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Application of advanced graphical models (GGE biplot, AMMI, WAASB) for assessing yield stability in practical breeding of winter hexaploid triticale

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Abstract: This study presents the application of advanced graphical and statistical models – GGE biplot, AMMI, and WAASB for the assessment of productivity and yield stability in winter hexaploid triticale. Sixteen genotypes (four standard varieties and twelve advanced breeding lines) were evaluated across three agro-ecologically contrasting growing seasons (2021–2024). The primary objective was to identify genotypes that combine high yield potential with stability across diverse environments. The results indicated considerable variability in yield performance depending on year and environmental conditions. The use of GGE biplot and AMMI models enabled a comprehensive analysis of genotype × environment interaction, revealing that lines G14 (193т/112-1), G7 (202/10-246), and G11 (107/09-273) exhibited both consistently high yields and notable stability, rendering them particularly promising for breeding and cultivation. The WAASB model provided an integrated evaluation of both productivity and stability, while the WAASBY index ranking further substantiated the superiority of these genotypes. The study also discusses the methodological limitations and emphasizes the necessity for further analyses employing advanced bioinformatics tools and a broader range of selection criteria. The practical relevance of these findings is the recommendation of stable, high-yielding genotypes suitable for a wide range of agro-ecological conditions.

Keywords: triticale; yield stability; genotype × environment; GGE biplot; AMMI analysis

INTRODUCTION

The breeding and development of new triticale varieties is a complex process, related both to the specifics of the crop and the traits targeted for improvement. According to Naroui Rad et al. (2025), the breeder's experience and the genetic diversity within the crop are key factors in the breeding process. At the same time, Milgate et al. (2015) pointed out that the evaluation of genetic resources under modern production practices is essential for determining the diversity that can be utilized in developing high-yielding varieties. Therefore, a key step in identifying desirable genotypes is the assessment of genetic diversity. In the selection of advanced, high-yielding triticale genotypes, both the empirical evaluation of yield and the assessment of its stability are of particular importance (Stoyanov et al., 2017; Stoyanov and Baychev, 2023; Stoyanov, 2024).

While the identification of genotypes with different yield potential is relatively straightforward, evaluating yield stability is a much more complex process. Because it relies on statistical procedures of different mathematical nature, expertise is required to correctly interpret a stability parameter. This aspect is particularly important in practical breeding, since combining productivity and stability requires precise evaluation. Otherwise, the selection of an unsuitable genotype may result in unfavorable outcomes. According to Tsenov et al. (2022), the choice of an appropriate method for determining stability faces several challenges, one of the most critical being the differing informativeness of individual methods. The same study, as well as Cheshkova et al. (2020), stated that the choice of a stability model should be dictated by the breeding objective. However, our previous research (Stoyanov, 2025) concluded that the choice of method is more closely related to the traits of the genotypes, their contrast, and the nature of the phenological results obtained. This reflects the fact that environmental conditions influence and modify genotype × environment interactions (Motzo et al., 2001; Stoyanov and Baychev, 2023).

One of the methods that removes the main environmental effects, while combining the genotype effect with the genotype × environment interaction, is the GGE biplot (Yan and Holland, 2010). This graphical approach provides a powerful tool for stability analysis in the context of multi-environment trials (MET) (Jandong et al., 2011; Yan et al., 2007). There are differing opinions regarding whether GGE biplot or AMMI graphical analysis is more suitable for stability assessment, as the respective authors (Gauch, 2006; Yan et al., 2007; Gauch et al., 2008) outlined their advantages and limitations. Recent studies (Ashango et al., 2016; Bornhofen et al., 2017; Mossie et al., 2024) did not show a clear preference, often applying both together to achieve more robust results. More recently, the WAASB method developed by Olivoto et al. (2019) has gained popularity, as it allows the simultaneous evaluation of productivity and stability through a two-dimensional visualization that considers multiple IPCAs rather than relying solely on IPCA1, as in the AMMI1 biplot.

Regarding triticale, the application of these modern graphical methods remains limited. Existing publications (Goyal et al., 2011; Kendal et al., 2016; Kendal and Sayar, 2016; Bilgin et al., 2018; Oral, 2018; Kendal et al., 2019; Güngör et al., 2022; Saed-Moucheshi et al., 2024) represent some of the few examples employing GGE biplot alone or in combination with AMMI analysis. In Bulgaria, GGE biplot and WAASB have not yet been implemented in practical triticale breeding, and no published studies demonstrate their application.

The aim of the present study is to apply advanced graphical models for the assessment of productivity and stability of triticale lines under contrasting environmental conditions, with the goal of identifying genotypes that combine high yield potential and stability.

MATERIALS AND METHODS

Plant material and growing conditions

The study was conducted with sixteen genotypes of triticale (×*Triticosecale* Wittmack) (Table 1). The first four genotypes – AD-7291, Vihren, Rakita, and Kolorit – were used as local standard varieties serving as control variants in the trial. The remaining twelve were advanced lines developed by the method of combinative breeding. Each genotype was designated by a unique index (G1–G16) and name. The trial was established as a competitive varietal trial over three consecutive growing seasons: 2021/2022, 2022/2023, and 2023/2024. Sowing was performed mechanically in experimental plots with five replications, and the area of each plot was 10 m². The yield from each plot was measured at full technological maturity of the grain.

Meteorological conditions

The analysis of monthly temperatures and precipitation for the three growing seasons (Tables 2 and 3) revealed clearly pronounced differences compared to the long-term average (1960–2024). In 2021/2022, temperatures were close to the multi-year average, with more evenly distributed precipitation, but with higher total rainfall during the summer months. The 2022/2023 season was characterized by higher winter temperatures and a pronounced precipitation deficit in autumn and summer, significantly below the multi-year average. In 2023/2024, higher temperature levels were recorded at the beginning of the growing season, with intense rainfall in November and April, while summer precipitation was minimal. The contrast among the three years, especially compared to the multi-year values, confirmed that the agro-ecological conditions during the trial were highly variable and suitable for evaluating the adaptability of the genotypes. The mean values for the three-year period (2021–2024) were intermediate between the annual extremes and generally close to the long-term averages (1960–2024), indicating that the selected seasons captured a representative range of climatic variation.

Table 1. Triticale genotypes used in the study

Genotype		Origin
Index	Name	
G1	AD-7291	Local check
G2	Vihren	Local check
G3	Rakita	Local check
G4	Kolorit	Local check
G5	48/10-213	Advanced line
G6	48/10-224	Advanced line
G7	202/10-246	Advanced line
G8	200/10-234	Advanced line
G9	174/10-190	Advanced line
G10	158/10-222	Advanced line
G11	107/09-273	Advanced line
G12	106/11-196	Advanced line
G13	19/12-100	Advanced line
G14	193т/112-1	Advanced line
G15	200/09-254	Advanced line
G16	200/10-237	Advanced line

Statistical models and data analysis

The statistical processing of the experimental data included the application of modern approaches for multicomponent assessment of productivity, stability, and genotype × environment interaction. The evaluation of yields and the interactions between genotypes and environmental conditions was carried out using GGE biplot analysis, which allowed simultaneous visualization of mean productivity, stability, and the specific adaptability of genotypes to different agroecological conditions. For a more in-depth study of the main effects and interactions, the AMMI (additive main effects and multiplicative interaction) model was applied, which enabled separate assessment of additive effects and the multiplicative components of the interaction. For an integrated evaluation of the stability and productivity

Table 2. Mean monthly temperatures (°C)

Period	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2021/2022	16,8	10,2	8,3	3,5	1,5	3,9	2,5	10,8	15,6	20,2	22,7
2022/2023	17,5	12,9	9,1	4,8	5,3	2,8	6,6	9,5	14,6	20,1	24,1
2023/2024	20,4	16,1	8,8	5,2	1,7	7,3	7,5	14,4	14,1	22,8	25,9
2020/2024	18,2	13,1	8,7	4,5	2,8	4,7	5,5	11,6	14,8	21,0	24,2
1960/2024	17,0	11,8	6,9	2,1	0,0	1,4	4,7	9,9	15,2	21,9	21,6

Table 3. Total monthly precipitation (mm)

Period	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2021/2022	8,0	91,6	42,4	89,2	31,4	30,8	19,0	76,0	25,6	76,4	40,4
2022/2023	93,6	6,0	29,4	28,4	29,0	7,4	38,8	79,0	34,2	2,8	40,6
2023/2024	0,6	66,0	126,4	53,0	20,2	2,0	15,6	107,4	61,0	0,8	12,0
2020/2024	34,1	54,5	66,1	56,9	26,9	13,4	24,5	87,5	40,3	26,7	31,0
1960/2024	45,5	42,8	44,2	42,9	37,1	32,8	34,8	42,2	51,6	60,9	50,1

of the studied genotypes, the WAASB (weighted average of absolute scores from BLUPs) approach was used, and the productivity assessment was performed using BLUP (best linear unbiased prediction). The ranking of genotypes according to the WAASBY index was applied for a combined selection assessment, simultaneously considering both stability and yield. All statistical analyses, as well as the generation of tabular and graphical results, were performed using R software and the *metan* package (Olivoto & Lúcio, 2020).

RESULTS

Dynamics of triticale genotype productivity depending on agro-ecological conditions

During the three-year field trial, significant variability in the productivity of the studied triticale genotypes was observed, depending on the agro-ecological conditions in each growing season (Table 4).

In the 2021/2022 season, the highest average yields were recorded for G6 (48/10-224, 11.06 t/ha), G14 (193т/112-1, 10.86 t/ha), and G7 (202/10-246, 10.57 t/ha). All of these exceeded the experimental mean significantly. In addition, G12 (106/11-196, 10.57 t/ha) and G15 (200/09-254, 10.41 t/ha) also surpassed the mean for the studied population. The lowest productivity was observed for G4 (Kolorit, 9.50 t/ha), G2 (Vihren, 9.22 t/ha), and G1 (AD-7291, 7.79 t/ha).

In the 2022/2023 season, the leading genotypes in terms of productivity were G14 (193т/112-

Table 4. Mean yields (t/ha) of the studied triticale genotypes

Genotype		2021/2022	2022/2023	2023/2024	Average
Index	Name				
G1	AD-7291	7,79---	5,23	7,63---	6,88---
G2	Vihren	9,22---	5,28	7,82--	7,44-
G3	Rakita	9,62	4,91	7,69---	7,41--
G4	Kolorit	9,50-	3,50---	7,83-	6,94---
G5	48/10-213	10,26	4,39---	8,41+++	7,68
G6	48/10-224	11,06+++	4,73-	8,76+++	8,18+++
G7	202/10-246	10,57++	5,98+++	8,10	8,22+++
G8	200/10-234	9,79	5,39	8,08	7,75
G9	174/10-190	10,05	5,17	8,07	7,76
G10	158/10-222	10,03	4,48--	7,77---	7,42-
G11	107/09-273	10,20	6,40+++	8,27+	8,29+++
G12	106/11-196	10,57++	4,69-	7,84-	7,70
G13	19/12-100	10,03	5,63+	7,62---	7,76
G14	193т/112-1	10,86+++	6,71+++	8,56+++	8,71+++
G15	200/09-254	10,41+	4,56--	8,20	7,72
G16	200/10-237	10,10	5,19	8,30++	7,87
Average		10,01	5,14	8,06	7,74
LSD0,05		0,39	0,40	0,17	0,24
LSD0,01		0,51	0,53	0,23	0,31
LSD0,001		0,65	0,68	0,29	0,40

Legend: *Symbols indicate statistical significance relative to the mean: +++ (p < 0.001), ++ (p < 0.01), + (p < 0.05) – significantly above the mean; ---, --, - – significantly below the mean at the same levels; no symbol – not significantly different (ns).*

1, 6.71 t/ha), G11 (107/09-273, 6.40 t/ha), and G7 (202/10-246, 5.98 t/ha). Notably higher-than-average yields were also obtained for G13 (19/12-100, 5.63 t/ha) and G7 (202/10-246, 5.98 t/ha). The lowest values for this season were recorded for G10 (158/10-222, 4.48 t/ha), G5 (48/10-213, 4.39 t/ha), and G4 (Kolorit, 3.50 t/ha).

During the 2023/2024 season, the highest yields were achieved by G6 (48/10-224, 8.76 t/ha), G14 (193т/112-1, 8.56 t/ha), and G5 (48/10-213, 8.41 t/ha). Significantly higher productivity than the average was also recorded for G11 (107/09-273, 8.27 t/ha) and G16 (200/10-237, 8.30 t/ha). The lowest-yielding genotypes in this season were G3 (Rakita, 7.69 t/ha), G1 (AD-7291, 7.63 t/ha), and G13 (19/12-100, 7.62 t/ha).

When analyzing the average yield for the entire study period (2021–2024), the most productive genotypes were G14 (193т/112-1, 8.71 t/ha), G11 (107/09-273, 8.29 t/ha), and G7 (202/10-246, 8.22 t/ha), which significantly exceeded the mean value for the studied population ($p < 0.05$). The lowest average yields for the entire experiment were recorded for G3 (Rakita, 7.41 t/ha), G4 (Kolorit, 6.94 t/ha), and G1 (AD-7291, 6.88 t/ha).

Comprehensive GGE biplot analysis for evaluation of productivity, stability, and genotype × environment interaction

Within the present study, GGE biplot analysis (Figures 1–7) was applied for a multicomponent assessment of productivity, stability, and genotype × environment interaction. The analysis was structured in seven complementary biplot visualizations, each highlighting specific aspects of genotype performance and the selective behavior of environments.

The first two principal components (PC1 – 56.62%, PC2 – 39.23%) together explained 95.85% of the total variation, providing high informativeness of the analysis (Figure 1). Genotypes, such as G7 (202/10-246), G8 (200/10-234), G9 (174/10-190), G10 (158/10-222), G12 (106/11-196), G13 (19/12-100), G14 (193т/112-1), and G16 (200/10-237), were located close to the horizontal axis, indicating higher stability (i.e., lower PC2 scores). In contrast, genotypes positioned farther from the axis, such as G1 (AD-7291), G4 (Kolorit), G6 (48/10-224), G11 (107/09-273), and G15 (200/09-254), displayed greater variability and stronger genotype × environment interaction. Thus, the PC2 values were the basis for assessing stability, while PC1 primarily reflected mean productivity. Regarding the test environments, 2021/2022 formed the longest vector and was positioned in the upper right quadrant, indicating that the conditions during this period favored the expression of high-yielding genotypes. The 2022/2023 season was located in the opposite direction, suggesting contrasting responses, while 2023/2024 occupied an intermediate position, balancing genotype performance.

In Figure 2, the genotypes were evaluated according to two key characteristics: mean productivity (their projection on the average environment coordinate, AEC abscissa) and stability (their distance from this axis). Genotypes G11 (107/09-273), G7 (202/10-246), and G14 (193т/112-1) were positioned closest to the tip of the AEC abscissa, identifying them as the most productive and simultaneously stable across environments. In contrast, G1 (AD-7291) and G4 (Kolorit) showed lower productivity and stabil-

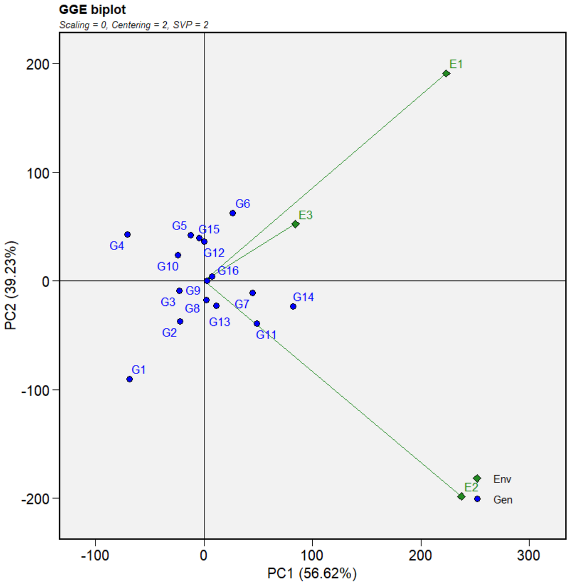

Figure 1. GGE biplot (PC1 × PC2) for positioning of genotypes and environments

ity, while G2 (Vihren) and G3 (Rakita) exhibited moderate productivity, but relatively higher stability. These results demonstrated that the standard varieties varied strongly in their response to environmental conditions, highlighting their limited suitability for universal use, but potential applicability as parental forms in targeted breeding for specific stress conditions.

Figure 3 presented the which-won-where GGE biplot, which allowed visualization of specific adaptation and competitiveness of the studied genotypes under different environments. Through a convex polygon, five genotypes forming its vertices were identified: G1 (AD-7291), G4 (Kolorit), G6 (48/10-224), G14 (193т/112-1), and G11 (107/09-273). Each of these genotypes acted as a "winner" in at least one sector, achieving the highest yield under specific conditions. For example, G1 (AD-7291) was located farthest from the environments, suggesting a narrow adaptation and productivity advantage only under specific conditions.

Kolorit (G4) exhibited a similar pattern, although it was located closer to the conditions of 2023/2024, which indicated potential for use under more favorable agro-ecological conditions. G6 (48/10-224) stood out for its high productivity and stability under conditions resembling those of the same growing season. In contrast, G14 (193т/112-1) demonstrated broad adaptation, being positioned near the sector between 2021/2022 and 2023/2024. Accordingly, G11 (107/09-273) was identified as competitive under the conditions of 2022/2023. Genotypes located within the interior of the polygon, such as G2 (Vihren), G3 (Rakita), G7 (202/10-246), and others, were characterized by more balanced performance across environments, without dominating in any of them. This spatial distribution was considered an indicator of higher stability, since the absence of extremely high yields in individual environments was compensated by relatively uniform performance across all tested conditions. Thus, the biplot enabled an objective evaluation of both specific and general adaptability of the genotypes, providing a clear basis for comparing their competitive advantages under variable agro-ecological conditions. The which-won-where visualization clearly distinguished genotypes with maximum yield potential in specific environments from those exhibiting more stable and uniform performance.

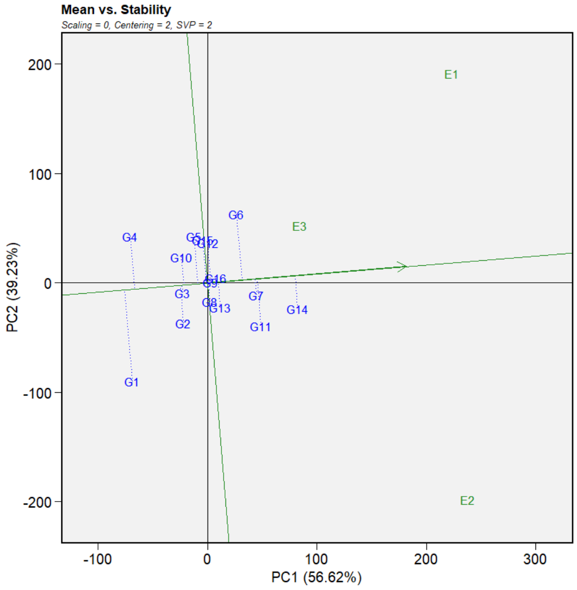

Figure 2. Mean vs. stability biplot for evaluation of mean productivity and stability of genotypes

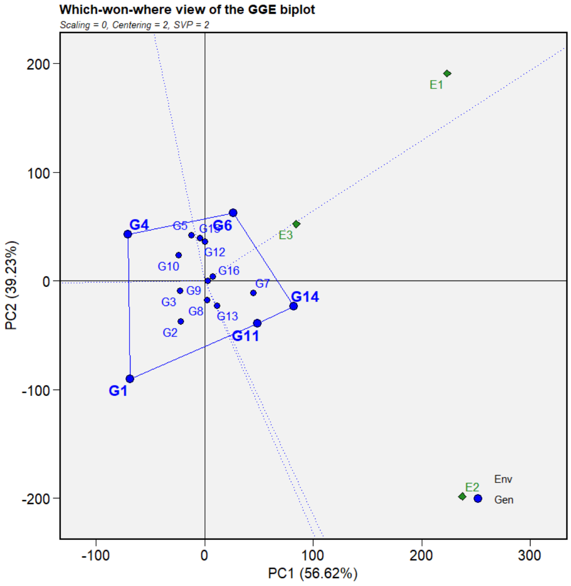

Figure 3. Which-won-where biplot for identifying the best-performing genotypes in each environment

Figure 4 presented the Discriminativeness vs. Representativeness biplot, a specific GGE biplot visualization that enabled simultaneous assessment of the environments' ability to discriminate among genotypes (discriminativeness) and their proximity to the "ideal" environment (representativeness). In this biplot, each environment was represented as a vector originating from the center of the coordinate system.

The length of the vector for each environment was an indicator of its discriminativeness – that is, its ability to reveal variation among different genotypes. The longer the vector, the more strongly the environment distinguished genotype performance, thereby facilitating the identification of productivity differences. At the same time, the angle between the environmental vector and the mean axis (representativeness axis) reflected its representativeness relative to the mean of all environments. Environments, whose vector was closer to this axis, were considered more representative, meaning they best reflected the average agro-ecological conditions of the trial.

In the presented analysis, 2021/2022 stood out with the greatest vector length and the smallest angle relative to the mean axis. This result indicated that this growing season was both the most discriminative and the most representative. From a breeding perspective, such conditions were particularly valuable, as they not only provided the clearest distinction among genotypes by productivity but also reflected average environmental conditions. In the context of variety testing, this season was therefore considered optimal for evaluating new lines, especially when the goal was the identification of stable and broadly adaptable genotypes.

The 2022/2023 season was also characterized by a long vector, but its angle relative to the mean axis was significantly greater, indicating that despite high discriminativeness, it was less representative of the average conditions of the trial. This environment functioned as a differentiator for specific or stress adaptation, but it was less suitable for evaluating genotypes intended for wide adaptation. The 2023/2024 season displayed a shorter vector and a small angle to the mean axis, corresponding to moderate discriminativeness and high representativeness. This environment allowed the evaluation of genotypes in terms of stability, although with limited capacity to identify those with extreme productivity potential.

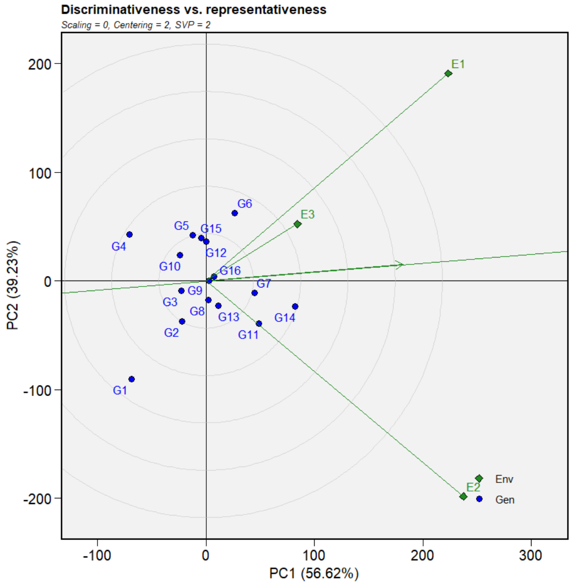

Figure 4. Discriminativeness vs. representativeness biplot – assessment of the discriminativeness and representativeness of environments and genotypes

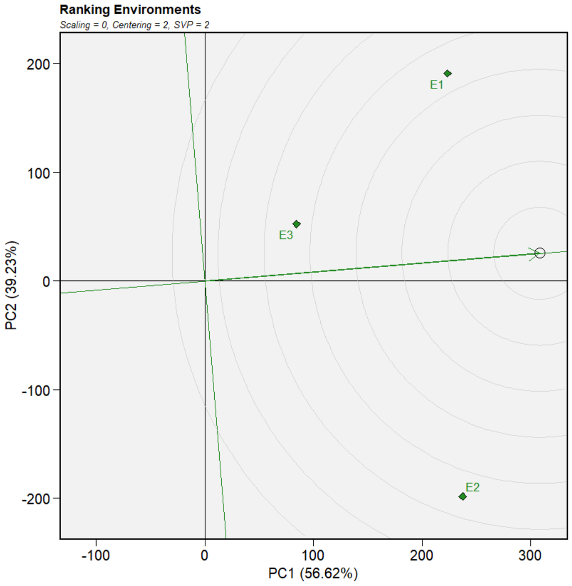

Figure 5. Ranking environments biplot – ranking of testing environments

The visualization in Figure 5 provided a synthesized ranking of environments according to their value for the breeding process. The 2021/2022 season occupied a leading position, combining the highest levels of discriminativeness and representativeness, which made it optimal for field trials. The 2023/2024 season also showed favorable positioning, while 2022/2023 was identified as the least representative, suggesting its use mainly for breeding programs targeting specific conditions rather than for routine variety testing.

Figure 6 presented the angular and vector correlations among the environments. The smaller angle between 2021/2022 and 2023/2024 indicated a high correlation in genotype responses across these years. By contrast, 2022/2023 formed a larger angle compared with the other two seasons, reflecting its distinct selectivity and environmental specificity.

Figure 7 showed the Ranking Genotypes GGE biplot, which provided a comprehensive visual assessment of the triticale genotypes based on the combination of mean productivity and stability across all tested environments. The axis directed toward the ideal genotype defined the breeding optimum – the point representing maximum productivity combined with high stability. Genotypes G7 (202/10-246), G11 (107/09-273), and G14 (193т/112-1) were positioned in closest proximity to this ideal point, identifying them as the most promising breeding candidates, since they demonstrated both consistently high yield and stability across environments.

On the other hand, genotypes such as the standard varieties G1 (AD-7291), G4 (Kolorit), G3 (Rakita), and G2 (Vihren), which were positioned farther from the ideal point, exhibited either lower stability or lower mean productivity. These genotypes were characterized by pronounced specific adaptability, and therefore, were considered suitable for breeding strategies targeting limited or stress-prone agro-ecological conditions. The remaining lines located within the inner concentric circles, such as G5 (48/10-213), G10 (158/10-222), G13 (19/12-100), and G15 (200/09-254), showed a more balanced response in terms of stability and productivity, making them appropriate for regions with highly variable growing conditions.

The applied GGE biplot analysis demonstrated a clear differentiation among genotypes with respect to productivity and stability, with G6 (48/10-224), G7 (202/10-246), and G14 (193т/112-1), achieving the highest combined values. These

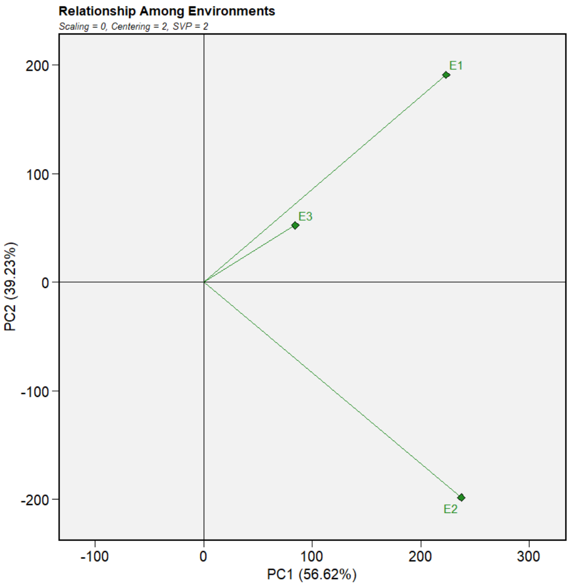

Figure 6. Relationship among environments biplot – analysis of correlations between environments

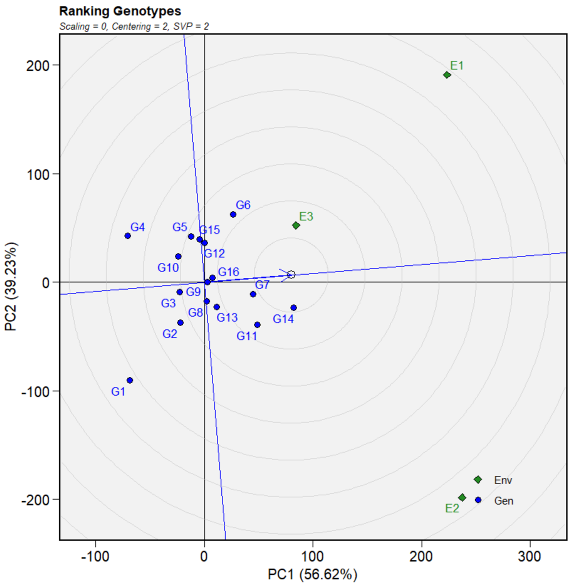

Figure 7. Ranking genotypes GGE biplot

results confirmed the effectiveness of the multivariate graphical approaches employed for breeding evaluation. The identification of specifically adaptable as well as stable genotypic responses provided new insights into genotype × environment interaction and supported the practical selection of candidate genotypes combining high productivity and stability.

AMMI analysis of genotype × environment interaction: productivity, stability, and adaptability

On the AMMI1 biplot (Figure 8), a combination of mean yield and the values of the first principal component of the interaction (IPCA1), which explained 79.3% of the G × E variation, was presented. The spatial distribution of the genotypes and environments allowed for simultaneous interpretation of productivity and stability. The standard variety G3 (Rakita) and the lines G7 (202/10-246), G8 (200/10-234), G9 (174/10-190), and G16 (200/10-237) were located close to the abscissa (IPCA1 ≈ 0), which indicated broad adaptability and stable productivity under all analyzed environmental conditions. These genotypes exhibited a weak response to changes in agro-ecological conditions, and their relatively high yield values identified them as promising breeding material. However, they were not the genotypes with the highest mean productivity. Genotypes with higher yields displayed stronger interaction with the environments, such as G6 (48/10-224), G14 (193т/112-1), and G11 (107/09-273).

The standard varieties G1 (AD-7291) and G2 (Vihren) were positioned in the lower left part of the biplot, which indicated specific adaptability to the conditions of 2022/2023 and a targeted response to limiting environmental factors. In contrast, G4 (Kolorit) and the lines G5 (48/10-213), G6 (48/10-224), G10 (158/10-222), G12 (106/11-196), and G15 (200/09-254) were associated with the 2021/2022 season, demonstrating a positive response in a favorable environment characterized by high mean yield. Among the environments, 2022/2023 showed the lowest yield values and strongly negative IPCA1 scores, while 2023/2024 occupied an intermediate position.

The AMMI2 biplot (Figure 9) combined the first and second principal components (IPCA1 and IPCA2, accounting for 79.3% and 20.7% of the variation, respectively), thereby visualizing the majority of the interaction variation. Genotypes located near the origin of the coordinate system,

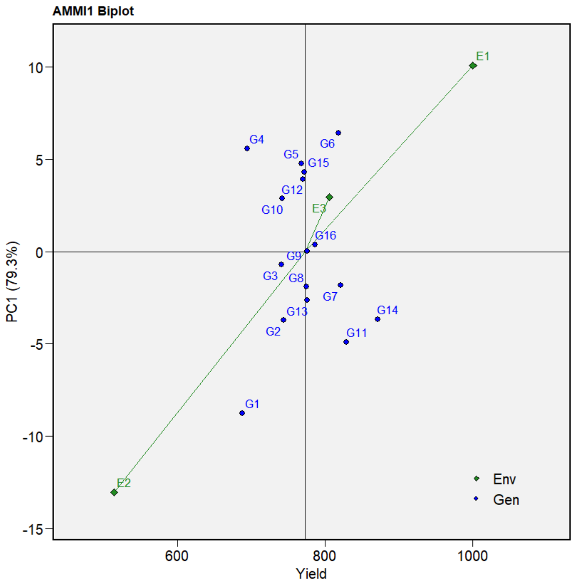

Figure 8. AMMI1 biplot

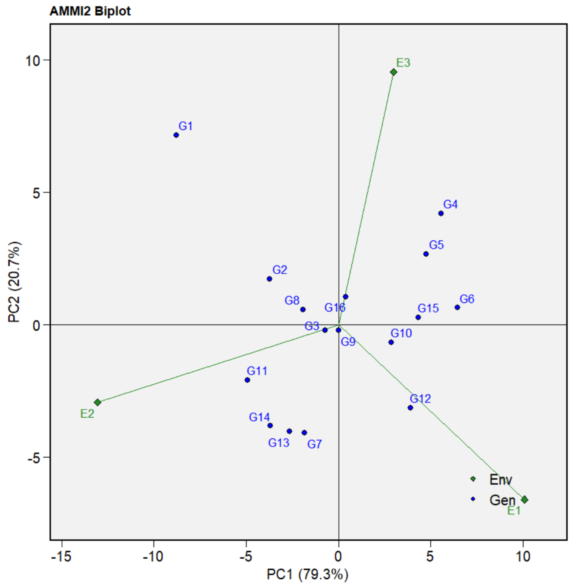

Figure 9. AMMI2 biplot

including the standard G3 (Rakita) and the lines G9 (174/10-190) and G16 (200/10-237), exhibited minimal interaction with environmental factors and were characterized by broad adaptability and high yield stability, which was particularly valuable under variable weather conditions. By contrast, the standard varieties G1 (AD-7291) and G2 (Vihren) were positioned at the periphery of the biplot, reflecting strong genotype × environment interaction and specific adaptation.

G3 (Rakita) was positioned closer to the center, which indicated more limited interaction and broader adaptability. In contrast, G4 (Kolorit) was located near the sector of the 2023/2024 season, and was characterized as productive only under exceptionally favorable environmental conditions.

The spatial distribution of the years under study showed that E3 (2023/2024) had high positive values for the principal components, which characterized it as both productive and selective. E2 (2022/2023) displayed negative values for both main components, defining it as a limiting environment, while E1 (2021/2022) occupied an intermediate position in terms of discriminative ability. The mutual positioning of genotypes relative to the environments allowed for a more precise breeding evaluation of productivity, stability, and adaptability.

Integrated assessment of productivity, stability, and adaptability of genotypes using the WAASB approach

The WAASB model, developed by Olivoto et al. (2019), combined the advantages of AMMI (Additive Main Effects and Multiplicative Interaction) and BLUP (Best Linear Unbiased Prediction), which enabled a simultaneous and precise analysis of mean productivity, stability, and specific adaptability of genotypes.

In the Y × WAAS biplot (Yield versus WAASB; Figure 10), an overall visualization of the productivity and stability of the genotypes across environments was presented. The abscissa represented the mean yield, while the ordinate showed the weighted stability index WAASB (Weighted Average of Absolute Scores from BLUPs), where lower values indicated greater stability. The arrangement of genotypes and environments in the four quadrants of the graph allowed the identification of varieties and lines that combined optimal levels of productivity and stability.

Genotypes positioned in the lower right quadrant (IV) – G7 (202/10-246), G8 (200/10-234), G9 (174/10-190), G13 (19/12-100), G14 (193т/112-1), G15 (200/09-254), and G16 (200/10-237) demonstrated both high yield and low WAASB values, identifying them as stable and highly productive. Among these, G9 (174/10-190), G16 (200/10-237), G7 (202/10-246), and G14 (193т/112-1) showed a trend where yield increased in parallel with WAASB values, suggesting slightly reduced stability at higher yield levels.

The upper right quadrant (II) contained high-yielding but less stable genotypes, notably G11 (107/09-273) and G6 (48/10-224). This quadrant also included environment E1 (2021/2022), which stood out with high yield but significantly higher WAASB, indicating stronger interaction with individual genotypes. Environment E3 (2023/2024) was also located in this quadrant, but it was positioned closer to the mean WAASB value, reflecting a more balanced combination of productivity and stability.

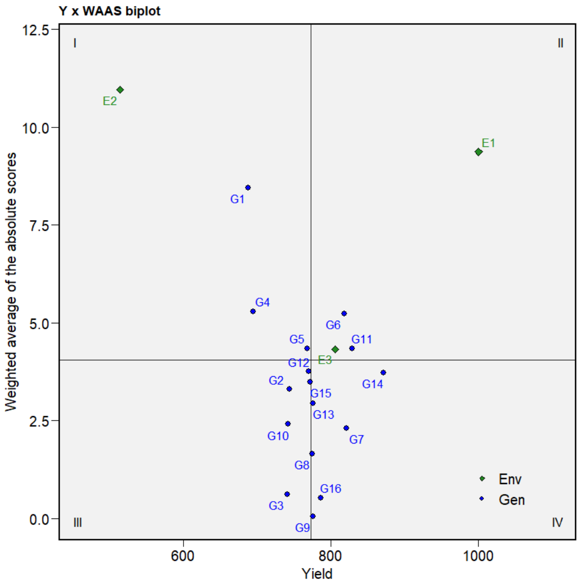

Figure 10. Y × WAAS biplot

The lower left quadrant (III) was dominated by genotypes such as the standard varieties G2 (Vihren) and G3 (Rakita), together with G10 (158/10-222), G12 (106/11-196), and G15 (200/09-254). These genotypes exhibited good stability (WAASB values below the mean) but relatively lower yields, though still close to the mean yield of the studied set.

The upper left quadrant (I) contained combinations of low yield and low stability. In this group, environment E2 (2022/2023) stood out with the highest WAASB values and the lowest mean yield, indicating that the conditions during this year were particularly stressful. This quadrant also included the standard varieties G1 (AD-7291), G4 (Kolorit), and G5 (48/10-213).

The nominal yield plot (Figure 11) illustrated the response of all 16 studied genotypes to the first principal component (IPCA1) of the environment, expressed as the square root of yield. Each genotype was represented by a separate line, showing its nominal yield under the respective environmental conditions E1, E2, and E3. The standard variety G4 (Kolorit) and the lines G5 (48/10-213), G6 (48/10-224), G10 (158/10-222), G12 (106/11-196), and G15 (200/09-254) demonstrated a pronounced positive response with increasing IPCA1, which indicated a narrower adaptability to more favorable environmental conditions.

Genotypes such as the standard varieties G1 (AD-7291) and G2 (Vihren), together with the lines G7 (202/10-246), G8 (200/10-234), G11 (107/09-273), G13 (19/12-100), and G14 (193т/112-1), were characterized by a negative slope of their lines, which suggested better performance under stressful or unfavorable environmental conditions. Other genotypes, such as G3 (Rakita), G9 (174/10-190), and G16 (200/10-237), displayed almost horizontal lines, which were interpreted as a stable response combined with broad adaptability – i.e., stable yield without strong fluctuations under different environmental conditions.

This graphical interpretation of the lines allowed the identification of genotypes with a “which-won-where” type of behavior, in which some genotypes dominated under specific environmental conditions, while others maintained broader adaptability.

The ranking of genotypes by the integrated WAASBY index (Figure 12) allowed the simultaneous consideration of productivity and stability. All 16 genotypes were arranged on the ordinate, while the WAASBY values were shown

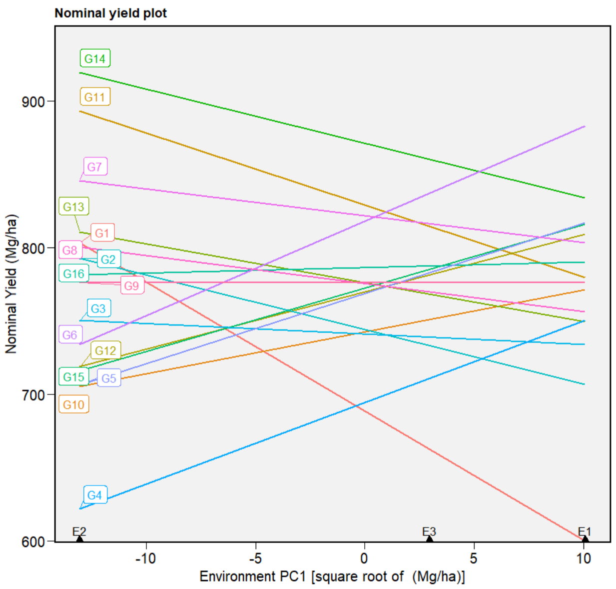

Figure 11. Nominal yield plot

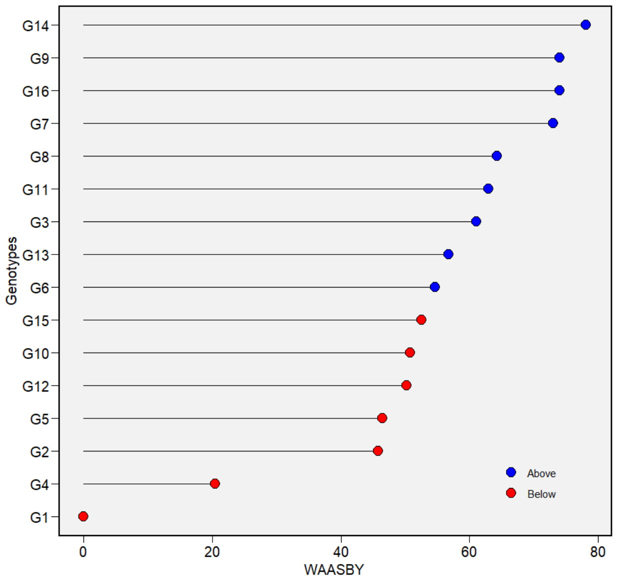

Figure 12. Ranking of the studied triticale genotypes by WAASBY

on the abscissa. G14 (193т/112-1) stood out with the highest WAASBY value, indicating an optimal combination of high yield and yield stability across environments. It was followed by G9 (174/10-190), G16 (200/10-237), G7 (202/10-246), and G8 (200/10-234), which also demonstrated favorable combinations of productivity and stability. In contrast, G1 (AD-7291), G4 (Kolorit), G2 (Vihren), and G5 (48/10-213) had the lowest WAASBY values, positioning them as less suitable for regions with high variability in climatic and agro-ecological conditions.

The effect of the number of principal components (IPCA) included in the stability ranking (Figure 13), illustrated the complex dynamics of the WAASB index when different interaction components were considered. For each component (IPCA1, IPCA2), the genotype ranks were visualized, with darker colors indicating better (lower) stability ranks. When either of the principal components was applied, G9 (174/10-190), G3 (Rakita), and G16 (200/10-237) emerged as the most stable. The least stable genotypes were G1 (AD-7291), G4 (Kolorit), and G5 (48/10-213). However, while the two standard varieties were characterized by low productivity, G5 (48/10-213) exhibited comparatively high productivity. The observed changes in ranks were minor, supporting earlier literature that emphasized the need to consider multiple components when analyzing complex G × E structures. No genotype displayed substantial shifts in rank, suggesting the importance of further in-depth analysis of the interaction.

When evaluating the ranking under different proportions between WAASB and mean yield (GY), the stability of each genotype's position was determined as the priorities between stability and productivity were shifted, complementing the information from the previous graph. The horizontal axis represented the different ratios between WAASB and yield – from 100% stability / 0% yield to 0% stability / 100% yield, while the vertical axis listed all genotypes. The standard variety G3 (Rakita) and the lines G14 (193т/112-1), G9 (174/10-190), G16 (200/10-237), G8 (200/10-234), G7 (202/10-246), and G13 (19/12-100) maintained high (i.e., low-rank) values in all scenarios, indicating that they combined stability and productivity and were identified as the most suitable for diverse soil and climatic conditions.

Other genotypes, such as G1 (AD-7291) and G4 (Kolorit), showed consistently high ranks un-

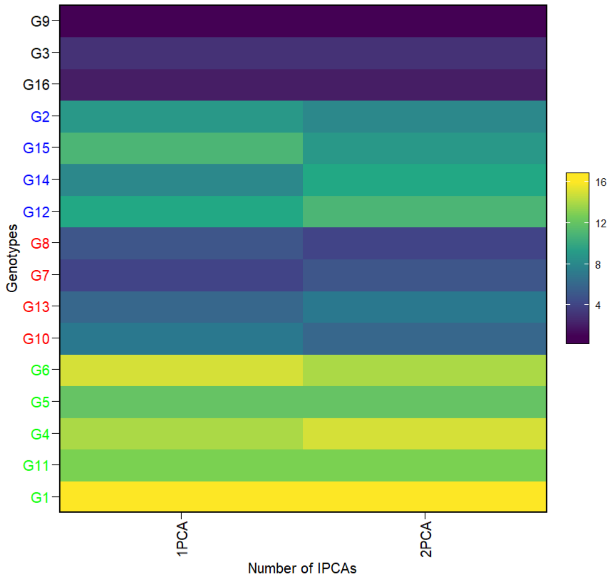

Figure 13. Influence of the principal components of interaction (IPCA) on stability ranking

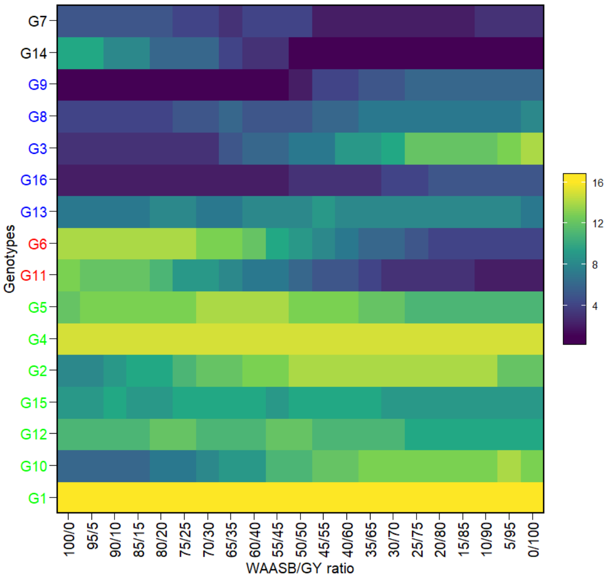

Figure 14. Ranking under different ratios between WAASB and mean yield of the studied genotypes

der every ratio, which characterized them as low in both productivity and stability. The standard variety G2 (Vihren) and the lines G10 (158/10-222), G12 (106/11-196), and G15 (200/09-254) performed well only when maximum emphasis was placed on stability, but lost their ranking position when high yield was prioritized. The opposite trend was observed for G6 (48/10-224) and G11 (107/09-273), which ranked highly when productivity was prioritized, but declined when stability received greater weight. These results confirmed the flexibility of the WAASBY index as a breeding tool, allowing for dynamic weighting according to the specific objectives of the breeding program or the prevailing agro-ecological conditions.

The combined analysis of all graphical approaches confirmed the advantages of modern multifactorial and integrated methods, in which the combination of AMMI and BLUP allowed for the simultaneous consideration of mean performance, stability, and specific adaptability of the genotypes. According to the rankings from the applied models, the lines G14 (193т/112-1), G9 (174/10-190), G16 (200/10-237), G8 (200/10-234), G7 (202/10-246), and G13 (19/12-100) emerged as the most promising for future breeding and broader implementation. This analytical framework provided a robust basis for recommending genotypes with optimal combinations of productivity and stability, tailored to both specific and variable growing conditions.

DISCUSSION

Significance of the obtained results

Precise assessment of genotype × environment (G × E) interaction is a fundamental requirement in modern plant breeding (Gauch, 1992; Stoyanov, 2021). In the present study, models such as AMMI (Additive Main Effects and Multiplicative Interaction) and GGE biplot (Genotype plus Genotype × Environment interaction) were successfully applied, both of which are established standards in the analysis of data from competitive varietal trials. The AMMI model combines the advantages of analysis of variance (for main effects) and singular value decomposition (SVD), enabling the identification of genotypes with either broad or specific adaptability. According to Gauch et al. (2008), AMMI biplots provide a clear geometric interpretation of nominal yields and adaptive responses, while AMMI2 offers more detailed visualization for complex datasets. Recent developments, such as Bayesian AMMI (BAMMI), further expand applicability by allowing analyses with unbalanced data (de Melo et al., 2023).

GGE biplot analysis, in turn, enables visualization of the “which-won-where” effect, integrating the main genotype effect with the G × E interaction (Yan and Kang, 2002). Additional interpretations, such as the heritability-adjusted HA-GGE biplot, further refine stability analysis by considering trait heritability (Yan and Holland, 2010). In recent years, new approaches such as BLUP (best linear unbiased prediction), BLUE (best linear unbiased estimates), and the development of stability indices (e.g., SID, APCV, Pcor) have been introduced to increase reliability and interpretability of results under stress and heterogeneous conditions (Olivoto et al., 2019; Ayalew et al., 2022; Dyulgerova and Dyulgerov, 2024; Saed-Moucheshi et al., 2024; Naroui Rad et al., 2025).

In the present study, advanced graphical and multidimensional models revealed clear differences in productivity and stability among triticale genotypes across the tested environments. The high degree of interaction was consistent with trends reported in previous national and international studies (Kaya and Ozer, 2014; Lule et al., 2014; Ferreira et al., 2015; Milgate et al., 2015; Kutlu & Gülmezoğlu, 2017; Đekić et al., 2018; Stoyanov and Baychev, 2018; Georgieva and Kirchev, 2020; Bocianowski et al., 2021; Grebennikova et al., 2021; Stoyanov, 2021; Güngör et al., 2022; Stoyanov and Baychev, 2023; Neykov, 2024; Stoyanov, 2024), confirming that effective selection in triticale requires accurate evaluation of adaptability and stability. The application of AMMI and GGE biplot analyses enabled both graphical and quantitative description of the G

× E effect and identified genotypes with promising combinations of stability and productivity. In particular, G7 (202/10-246) and G14 (193т/112-1) emerged as consistently superior across methods, displaying high productivity, relatively good stability, and adaptability under the studied conditions. Such convergence across models is in line with findings of Kaya et al. (2006) and Derbew et al. (2024), who reported that combining complementary methods increases the robustness of genotype recommendations.

Practical significance and limitations of the models in practical triticale breeding

The results of this study are aligned with current advances in triticale breeding and evaluation. Derejko et al. (2020) reported that even with advanced models, such as linear mixed models and GGE biplot, genotype rankings can vary substantially between locations. Similarly, Goyal et al. (2011) found that certain introduced triticale lines demonstrated high stability and productivity under specific agro-ecosystems. Saed-Moucheshi et al. (2024) emphasized that the use of new indices within AMMI analyses facilitates selection under both stress and normal conditions. Numerous studies (Kendal et al., 2016; Kendal and Sayar, 2016; Kendal et al., 2019; Bilgin et al., 2018; Güngör et al., 2022) confirm that GGE biplot and AMMI analyses, individually or combined, provide powerful visualization of G × E interaction and support practical breeding decisions.

The practical significance of the present results lies in the identification of genotypes with both stability and productivity that can be further tested under production environments with variable ecological conditions. In accordance with the findings of Milgate et al. (2015) and Goyal et al. (2011), who emphasized that effective selection in triticale is possible even under intensive management systems, the results here suggest potential for developing varieties that combine high mean productivity and stability. Similar conclusions have been drawn by Bilgin et al. (2018), who demonstrated that GGE biplot successfully identifies genotypes with desirable stability profiles, suitable for either specific or broader adaptation zones depending on the breeding objectives. Importantly, the effectiveness of selection was enhanced by combining complementary statistical approaches, particularly in crops such as triticale and wheat, where G × E interaction is pronounced.

Nevertheless, this study also has limitations. The environments included covered only three consecutive growing seasons, which may limit the extent to which results can be generalized across all possible agro-ecological conditions. Therefore, the conclusions should be interpreted as indicative rather than definitive, highlighting genotypes with potential adaptability that require further validation across additional sites and years. Moreover, some of the latest bioinformatics tools, such as machine learning-based predictive models already applied in cereal breeding, were not included in this analysis. Future research should aim to broaden the dataset by incorporating more environments, additional morpho-agronomic and physiological traits, and genomic selection data. Expanding analyses to multi-objective stability indices and Bayesian AMMI approaches would further strengthen interpretation of complex G × E interactions.

CONCLUSIONS

As a result of the conducted study and the obtained results, the following conclusions can be drawn:

1. The practical application of GGE biplot, AMMI, and WAASB enabled a reliable assessment of productivity and stability in triticale across the three tested environments. The use of integrated indices such as WAASBY increased the efficiency of the breeding process by providing a more objective ranking of genotypes.
2. Genotypes G14 (193т/112-1), G7 (202/10-246), and G11 (107/09-273) emerged as the most promising, combining high mean productivity with relatively good stability under the studied conditions, suggesting potential for broader testing in future breeding programs.
3. The lines G9 (174/10-190), G16 (200/10-237), G13 (19/12-100), and G8 (200/10-234) dem-

onstrated a balanced combination of adaptability, stability, and productivity, making them potentially suitable for regions with more extreme or variable climatic conditions.

4. G6 (48/10-224) and G11 (107/09-273) showed selective adaptation and high productivity under favorable conditions but also displayed stronger interaction with environmental factors, which may limit their broader applicability.

5. The standard varieties G1 (AD-7291), G4 (Kolorit), and G2 (Vihren), together with G5 (48/10-213), exhibited lower mean productivity and stability compared to the advanced lines, which limited their potential for widespread use. However, they remain valuable as donors of specific adaptive traits and confirm their suitability as local standards.

6. The spatial positioning of genotypes in the biplot analyses supported the identification of lines combining productivity and stability under the tested environments. These results highlighted the usefulness of integrated models such as GGE biplot, AMMI, and WAASB, while also emphasizing the need for validation across a broader range of environments and for integration with emerging bioinformatic approaches.

Conflict of interest: none.

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