RESEARCH ARTICLE Legume Research- An International Journal, Volume 48 Issue 12: 2083-2088 (December 2025)

Yield Performance and Adaptation of Common Bean (*Phaseolus vulgaris* L.) Genotypes in Two Contrasting Agro-ecologies of Turkey

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10.18805/LRF-892

ABSTRACT

Background: Evaluating genotype performance in target environments is crucial for crop improvement. This preliminary study was conducted to assess the seed yield, stability and adaptation of seven common bean genotypes in two contrasting agro-ecologies in Turkey: the cool, high-altitude environment of Bayburt and the hot, lowland environment of Kahramanmaras.

Methods: Field trials were conducted in Bayburt (2019) and Kahramanmaras (2021) using a randomized complete block design. Data were analyzed using combined analysis of variance, GGE biplot and Wricke's Ecovalence (W^2_i).

Result: Our investigations revealed significant effects for genotype (G), environment (E) and their interaction (G×E), confirming that genotypes responded differently to the test environments. The GGE biplot analysis showed that the Suludere genotype was the top performer in Bayburt, whereas Mollakoy and Aydintepe genotypes were superior in Kahramanmaras. According to Wricke's Ecovalence analysis, Yukarikirzi was the most stable genotype, while Suludere was the least stable, confirming its specific adaptation. The Mollakoy genotype was identified as a desirable genotype, combining high average yield with relative stability. These preliminary findings highlight the importance of targeted genotype selection. 'Mollakoy' is a promising candidate for broader evaluation, while 'Suludere' appears specifically adapted to cooler, high-altitude conditions similar to Bayburt.

Key words: Adaptation, Genotype × Environment interaction, GGE biplot, Seed yield, Wricke's ecovalence.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is a staple foodstuff in human nutrition worldwide and in Turkey and it is a legume species rich in protein, fiber, vitamins and minerals (Broughton *et al.,* 2003). Turkey is among the important countries in terms of common bean production and consumption and improving yield and quality is of great importance for meeting local consumption and increasing export potential. Bean yield is significantly affected by the environmental conditions in which it is grown, as well as its genetic potential. Performance changes of genotypes in different environmental conditions are called genotype × environment (G×E) interaction and this interaction is a complex phenomenon that directly affects the selection of superior genotypes and the effectiveness of breeding programs (Annicchiarico, 2002; Hill and Mackay, 2004).

The presence of G×E interaction means that a genotype performing superiorly in one environment may not show the same success in another. This challenge of inconsistent performance is a significant hurdle in breeding programs for many important legume crops, complicating the development of improved varieties in species such as mungbean (Arya *et al.,* 2024). This requires breeders to develop either genotypes with broad adaptation ability, *i.e.*, stable and high-yielding in different environments or genotypes specifically adapted to particular environmental conditions (Ceccarelli, 1996; Kang, 1997; Romagosa and Fox, 1993). Accurate analysis and interpretation of G×E interaction is a critical step in achieving these goals. Stability analyses in plant breeding are widely used to evaluate the performance consistency of genotypes across different environments (Becker and Léon, 1988).

Various statistical methods have been developed to evaluate G×E interaction and genotype stability. Among these, the Genotype main effect + Genotype × Environment interaction (GGE) Biplot analysis stands out as a powerful tool for visualizing and interpreting data obtained from multi-environment trials. GGE Biplot allows simultaneous evaluation of the average performance of genotypes ("which-won-where" pattern) and their stability and also reveals the discriminativeness and representativeness of test environments (Yan *et al.,* 2000; Yan and Kang, 2003; Yan and Tinker, 2006; Gauch, 2006). Another commonly used stability parameter is Wricke's Ecovalence (W^2_i)

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How to cite this article: Cokkizgin, A. (2025). Yield Performance and Adaptation of Common Bean (*Phaseolus vulgaris* L.) Genotypes in Two Contrasting Agro-ecologies of Turkey. *Legume Research.* **48(12):** 2083-2088. doi: 10.18805/LRF-892.

Submitted: 29-07-2025 **Accepted:** 22-09-2025 **Online:** 05-11-2025

(Wricke, 1962). This parameter measures the contribution of each genotype to the total G×E interaction sum of squares; genotypes with low W^2_i values are considered more stable.

The aim of this study is therefore not to conduct a comprehensive G×E interaction analysis, which would require more environments, but rather to perform a preliminary assessment of seven common bean genotypes under two distinctly contrasting agro-ecologies in Turkey (the cool, high-altitude conditions of Bayburt and the hot, lowland conditions of Kahramanmaras). By using these two opposing environments, we specifically aimed to observe potential crossover interactions, evaluate yield stability using GGE Biplot and Wricke's Ecovalence and provide initial insights into the specific adaptation of these genotypes, thereby identifying promising candidates for these or similar target regions.

MATERIALS AND METHODS

Plant material and experimental sites

Seven common bean (*Phaseolus vulgaris* L.) genotypes (Aydintepe, Alaciftci, Mollakoy, Konursu, Mispir, Yukarikirzi and Suludere) were used in the study. Field trials were conducted in two locations in Turkey with different agro-ecological characteristics:

Bayburt

The experiment was carried out between June and September 2019 in Bayburt University, Aydintepe Vocational School, Agricultural Application and Research Center Experimental Area (40.401654, 40.144059). According to long-term climate data (1959-2023) from the Turkish State Meteorological Service (MGM, 2023), Bayburt has continental climate characteristics. The annual average temperature is 7.1°C and during the bean growing period (June-September), the average temperatures are 15.3°C, 18.8°C, 18.9°C and 14.8°C, respectively. The average monthly total precipitation during the same period is 51.8 mm, 21.0 mm, 16.0 mm and 21.9 mm, respectively. The annual average total precipitation is 449.9 mm. The region experiences cold and snowy winters and short, cool and relatively dry summers.

Kahramanmaras

Kahramanmaras Sutcu Imam University, Faculty of Agriculture, Department of Field Crops Experimental Area (37.589223, 36.816617). The experiment was carried out between March and July 2021. According to long-term climate data (1930-2023) from MGM (2023), Kahramanmaras shows a transitional characteristic between Mediterranean and continental climates. The annual average temperature is 16.7°C and during the bean growing period (March-July), the average temperatures are 10.4°C, 15.1°C, 20.1°C, 24.9°C and 28.3°C, respectively. The average monthly total precipitation during the same period is 95.1 mm, 73.0 mm, 38.8 mm, 8.6 mm and 2.7 mm, respectively. The annual average total precipitation is 721.6 mm. Summers in the region are hot and dry, while winters are mild and rainy. The average sunshine duration is high, especially in May-July (8.1-10.5 hours/day).

Experimental design, growing conditions and data collection

In both locations, the experiments were established according to a randomized complete block design with three replications (Steel and Torrie, 1980). Each plot was structured with four rows, each measuring 5 meters in length. The spacing between rows was 50 cm, while the distance between plants within each row was 10 cm. Sowing in the Kahramanmaras location was done in March (2021) and in the Bayburt location in June (2019). Cultural practices such as soil preparation, fertilization (DAP fertilizer was applied at a rate to supply 1.5 kg of nitrogen and 4 kg of phosphorus per decare), irrigation (drip irrigation was applied according to plant needs, especially important considering summer drought in Kahramanmaras) and weed control were carried out according to the standard agricultural practices of each location and the requirements of bean cultivation. Harvest was done manually when the plants reached physiological maturity, in July (2021) in Kahramanmaras and in September (2019) in Bayburt. Seeds obtained from each plot were threshed, adjusted to 12-14% moisture content and seed yield was calculated as kilograms per decare (kg/da).

Statistical analyses

The obtained seed yield data were first subjected to individual analysis of variance for each location and then the homogeneity of error variances was checked using Bartlett's test. After determining that the error variances were homogeneous, the data were subjected to a combined analysis of variance (ANOVA) to determine the significance of genotype (G), environment (E) and genotype × environment (G×E) interactions using the F-test. ANOVA was performed in Python programming language (version 3.x) using the statsmodels library (Seabold and Perktold, 2010).

For a more detailed examination of genotype main effects and G×E interactions, the GGE Biplot method was employed. This graphical analysis approach is highly effective for visualizing performance and stability in multi-environment trials and its application is well-established in recent legume research (Sharma *et al.,* 2025). The analysis is based on the "Genotype Main Effect (G) + Genotype × Environment Interaction (GE)" model, which is generated by applying principal component analysis (PCA) to environment-centered yield data (Yan *et al.,* 2000; Crossa *et al.,* 2002). The scikit-learn library (Pedregosa *et al.,* 2011) was used for the analysis and the matplotlib library (Hunter, 2007) for plotting.

Wricke's Ecovalence (W^2_i) parameter was calculated to quantitatively determine the stability of genotypes according to the following formula (Wricke, 1962):

$$W_i^2 - \sum_{j-1}^{q} (Y_{ij} - \overline{Y}_{i.} - \overline{Y}_{j.} + \overline{Y}..)^2$$

Y_{ij} = Yield of the i^{th} genotype in the j^{th} environment.
$\overline{Y}_{i.}$ = Mean yield of the i^{th} genotype across environments.
$\overline{Y}_{j.}$ =Mean yield of the j^{th} environment across genotypes.
$\overline{Y}..$ = Overall mean.

RESULTS AND DISCUSSION

Analysis of variance

The combined analysis of variance results for the seed yields of common bean genotypes in two different locations in 2019 (Bayburt) and 2021 (Kahramanmaras) in summer season are presented in Table 1. According to the ANOVA results, statistically significant differences were found for genotypes (G) (P=0.0122), environments (E) (P=0.0005) and genotype × environment (G×E) interaction (P=0.0053) in terms of seed yield. The significance of the G×E interaction indicates that the studied common bean genotypes responded differently to different environmental conditions and this situation needs to be examined in more detail with stability analyses.

Mean performances and environmental effects

The average seed yields of the seven common bean genotypes in Bayburt and Kahramanmaras locations and their overall averages are given in Table 2. Significant yield differences were observed between locations; the overall average yield of the Bayburt location (123.98 kg/da) was found to be higher than the overall average yield of the Kahramanmaras location (93.94 kg/da).

There were also clear yield differences among genotypes. In the Bayburt location, the Suludere genotype (154.67 kg/da) gave the highest yield, while the Alaciftci genotype (93.37 kg/da) provided the lowest yield. In the Kahramanmaras location, Mollakoy (132.32 kg/da) and Aydintepe (127.68 kg/da) genotypes exhibited the highest yields and the lowest yield was recorded for the Suludere genotype (55.42 kg/da). Looking at the overall averages, Mollakoy (139.69 kg/da) emerged as the genotype with the highest average yield, followed by Aydintepe (123.12 kg/da) and Yukarikirzi (117.16 kg/da). The lowest overall average yield belonged to the Mispir genotype (86.71 kg/da).

GGE biplot analysis

The graph obtained from the GGE Biplot analysis applied to the seed yield data of common bean genotypes is presented in Fig 1. The first two principal components (PC1 and PC2) explained 100% of the total G+GE variation (PC1: 57.16%, PC2: 42.84%). This indicates that the biplot graph fully represents the variation in the data.

The following interpretations can be made from the GGE Biplot graph (Fig 1):

"Which-Won-Where" pattern

Environments (Bayburt and Kahramanmaras) are located in different sectors on the biplot. The Suludere genotype is located at the apex of the sector where the Bayburt environment vector is found, indicating it is the highest-yielding genotype in this environment. Mollakoy and Aydintepe genotypes are located in the sector where the Kahramanmaras environment vector is found, showing the best performance in this environment. Other genotypes were not among the highest-yielding genotypes in these two locations.

Genotype performance and stability

The average environment coordinate (AEC) axis (the horizontal axis of the biplot) shows the average yield performance of the genotypes. Mollakoy, having the furthest projection on the AEC axis, can be considered one of the genotypes with the highest average yield. The vertical line perpendicular to the AEC axis represents stability; genotypes close to this line are considered more stable (Yan and Kang, 2003). Yukarikirzi genotype is positioned relatively close to the AEC axis, suggesting it exhibits a more stable performance compared to other genotypes. The Suludere genotype, on the other hand, is located quite far from the AEC axis and close to the Bayburt vector, showing strong specific adaptation to this environment but low overall stability.

Evaluation of environments

The angle between the Bayburt and Kahramanmaras environment vectors is greater than 90 degrees, indicating a negative correlation or a strong "crossover" G×E interaction between the two environments (Yan and Tinker,

Table 1: Combined analysis of variance results for seed yield (kg/da) of common bean genotypes.

Source of variation	Degrees of freedom (df)	Sum of squares (SS)	Mean square (MS)	F value	P value
Environment (E)	1	9471.01	9471.01	15.38**	0.0005
Genotype (G)	6	12536.88	2089.48	3.39*	0.0122
G×E interaction	6	14698.08	2449.68	3.98**	0.0053
Error	28	17246.81	615.96		
Total	41	53952.78			

**,* significant at P<0.01 and P<0.05.

2006). That is, genotypes performing well in one environment may not perform similarly in the other. The length of both environment vectors indicates their high power in discriminating genotypes.

Wricke's ecovalence (W^2_i)

Wricke's Ecovalence (W^2_i) values, which quantitatively estimate the contribution of each genotype to the G×E interaction, are presented in Table 3. According to this parameter, 'Yukarikirzi' had the lowest W^2_i value (99.40), suggesting it was the most stable genotype across the two environments. Conversely, 'Suludere' had the highest W^2_i value (2395.01), indicating the largest contribution to the interaction sum of squares. However, interpreting this high value simply as 'instability' can be misleading when viewed in isolation, as a single univariate parameter does not capture the full nature of a genotype's response. The GGE biplot provides the necessary context, revealing that Suludere's high W^2_i value was not due to erratic performance, but rather a strong and positive specific adaptation to the Bayburt environment, where it was the top-performing genotype.

Table 2: Average seed yields (kg/da) of common bean genotypes in locations and overall averages.

Genotype	Bayburt	Kahramanmaras	Average
Aydintepe	118.57	127.68	123.12
Alaciftci	87.73	100.45	94.09
Mollakoy	147.07	132.32	139.69
Konursu	127.20	66.58	96.89
Mispir	93.37	80.06	86.71
Yukarikirzi	139.23	95.09	117.16
Suludere	154.67	55.42	105.04
Average	123.98	93.94	108.96

Table 3: Wricke's ecovalence (W^2_i) values and stability ranking for seed yield (kg/da) of common bean genotypes.

Genotype	Wricke's ecovalence (W^2_i)	Stability rank
Yukarikirzi	99.40	1
Mollakoy	116.89	2
Mispir	139.95	3
Konursu	467.56	4
Aydintepe	766.36	5
Alaciftci	914.22	6
Suludere	2395.01	7

The findings of this study should be interpreted within the context of its primary limitation: the evaluation was conducted in only two locations and in different years. Therefore, this work does not represent a comprehensive G×E interaction analysis but rather a preliminary study aimed at assessing genotype adaptation to two distinctly contrasting agro-ecologies. The choice of Bayburt (cool, high-altitude) and Kahramanmaras (hot, lowland) was deliberate, designed to maximize environmental contrast and observe potential crossover interactions, where the ranking of genotypes changes between environments. The statistically significant G×E interaction found in our ANOVA results confirms that this objective was achieved, as genotypes indeed responded very differently to these two specific conditions.

The GGE biplot analysis proved to be a particularly effective tool for visualizing the strong crossover interaction suggested by the ANOVA (Yan *et al.,* 2007). This approach is consistent with recent studies in other legumes, where GGE biplot has been successfully used to identify stable and specifically adapted genotypes in crops such as pigeonpea (Arulselvi *et al.,* 2025). The 'which-won-where' pattern clearly showed that different genotypes were superior in each contrasting environment: 'Suludere' was the highest-yielding genotype in the cool climate of Bayburt,

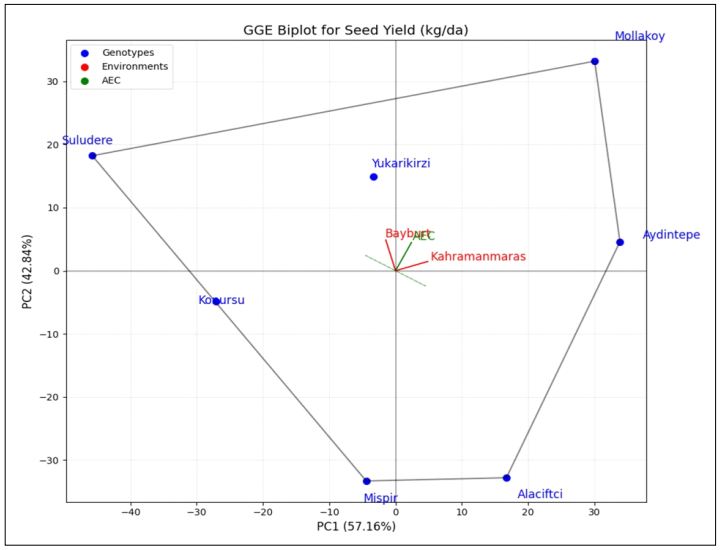


Fig 1: GGE Biplot graph (PC1 vs PC2) for seed yield (kg/da) of seven common bean genotypes in two locations.

while 'Mollakoy' and 'Aydintepe' excelled in the hotter conditions of Kahramanmaras. This finding is a classic illustration of specific adaptation, which can be highly valuable for targeted breeding (Ceccarelli, 1996). While a single univariate parameter like Wricke's Ecovalence (W^2_i) provides a quantitative stability score, its interpretation is greatly enhanced by the GGE biplot's visual context. For instance, 'Suludere' had the highest W^2_i value, indicating it was the least stable. However, the biplot clarifies that this is not simply instability, but rather a strong, positive adaptation to Bayburt's specific conditions. In contrast, 'Mollakoy' combined a high average yield with good relative stability, representing the type of broad adaptation that is often a primary goal in breeding programs (Annicchiarico, 2002). 'Yukarikirzi', with the lowest W^2_i value, confirmed its status as the most stable genotype, striking the balance between acceptable yield and high stability that breeders often seek (Kang, 1993). These findings-identifying genotypes with broad adaptation ('Mollakoy') alongside those with strong specific adaptation ('Suludere')-are strongly supported by similar research on common bean in comparable Mediterranean environments. For instance, Kargiotidou *et al.* (2019), also using GGE biplot analysis in Greece, similarly identified commercial cultivars with high yield and stability (wide adaptation) while noting that a local landrace was high-yielding but unstable, thus representing a valuable genetic resource for specific adaptation.

The two test environments, Bayburt and Kahramanmaras, discriminated genotypes differently on the GGE Biplot and showed a strong "crossover" G×E interaction between them (angle between vectors >90°). This is an expected result considering the different growing seasons of the two locations (Bayburt 2019; Kahramanmaras, 2021) and the distinct climatic differences detailed above (temperature, precipitation regime). The cooler and later vegetation period of Bayburt may have enabled some genotypes (Suludere, Yukarikirzi) to perform better under these conditions, while the hotter and earlier vegetation period of Kahramanmaras may have been more suitable for genotypes with different adaptation mechanisms, such as Mollakoy and Aydintepe. If there had been a positive correlation between test environments (angle between vectors <90°), the probability that selection made in one environment would also be valid for the other environment would have increased (Yan and Tinker, 2006). This strong negative correlation underscores the value of this study not for broad-scale G×E analysis, but for identifying specifically adapted genotypes for these types of contrasting mega-environments (Gauch and Zobel, 1997).

In conclusion, the combined use of GGE biplot and a stability parameter like Wricke's Ecovalence proved effective for interpreting genotype performance in this preliminary adaptation trial. While the findings are specific to the environments and years tested, they provide a strong rationale for future research. To validate the potential broad adaptation of 'Mollakoy' and the specific adaptation of 'Suludere', these genotypes should be tested across a wider range of locations and years, which would allow for a more comprehensive understanding of G×E interactions in Turkish common bean breeding programs.

CONCLUSION

This preliminary study, conducted in two contrasting Turkish agro-ecologies, successfully demonstrated a strong crossover G×E interaction. The combined analysis using GGE biplot and Wricke's Ecovalence provided key insights for genotype selection. The 'Mollakoy' genotype emerged as a promising candidate for broader adaptation, having combined a high average yield with good relative stability across the two distinct environments. In contrast, 'Suludere' exemplified specific adaptation, delivering superior yield only in the cool, high-altitude conditions of Bayburt, which makes it a valuable genetic resource for breeding programs targeting similar environments. Finally, 'Yukarikirzi' was confirmed as the most stable genotype across both locations. These findings highlight the importance of targeted environmental testing and provide a clear basis for selecting specific genotypes for further, more comprehensive multi-environment trials.

ACKNOWLEDGEMENT

The author received no financial support for the research, authorship and/or publication of this article.

Disclaimers

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Conflict of interest

The author declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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