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MULTI-ENVIRONMENT EVALUATION OF NEW WINTER WHEAT VARIETIES

SUMMARY

The stability of winter wheat yield formation under increasing contrasts in climatic and agronomic factors is determined not only by the hereditary potential of a variety, but also by the nature of its response to the environment. The present study used the results of a multi-environment trial of 15 winter wheat varieties in 17 regional testing sites during 2023-2025. The aim of the study was to identify varieties with high productivity, stable response and specific adaptation. For the Steppe zone, the most localized recommendations are required because high internal contrast was observed within the zone. The Forest-Steppe is characterized by a combination of high productivity and internal heterogeneity and therefore requires multi-location testing. Polissia had a more clearly expressed core of repeatedly leading varieties. The most representative environments were Sumy, Chernihiv, Chernivtsi, Khmelnytskyi, Kharkiv, Volyn and Rivne; the most discriminating were Kirovohrad, Dnipropetrovsk, Lviv, Ivano-Frankivsk, Vinnytsia, Kyiv and Ternopil. From a production standpoint, MIP Aelita can be considered the most balanced variety, Epitet as a high-yielding and sufficiently stable variety, MIP Dovira and Virnist Odeska as varieties with very high potential for suitable environments. Etual and Zahadka Odeska are of interest as sources of a stable response, whereas KVS Yuniversum, KVS Ultim, ZU VERMILLON and Momentum forms with specific adaptation.

Keywords: variety, winter wheat, environment, AMMI analysis, productivity, adaptability, yield stability

INTRODUCTION

Stable grain production and the economic efficiency of growing major agricultural crops remain among the key tasks of modern breeding and crop production. For winter wheat varieties, it is no longer sufficient to demonstrate high yield potential only under optimal conditions (Abebe *et al.*, 2024). Such

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stability of yield realization determines not only the economic value of a variety but also the effectiveness of applying modern elements of cultivation technology (Nazarenko *et al.*, 2023). At the same time, the same variety may perform differently depending on the conditions of the year, the characteristics of a particular testing environment 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 an unstable varietal response is genotype-environment interaction. Therefore, evaluation based only on mean yield often does not provide a complete picture of the actual economic and breeding value of a variety, especially under conditions of pronounced environmental heterogeneity and increasing climatic instability (Saeidnia *et al.*, 2022). Detailed analysis of genotype-environment interaction reduces the probability of excluding valuable varieties with specific adaptation and increases the reliability of recommendations for their placement in specific growing zones (Gupta *et al.*, 2023).

AMMI and GGE biplot models occupy a special place because they are based on the use of principal components to reveal the structure of genotype-environment interaction (Yan, 2024; Gungor *et al.*, 2024; Nirmalaruban *et al.*, 2026). Traditional analysis of variance allows the overall effects of genotype, environment and their interaction to be estimated, but it does not show the internal structure of the interaction itself. In contrast, principal component analysis effectively reflects complex patterns of variability, but it does not directly account for the main additive effects. The combination of these two approaches forms the basis of the AMMI model, which integrates the advantages of ANOVA and PCA into a single analytical scheme (Ye *et al.*, 2019). This makes it possible to separate stable and reproducible interaction patterns from random noise and thereby substantially improve the interpretability of the obtained results (Murphy *et al.*, 2020).

The results of AMMI analysis are especially important because they allow genotypes to be compared not only by mean yield level, but also by the nature of their adaptive features. AMMI allows the environments themselves to be assessed in terms of representativeness, contrast and their ability to differentiate varieties (Dang *et al.*, 2024). This provides a basis for a more rational testing system through the selection of the most informative environments and conditions for yield evaluation (Nazarenko *et al.*, 2019; Brkovic *et al.*, 2025). For winter wheat, short-term but intense stress effects, uneven precipitation distribution and disruptions of normal overwintering are becoming increasingly important. The situation is further complicated by increased susceptibility of crops to diseases, because weakened and uneven plant development creates additional risks (Omran *et al.*, 2022; Iwanska *et al.*, 2025). Genetic improvement programs should focus on developing varieties that combine sufficient yield potential with resistance to stress factors and a lower risk of substantial losses in unfavorable years (Nazarenko *et al.*, 2023; Mohammadi *et al.*, 2025).

The aim of the present study was to determine the extent to which 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 aim 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 (Urbanaviciute *et al.*, 2024). This is especially important because different varieties may realize their potential in different ways: some perform better under optimal conditions, whereas others are characterized by more stable expression of the trait under stress conditions (Abebe *et al.*, 2024).

Accordingly, the study was aimed at identifying two key categories of varieties as elements of cultivation technology. The first includes broadly adapted varieties characterized by relatively stable yields across environments and, consequently, lower production risk (Murphy *et al.*, 2020). The second includes genotypes with specific adaptation that can outperform other forms under particular conditions.

MATERIAL AND METHODS

The study was based on a multienvironment trial of 15 winter wheat varieties Soliflor KS, KVS Yuniversum, KVS Ultim, ZU VERMILLON from Germany; Epitet, Tvorchist Odeska, Etual, Virnist Odeska, MIP Dovira, Zahadka Odeska, MIP Aelita from Ukraine, Momentum, Obivan, CO1914, Papillon from France. The accounting plot area was 20 m², and the trial was arranged in three replications. The experiment was conducted over 2023–2025. In all environments, black fallow was used as the preceding crop and crop management practices followed the agronomic recommendations generally accepted for the corresponding soil and climatic conditions of each growing zone. The experimental data were analyzed using a combined analysis of variance and an additive main effects and multiplicative interaction model.

Grain yield was recorded in three replications for each combination of year, genotype and testing environment. 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),

Khmelnyskyi 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 2023 harvest year may be considered the most favorable and closest to a moderately typical background, especially for the Forest-Steppe and Polissia zones. The 2024 harvest year was affected by autumn drought during sowing and early development in the central and southern regions 40–60% from normal rainfall was recorded; air temperature exceeded the norm by 2–4 °C.

The 2025 harvest year was formed under a moisture deficit at the start of the growing cycle in Steppe and partly Forest-Steppe (Sumy, Kharkiv regions) zones. However, overwintering conditions were generally satisfactory for all three years period. At the same time, soil moisture reserves were reduced for 2025 May-June period for Dnipropetrovsk, Kirovohrad, Odesa, Kharkiv, Sumy and Rivne regions.

For AMMI analysis, the year and environment factors were combined into a single environmental index, representing each year–environment combination. Mean grain yield values were calculated for each genotype within each year–environment combination. The resulting two-way genotype $\times$ environment matrix was used for AMMI modelling.

The AMMI model is described by the following equation $Y_{ij} = \mu + G_i + E_j + \sum \lambda_k \alpha_{ik} \gamma_{jk} + \varepsilon_{ij}$, 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. The genotype $\times$ environment interaction matrix was obtained by removing genotype means, environment means and the grand mean from the two-way yield matrix. The first two interaction principal component axes, IPCA1 and IPCA2, were used to construct AMMI biplots.

The AMMI Stability Value was calculated for each genotype according to the following formula: $ASV = \sqrt{((SSIPCA1/SSIPCA2) \times IPCA1)^2 + IPCA2^2}$, where SSIPCA1 and SSIPCA2 are the sums of squares explained by the first and second interaction principal components, respectively. Lower ASV values indicate higher stability of genotype performance across environments.

The Yield Stability Index was calculated by combining the rank of mean grain yield and the rank of ASV: $YSI = RY + RASV$, where RY is the rank of genotype mean yield and RASV is the rank of AMMI Stability Value. Genotypes with lower YSI values were considered more desirable because they combined high grain yield with relatively stable performance.

AMMI biplots were generated using the first two interaction principal component axes. All statistical analyses and graphical procedures were performed in R. The main R packages used for data preparation, analysis and visualization were “tidyverse”, “readxl”, “agricolae”, “ggplot2”, “FactoMineR” and “factoextra”.

RESULTS AND DISCUSSION

The obtained results showed that the environmental effect was in fact the leading source of variability. Its contribution to the total sum of squares was 39.94%, which reflects a high level of variability and contrast in ecological conditions among individual environments. Thus, the experimental design was as comprehensive as possible for monitoring yield performance. However, an even greater contribution was associated with the environment $\times$ variety interaction, at 43.30%. This means that the varieties responded to changes in environmental conditions very differently from one another, and so specifically that this differentiation determined the main part of the differences in the final analysis. The variety effect was 7.98%, and the year effect 5.82%, which were also statistically significant but lower than the environmental and genotype-environment effects. This is also very important because it indicates the stability of the varietal set in trait expression and the typicality of the years included in the study, which makes it possible to identify genotypes that are truly stable in the expression of yield as a trait (Table 1).

Table 1. Results of ANOVA analyze.

Factors	Degrees of freedom	Mean squares	F values	Significance levels
Year	2	48493.50	7770.41	$p < 0.001$
Variety	14	66433.76	1520.73	$p < 0.001$
Environment	16	332554.56	6660.90	$p < 0.001$
Year $\times$ Variety	28	1184.09	13.55	$p < 0.001$
Year $\times$ Environment	32	1988.29	19.91	$p < 0.001$
Variety $\times$ Environment	224	360517.14	515.78	$p < 0.001$
Year $\times$ Variety $\times$ Environment	448	16616.60	11.89	$p < 0.001$
Residual	1530	4774.21		
Total	2294	832562.13		

AMMI analysis made it possible to characterize the structure of the multifactorial component of genotype-environment interaction. The first component, IPCA1, explained 49.23% of the interaction sum of squares, while the second component, IPCA2, explained 24.47%. Together, they accounted for 73.71% of the explained structure of the genotype-environment interaction, which provides a sufficient basis for interpreting two-dimensional AMMI biplots. In practical terms, this means that the main part of the justified response of genotypes to variability in growing conditions is concentrated in the IPC1-IPC2 plane (Table 2).

The following components had a much smaller contribution. Therefore, focusing the interpretation on the first two coordinates is an optimal compromise between the complete-ness of interaction description and the clarity of practical conclusions.

Under the conditions of this experiment, the high share of IPCA1 indicates the presence of a main ecological gradient along which the varieties were most strongly classified. This gradient was most likely associated with the climatic conditions of the environments. IPCA2 reflects a second, independent source of differentiation, which makes it possible to separate genotypes with a similar response along the first axis but with different types of specificity. Together, these components allow the overall adaptive potential and the local suitability of a variety to be assessed simultaneously.

Table 2. Contribution of individual IPC components to the explained genotype–environment interaction

Component	SS (GE)	Part of interaction, %	Cumulative, %
IPCA1	177493.51	49.23	49.23
IPCA2	52173.75	24.47	73.71
IPCA3	21669.16	5.78	79.49
IPCA4	16806.68	4.44	83.93
IPCA5	16082.69	4.24	88.16
IPCA6	12648.41	3.34	91.50
IPCA7	9694.32	2.69	94.19
IPCA8	6639.94	1.84	96.03
IPCA9	6337.56	1.76	97.79
IPCA10	3871.15	1.07	98.87
IPCA11	2098.05	0.58	99.45
IPCA12	1163.58	0.32	99.77
IPCA13	629.09	0.18	99.9
IPCA14	209.18	0.06	100

It is important to emphasize that a high absolute IPCA coordinate is not a direct indicator of high yield. It primarily indicates the strength of the response to the environment. Therefore, genotypes located far from the origin may be valuable as carriers of specific adaptation, but they are not necessarily the best for broad use. Conversely, varieties located closer to the center usually have a more stable response and a lower dependence on a particular ecological environment.

Comparison of varieties by mean yield, ASV and YSI parameters shows (Table 3) that the varietal hierarchy changes substantially depending on the criterion used to evaluate adaptability. The highest mean yields were formed by MIP Dovira, Virnist Odeska, KVS Ultim, Epitet and Soliflor KS. This group reflects high potential yield capacity; however, not all of these varieties were simultaneously characterized by high stability of this trait expression under varying conditions.

The ASV indicator made it possible to move from the assessment of mean yield to the assessment of response stability. The minimum ASV value was recorded for Etual, indicating the most stable response in the IPCA1-IPCA2 plane. It was followed by MIP Aelita, Zahadka Odeska, Papillon and CO1914.

These genotypes had a relatively small distance from the center of the AMMI space, which indicates a weaker specific dependence on the environment.

The integrated YSI index combines yield rank and stability rank and is therefore a more practical criterion for variety selection. According to this indicator, the best variety was MIP Aelita, which combined a mean yield level of 7.38 t ha⁻¹ with a very low ASV. Epitet occupied the second position, while MIP Dovira and Virnist Odeska shared the third position. Soliflor KS also belonged to the most promising varieties in terms of the combined parameters. Thus, the set does not contain a single universal leader but rather a group of varieties with different structures of advantages.

Table 3. Evaluation of main components

N	Variety	Origin	Yield 2023 -2025, t ha ⁻¹	ASV	Rank ASV	YSI	Rang e YSI
G14	MIP Aelita	UA	7.38	39.40	2	10	1
G02	Epitet	UA	7.82	79.07	7	11	2
G12	MIP Dovira	UA	8.22	131.75	11	12	3
G08	Virnist Odeska	UA	8.01	117.64	10	12	3
G01	Soliflor KS	GE	7.81	97.88	8	13	5
G11	CO1914	FR	7.12	57.07	5	14	6
G10	Zahadka Odeska	UA	6.93	40.54	3	14	6
G06	Etual	UA	6.65	30.79	1	15	8
G03	Obivan	FR	7.49	103.72	9	16	9
G09	KVS Ultim	GE	7.95	200.88	14	17	10
G04	Tvorchist Odeska	UA	6.89	76.90	6	18	11
G13	ZU VERMILLO N	GE	7.51	181.71	13	19	12
G07	Papillon	FR	6.43	55.54	4	19	12
G15	Momentum	FR	7.11	167.31	12	22	14
G05	KVS Yuniversum	GE	6.66	241.81	15	28	15

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

MIP Aelita, Epitet, MIP Dovira, Virnist Odeska and Soliflor KS should be regarded as the key valuable varieties within the studied set of genotypes. In the context of the analysis performed, these genotypes were characterized by a significantly better integrated balance of yield and stability. These varieties combine particularly high adaptability with good yield performance, especially the first three MIP Aelita, Epitet and MIP Dovira.

The next group comprises genotypes with a more contrasting response. KVS Ultim, ZU VERMILLON, Momentum, KVS Yuniversum and Obivan formed high mean yields while having an extremely large negative IPCA1 coordinate or an extreme position in the AMMI space and high ASV values.

Their value may be considerable if they are grown within a suitable ecological niche.

Etual and several subsequent varieties clearly illustrate the need for a comprehensive evaluation of varieties. Etual was the most stable according to ASV but had one of the lowest mean yield levels. In breeding programs, it may serve as a source of stability, plasticity or specific adaptive traits across a wide range of weather scenarios. Zahadka Odeska also showed very high stability with moderate yield and was generally similar in this respect. Papillon was also characterized by low productivity combined with a relatively favorable ASV. CO1914 was characterized by an intermediate yield level and moderate response stability. Tvorchist Odeska represents an intermediate type that retains breeding value as a carrier of specific adaptive traits.

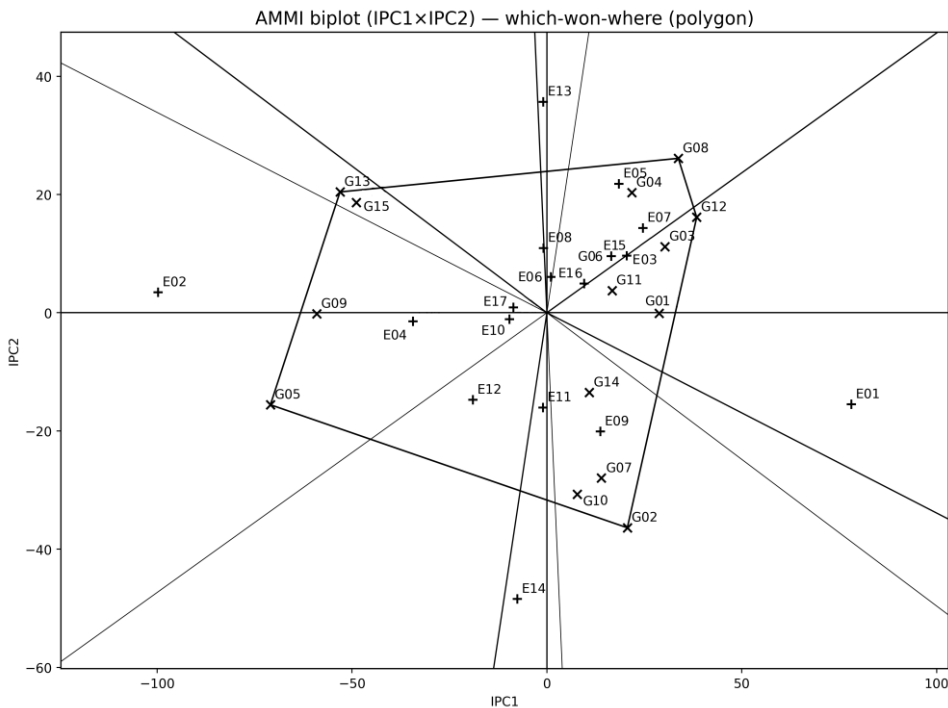


Figure 1. AMMI biplot (IPC1×IPC2)

The polygon view of the AMMI biplot (Figure 1) reflects the differentiation of varieties by their ability to realize yield under contrasting regional conditions. The most important gradients in this experiment were associated with moisture availability in autumn and spring, the probability of heat

stress during grain filling, differences in overwintering conditions. These factors were especially relevant because the year effect was significant but smaller than the environmental and genotype x environment effects.

The varieties KVS Yuniversum, KVS Ultim, ZU VERMILLON and Momentum formed a group with a contrasting and clearly specific response. Their agronomic value should therefore be interpreted through targeted placement rather than through broad recommendation. Such genotypes are likely to express their advantage only when the regional conditions correspond to their adaptive niche. This may include environments where the crop is exposed to early-season moisture limitation.

MIP Dovira, Virnist Odeska, Epitet and Soliflor KS combined high mean yield with a stronger response to environmental improvement. Their performance suggests a capacity to use favorable conditions, especially sufficient spring moisture and a longer period of effective grain filling. MIP Dovira and Virnist Odeska should be considered responsive high-potential varieties. Epitet and Soliflor KS are also productive, but they appear more suitable for environments with a relatively predictable agroecological background.

The discriminating environments were not merely statistically distant from the center of the AMMI space. Kirovohrad and Dnipropetrovsk represented the central and eastern Steppe conditions, where water deficit and heat stress during reproductive development can sharply separate varieties by drought tolerance, water-use efficiency and ability to maintain grain filling. Lviv and Ivano-Frankivsk represented western environments, where cooler and more humid conditions were weather conditions more preferable. The stronger discriminating ability can be explained by their ability to reveal different physiological mechanisms of adaptation. Sumy, Chernihiv, Chernivtsi, Khmelnytskyi, Kharkiv, Volyn and Rivne more closely reflected the average response.

The AMMI biplot based on mean response and stability (Figure 2) provides a practical transition from statistical differentiation to varietal recommendation. The main question is not only which genotype has the highest yield, but also whether this yield is formed consistently across contrasting seasons and zones. Under the weather conditions of 2023-2025, broad adaptation was especially important because the seasons included both relatively favorable (2023-2024) and more stressful hydrothermal (2025) backgrounds.

MIP Aelita had the most balanced agronomic profile. It indicate ecological plasticity. This type of response may be associated with the ability to compensate for moderate moisture or temperature stress during spring development and grain filling. MIP Aelita can be recommended as a stabilizing variety in the crop structure. MIP Dovira and Virnist Odeska represented another strategy, high productivity combined with a more pronounced environmental response. Their advantage is most likely realized in environments with sufficient soil moisture and favorable conditions during grain filling. However, in years with dry autumns or heat during grain filling, these varieties may require better agronomic support. Etual, Zahadka Odeska and CO1914 illustrate the biological difference between stability and maximum productivity. Their lower instability indicates a weaker

dependence on a specific environment. Such genotypes may be useful as sources of ecological plasticity in breeding programs or as a limited component of the varietal structure.

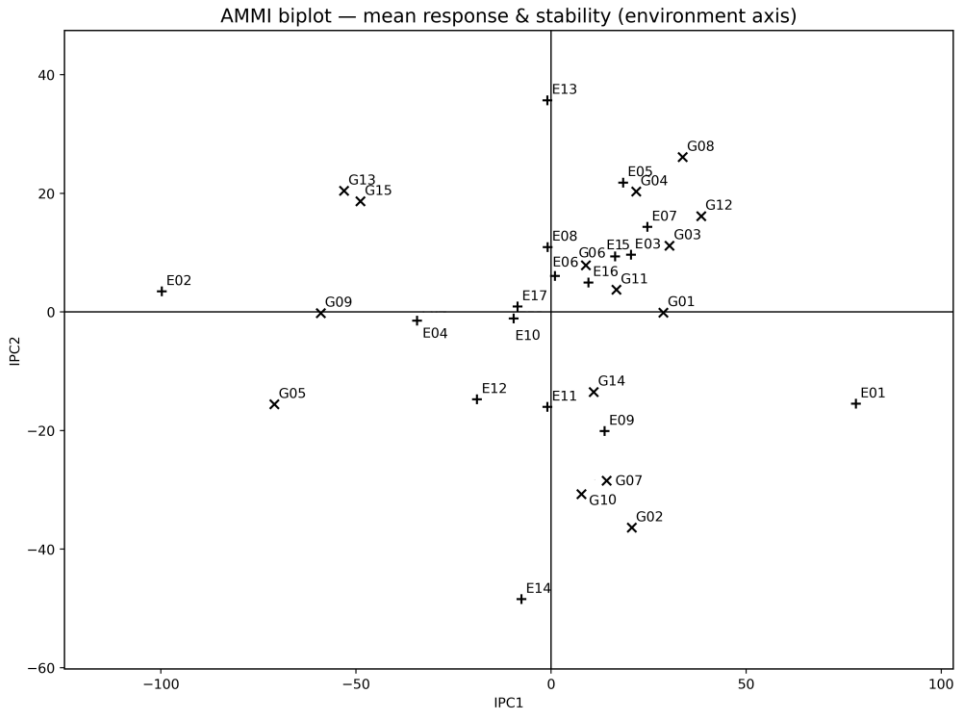


Figure 2. AMMI biplot, mean response and ecological stability (environment axis)

Because the testing network covered the Steppe, Forest-Steppe and Polissia zones, the ideal type (Figure 3) should combine responsiveness to favorable conditions with tolerance to moisture deficit, winter stress and excessive humidity-related risks.

MIP Aelita was the closest to this practical concept of an ideal variety because it combined acceptable productivity with broad adaptation. Its value lies in the lower dependence on a single ecological niche. Epitet and Soliflor KS are more yield-oriented and can be important in regions with a more stable climatic background, where the probability of severe drought or other stress factors is lower. CO1914 and Zahadka Odeska had greater value as stable-response genotypes, although their production use should be considered mainly where risk reduction is a priority.

KVS Yuniversum, KVS Ultim, ZU VERMILLON and Momentum may be relevant for specific regional niches, for example where local soil moisture dynamics or temperature regime differs strongly from the national average. They may also be useful breeding material for improving adaptive response to a particular stress factor.

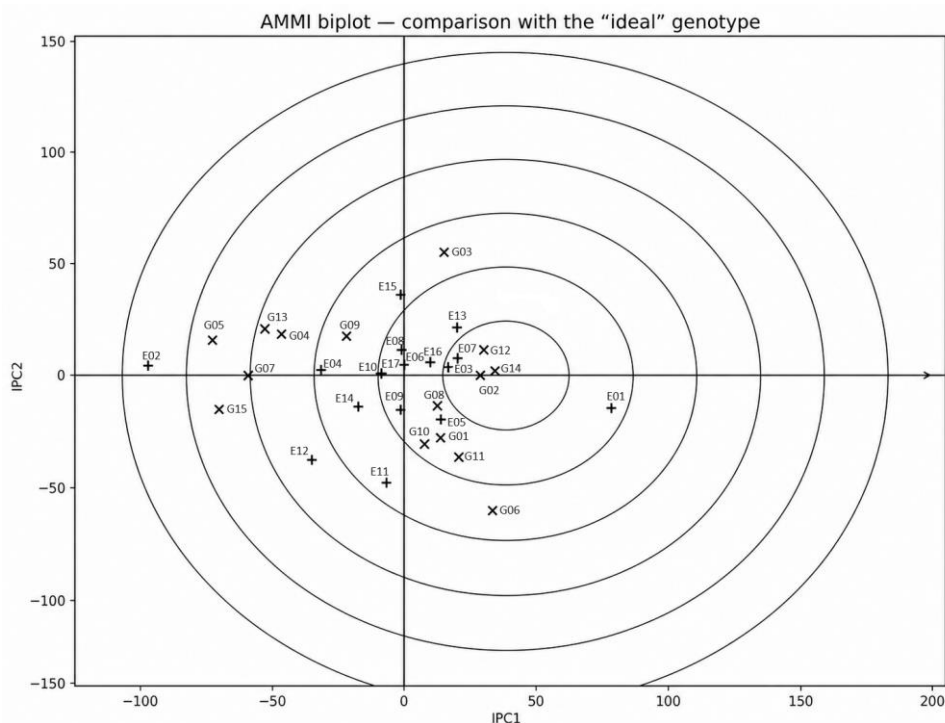


Figure 3. GgE biplot identification of the ideal variety

Identification of variety suitability for specific environments is particularly important because it allows a transition from a general yield assessment to specific adaptability. Table 4 presents the TOP-3 varieties for each testing environment depending on the zone. These positions reflect the adaptive suitability of a variety in a particular region and show where exactly the variety is able to realize its genetic advantage.

Varieties MIP Aelita and MIP Dovira appear to be the most universal. MIP Aelita was included in the TOP-3 in 13 environments and MIP Dovira in 12. These varieties most often maintained competitive positions when the region changed. Epitet, Soliflor KS and Virnist Odeska were included in the top three five times, which also indicates high overall adaptive potential. ZU VERMILLON occurred in the TOP-3 four times, while KVS Yuniversum and KVS Ultim occurred three times each.

In the Steppe zone, the ranking was heterogeneous. MIP Dovira was the best in Dnipropetrovsk, MIP Aelita in Kirovohrad and MIP Dovira in Odesa; all of these varieties were created at the same breeding institute. In the Steppe, higher contrast is especially evident from the position of Kirovohrad. In the Forest-Steppe, MIP Aelita, MIP Dovira and Virnist Odeska were repeated more often. The Forest-Steppe is a zone where a wide range of stable responses is expressed. In Polissia, MIP Dovira and MIP Aelita occurred most frequently. Polissia is not a completely homogeneous zone, but a stable core of varieties MIP Dovira, MIP Aelita, Epitet and KVS Ultim can be identified within it.

Table 4. Comparison of genotypes under the environment conditions.

No	Region	Zone	TOP-1	TOP -2	TOP -3
E01	Dnipropetrovsk	Steppe	MIP Dovira	Epitet	Soliflor KS
E02	Kirovohrad	Steppe	MIP Aelita	KVS Yuniversum	ZU VERMILLON
E03	Odesa	Steppe	MIP Dovira	Virmist Odeska	MIP Aelita
E04	Vinnitsia	Forest- Steppe	MIP Aelita	ZU VERMILLON	KVS Yuniversum
E05	Kyiv	Forest- Steppe	MIP Aelita	MIP Dovira	Obivan
E06	Sumy	Forest- Steppe	MIP Dovira	Virmist Odeska	MIP Aelita
E07	Ternopil	Forest- Steppe	MIP Aelita	Virmist Odeska	Soliflor KS
E08	Kharkiv	Forest- Steppe	MIP Dovira	Virmist Odeska	MIP Aelita
E09	Cherkasy	Forest- Steppe	Epitet	MIP Dovira	Soliflor KS
E10	Chernivtsi	Forest- Steppe	MIP Aelita	MIP Dovira	ZU VERMILLON
E11	Volyn	Polissia	Epitet	KVS Ultim	MIP Dovira
E12	Zakarpattia	Polissia	KVS Ultim	Epitet	KVS Yuniversum
E13	Ivano-Frankivsk	Polissia	Virmist Odeska	MIP Dovira	MIP Aelita
E14	Lviv	Polissia	Epitet	MIP Aelita	KVS Ultim
E15	Rivne	Polissia	MIP Dovira	MIP Aelita	Soliflor KS
E16	Khmelnyskyi	Polissia	MIP Dovira	MIP Aelita	Soliflor KS
E17	Chernihiv	Polissia	MIP Aelita	MIP Dovira	ZU VERMILLON

The most favorable environments were Odesa, Cherkasy, Kharkiv, Sumy, Rivne, Ivano-Frankivsk and Volyn. However, a high mean level in an environment does not always indicate high selectivity. The most representative environments were Sumy, Chernihiv, Chernivtsi, Khmelnytskyi, Kharkiv, Volyn and Rivne. These environments can be used as key locations for primary or integrated variety assessment. The most discriminating environments were Kirovohrad, Dnipropetrovsk, Lviv, Ivano-Frankivsk, Vinnitsia, Kyiv and Ternopil. These environments had long IPC vectors they most strongly separated varieties by response.

The Steppe zone showed the most contrast, the Forest-Steppe performed a dual function (several environments had a high mean yield background and certain environments such as Vinnytsia, Kyiv and Ternopil were sufficiently discriminating). Polissia showed a complex structure, some environments were representative, but two had pronounced discriminating features.

The obtained results confirm that the genotype $\times$ environment interaction was not only a statistical effect, but also reflected real differences in the ecological response of winter wheat varieties to regional and annual growing conditions (Al-Ashkar *et al.*, 2022). The large contribution of the variety $\times$ environment interaction indicates that the same genotype could not maintain the same relative advantage under all combinations of ecological factors (Cohen *et al.*, 2021; Kassie *et al.*, 2025). The climatic background of the three years helps explain this result. The 2023 harvest year was generally more favorable and closer to a moderately typical background, especially in the Forest-Steppe and Polissia zones. The 2024 season was additionally characterized by heat stress during grain filling in several southern, central and eastern environments. The 2025 season began under an autumn drought, although overwintering conditions were generally satisfactory.

The comparison of mean yield, ASV and YSI demonstrated a typical breeding and production trade-off between productivity and stability (Jha *et al.*, 2017). MIP Dovira and Virnist Odeska had the highest mean yields, but their stability parameters were not the lowest. Etual showed the opposite type of response. It was the most stable according to ASV, but its mean yield was lower than that of the leading varieties. MIP Aelita was the most balanced variety according to YSI. Its advantage was not based on absolute yield leadership in all environments, but on the combination of sufficiently high productivity and relatively stable expression across contrasting regions (Khare *et al.*, 2024; Bhandari *et al.*, 2026). Epitet and Soliflor KS can be interpreted as productive varieties with acceptable stability. Their practical value is most evident in environments with relatively predictable soil and climatic conditions, where the probability of strong drought is lower (Ejaz *et al.*, 2023; Mohammadi *et al.*, 2025). MIP Dovira and Virnist Odeska represent a high-potential and responsive group. They can effectively use favorable growing conditions, including sufficient spring moisture and a longer period of active vegetation. KVS Yuniversum, KVS Ultim, ZU VERMILLON and Momentum should be considered genotypes with specific adaptation. Their value lies in the possibility of occupying particular ecological niches (Tshikunde *et al.*, 2019).

The distribution of environments by representativeness and discriminating ability showed that Sumy, Chernihiv, Chernivtsi, Khmelnytskyi and Kharkiv provided a more averaged background for assessing the general adaptive capacity of varieties. Such environments are useful for identifying broadly adapted genotypes because they do not exaggerate the response of individual varieties to extreme local conditions (El Baouchi *et al.*, 2024). In contrast, Kirovohrad, Dnipropetrovsk, Lviv, Ivano-Frankivsk more strongly differentiated varieties.

Their discriminating role may be associated with sharper contrasts in moisture supply and temperature regime. Therefore, these environments are especially useful for detecting specific adaptation (Ahmadi *et al.*, 2012).

The zonal analysis confirmed that the natural-climatic zone is an important but insufficient level for final varietal recommendation (Yan, 2024). The Steppe zone was the most contrasting because it combined autumn moisture deficit, higher probability of drought and heat stress during grain filling. The Forest-Steppe zone had a more balanced but heterogeneous background. It combined relatively favorable productivity with local contrasts in moisture supply and spring temperature fluctuations. In this zone, the best varieties were those that could combine responsiveness to improved agronomic conditions with sufficient tolerance to temporary stress. This explains the frequent occurrence of MIP Aelita, MIP Dovira and Virnist Odeska among the leading varieties.

Polissia differed from the Steppe and Forest-Steppe by a generally cooler and more humid background. The repeated presence of MIP Aelita, MIP Dovira, Epitet and KVS Ultim among leading varieties suggests that these genotypes were better able to maintain productivity under the conditions of this zone. Polissia should be considered as more homogeneous.

The optimal strategy is the formation of a differentiated varietal structure (Kebede *et al.*, 2023; Korpetis *et al.*, 2026). MIP Aelita may be used as a broadly adapted and relatively low-risk component. Epitet and Soliflor KS are suitable as productive varieties for more predictable environments. MIP Dovira and Virnist Odeska should be recommended where high yield potential can be realized. Etual and Zahadka Odeska are valuable as sources of stable response and ecological plasticity. KVS Yuniversum, KVS Ultim, ZU VERMILLON and Momentum may be useful as components for specific adaptation.

The value of the study is that the combined use of ANOVA, AMMI, ASV, YSI and environmental ranking allowed the separation of three different varietal characteristics: mean productivity, stability and specific adaptation (Roostaei *et al.*, 2022). Such an approach reduces the risk of one-sided conclusions and makes it possible to transform statistical interaction into agronomically useful recommendations (Bishwas *et al.*, 2021; Eskezia *et al.*, 2025).

High-yielding responsive genotypes can be used as donors of productivity and responsiveness to favorable conditions (Abdolshahi *et al.*, 2015; Menzir *et al.*, 2025). Stable varieties may serve as sources of ecological plasticity and lower production risk. Specifically adapted genotypes may be useful for breeding programs aimed at particular stress conditions or regional ecological niches (Tanin *et al.*, 2022).

CONCLUSIONS

Varietal productivity depended substantially on growing conditions and ranking by mean yield alone cannot provide a sufficient basis for production recommendations. The most representative environments were Sumy, Chernihiv, Chernivtsi, Khmelnytskyi, Kharkiv, Volyn and Rivne; the most discriminating

were Kirovohrad, Dnipropetrovsk, Lviv, Ivano-Frankivsk, Vinnytsia, Kyiv and Ternopil. The zonal approach should be supplemented by regional interpretation. Variety MIP Aelita can be considered the most balanced variety, Epitet as high-yielding and sufficiently stable, MIP Dovira and Virnist Odeska as varieties with very high potential for suitable environments and Soliflor KS as a productive option with acceptable stability. Etual and Zahadka Odeska are of interest as sources of a stable response. Overall, the results confirm that an effective recommendation system for winter wheat should be based on the integrated use of ANOVA, AMMI/PCA, ASV, YSI, environmental evaluation and regional ranking.

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