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Multifactor evaluation of productivity and ecological stability of winter wheat agrocenoses

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The stability of winter wheat yield formation under increasing climatic and agroecological contrast depends not only on the hereditary potential of a variety, but also on the nature of its response to the environment. Therefore, the evaluation of genotype × environment interaction is an essential component of modern varietal testing. The present study was based on the results of a multi-environment trial of 15 winter wheat varieties and breeding lines conducted in 17 regions of Ukraine during 2023–2025. The objective of the research was to identify genotypes combining high yield, ecological stability, and adaptive suitability for specific growing zones. According to the AMMI analysis, the first interaction component, IPCA1, explained 39.77% of the interaction, while the second, IPCA2, accounted for 25.16%, giving a combined contribution of 64.93%. The highest mean yields were produced by MIP Vidznaka, Bila, FORSAIT, and MIP Darunok. The lowest ASV value was recorded for Biskvit; however, the most favorable combination of productivity and stability according to the YSI index was shown by MIP Darunok. The variety Bila was also identified as highly productive and sufficiently stable, whereas MIP Vidznaka and FORSAIT should be regarded as genotypes with high potential but a pronounced specific response. Analysis of the TOP-3 genotypes across environments revealed considerable heterogeneity among zones: the Steppe required the most localized recommendations, the Forest-Steppe combined a broad spectrum of leading genotypes, and in Polissia the role of FORSAIT, Foks, Bila, and MIP Darunok became more pronounced. The obtained results confirm that the final assessment of the potential use of a given form should be based on the combined evaluation of productivity, stability, and specific adaptation. The identification of general patterns and principles for the use of individual genotypes appears to be feasible primarily for the Polissia zone, whereas the other two ecological and geographical zones demonstrate excessively strong differentiation depending on the specific location, making any broad generalizations or model construction unlikely. It is also advisable to substantially increase the number of testing locations in the Steppe zone of Ukraine, while for Polissia the current number of sites for this crop may even be excessive.

Keywords: winter wheat; genotype; environment; AMMI analysis; principal components; productivity; adaptability; stability.

Introduction

The stability of winter wheat agrocenoses remains one of the key objectives of modern agroecology, since this crop contributes substantially to the food balance and serves as a fundamental component of productivity under climate change conditions. For practical use, a genotype must possess not only a high potential level of productivity, but also the capacity to maintain it under varying weather scenarios, soil and climatic conditions, and technological backgrounds. In this respect, simple comparison based on mean performance is no longer sufficient, because it does not reveal the basis of the advantage: whether it results from broad plasticity, responsiveness to intensive management, or, conversely, from adaptation to a relatively narrow ecological niche (Iwańska et al., 2025; Nazarenko et al., 2026).

Particular importance should be given to genotype × environment interaction, which reflects changes in varietal ranking when moving from one growing environment to another. If a variety performs as a leader in one region but sharply reduces its productivity in another, its production value depends heavily on precise placement. By contrast, if a variety consistently ranks among the best across most testing sites, it may be regarded as a more reliable component of cultivation technology. Therefore, within scientific varietal testing systems, it is necessary to assess productivity, stability, and the nature of genotype-specific responses simultaneously (Güngör et al., 2024; Kassie et al., 2025).

Multi-environment trials make it possible to treat each environment not as a random background, but as an independent complex of factors that includes water availability, temperature regime, soil characteristics, agronomic management, and year-specific weather deviations. This is especially important for winter wheat, since its final yield is formed over a long period, from autumn development and overwintering to spring tillering, stem elongation, grain filling, and the completion of vegetation. At each of these stages, a variety may exhibit a different level of resistance to limiting factors, ultimately resulting in a complex structure of genotype × environment interaction (Abdolshahi et al., 2015; Eskezia et al., 2025).

In recent years, the importance of such evaluation has increased because of growing climatic instability. The Steppe and Forest-Steppe zones are characterized by periods of spring drought, sharp temperature fluctuations, uneven precipitation distribution, and a high risk of overheating during the stages of productive-organ formation. In Polissia, alongside more favorable water availability, important roles may be played by overwintering conditions, temporary waterlogging of certain fields, variation in phytosanitary background, and soil heterogeneity. Consequently, the same genotype may display substantially different types of adaptive response within a single country, and regional recommendations should be based on quantitative analysis rather than on visual comparison of yield alone (Murphy et al., 2020; Nazarenko et al., 2023).

Classical analysis of variance allows the overall significance of factors to be established, but it does not reveal the internal structure of genotype × environment interaction. By contrast, multivariate approaches make it possible to identify which particular varieties and environments determine the major directions of variability. Among such methods, the AMMI and GGE biplot models are widely used. These approaches combine the advantages of principal component analysis with agronomic interpretation and allow simultaneous evaluation of mean yield, response stability, and specific adaptation (Ye et al., 2019; Bhandari et al., 2026).

The AMMI model is particularly convenient for the analysis of multi-environment trial data because the additive part of the model describes the main effects of genotypes and environments, whereas the multiplicative part decomposes the interaction into several principal component axes. The first components usually reflect the most stable and reproducible patterns of response, whereas subsequent components are often associated with more local effects or statistical noise. Therefore, interpretation of IPCA1 and IPCA2 coordinates is a key step in identifying varieties with broad or specific adaptive types (Dang et al., 2024; Urbanaviciute et al., 2024).

The practical value of AMMI analysis lies in its ability to avoid two common evaluation errors. The first is the overestimation of a genotype with high productivity but extreme instability, which requires a narrowly defined environment. The second is the underestimation of genotypes that are not absolute leaders in productivity but provide a more reliable result under changing growing conditions. For this reason, applied varietal assessment should rely on integrated indices that combine productivity rank with stability rank (Ahmadi et al., 2012; Tanin et al., 2022).

The objectives of the present study were to evaluate the productivity and ecological stability of 15 winter wheat varieties and breeding lines in a system of 17 testing environments during 2023–2025 using the AMMI approach, to determine the contribution of the first interaction axes, to identify genotypes with the most favorable combination of productivity and stability, and to characterize zones and individual regions according to the composition of leading varieties. Particular attention was paid not only to ranking genotypes by mean yield, but also to interpreting their spatial positions on biplots, since this reflects both the direction and the magnitude of their response to the environmental background.

Materials and methods

The study was based on a multi-environment trial of 15 winter wheat varieties: Novatus, Barentus, DSV1929113, and DSV1929121 from Germany; MIP Vidznaka, MIP Darunok, Biskvit, Ambitsiia, Syntetyk 240, Blahodatna, Troiana, and Bila from Ukraine; and Ormesson, FORSAIT, and Foks from France. Field evaluation was carried out over three consecutive growing seasons (2023–2025) in a replicated multi-environment trial. Each experimental plot had an accounting area of 20 m², and every treatment was represented in three replications. In all locations, black fallow was used as the preceding crop. Agronomic management was maintained in accordance with the standard recommendations adopted for the corresponding edaphic and climatic conditions of each target growing zone.

The testing network covered seventeen locations distributed across the principal agroecological regions of Ukraine. The Steppe zone was represented by plots in Dnipropetrovsk Oblast (E01; 48°51′06.55″N, 35°25′23.08″E), Kirovohrad Oblast (E02; 48°18′33.18″N, 30°16′48.40″E), and Odesa Oblast (E03; 46°27′21.08″N, 30°40′06.78″E). The Forest-Steppe zone was represented by plots in Vinnytsia Oblast (E04; 48°33′14.95″N, 28°41′34.22″E), Kyiv Oblast (E05; 49°46′18.96″N, 30°06′39.92″E), Sumy Oblast (E06; 50°59′42.38″N, 34°31′31.33″E), Ternopil Oblast (E07; 49°27′55.58″N, 25°32′09.68″E), Kharkiv Oblast (E08; 49°53′10.15″N, 36°24′55.17″E), Cherkasy Oblast (E09; 49°24′17.19″N, 31°58′48.49″E) and Chernivtsi Oblast (E10; 48°25′21.34″N, 25°43′25.96″E). In the Polissia zone, the studies were conducted in Volyn Oblast (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 Oblast (E13; 48°51′28.73″N, 25°00′57.99″E), Lviv Oblast (E14; 49°52′50.77″N, 24°07′04.11″E), Rivne Oblast (E15; 50°38′02.22″N, 26°19′51.70″E), Khmelnytskyi Oblast (E16; 49°26′18.79″N, 27°02′12.09″E), and Chernihiv Oblast (E17; 51°35′37.18″N, 31°17′20.24″E).

Grain yield was recorded separately for every combination of genotype, year, and trial site, with replication retained at the measurement stage. To interpret the data structure, a combined analytical framework was applied that integrated classical analysis of variance with the Additive Main Effects and Multiplicative Interaction (AMMI) model. In preparation for AMMI analysis, the separate effects of year and location were merged into a composite environmental unit, so that each year × location combination was treated as an independent environment. For every such environment, mean grain yield was calculated for each genotype, and the resulting genotype-by-environment table served as the basis for subsequent modeling.

Within the AMMI approach, the additive portion of variation was attributed to genotype and environment main effects, whereas the interaction component was decomposed through principal component analysis of the genotype × environment interaction residuals. The general model took the form: $Y_{ij} = \mu + G_i + E_j + \Sigma \lambda_k \alpha_{ik} \gamma_{jk} + \varepsilon_{ij}$, where Y_{ij} is the expected performance of the i-th genotype in the j-th environment, μ is the overall mean, G_i is the genotypic main effect, E_j is the environmental main effect, λ_k is the singular value associated with the k-th interaction principal component, α_{ik} and γ_{jk} are the genotype and environment eigenvectors for that component, and ε_{ij} is the residual term.

To obtain the interaction matrix, the grand mean together with genotype and environment marginal means were subtracted from the original two-way yield matrix. Singular value decomposition was then applied to the centered interaction table. The first two interaction principal component axes, IPCA1 and IPCA2, were retained for graphical interpretation and for describing the major interaction patterns.

Genotypic stability was assessed using the AMMI Stability Value (ASV), which was calculated as ASV = sqrt([(SSIPCA1 / SSIPCA2) × IPCA1]^2 + IPCA2^2), where SSIPCA1 and SSIPCA2 denote the sums of squares explained by the first and second interaction principal components. Lower ASV values were interpreted as evidence of greater performance stability over contrasting environments.

To combine productivity and stability into a single selection criterion, the Yield Stability Index (YSI) was computed according to the expression: YSI = RY + RASV, where RY represents the rank of the genotype for mean grain yield and RASV is the rank based on ASV. Genotypes with smaller YSI values were regarded as the most desirable, since they combined superior productivity with comparatively stable environmental response.

Graphical interpretation of the AMMI results was performed using several complementary biplot formats. The IPCA1–IPCA2 biplot was used to visualize the structure of genotype × environment interaction. A polygon-based "which-won-where" display was employed to identify genotypes with specific adaptation to particular groups of environments. The mean-performance versus stability biplot was used to compare genotypes in terms of productivity and interaction sensitivity, whereas the ideal genotype biplot enabled comparison of actual entries with a hypothetical genotype combining high mean yield and minimal environmental interaction. All statistical procedures, data processing steps, and visualizations were carried out in the R environment. The main packages used for dataset preparation, statistical analysis, and figure generation were "tidyverse", "readxl", "agricolae", "ggplot2", "FactoMineR", and "factoextra".

Results and discussion

The first stage of interpretation was to determine how informative the interaction structure represented by the principal components was. In AMMI analysis, it is important not only to establish the presence of genotype × environment interaction, but also to understand how well this interaction is described by the first axes. If the first two components explain a substantial proportion of the interaction, IPC1–IPC2 biplots can be used as a sufficiently reliable basis for agronomic conclusions.

In the present experiment, the first component, IPCA1, explained 39.77% of the interaction sum of squares, while the second component, IPCA2, accounted for 25.16%. Together, these two axes covered 64.93% of the explained structure of the genotype × environment interaction (Table 1). Therefore, the main patterns can be interpreted in a two-dimensional plane.

A comparison of the components shows that there was a rather pronounced relationship between IPCA1 and IPCA2: the first axis was dominant and most likely reflected the main ecological gradient associated with differences between zones and individual environments. The second axis complemented this gradient by separating genotypes that had similar responses along the first coordinate but differed in the direction of their specific adaptation.

The hierarchy of varieties according to mean yield, ASV, and YSI is presented in Table 2. In terms of yield level, MIP Vidznaka ranked first, with 80.94 t/ha. The variety Bila had a very similar value, 80.75 t/ha. It was followed by FORSAIT (78.59 t/ha), MIP Darunok (78.42 t/ha), and DSV1929121 (75.70 t/ha). This group demonstrates the highest genetically determined productivity potential; however, the stability pattern within the group was not uniform. Therefore, simple ranking by yield alone does not fully determine the practical value of each variety.

According to the ASV index, the most stable variety was Biskvit, with a value of 13.02. This indicates the smallest distance from the center of the AMMI space among all genotypes. MIP Darunok ranked second in stability (ASV 21.36), followed by Barentus (29.54), Novatus (33.32), Ormesson (41.59), Ambitsiia (46.63), and Bila (54.33). Thus, stability and high yield did not coincide in all varieties: Some genotypes with low ASV had a comparatively moderate level of productivity, whereas some yield leaders were characterized by a more pronounced specific response.

The integrated Yield Stability Index (YSI) made it possible to combine productivity and stability into a single applied assessment. According to this criterion, the best variety was MIP Darunok, which ranked fourth in yield and second in ASV, resulting in the lowest YSI value of 6. Therefore, this variety can be regarded as the most balanced among the studied set. It combined a high level of productivity with a very stable response, which is especially important when placing a variety under different ecological conditions.

Table 1
Contribution of individual IPC components to the explained genotype–environment interaction

Component	SS (GE)	Part of interaction, %	Cumulative, %
IPCA1	261.68	39.77	39.77
IPCA2	185.77	25.16	64.93
IPCA3	96.45	6.40	71.33
IPCA4	89.73	5.78	77.11
IPCA5	82.86	5.12	82.23
IPCA6	78.63	4.51	86.74
IPCA7	73.04	3.89	90.63
IPCA8	67.02	3.27	93.90
IPCA9	50.22	1.84	95.74
IPCA10	47.81	1.67	97.41
IPCA11	40.31	1.18	98.59
IPCA12	32.73	0.78	99.37
IPCA13	21.53	0.34	99.71
IPCA14	19.90	0.29	100.00

Table 2
Evaluation of main components

N	Variety	Origin	Yield 2023–2025, t/ha	IPC1	IPC2	ASV	Rank yield	Rank ASV	YSI
G13	MIP Darunok	UA	78.42	–18.40	3.65	21.36	4	2	6
G15	Bila	UA	80.75	–28.22	–43.71	54.33	2	7	9
G05	Biskvit	UA	68.86	–0.03	13.02	13.02	10	1	11
G07	MIP Vidznaka	UA	80.94	–59.63	–36.29	77.26	1	11	12
G14	DSV1929121	GE	75.70	–15.45	67.61	69.88	5	10	15
G08	FORSAIT	FR	78.59	106.71	21.91	124.01	3	13	16
G10	DSV1929113	GE	72.27	–38.60	–44.81	62.91	7	9	16
G03	Ambitsiia	UA	68.11	–39.46	–11.69	46.63	11	6	17
G04	Ormesson	FR	67.85	–20.45	–34.40	41.59	12	5	17
G06	Barentus	GE	65.96	–10.74	26.86	29.54	14	3	17
G09	Syntetyk 240	UA	72.61	–34.18	72.01	81.94	6	12	18
G02	Novatus	GE	61.80	–5.98	–32.61	33.32	15	4	19
G01	Troiana	UA	67.13	–23.44	53.20	59.57	13	8	21
G12	Foks	FR	71.88	84.48	–102.95	141.19	8	15	23
G11	Blahodatna	UA	69.84	103.38	48.18	127.69	9	14	23

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

The second position was occupied by Bila. Its advantage was associated with a very high yield level and acceptable stability: While ranking second in yield, it had the seventh rank for ASV. This type of variety can be considered valuable for production, since it is capable of forming a high yield and at the same time does not belong to the most unstable genotypes. Bila is especially important as a variety that frequently appears among the leaders in individual environments while also maintaining a strong position in the overall ranking system.

The third position in the integrated assessment was occupied by Biskvit. Its mean yield was lower than that of the leaders; however, its exceptionally low ASV made it one of the most interesting genotypes from the standpoint of stability. In production terms, Biskvit may be useful where the priority is to reduce the risk of yield fluctuations.

MIP Vidznaka was the absolute leader in mean yield, but its ASV value was 77.26, corresponding to the eleventh rank for stability. This indicates that the high yield of this variety was associated with a pronounced response to the environment. Such a genotype may be especially valuable for targeted placement in conditions where its adaptive specificity can be realized most fully.

FORSAIT was also characterized by a high mean yield (78.59 t/ha), but it had one of the highest ASV values, 124.01. Its IPC1 and IPC2 coordinates indicate a strong specific response. From a practical point of view, this is not necessarily a disadvantage if the variety is placed in an appropriate ecological niche. On the contrary, such genotypes often produce maximum yields in particular environments.

DSV1929121 occupied an intermediate position: Its yield was sufficiently high, but its ASV also remained considerable. DSV1929113 had moderate yield and an intermediate level of stability. The varieties Barentus, Novatus, Ormesson, and Ambitsiia are of interest primarily as relatively stable or moderately stable genotypes, although their mean yield was lower than that of the leaders. Foks and Blahodatna, by contrast, were characterized by very high ASV values, which identify them as forms with pronounced specific adaptation. Their value should therefore be assessed only through the prism of particular environments.

Figure 1 visualizes the interaction structure in the IPC1 × IPC2 plane using the "which-won-where" approach. In such biplots, the vertices of the polygon are usually formed by genotypes with the most extreme coordinates, that is, varieties that respond most strongly to changes in growing conditions. In the present experiment, the peripheral forms included MIP Vidznaka (G07), Syntetyk 240 (G09), DSV1929121 (G14), Blahodatna (G11), FORSAIT (G08), Foks (G12), and Bila (G15). Their location shows that these genotypes determined the main directions of varietal differentiation.

The left part of the biplot is associated primarily with genotypes having negative IPC1 values. MIP Vidznaka is particularly prominent in this sector, as it was both the leader in mean yield and had a pronounced negative IPC1 coordinate. This indicates high productivity of the variety together with a specific ecological response. DSV1929113, Syntetyk 240, DSV1929121, and some of the more stable genotypes are also located in this sector. Therefore, the negative direction of the first axis combines different types of varieties, but for the leading forms it is associated with particular environments in which their advantage is most fully expressed.

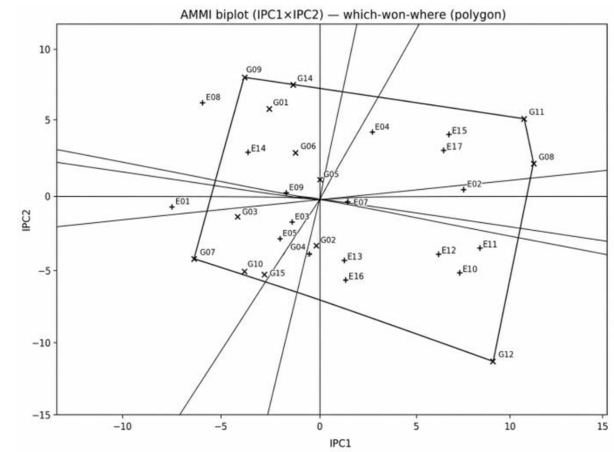

Fig. 1. AMMI biplot (IPC1×IPC2) – which-won-where

The right part of the plot is formed by FORSAIT, Blahodatna, and Foks. These genotypes have positive IPC1 values and high ASV values, which is in good agreement with the tabular assessment. From a practical standpoint, this is a group of varieties that cannot be evaluated solely by mean yield. FORSAIT has high yield potential and frequently becomes a leader in specific regions, whereas Blahodatna and Foks demonstrate a more contrasting response that is useful for identifying specific niches.

Figure 2 shows the relationship between mean response and ecological stability. Under this interpretation, genotypes located closer to the center of the coordinate system are characterized by a weaker expression of interaction with the environment. The variety Biskvit is the closest to the center, which fully agrees with the minimum ASV value presented in Table 2. MIP Darunok, Bila, Ormesson, Ambitsiia, and Barentus also occupy relatively favorable positions. These varieties do not form a single group in terms of yield, but they show a more moderate response than strongly peripheral genotypes.

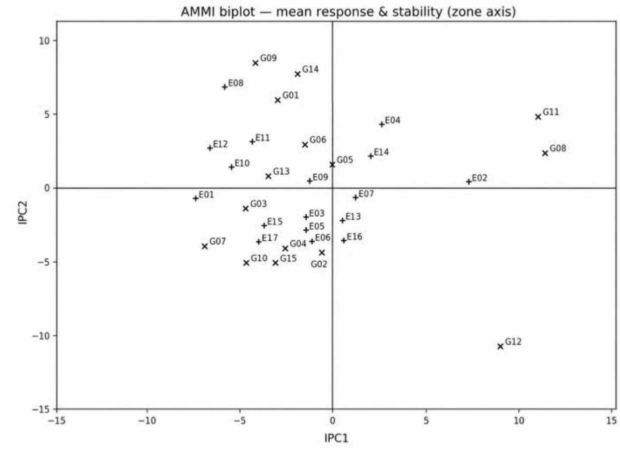

Fig. 2. AMMI biplot – mean response and ecological stability (environment axis)

MIP Darunok is particularly important in this plot because its position combines proximity to the center with a high yield level. This explains its minimum YSI value. Unlike Biskvit, which is stable but inferior to the leading varieties in productivity, MIP Darunok maintains a balance between the two criteria. Therefore, it can be regarded as the most suitable variety for broad use under conditions where farms aim both to obtain a high yield and to reduce the risk of sharp losses caused by changes in weather conditions.

The variety Bila occupies a somewhat more distant position; however, in combination with its very high mean yield, this makes it one of the main candidates for production areas. Compared with MIP Vidznaka, Bila is less extreme in the AMMI space, and therefore its value is determined not only by its high potential but also by its relatively better balance. MIP Vidznaka, FORSAIT, Blahodatna, and Foks are located farther from the center, indicating pronounced specificity.

Figure 3 is used to compare the studied varieties with a conditional ideal genotype. The concentric circles indicate the distance from the desirable direction, that is, from the combination of high yield and lower dependence on the environment. According to this logic, the most valuable genotypes are those that simultaneously maintain high mean productivity and do not move too far into the zone of specific response. The tabular data make it possible to link the graphical interpretation with YSI: the core of the most promising varieties is formed by MIP Darunok, Bila, Biskvit, and MIP Vidznaka, although each of them represents a different type of value.

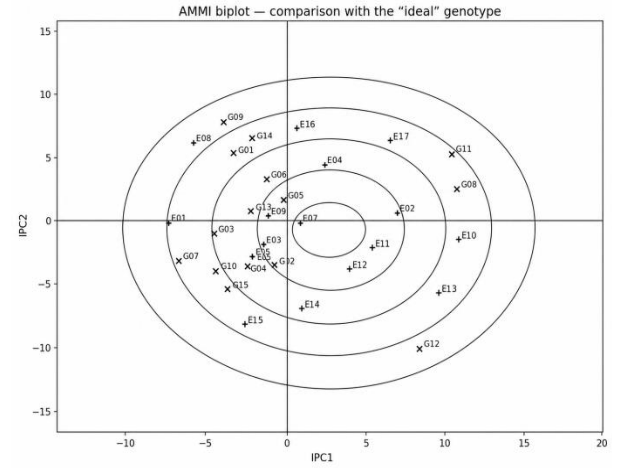

Fig. 3. GgE biplot identification of the ideal variety

MIP Darunok was closest to the optimal balance because it combined high yield with a low ASV value. Bila was shifted toward high productivity while maintaining acceptable stability. Biskvit was closer to the stable type, although its mean yield limited its direct production value. MIP Vidznaka was located in the group of high-yielding but more specifically adapted genotypes. Thus, the ideal-variety plot does not indicate a single absolute answer, but rather several functional roles of varieties depending on the production objective. Genotypes located farther from the ideal center should not be considered useless. Blahodatna, Foks, and FORSAIT showed a pronounced specific response; for these varieties, accurate regional targeting is especially important. Syntetyk 240 and DSV1929121 may also be important in particular environments, as confirmed by their inclusion in the TOP-3 in some regions.

The identification of the TOP-3 varieties within individual environments makes it possible to move from a general AMMI-based assessment to specific regional recommendations (Table 3). Such a table is especially important because even a genotype with a high mean yield may not be the best in every region, while a variety with a moderate overall position may demonstrate a local advantage.

In the Steppe zone, pronounced contrast was observed. In Dnipropetrovsk Oblast, the leading varieties were MIP Darunok, Bila, and DSV1929113, whereas in Odesa Oblast the leaders were MIP Darunok, Bila, and MIP Vidznaka. These two environments demonstrated a similar pattern, in which the basis of recommendations consisted of varieties with high overall productivity and relatively acceptable stability. However, Kirovohrad Oblast differed sharply, with the leading varieties being FORSAIT, Blahodatna, and Foks. This change in leaders indicates a high internal heterogeneity of the Steppe zone.

In the Forest-Steppe zone, the structure of leading varieties was the most diverse. MIP Darunok was included in the TOP-3 in the Kyiv, Sumy, Ternopil, Cherkasy, and Chernivtsi oblasts, confirming its broad adaptation. The variety Bila also frequently occupied high positions, especially in the Kyiv, Ternopil, Cherkasy, and Chernivtsi environments. FORSAIT was the leading variety in the Vinnytsia and Ternopil oblasts and ranked second in Chernivtsi Oblast. This distribution indicates that the Forest-Steppe combines both environments favorable for universally stable varieties and environments where the pronounced specific response of FORSAIT provides an advantage.

Table 3
Comparison of genotypes under the environment conditions

No	Region	Zone	TOP-1	TOP -2	TOP -3
E01	Dnipropetrovsk	Steppe	MIP Darunok	Bila	DSV1929113
E02	Kirovohrad	Steppe	FORSAIT	Blahodatna	Foks
E03	Odesa	Steppe	MIP Darunok	Bila	MIP Vidznaka
E04	Vinnytsia	Forest-Steppe	FORSAIT	Blahodatna	DSV1929121
E05	Kyiv	Forest-Steppe	MIP Darunok	Bila	DSV1929113
E06	Sumy	Forest-Steppe	MIP Darunok	Ambitsiia	Foks
E07	Ternopil	Forest-Steppe	FORSAIT	Bila	MIP Darunok
E08	Kharkiv	Forest-Steppe	Syntetyk 240	DSV1929121	MIP Vidznaka
E09	Cherkasy	Forest-Steppe	MIP Darunok	Bila	MIP Vidznaka
E10	Chernivtsi	Forest-Steppe	Bila	FORSAIT	MIP Darunok
E11	Volyn	Polissia	FORSAIT	Foks	Ambitsiia
E12	Zakarpattia	Polissia	FORSAIT	Blahodatna	Foks
E13	Ivano-Frankivsk	Polissia	Foks	Bila	MIP Darunok
E14	Lviv	Polissia	DSV1929121	Syntetyk 240	FORSAIT
E15	Rivne	Polissia	Bila	MIP Darunok	FORSAIT
E16	Khmelnytskyi	Polissia	FORSAIT	DSV1929121	Troiana
E17	Chernihiv	Polissia	Bila	MIP Darunok	FORSAIT

Kharkiv Oblast deserves special attention, where the leading genotypes were Syntetyk 240, DSV1929121, and MIP Vidznaka. This set differs from most other Forest-Steppe environments and indicates a specific structure of factors that favor varieties with a more contrasting position in the AMMI space. Vinnytsia Oblast was also oriented toward FORSAIT and Blahodatna, which brings it closer to part of the right sector of the biplot. Consequently, the Forest-Steppe cannot be regarded as a homogeneous zone, and varietal recommendations should take into account at least several subzones or groups of environments.

In Polissia, a combination of universal and specifically adapted leaders was also observed. FORSAIT ranked first in the Volyn, Zakarpattia, and Khmelnytskyi oblasts and was also included in the TOP-3 in the Lviv, Rivne, and Chernihiv regions. This shows that, despite its high ASV, the variety has considerable potential for a number of Polissia conditions. The variety Foks was the leader in Ivano-Frankivsk Oblast and entered the TOP-3 in the Volyn and Zakarpattia oblasts, confirming its pronounced local adaptation. Bila and MIP Darunok were particularly important in the Rivne and Chernihiv oblasts, where they occupied the first two positions.

The obtained results show that a multifactorial evaluation of winter wheat varieties should be based on a combination of several criteria. Mean yield remains the central indicator of varietal value, but it does not reveal how a genotype behaves when growing conditions change (Abdolshahi et al., 2015; Eskezia et al., 2025). In the present dataset, it is particularly clear that the variety with the highest yield is not necessarily the best according to an integrated index. MIP Vidznaka was the leader in productivity, but it was inferior to MIP Darunok and Bila when yield and stability were considered together.

The genotype MIP Darunok stood out because of its optimal balance. Its position was confirmed by several indicators at once: high productivity, the second ASV rank, the lowest YSI value, and frequent occurrence among the TOP-3 genotypes in different regions. This combination of characteristics makes the genotype suitable as a universal and highly stable variety (Cohen et al., 2021; Menzir et al., 2025). Such varieties are often the most valuable because they combine high productivity with a high degree of ecological stability.

Bila represents a somewhat different type. This genotype had almost maximum productivity and consistently ranked among the leaders in a number of environments. Its ASV was higher than that of MIP Darunok and Biskvit, but did not reach the extreme values typical of FORSAIT, Foks, or Blahodatna. Therefore, Bila can be recommended as a genotype with acceptable adaptability. It can form productive agrocenoses, especially in regions where its leading position was confirmed by the trial results (Saeidnia et al., 2022).

Biskvit demonstrates that stability alone is not equivalent to high efficiency. Its minimum ASV value makes it the most stable genotype in terms of response to the environment, but its productivity remained at an intermediate level. It may be useful under high-risk conditions where the main objective is to stabilize the overall result, but it should not be regarded as the basis of a highly productive cereal agrocenosis. At the same time, it has particular value as a source of low sensitivity to environmental change (Roostaei et al., 2017).

FORSAIT is an example of a variety with high potential and pronounced specific adaptation. It frequently became a leader in individual regions, especially in the Kirovohrad, Vinnytsia, Ternopil, Volyn, Zakarpattia, and Khmelnytskyi environments. However, its high ASV indicates that its advantage is not universal. This is a typical variety for targeted placement: under correctly selected conditions it can be one of the best (Sallam et al., 2019; Saeidnia et al., 2022), but under broad and unconditional distribution it may increase yield variability (Roostaei et al., 2017; Menzir et al., 2025).

The genotypes Foks and Blahodatna showed an even more contrasting pattern. They were not leaders in mean productivity, but they occupied high positions in specific environments, indicating the presence of specific adaptive advantages. Such genotypes are important for understanding the ecological structure of the trial. They demonstrate that individual environments can create conditions under which the overall mean assessment of a variety may be insufficient (Jha et al., 2017; Khare et al., 2024). In breeding, such forms may serve as sources of local resistance traits or responses to particular combinations of environmental factors.

DSV1929121 and Syntetyk 240 occupied an intermediate position. They were not the best according to YSI, but they showed high suitability in certain regions. DSV1929121 was included in the TOP-3 in the Vinnytsia, Kharkiv, Lviv, and Khmelnytskyi environments, while Syntetyk 240 was the leader in Kharkiv region and ranked second in Lviv region. This indicates the possibility of using these genotypes in regionally oriented recommendations, especially where their specific response type corresponds to the local environmental background (Nazarenko & Okselenko, 2026).

From the standpoint of zonal placement, the Steppe zone requires the most cautious approach. The Dnipropetrovsk and Odesa environments were observed to be favorable for MIP Darunok and Bila as productive genotypes, whereas the Kirovohrad environment clearly favored FORSAIT, Blahodatna, and Foks. In the Forest-Steppe, the frequent occurrence of MIP Darunok and Bila among the top genotypes indicates their broad suitability, although some environments were clearly oriented toward other genotypes. In Polissia, the role of FORSAIT and Foks became more pronounced, but in Rivne and Chernihiv regions Bila and MIP Darunok again occupied leading positions. Therefore, it is not possible to create a single universal list of varieties for all zones (Jha et al., 2017; El Baouchi et al., 2024).

Overall, the results are consistent with current views that stable productivity requires a combination of broadly adapted varieties and varieties intended for specific environments. Broadly adapted genotypes provide baseline stability, whereas specifically adapted ones make it possible to obtain maximum performance under favorable or particular local conditions (Abdolshahi et al., 2015; Eskezia et al., 2025). Therefore, the most rational strategy is not to select a single variety, but to form a varietal set in which MIP Darunok and Bila can play the basic role, Biskvit can serve as a stabilizing component, and FORSAIT, MIP Vidznaka, Foks, DSV1929121, and Syntetyk 240 can be used for targeted locations.

Conclusion

The AMMI analysis conducted in the present study showed that the genotype × environment interaction in the investigated winter wheat varieties had a pronounced and sufficiently complex structure. The first two IPCA components explained a major share of the interaction, which makes it possible to use two-dimensional biplots to interpret the main patterns, while at the same time indicating the need to take regional specificity into account when formulating recommendations. The most balanced variety in terms of the combined expression of yield and stability was MIP Darunok. The variety Bila was characterized by very high productivity together with acceptable stability. Biskvit stood out for its minimum ASV value and the most stable response; its value is associated primarily with yield stabilization and with its possible use in breeding as a source of plasticity. MIP Vidznaka and FORSAIT exhibited high potential, but were characterized by more pronounced specific adaptation. Their use should therefore be linked to particular regions. The varieties Foks, Blahodatna, DSV1929121, and Syntetyk 240 also appear to be important for local adaptation. The zonal analysis showed that the Steppe, Forest-Steppe, and Polissia differed in the composition of leading varieties. The more universal varieties were MIP Darunok and Bila, whereas FORSAIT, MIP Vidznaka, Foks, DSV1929121, and Syntetyk 240 require more precise regional targeting. The obtained results confirm the necessity of integrated evaluation based on yield, stability, and specific adaptation.

References

Abdolshahi, R., Nazari, M., Safarian, A., Sadathossini, T., Salarpour, M., & Amiri, H. (2015). Integrated selection criteria for drought tolerance in wheat (*Triticum aestivum* L.) breeding programs using discriminant analysis. Field Crops Research, 174, 20–29.

Ahmadi, J., Mohammadi, A., & Najafi Mirak, T. (2012). Targeting promising bread wheat (*Triticum aestivum* L.) lines for cold climate growing environments using AMMI and SREG GGE biplot analyses. Journal of Agricultural Science and Technology, 14, 645–657.

Bhandari, R., Poudel, M. R., Paudel, H., Neupane, M. P., Solanki, P., & Kushwaha, U. K. S. (2026). Breeding climate-resilient wheat for Nepalese agricultural system under diverse abiotic stresses using an integrated AMMI, GGE and stress tolerance indices. Scientific Reports, 16, 1751.

Cohen, I., Zandalinas, S. I., Huck, C., Fritschi, F. B., & Mittler, R. (2021). Meta-analysis of drought and heat stress combination impact on crop yield and yield components. Physiologia Plantarum, 171(1), 66–76.

Dang, X., Hu, X., Ma, Y., Li, Y., Kan, W., & Dong, X. (2024). AMMI and GGE biplot analysis for genotype × environment interactions affecting the yield and quality characteristics of sugar beet. PeerJ, 12, e16882.

El Baouchi, A., Ibriz, M., Dreisigacker, S., Lopes, M. S., & Sanchez-Garcia, M. (2024). Dissection of the genetic basis of genotype by environment interactions for morphological traits and protein content in winter wheat panel grown in Morocco and Spain. Plants, 13(11), 1477.

Eskezia, A., Kefale, H., & Asrat, M. (2025). Genotype by environment interaction and yield stability analysis of bread wheat (*Triticum aestivum* L.) varieties in East Gojjam Zone, Northwest Ethiopia. Heliyon, 11, e43500.

Güngör, H., Türkoğlu, A., Çakır, M. F., Dumlupınar, Z., Piekutowska, M., Wojciechowski, T., & Niedbała, G. (2024). GT biplot and cluster analysis of barley (*Hordeum vulgare* L.) germplasm from various geographical regions based on agro-morphological traits. Agronomy, 14(10), 2188.

Iwańska, M., Paderewski, J., & Stępień, M. (2025). Prediction of winter wheat cultivar performance using mixed models and environmental mean regression from multi-environment trials for cultivar recommendation to reduce yield gap in Poland. Agronomy, 15(10), 2309.

Jha, U. C., Bohra, A., & Jha, R. (2017). Breeding approaches and genomics technologies to increase crop yield under low-temperature stress. Plant Cell Reports, 36, 1–35.

Kassie, M. M., Abebe, T. D., Desta, E. A., & Tadesse, W. (2025). Multi-environment evaluation of bread wheat genotypes for yield stability in Ethiopia using AMMI and GGE-biplot analyses. Crop Breeding, Genetics and Genomics, 7(2), e250004.

Khare, V., Shukla, R. S., Pandey, S., Singh, S. K., & Singh, C. (2024). Exploring the genotype-environment interaction of bread wheat in ambient and high-temperature planting conditions: A rigorous investigation. Scientific Reports, 14, 2402.

Menzir, A., Firew, Y., Kassaye, M., & Mequanint, G. (2025). Yield performance and stability of durum wheat varieties in northwestern Ethiopia. BMC Plant Biology, 25, 1710.

Murphy, M. E., Boruff, B., Callow, J. N., & Flower, K. C. (2020). Detecting frost stress in wheat: A controlled environment hyperspectral study on wheat plant components and implications for multispectral field sensing. Remote Sensing, 12(3), 477.

Nazarenko, M., & Okselenko, O. (2026). Assessment of positive changes in winter wheat varieties under mutagen treatment. Agriculture and Forestry, 72(1), 77–92.

Nazarenko, M., Horshchar, V., & Izhboldin, O. (2026). Evaluation of new winter wheat varieties in diverse environments. Regulatory Mechanisms in Biosystems, 17(2), e26049.

Nazarenko, M., Okselenko, O., & Pozniak, V. (2023). Ecology- and geography-related features of winter wheat varieties for the areas of insufficient humidification. Agriculture and Forestry, 69(3), 159–177.

Roostaei, M., Jafarzadeh, J., Roohi, E., Nazary, H., Rajabi, R., Mohammadi, R., Khalilzadeh, G. R., Seif, F., Mirfatah, S. M. M., Seif Amiri, S., Hatamzadeh, H., & Ahmadi, M. M. (2022). Genotype × environment interaction and stability analyses of grain yield in rainfed winter bread wheat. Experimental Agriculture, 58, e37.

Saeidnia, F., Majidi, M. M., Dehghani, M. R., Saeidi, G., & Mirlohi, A. (2022). Drought tolerance and stability of native Iranian tall fescue genotypes: Comparison of AMMI and GGE biplot analyses. Agronomy Journal, 114, 2180–2185.

Sallam, A., Alqudah, A. M., Dawood, M. F. A., Baenziger, P. S., & Börner, A. (2019). Drought stress tolerance in wheat and barley: Advances in physiology, breeding and genetics research. International Journal of Molecular Sciences, 20(13), 3137.

Tanin, M. J., Sharma, A., Saini, D. K., Singh, S., Kashyap, L., Srivastava, P., Mavi, G. S., Kaur, S., Kumar, V., Kumar, V., Grover, G., Chhuneja, P., & Sohu, V. S. (2022). Ascertaining yield and grain protein content stability in wheat genotypes having the Gpc-B1 gene using univariate, multivariate and correlation analysis. Frontiers in Genetics, 13, 1001904.

Urbanaviciute, I., Bonfiglioli, L., & Pagnotta, M. A. (2024). Selection of durum wheat and SSR markers for agronomic farming in central Italy using AMMI analysis. Agronomy, 14(3), 458.

Ye, X., Li, J., Cheng, Y., Yao, F., Long, L., Wang, Y., Wu, Y., Li, J., Wang, J., Jiang, Q., Kang, H., Li, W., Qi, P., Lan, X., Ma, J., Liu, Y., Jiang, Y., Wei, Y., Chen, X., Liu, C., & Chen, G. (2019). Genome-wide association study reveals new loci for yield-related traits in Sichuan wheat germplasm under stripe rust stress. BMC Genomics, 20, 640.