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RESEARCH ARTICLE

Genotype × environment interaction and parametric stability of grain yield in durum wheat (*Triticum durum* Desf.) under contrasting agroecological conditions

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Abstract

The aim of this study was to evaluate grain yield, ecological plasticity, and stability of ten durum wheat (*Triticum durum* Desf.) cultivars in multi-environment trials in terms of their suitability for dissemination under the conditions of the Western region of Ukraine. Field experiments were conducted over two growing seasons (2023-2024 and 2024-2025) at three agroecologically distinct locations, which in combination with years constituted six environments. Grain yield data were analyzed using combined analysis of variance and parametric stability approaches, including the Eberhart-Russell regression model and a set of nine stability parameters. The ANOVA results revealed a predominant contribution of the genotype effect to grain yield formation (over 90% of the total variation), while the effects of environment and genotype × environment interaction were statistically significant but comparatively smaller. Analysis of the G × E structure indicated the dominance of a linear, predictable component, suggesting that cultivar responses to changing growing conditions can be adequately described using regression coefficients. The cultivars differed markedly in their levels of plasticity and stability: high-yielding genotypes exhibited specific adaptation to favorable environments, whereas more stable cultivars produced moderate yield levels. The obtained results confirm the relevance of an integrated assessment of durum wheat cultivars that combines yield performance, stability, and plasticity as a scientifically sound basis for cultivar recommendation under conditions of increasing climatic variability.

Keywords: *Triticum durum*, Grain yield, Genotype × environment interaction, Ecological stability, Plasticity, Multi-environment trials

Introduction

Durum wheat (*Triticum durum* Desf.) has traditionally been regarded as a crop well adapted to semi-arid environments; however, its yield and quality traits vary considerably depending on growing conditions. Recent studies indicate that even within relatively homogeneous regions, environmental factors and their interaction with genotype can substantially alter cultivar ranking for grain yield, thereby complicating reliable cultivar recommendation for production (Göçmen, 2025).

One of the fundamental sources of yield variability is the genotype × environment interaction, which reflects differential responses of genotypes to changes in environmental conditions (Crossa, et al. 2017, Smith, et al. 2005). From a practical perspective, this implies that results obtained from a limited number of locations or seasons may be insufficient for reliably predicting cultivar performance in other agroecological contexts (Piepho, et al. 2008).

In this context, the analysis of G × E interaction is considered not merely a statistical procedure but a fundamental basis for decision-making regarding regional cultivar deployment. Among the most widely applied approaches for evaluating genotype stability and adaptability are parametric models, particularly the Eberhart-Russell regression method, as well as multivariate techniques such as Additive Main Effects and Multiplicative Interaction (AMMI) and Genotype and Genotype × Environment (GGE) biplot analyses (Gauch and Zobel, 1997, Yan and Kang, 2002). Cultivars with high dissemination potential contribute to reduced production risks, greater economic stability, and more efficient resource use, which is especially critical under uncertain climatic scenarios (Gauch, 2013).

The concept of stability is closely related to genotype plasticity, which describes the ability of a cultivar to modify trait expression in response to environmental variation. Highly plastic genotypes generally achieve superior performance under favorable conditions but may exhibit increased sensitivity to stress factors, thereby reducing their reliability in regions characterized by high environmental variability (Finlay and Wilkinson, 1963, Eberhart and Russell, 1966). Conversely, genotypes with low plasticity tend to show smaller yield fluctuations, making them more suitable for unstable environments, even if their maximum productivity is relatively lower (Mohammadi and Amri, 2013).

The Finlay-Wilkinson regression and the Eberhart-Russell model describe genotype responses along an environmental gradient using regression coefficients and deviation variances, allowing simultaneous evaluation of yield plasticity and stability (Finlay and Wilkinson, 1963, Eberhart and Russell, 1966). The relevance of stability and plasticity analysis becomes particularly pronounced when cultivars are introduced beyond their original testing regions. Insufficient consideration of G × E interaction at early stages of breeding or variety testing may result in reduced efficiency of cultivar adoption, economic losses, and increased production risks (Crossa, et al. 2017).

The objective of this study was to conduct an integrated evaluation of durum wheat genotypes based on grain yield, ecological stability, and plasticity across diverse growing conditions, using multi-location and multi-year data. The study aimed to apply parametric models of genotype × environment interaction to provide a scientifically grounded assessment of cultivar suitability for dissemination and to mitigate production risks under conditions of increasing climatic variability.

Materials and Methods

Field experiments were conducted over two consecutive growing seasons, 2023-2024 and 2024-2025, at three agroecologically distinct locations in the Western region of Ukraine: Chornyi Ostriv, Zastavna, and Shymkivtsi (Tab. 1). Each location-year combination was considered as a separate environment, in accordance with the classical approach to genotype × environment (G × E) interaction analysis commonly applied in parametric stability studies of cereal crops (Finlay and Wilkinson, 1963, Eberhart and Russell, 1966, Akcura, et al. 2006).

Table 1. Environmental conditions and soil characteristics of experimental sites.

Environment code	Growing season	Location	Latitude	Longitude	pH	Soil texture	Precipitation, mm	Max. temp	Min. temp	Sowing date	Harvest date
E1	2023-2024	Chornyi Ostriv	49.42616928	24.24526070	5.3	Light loam soils	663.1	35.2	-20.3	10.10.2023	06.07.2024
E2	2024-2025	Chornyi Ostriv	49.38385632	24.36072610	4.9	Light loam soils	533.4	37.0	-12.9	12.10.2024	15.07.2025
E3	2023-2024	Zastavna	48.65843319	25.61793505	5.4	Medium loam soils	490.2	37.2	-6.4	15.10.2023	01.07.2024
E4	2024-2025	Zastavna	48.64429193	25.64545635	5.2	Medium loam soils	373.4	37.0	-12.4	17.10.2024	08.07.2025
E5	2023-2024	Sukhodoly	50.06456638	25.24205238	7.3	Light loam soils	514.2	36.1	-20.3	11.10.2023	03.07.2024
E6	2024-2025	Sukhodoly	50.06865668	25.24617737	7.4	Light loam soils	207.8	34.8	-13.6	15.10.2024	14.07.2025

Thus, six environments (3 locations × 2 years) were defined in the study, differing in meteorological conditions during the growing season, particularly in temperature regimes and precipitation amounts.

The plant material consisted of ten durum wheat (*Triticum durum* Desf.) cultivars evaluated across all locations and years (Tab. 2). The cultivars originated from different European breeding programs (Austria, Germany, Poland, and Italy), allowing the assessment of a wide range of genetic variability in grain yield and adaptive traits.

Table 2. **Varieties used in the experiment.**

Genotype code	Cultivar name	Country of origin	Genotype code	Cultivar name	Country of origin
G1	Sambadur	Austria	G6	Winterstern	Germany
G2	Durofinus	Austria	G7	Tetida	Poland
G3	Diadur	Austria	G8	Metis	Poland
G4	Tennodur	Austria	G9	Flexadur	Italy
G5	Wintergold	Germany	G10	Duriamo	Italy

The experiments were arranged in a Randomized Complete Block Design (RCBD) with three replications in each environment, following standard procedures for multi-environment trials (Eberhart and Russell, 1966, Akcura, et al. 2006). Sowing was carried out at optimal dates specific to each agroecological zone (Tab. 1). Agronomic practices, including seeding rate, fertilization regime, and crop protection measures, were standardized within each location and year according to regional recommendations to minimize uncontrolled technological variability among cultivars. Harvesting was performed by complete plot harvesting, and grain yield was calculated and expressed in t ha-1.

The first step of data analysis involved a combined Analysis Of Variance (ANOVA) to evaluate the effects of Environment (E), Genotype (G), and their interaction (G × E) on grain yield. All factors were treated as fixed effects. The significance of effects was assessed using the F-test, consistent with classical approaches for multi-location field experiments (Fellahi, et al. 2024, Rebouh, et al. 2025).

Genotype plasticity and stability were assessed using the parametric Eberhart- Russell model, which partitions the G × E interaction into linear and non-linear components (Eberhart and Russell, 1966). For each cultivar, the regression coefficient (b_i), the variance of deviations from regression (S^2di), and additional parametric stability indices widely applied in cereal studies were calculated (Lin, et al. 1986, Kang, 2015).

According to the methodology proposed by Akcura, et al. 2006, a cultivar was considered stable if its mean grain yield was not lower than the overall mean of the experiment and if it met stability criteria in at least five out of nine parametric stability indices. This approach reduces subjectivity associated with reliance on a single index and provides an integrated assessment of genotype stability.

Spearman's rank correlation coefficients were calculated to examine relationships between mean grain yield and parametric stability indices. This analysis enabled the identification of stability parameters describing similar aspects of adaptability and those representing independent responses of cultivars to environmental variation (Fellahi, et al. 2024, Rebouh, et al. 2025).

Statistical analyses of experimental data, including combined ANOVA, evaluation of genotype × environment interaction, and parametric stability analysis, were performed using the R statistical environment, version 4.4.1, following approaches reported in recent methodological studies (Fellahi, et al. 2024, Achilli, et al. 2025).

Results and Discussion

The combined analysis of variance for grain yield indicated that, under the conditions of the present study, the genotype effect was the dominant factor determining productivity, accounting for 91.06% of the total sum of squares, whereas the contributions of environment and genotype × environment (G × E) interaction were substantially lower, amounting to 1.91% and 4.77%, respectively (Tab. 3). All sources of variation were statistically significant, confirming the presence of pronounced differences among cultivars and their differential responses to changes in growing conditions.

Table 3. **Analysis Of Variance (ANOVA) for grain yield of 10 durum wheat genotypes tested across 6 environments.**

Source	df	Sum of squares	Mean square	F	Explained (%)
Model	71	260.697	3.672	72.878	-
Environment (E)	5	5.077	1.015	20.155	1.908
Rep (E)	12	0.579	0.048	0.957	0.217
Genotype (G)	9	242.345	26.927	534.453	91.060
E × G	45	12.696	0.282	5.600	4.770
Pooled error	108	5.441	0.050	-	-
Corrected total	179	266.138	-	-	100.000

The observed variance structure differs markedly from that reported in many multi-location studies on durum and bread wheat, in which the environment is typically the predominant source of variation, often accounting for more than 60-80% of the total yield variability (Mohammadi and Amri, 2013, Bocianowski, et al. 2019, Ninou, et al. 2023). However, a similar dominance of the genotype effect has been documented in recent studies conducted under conditions characterized by a limited environmental gradient. In particular, Fellahi et al. 2024 demonstrated under Mediterranean conditions that, within a relatively homogeneous climatic background, the contribution of the genotype factor may exceed that of the environment. Comparable conclusions were also reported by Rebouh, et al. 2025, who emphasized that under uniform agroecological conditions and standardized agronomic practices, genetic differences among cultivars constitute the primary source of yield variability.

Despite the relatively small proportion of the genotype × environment interaction in the overall variance, its statistical significance indicates changes in cultivar ranking across locations and years. This finding is consistent with the concept proposed by Crossa et al. 2017, according to which even a modest contribution of G × E can be critical for assessing the practical suitability of cultivars for wide-scale agricultural deployment.

Partitioning of the genotype × environment interaction using the Eberhart- Russell model revealed that the linear component of the interaction was statistically significant (Tab. 4), indicating a predictable pattern in the response of the tested cultivars to environmental changes. The predominance of the linear component suggests that genotype adaptive responses can be adequately characterized by the regression coefficient (b_i), which reflects their level of ecological plasticity.

Table 4. Stability analysis (Eberhart and Russell partition) for grain yield across 6 environments.

Source of variation	df	Sum of squares	Mean square	F (*vs.* pooled error)
Genotypes (G)	9	242.345	26.927	534.453
Environment (E)+G × E	50	17.773	0.355	7.055
E (linear)	1	5.077	5.077	100.775
G × E (linear)	9	2.501	0.278	5.516
Pooled deviations	36	10.195	0.283	5.621
Pooled error	120	5.441	0.050	–

Similar findings have been reported in recent studies on durum wheat. Rebouh, et al. 2025 demonstrated that the linear component of the interaction accounts for the major proportion of G×E variability in multi-environment trials, thereby supporting the applicability of regression-based models for evaluating cultivar adaptability. Comparable conclusions were reached by Fellahi, et al. 2024, who interpreted the predominance of linear interaction as evidence of stable and predictable genotype responses along the environmental productivity gradient.

At the same time, the presence of statistically significant pooled deviations from regression (Tab. 4) indicates the occurrence of non-linear, genotype-specific responses that are not fully captured by the linear model. A similar G × E interaction structure was described by Bocianowski, et al. 2019 and Nouri, et al. 2016, who emphasized that non-linear effects may restrict wide adaptation even in high-yielding genotypes, particularly under conditions of increasing climatic variability.

The mean grain yield of the evaluated cultivars ranged from 4.44 to 8.16 t ha^{-1}, which is consistent with productivity levels reported in recent European studies on durum wheat (Ninou, et al. 2023, Fellahi, et al. 2024). The highest average yield was recorded for the cultivar Sambadur (8.16 t ha-1), which was characterized by a regression coefficient markedly greater than unity (b_i=2.59). This indicates a high degree of ecological plasticity and pronounced sensitivity to improvements in growing conditions.

According to the Finlay-Wilkinson concept, genotypes with b_i>1.0 are best suited for intensive or high-yielding environments, whereas their cultivation under stressful conditions is associated with an increased risk of yield reduction (Finlay and Wilkinson, 1963). In contrast, cultivars with b_i<1.0 (Diadur, Tetida, Metis) exhibited enhanced stability under less favorable conditions but achieved lower mean yield levels. This trade-off between yield stability and productivity potential has been widely documented in the literature (Mohammadi and Amri, 2013, Rebouh, et al. 2025).

Conclusion

The obtained results indicate that grain yield formation of durum wheat cultivars under the conditions of the Western region of Ukraine is primarily determined by genotypic characteristics. The combined analysis of variance revealed the dominance of the genotype effect, which accounted for 91.06% of the total sum of squares, whereas the contributions of the environment and the genotype × environment (G × E) interaction were substantially lower but statistically significant. This variance structure reflects a high differentiation among cultivars in terms of yield potential under a relatively uniform agroecological background, while simultaneously confirming the necessity of considering G × E effects in cultivar evaluation.

Partitioning of the G × E interaction using the Eberhart-Russell model demonstrated the predominance of a linear, predictable component, indicating that cultivar adaptive responses can be effectively described using regression coefficients. The wide range of plasticity index values (b_i) reflects the presence of different adaptation types, ranging from specific to relatively stable responses.

References

Achilli AL, Avci MI, Haile TA, Martínez Peña R, Peters Haugrud AR. (2026). Genetic gains in durum wheat (*Triticum turgidum* ssp. durum) across the globe: Yield, quality and adapting for variable weather patterns. *Plant Breeding*. **145**:142-65.

Akcura M, Kaya Y, Taner S, Ayranci R. (2006). Parametric stability analyses for grain yield of durum wheat. *Plant Soil and Environ*. **52**:254.

Bocianowski J, Warzecha T, Nowosad K. (2019). Genotype by environment interaction for grain yield of winter wheat. *Agron*. **9**:1-15.

Crossa J, Pérez-Rodríguez P, Cuevas J, Montesinos-López O, Jarquín D, De Los Campos G, Burgueño J, González-Camacho JM, Pérez-Elizalde S, Beyene Y, Dreisigacker S. (2017). Genomic selection in plant breeding: methods, models, and perspectives. *Trends Plant Sci*. **22**:961-75.

Eberhart SA, Russell WA. (1966). Stability parameters for comparing varieties. *Crop Sci*. **6**:36-40.

Fellahi ZE, Boubellouta T, Hannachi A, Belguet H, Louahdi N, Benmahammed A, Utkina AO, Rebouh NY. (2024). Exploitation of the genetic variability of diverse metric traits of durum wheat (*Triticum turgidum* L. ssp. *durum* Desf.) cultivars for local adaptation to semi-arid regions of Algeria. *Plants*. **13**:934.

Finlay KW, Wilkinson GN. (1963). The analysis of adaptation in a plant-breeding programme. *Aust J Agric Res*. **14**:742-54.

Gauch Jr HG. (2013). A simple protocol for AMMI analysis of yield trials. *Crop Sc*i. **53**:1860-1869.

Göçmen DB. (2025). Grain yield stability of durum wheat genotypes: A graphical approach. *Turk J Field Crops*. **30**:164-174.

Gauch Jr HG, Zobel RW. (1997) Identifying mega environments and targeting genotypes. *Crop Sci*. **37**:311-26.

Lin CS, Binns MR, Lefkovitch LP. (1986). Stability analysis: where do we stand? *Crop Sci*. **26**:894-900.

Mohammadi R, Amri A. (2013). Genotype × environment interaction and genetic improvement for yield and yield stability of rainfed durum wheat in Iran. *Euphytica*. **192**:227-249.

Ninou E, Tsivelika N, Sistanis I, Katsenios N, Korpetis E, Vazaneli E, Papathanasiou F, Didos S, Argiriou A, Mylonas I. (2023). Assessment of durum wheat cultivars' adaptability to Mediterranean environments using G × E interaction analysis. *Agron*. **14**:102.

Piepho HP, Möhring J, Melchinger AE, Büchse A. (2008). BLUP for phenotypic selection in plant breeding and variety testing. *Euphytica*. **161**:209-28.

Rebouh NY, Utkina AO, Hannachi A, Louahdi N. (2025). Genotype × environment interaction and adaptive responses of durum wheat under contrasting agro-climatic conditions. *BMC Genomics*. **26**:581.

Shim KB, Shin SH, Shon JY, Kang SG, Yang WH, Heu SG. (2015). Interpretation of genotype× environment interaction of sesame yield using GGE biplot analysis. *Korean J Crop Sci*. **60**:349-54.

Smith EN, Kruglyak L. (2008). Gene-environment interaction in yeast gene expression. *PLoS Biol*. **6**:e83.

Yan W, Kang MS. (2002). GGE biplot analysis: A graphical tool for breeders. *CRC Press*.