtually all environments, LG Orlice and CHIKO dominate, demonstrating consistently high yield levels under conditions of increased moisture and less fertile soils. This repeatability reflects their strong adaptation specifically to this type of environment, where key determinants may include tolerance to excess moisture, the ability to maintain productivity on more acidic or lighter soils, and efficient utilization of nutrients under less favorable fertility conditions. In effect, these two varieties can form the core of the cultivar set for Polissia as the most reliable components, minimizing the risk of yield reduction in years with unfavorable weather conditions.

In addition to LG Orlice and CHIKO, the varieties Bosporus and LG Quadrant are also promising for Polissia and may be used as high-yielding components of the cultivar structure, particularly to diversify plantings and strengthen yield potential in favorable seasons. They are advisable as complements to the main leaders, especially when a farm seeks to combine stability with the possibility of maximizing performance. Thus, for Polissia, an approach can be recommended in which LG Orlice and CHIKO serve as the base varieties for broad use, while Bosporus and LG Quadrant are promising options for expanding the cultivar set and increasing overall productivity, provided that agronomic practices and the local production background are appropriately matched.

Discussion

Multienvironment variety testing is a key tool for assessing the adaptability of genotypes to diverse soil and climatic conditions. The AMMI analysis showed that the largest share of the total variance was explained by the genotype × environment interaction (G×E), which exceeded the contributions of both genotypes and environments considered separately (Abdelghany et al., 2024). Such a variance structure is typical of field experiments conducted under contrasting agroecological conditions in Ukraine and indicates substantial changes in cultivar rankings depending on the growing location. The dominant role of G×E confirms the need for approaches focused not only on mean yield, but also on adaptability and stability, because interaction effects largely determine shifts in cultivar ranking across locations and years. The obtained results are practically important for improving the accuracy of cultivar recommendations and minimizing production risks under climatic instability, since correct matching of cultivars to specific agroecological zones can ensure more predictable yield returns and higher economic efficiency of plant production technologies (Jha et al., 2017).

A high contribution of genotype–environment interaction implies that mean yield cannot serve as the sole criterion for cultivar evaluation. In such cases, the AMMI model enables simultaneous assessment of overall genotype productivity, stability, and specific adaptation to particular conditions (Ejaz et al., 2023; Mullualem et al., 2024). Among the tested genotypes, the highest mean yields were recorded for LG Orlice, CHIKO, Bosporus, Khvylia Dnipra, and LG Quadrant. These cultivars are characterized by high yield potential and may be considered sources of enhanced productivity for breeding programs (Ahmadi et al., 2012; Cohen et al., 2021). Special attention should be given to LG Orlice, which ranked among the leaders in most environments and demonstrated the broadest adaptability.

Evaluation of IPC scores indicated that the most stable genotype was MIP Roksolana. This variety is characterized by minimal interaction with the environment, reflecting high ecological plasticity. Despite a somewhat lower mean yield compared with the leaders, it may be recommended for farms operating under unstable weather conditions (Abebe et al., 2024). Such stability is a key attribute of broadly plastic varieties that can reduce production risks in years with stress factors (drought, temperature extremes, limited moisture during critical developmental stages) (Murphy et al., 2020; Bhandari et al., 2026). From a practical perspective, MIP Roksolana can be recommended as a risk-buffering component of variety portfolios, especially for farms facing high weather variability or limited capacity for intensive technological support (Mullualem et al., 2024). The group of relatively stable varieties also included LG Quadrant, CHIKO, and LG Orlice. Considering the combination of high yield and stability, the most promising varieties were LG Orlice, CHIKO, and LG Quadrant. These genotypes demonstrate the ability to produce high yields under diverse agroecological conditions and can be regarded as universally adapted varieties suitable for broad deployment. Such genotypes are most appropriate for large-scale adoption in production systems where predictability under varying weather scenarios is essential, and they can underpin regional recommendations at the level of administrative regions and agroclimatic zones. The presence of a group of universal varieties is critical for improving the stability of grain production, because it reduces dependence of final outcomes on local extremes and enhances the resilience of agricultural systems under climate change (Dehghani et al., 2017; Bhandari et al., 2026). Their performance indicates a high capacity to realize yield potential under favorable and moderately stressful conditions, making these genotypes promising both for production use and as parental material in breeding programs aimed at combining high output with adaptability (Bishwas et al., 2021). Importantly, such varieties can form the core of on-farm varietal structures, as they allow maximum yield levels when agronomic practices are optimized and resources are adequately supplied (Kebede et al., 2023).

Several genotypes exhibited pronounced response specificity, indicating suitability for cultivation in particular conditions. The most clearly specifically adapted varieties were Khvylia Dnipra, Tika Taka, Tenor, LG Litopys, Bosporus, and MIP Nika. Such cultivars may deliver exceptionally high yields under favorable conditions, but they are not always stable across other regions. Specific adaptation is a valuable trait if used correctly: Such cultivars can provide maximum returns in their target conditions or under specific technological packages, but may lose advantage when transferred to other environments (Urbanaviciute et al., 2024). Therefore, they are best recommended as elements of targeted technologies or local production niches (e.g., after the best preceding crops, under increased fertilization, or under irrigation), where their advantages can be realized most fully (Güngör et al., 2024).

Steppe environments are characterized by highly contrasting conditions and substantial yield variability. In the Dnipropetrovsk and Odesa regions, the best performance was shown by CHIKO, LG Orlice, and LG Quadrant, whereas Kirovohrad proved to be the most discriminating environment, where Khvylia Dnipra, Bosporus, and Tenor dominated. This reflects the specific conditions of the central Steppe, drought, temperature stress, and unstable moisture supply. The Forest-Steppe environments generally exhibited the highest production potential, and the most frequent leaders were Bosporus, Khvylia Dnipra, LG Orlice, and CHIKO. In the Kyiv environment, specifically adapted varieties such as Tika Taka, MV Nador, and Tenor performed best, which may be related to local soil patterns and agronomic background. The Polissia zone is characterized by more uniform conditions and increased moisture availability (Nazarenko et al., 2019). In virtually all the Polissia environments, LG Orlice and CHIKO dominated. Additional promising cultivars included Bosporus, LG Quadrant, and MV Mente. The stability of results in Polissia indicates good adaptation of these cultivars to sufficiently moist conditions (Taherian et al., 2024). This zonal grouping indicates that cultivar performance is determined not only by yield potential, but also by the match between adaptive traits and the leading limiting factors of each zone (moisture availability, temperature regime, length of the growing season, and soil fertility) (Nazarenko et al., 2022). The practical significance of these results lies in their potential use for optimizing varietal zoning, improving resource payback, and developing more precise recommendations for cultivar placement across farms in different zones (Saeidnia et al., 2023; Dang et al., 2024). In addition, this provides a basis for developing differentiated agronomic approaches (sowing dates, fertilization level, stand density regulation) that can enhance expression of cultivar potential under specific conditions (Yan, 2024). Overall, the data confirm the necessity of a zonal approach to cultivar deployment. Universally adapted genotypes can be used as the baseline, whereas specifically adapted ones can be employed to maximize yield potential in particular regions.

Conclusion

It was established that within the multienvironment testing system, the genotype × environment (G×E) interaction is the main source of variation in the yield of winter wheat. Among the evaluated genotypes, the highest-yielding varieties were LG Orlice, CHIKO, Bosporus, Khvylia Dnipra, and LG Quadrant. The most stable genotype was MIP Roksolana, characterized by minimal dependence of yield on growing conditions. Based on the combination of productivity and stability, the following widely adapted “universal” cultivars were identified: LG Orlice, CHIKO, and LG Quadrant. Zonal patterns of adaptability were also established: CHIKO, LG Orlice, and Khvylia Dnipra for the Steppe; Bosporus, Khvylia Dnipra, LG Orlice, and CHIKO for the Forest-Steppe; and LG Orlice, CHIKO, and Bosporus for Polissia. A number of varieties (Khvylia Dnipra, Tika Taka, Tenor, LG Litopys, Bosporus, and MIP Nika) showed specific adaptation to certain conditions, which should be taken into account when planning zone-specific variety placement. Future research perspectives include a deeper investigation of the causal nature of genotype-environment interaction by integrating multienvironment trial results with agrometeorological and soil covariates, which would allow adaptability to be interpreted not only statistically, but also in physiological and agronomic terms. Expanding the temporal scope of the dataset (including additional contrasting years) is advisable to increase the reliability of stability conclusions and to test cultivar responses under extreme weather scenarios. Another direction is refinement of zonal recommendations at the subzonal level and identification of benchmark environments that best discriminate genotypes and can serve as key locations within the testing network. The importance of the present study lies in its applied focus, the results directly support decision-making in variety policy, improve the efficiency of cultivar rotation, and contribute to stabilizing winter wheat grain production in Ukraine under conditions of increasing climatic variability.

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