

# Genotype × environment interactions and yield stability of common bean (*Phaseolus vulgaris*) genotypes in different altitudes

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**Abstract.** Hanifah FL, Saptadi D, Kendarini N, Kuswanto. 2026. Genotype × environment interactions and yield stability of common bean (*Phaseolus vulgaris*) genotypes in different altitudes. *Biodiversitas* 27 (5): d270515. <https://doi.org/10.13057/biodiv/d270515>. Common bean (*Phaseolus vulgaris*) is an important vegetable crop widely cultivated for its high nutritional and economic value, but its productivity is often affected by environmental variability. This research aimed to evaluate genotype × environment interactions, adaptability, and stability of four bush-type common bean genotypes and two check varieties in two agroecological zones, specifically high-altitude area and medium-altitude area. This research was arranged in a randomized block design with four replications per location. Nine parameters were observed, including plant height, number of leaves, days to flowering, days to harvest, number of pods per plant, pod length, pod diameter, pod weight per plant, and yield. A combined analysis of variance revealed significant effects of genotype, environment, and G × E interactions on most traits. Stability analysis was performed using parametric and nonparametric methods. GGE biplot analysis was applied to visualize genotype performance and stability simultaneously. The results indicate that genotypes AB (14.07 t ha<sup>-1</sup>) and AK (14.19 t ha<sup>-1</sup>) have the highest yields and broad adaptability, owing to their low contributions to G × E interactions, making them relatively stable at both medium and high altitudes. Genotype BK (12.82 t ha<sup>-1</sup>) has high yields only in the high altitudes, indicating specific adaptability to high altitude conditions. These findings highlight AB and AK as promising candidates for broad adaptability in high and medium altitude areas, and BK for targeted application in highland production areas.

**Keywords:** Genotype × environment interaction, high altitude, middle altitude, *Phaseolus vulgaris*, pod yield

## INTRODUCTION

Common bean (*Phaseolus vulgaris*) is an important vegetable crop due to its nutritional and economic value. It is rich in protein, fiber, vitamins, and essential minerals, such as iron, magnesium, and calcium (de la Vega et al. 2017). The species also contains bioactive compounds, such as flavonoids, alkaloids, phenols, saponins, steroids, and phaseolin, which play an important role in our health and are also a source of protein and amino acids (Nugrahani et al. 2016; Nchanji and Ageyo 2021; Maro et al. 2022). At a global scale, common bean production reached approximately 23.47 million tonnes in 2023, with China, Turkey, and Indonesia as major producers (FAO 2021). However, mean yields and yield stability vary widely between regions due to climatic differences and management practices.

Despite its global importance, productivity and yield stability remain major constraints in many producing countries. In Indonesia, national production declined by 6.31% in 2023, with a total production of 305,049 t ha<sup>-1</sup> (Indonesian Central Bureau of Statistics 2025). Meanwhile, the demand for common beans in the domestic market continues to increase to about 5 tons day<sup>-1</sup> (Syamruddin 2020). The gap between production and market demand for common beans indicates the need to increase both productivity and stability. This gap is aggravated by environmental heterogeneity, including wide range altitude

gradients, variable temperature regimes, irregular rainfall patterns, and increasing pest pressure in warmer zones, all of which affect yield performance.

Common bean is typically grown in high-altitude areas at elevations between 1,000 and 1,500 m asl. (Patra and Benjongtoshi 2023). It can grow throughout the year with an optimum temperature of 20-25°C for optimal growth and productivity (Dhakal et al. 2020). High-altitude environments generally have lower temperatures, higher humidity, and distinct rainfall patterns, which can affect physiological processes, such as photosynthesis and transpiration. According to Djuariah et al. (2016), bush-type common bean genotypes exhibit good adaptability at medium altitudes (400-500 m asl.). Similarly, Philipo et al. (2021) reported that the yield of common beans in medium altitude environments is not significantly different from those at higher elevations. Meanwhile, at lower altitudes, yield is reduced due to smaller pod size and lower quality, and is also affected by high temperatures (Kantikowati et al. 2024).

Genotype × environment interactions represent a major challenge, because they cause differential genotype responses across different environments (Ligarreto-Moreno and Pimentel-Ladino 2022). Environmental variation can influence the expression of quantitative traits, such as yield, making genotype selection challenging because genotypes with high yield potential in an environment may not necessarily show similar performance in another

environment (Elias et al. 2016). Altitude-driven microclimatic differences (temperature, humidity, rainfall) alter physiological processes (flowering time, assimilate partitioning, pod filling) and therefore modify genotypic rank and stability across environments. Given these complexities, multi-location evaluation and quantitative stability assessment are essential components of an effective breeding strategy.

Genotype  $\times$  environment interactions analysis is generally conducted by evaluating at least two genotypes tested in two different environments (Yan and Kang 2003). To address  $G \times E$ , stability analysis is required to assess yield consistency and adaptation across environments. Both parametric and nonparametric stability methods provide complementary insights. Parametric methods assume normally distributed residuals and nonparametric methods typically use genotype ranks across environments. GGE biplot is used to visualise  $G \times E$  patterns and to identify broadly or specifically adapted genotypes. Combining these approaches reduces the risk of misleading inference from any single metric and strengthens the reliability of selecting genotypes that are high-yielding and perform consistently across environments (Shahbazi 2019). Therefore, this research aimed to evaluate genotype  $\times$  environment interactions, adaptability, and yield stability of six bush-type common bean genotypes across medium and high altitudes of Indonesia, in order to identify high-yielding and stable genotypes and to recommend promising candidates for breeding programs with broad adaptability.

## MATERIALS AND METHODS

### Study area

The research was conducted at two altitudinal sites representing different agroecological zones. The first site was located in a high-altitude area, namely Bumiaji, Batu, East Java and the second location was a medium-altitude area, specifically Singosari, Malang, East Java, Indonesia (Table 1). Soil fertility was determined in the soil chemistry laboratory with samples from both locations to characterize the initial soil conditions before planting. At Bumiaji (E1), the soil had a pH (H<sub>2</sub>O 1:1) of 6.5, organic carbon content of 1.82%, total nitrogen of 0.17%, C/N ratio of 11, available phosphorus (Bray 1) of 94.25 mg kg<sup>-1</sup>, exchangeable potassium of 0.88 me 100 g<sup>-1</sup>, and cation exchange capacity of 17.49 me 100 g<sup>-1</sup>, whereas at Singosari (E2), soil analysis showed a pH (H<sub>2</sub>O 1:1) of 6.0, organic carbon content of 1.12%, total nitrogen of 0.11%, C/N ratio of 10, available phosphorus (Bray 1) of 48.24 mg kg<sup>-1</sup>, exchangeable potassium of 0.26 me 100 g<sup>-1</sup>, and cation exchange capacity of 17.49 me 100 g<sup>-1</sup>.

### Plant materials

The study used four test genotypes of bush-type common bean selected from pure lines, namely AB, AK, BB, and BK, as well as two check varieties, Balitsa and Gypsy. All plant materials were obtained from the seed collection of the Plant Breeding Laboratory, Faculty of Agriculture, Universitas Brawijaya.

## Procedures

### Research design

This study was conducted at two locations using a Randomized Complete Block Design (RCBD) at each location. A total of six treatments were evaluated, with four replications at each location, resulting in 24 experimental units at each location. Plots were randomly assigned within each block at every location to minimize spatial bias. Each experimental unit consisted of 15 plants with a planting distance of 40  $\times$  50 cm, following local agronomic recommendations for bush-type common beans from the Indonesian Ministry of Agriculture guidelines (2021) and was chosen to reflect farmer practice.

### Cultivation

Soil preparation and crop management followed the Indonesian Ministry of Agriculture (2021) recommendations. Basal fertilization was applied using chicken manure at 10 t ha<sup>-1</sup> and dolomite at 1-2 t ha<sup>-1</sup>. Additional fertilization was carried out by applying 5 g per plant of NPK 16:16:16 at 14, 21, 35, and 42 days after planting. Pest and disease management was conducted using insecticides containing fipronil (2 mL L<sup>-1</sup>) for caterpillar and grasshopper, abamectin (2 mL L<sup>-1</sup>) for aphids and thrips, and cartap hydrochloride (2 g L<sup>-1</sup>) for the leaf miner. A fungicide containing propineb (2 g L<sup>-1</sup>) was applied to prevent and control fungal infections. Applications were performed when symptoms of attack appeared and were directed to all plant parts to ensure effective control. Stakes were placed in an upright position approximately 20 days after planting to support plant growth and reduce damage due to wind and pod weight. All experimental sites received the same recommended fertilization and irrigation regimes to minimize environmental variation unrelated to genotype performance.

Common beans are harvested when they are 45-50 days old by picking the tips of the pods, leaving a small stem on the pods. Under optimal conditions, common bean can be harvested up to four or five times during the rainy season with a harvest interval of 2-3 days. The market desires of common beans are 12-14 cm long, seeds in pod are not protruding, straight pods, dark green pods, pods have no spots, wilt, and free from pest and disease, and free from mechanical damage such as bruises caused by harvesting tools, transportation equipment, and other objects (Supriatna and Amelia 2023).

**Table 1.** Descriptions of research locations in this research

Parameter	Environment 1 (E1)	Environment 2 (E2)
Location	Bumiaji, Batu, East Java	Singosari, Malang, East Java
Coordinate	7°50'06"S; 112°32'13"E	7°53'02"S; 112°40'43"E
Elevation (m asl.)	±1,060	±520
Temperature (°C)	20.8-22.1	22.9-24
Humidity (%)	87-90	76-78
Soil type	Andosol	Inceptisol
Soil texture	Loam	Sandy clay

### Parameters observed

The observation variables consisted of nine parameters, namely plant height, number of leaves, days to flowering, days to harvest, number of pods, pod length, pod diameter, pod weight per plant, and yield. Observations were conducted following standard evaluation procedures as described by the International Union for the Protection of New Varieties of Plants (UPOV 2015). Ten fresh pods were randomly selected from each of the five randomly selected plants per plot as data sources. Yield per plot (g) was converted to  $t\ ha^{-1}$  based on the standard calculation method described in the Decree of the Indonesian Minister of Agriculture No. 12/Kpts/SR.130/D/8/2019 concerning technical guidelines for the preparation of variety descriptions and testing of horticultural crops, using the formula as follows:

$$\text{Yield (t ha}^{-1}\text{)} = \frac{\text{Pod weight per plot (kg)}}{\text{Plot area (m}^2\text{)}} \times 10$$

### Data analysis

Data analysis was performed using combined analysis of variance at two locations to determine the genotype  $\times$  environment interactions on the observed traits (Syukur et al. 2015). A homogeneity test for variances from the two locations was also performed prior to the combined analysis of variances. In estimating yield stability, analysis is conducted using parametric and nonparametric analysis models. All of the analysis was performed using R Studio software version 4.4.2. The following are stability analysis formulas using various parametric and nonparametric approaches:

#### Wricke's ecovalence

A genotype is considered stable if its ecovalence ( $Wi^2$ ) value is low (Wricke 1962). This low ecovalence indicates that the genotype contributes to small genotype  $\times$  environment interactions. Wricke's ecovalence is calculated by the formula as follows:

$$Wi^2 = \sum (X_{ij} - \bar{X}_i - \bar{X}_j + \bar{X}_{..})^2$$

Where :

$Wi^2$  : Wricke ecovalence

$X_{ij}$  : Results of  $i$ th genotype in  $j$ th environment

$\bar{X}_i$  : Average results of  $i$ th genotype

$\bar{X}_j$  : Average results of  $j$ th environment

$\bar{X}$  : Total average

#### Shukla's stability variance

The stability of a genotype is determined by the stability variance ( $\sigma_i^2$ ) (Shukla 1972). A genotype with a smaller stability variance ( $\sigma_i^2$ ) is considered very stable because it shows a consistent response to various environments. Shukla's stability variance is calculated by the formula as follows:

$$\sigma_i^2 = \left[ \frac{p}{(p-2)(q-1)} \right] W^2 \frac{\sum W^2}{(p-1)(p-2)(q-1)}$$

Where :

$\sigma_i^2$  : Shukla's stability variance

$p$  : Number of genotypes

$q$  : Number of environments

$W^2$  : Ecovalence value

Environmental variance and coefficient of variation

A genotype is considered as stable if it has a low coefficient of variation, low environmental variance, and high average yield (Francis and Kannenberg 1978). Environmental variance and coefficient of variation are calculated by the formula as follows:

$$Si^2 = \frac{\sum i (\bar{Y}_{ij} - \bar{Y}_j)^2}{q-1} \quad CV = \left( \frac{\sqrt{Si^2}}{\bar{Y}_i} \right) \times 100\%$$

Where :

$Si^2$  : Environmental variance

CV : Coefficient of variation

$\bar{Y}_{ij}$  : Average value of  $i$ th genotype and  $j$ th environment

$\bar{Y}_j$  : Average of  $j$ th environment for all genotypes

$\bar{Y}_i$  : Average of  $i$ th genotype in all  $j$ th environments

$q$  : Number of environments

#### Superiority index

The superiority index ( $P_i$ ) is an indicator used to measure stability based on a comparison of productivity in various environments (Lin and Binns 1988). A genotype has a high level of stability, if it has a low  $P_i$  value. Meanwhile, the superiority index is defined as the average square difference between the response of the genotype tested in a location and the maximum response or best performance that can be achieved by the genotype in other locations.

#### Stability and adaptability of genotypes

Genotype stability and adaptability are evaluated using a stratified ranking approach based on relative yield performance across environments (Fox et al. 1990). In this method, genotypes are ranked according to their yield within each environment and subsequently classified into three categories, i.e., top, middle, and low. These strata represent the relative performance levels of genotypes under specific environmental conditions. Genotypes that consistently fall within the top category across multiple environments are considered to have broad adaptability and high stability, whereas those that rarely appear in this category are regarded as less stable or specifically adapted to certain environments.

#### Evaluation of genotype stability

The nonparametric method is ranking-based approach used to evaluate the stability of genotypes in various test environments (Nassar and Hühn 1987). This method does not rely on assumptions of normal distribution or variance homogeneity, making it suitable for data that does not meet the requirement for parametric analysis. The statistical method  $S^{(1)}$  is based on the average of the absolute differences in the ranking of a genotype across all test environments. The statistical method  $S^{(2)}$  is based on the variance across all test environments. It is calculated by the formula as follows:

$$S^{(1)} = \frac{2}{N(N-1)} \sum_{j=1}^{n-1} \sum_{j'=j+1}^n |r_{ij} - r_{ij'}| \quad S^{(2)} = \frac{\sum_{j=1}^n (r_{ij} - \bar{r}_i)^2}{N-1}$$

Where :

- S : Genotype stability  
 N : Number of environments  
 n : Number of genotype  
 j : Environmental index  
 $rij$  : Rank of  $i$ th genotype in  $j$ th environment based on adjusted data  
 $rij'$  : Rank of  $i$ th genotype in  $j'$ th environment based on adjusted data  
 $\bar{r}_i$  : Average genotype values of all environments

#### Genotype rank

Thennarasu (1995) proposed the use of four nonparametric statistics based on corrected rankings. These methods evaluate genotype stability by assessing the deviation of genotype ranks from the median rank, the variance of these deviations, and the consistency of ranks across environments. Genotypes with lower index values are considered to exhibit higher stability. It is calculated by the formula as follows:

$$N^{(1)} = \frac{1}{n} \sum_{j=1}^n |rij - Mdi| \quad N^{(2)} = \frac{1}{n} \sum_{j=1}^n \frac{|rij - Mdi|}{Mdi^*}$$

$$N^{(3)} = \frac{\sqrt{\frac{1}{n} \sum_{j=1}^n (rij - \bar{r}_i)^2}}{\bar{r}_i^*} \quad N^{(4)} = \frac{2}{n(n-1)} \left[ \sum_{j=1}^{n-1} \sum_{j'=j+1}^n \frac{|rij - rij'|}{\bar{r}_i^*} \right]$$

Where :

- N : Number of environments  
 $rij$  : Rank of  $i$ th genotype in  $j$ th environment based on adjusted data  
 $rij'$  : Rank of  $i$ th genotype in  $j'$ th environment based on adjusted data  
 Mdi : Median rank for  $i$ th genotype based on adjusted data  
 Mdi\* : Median rank for  $i$ th genotype based on unadjusted data  
 $\bar{r}_i$  : Mean rank for  $i$ th genotype based on adjusted data  
 $\bar{r}_i^*$  : Mean rank for  $i$ th genotype based on unadjusted data  
 n : Number of genotype  
 j : Environmental index

#### GGE Biplot

The GGE biplot method is used to visualize Genotype (G) interactions and Genotypes  $\times$  Environment (G  $\times$  E) interactions, as well as to analyze genotype stability and adaptation across various environments. The GGE biplot is created based on Principal Component Analysis (PCA) to reduce dimensions and display the relationship between genotype and environment in a two-dimensional diagram. This method was introduced by Yan et al. (2000) with the formula as follows:

$$Y_{ij} - \bar{Y}_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \xi_{ij}$$

Where :

- $Y_{ij}$  : Average yield of  $i$ th genotype in  $j$ th environment  
 $\bar{Y}_i$  : Overall average yield of genotype in  $j$ th environment  
 $\lambda_1, \lambda_2$  : Singular values (eigenvalues) for PC1 and PC2  
 $\xi_{i1}, \xi_{i2}$  : Scores of  $i$ th genotype on PC1 and PC2  
 $\eta_{j1}, \eta_{j2}$  : Scores of  $j$ th environment on PC1 and PC2  
 $\xi_{ij}$  : Residual values

The GGE biplot analysis was performed using R Studio software version 4.4.2. The analysis utilized the metan and ggplot2 packages.

## RESULTS AND DISCUSSION

### Combine analysis of variance

The results of the combined analysis of variance on the nine quantitative characters observed at both research locations are presented in Table 2. The combined analysis of variance was performed to evaluate the effects of Genotype (G), Environment (E), and Genotype  $\times$  Environment interaction (G  $\times$  E). The results of the combined analysis of variance at both locations showed that the magnitude of the effects of G, E, and G  $\times$  E varied, ranging from highly significant differences to no significant differences in all observed traits.

Based on the results of the combined variance analysis of common bean at two locations, the genotype factor has a significant effect on almost all quantitative traits observed, because genetic differences between genotypes largely determine the growth process and yield formation. However, the number of leaves did not differ significantly between genotypes, indicating that this trait is less sensitive to genetic variation. Meanwhile, the differences between the Bumiaji and Singosari environments also had a significant effect on most traits. The environment had a significant effect on plant height, days to flowering, days to fresh pod harvest, number of fresh pods, pod diameter, pod weight per plant, and yield (Table 2). This indicates that the research environment conditions were different, causing differences in several traits. Environmental factors representing differences in altitude and climatic conditions, such as medium altitude (Singosari) and high altitude (Bumiaji), can influence the phenotypic appearance response pattern of common bean. On the other hand, the characteristics of the number of leaves and pod length were not significantly affected by the environment, indicating that differences in environmental conditions did not sufficiently affect the number of leaves and pod length. Thus, this phenomenon confirms the important role of environmental factors such as temperature, humidity, and rainfall patterns in determining the phenotypic expression of common bean. These differences indicate the need to adapt variety recommendations to specific environmental conditions.

Differences in crop performance in response to changing environmental conditions indicate an interaction between genotype and environment. Genotype-environment interactions were found in plant height, number of pods per plant, pod weight per plant, and yield, suggesting that genotype performance responses are determined not only by genetic potential and environmental conditions (Table 2). The presence of genotype-environment interactions indicates that genotype rankings differ between locations, reflecting different physiological responses to location conditions. Differences in weather conditions will affect the pod filling stage, which will ultimately affect the yield. Meanwhile, no significant G  $\times$  E interactions were found for the number of leaves, days to flowering, days to fresh pod harvest, pod length, and pod diameter. Non-significant genotype-environment interactions were found in traits related to plant phenology associated with the timing of growth and development

phases, such as days to flowering and days to fresh pod harvest, as well as traits related to pod size, such as pod length and pod diameter, indicates that genotypes respond similarly across different environments.

Understanding genotype-environment interactions determines selection strategies for recommending varieties with broad or location-specific adaptability, and is influenced not only by genetic potential and environmental conditions, but also by  $G \times E$  interactions. Overall, these results emphasize the importance of evaluating genotypes across multiple environments to capture diverse responses.

### Stability analysis of yield

The significant influence of  $G \times E$  interactions on several traits indicates that genotype rankings vary between locations, thus requiring stability analysis to assess the consistency of genotype performance across locations. Yield stability was evaluated using a combination of parametric and nonparametric stability analysis methods (Tables 3 and 4). Each statistical stability model will highlight different aspects of stability. Based on the overall univariate stability analysis, AB and AK were the most superior, stable genotypes, and consistently ranked at the top across various environmental conditions (Table 4). This diverse stability model provides a comprehensive overview of adaptability and stability of each genotype. In parametric analysis, Wricke's ecovalence and Shukla's stability variance are classical measures capturing different aspects of  $G \times E$  stability. Wricke's ecovalence, quantifies the contribution of each genotype to  $G \times E$  interactions, and lower genotype value compared to other genotypes indicates that the genotype makes a smaller contribution. Among the genotypes, it was found that the most stable genotype was BB with the lowest  $W^2i$  (0.14), followed by AK (1.05) and AB (1.57). Meanwhile, BK, Balitsa, and

Gypsy showed low stability with values of 44.7, 5.12, and 3.15, respectively. Based on Shukla (1972), a genotype with a smaller stability variance than another genotypes indicates greater stability. Shukla's stability variance ( $\sigma^2$ ) is derived from Wricke which quantifies the squared deviation of each genotype from the additive genotype and environment effects, reflecting its contribution to  $G \times E$  interaction. The ecovalence values are then adjusted using correction factors based on the number of genotypes ( $p$ ) and environments ( $q$ ) to eliminate dimensional bias, resulting in stability variance as an unbiased measure of genotypic instability across environments. In the present results, AB and AK both have the lowest  $\sigma^2$  (0.11, 0.30), which is numerically smaller than another genotypes. This indicated that AB and AK are more stable according to Shukla's criterion. The main assumption of Shukla's stability variance is that the residuals of the ANOVA model are normally distributed and that variances are homogeneous across environments. Meanwhile, Francis and Kannenberg (1978), stated that a low coefficient of variation indicates consistency of results between environments, but should be associated with the average yield. The limitation of the coefficient of variation approach is that it assumes variability alone represents instability and does not explicitly account for  $G \times E$  interactions. Balitsa showed the lowest CV but also had a low average yield, so its stability reflected consistency at a production level that did not meet the criteria for superior genotypes. Conversely, AB ( $Y = 14.07 \text{ t ha}^{-1}$ ,  $CV = 17.7\%$ ) and AK ( $Y = 14.19 \text{ t ha}^{-1}$ ,  $CV = 14.5\%$ ) display a combination of high average yields with relatively moderate variation. The CV values for both genotypes are still acceptable in the selection of high-yielding genotypes that are agronomically stable.

**Table 2.** Combined analysis of variance for growth and yield related traits of common bean

Source of variation	Degrees of freedom	Mean squares								
		PH	NL	DF	DH	NP	PL	PD	PW	Y
Genotypes	5	40.51**	4.82 <sup>ns</sup>	5.37**	4.44**	601**	39.98**	0.92**	27922**	26.38**
Environment	1	128.7**	48.72 <sup>ns</sup>	165**	111**	636*	0.21 <sup>ns</sup>	1.08*	89782**	30.43*
$G \times E$	5	15.08*	6.27 <sup>ns</sup>	0.17 <sup>ns</sup>	0.47 <sup>ns</sup>	387*	0.19 <sup>ns</sup>	0.10 <sup>ns</sup>	21028*	11.16*

Note: PH: Plant Height, NL: Number of Leaves, DF: Days to Flowering, DH: Days to Harvest, NP: Number of Pods, PL: Pod Length, PD: Pod Diameter, PW: Pod Weight per plant, Y: Yield, \*: Significant ( $P \leq 0.05$ ), \*\*: Highly significant ( $P \leq 0.01$ ), <sup>ns</sup>: Not significant ( $P > 0.05$ )

**Table 3.** Parametric and nonparametric stability analysis on yield

Genotypes	Y	CV	$W^2i$	$\sigma^2$	Pi	Fox	$Si^{(1)}$	$Si^{(2)}$	$N^{(1)}$	$N^{(2)}$	$N^{(3)}$	$N^{(4)}$
AB	<b>14.07</b>	17.7	1.57	<b>0.11</b>	<b>0.60</b>	<b>2</b>	<b>1.00</b>	<b>0.50</b>	<b>0.50</b>	<b>0.20</b>	<b>0.20</b>	<b>0.40</b>
AK	<b>14.19</b>	14.5	1.05	0.30	<b>0.46</b>	<b>2</b>	<b>1.00</b>	<b>0.50</b>	<b>0.50</b>	0.33	0.33	0.67
BB	13.18	18.5	<b>0.14</b>	0.65	1.52	1	3.00	4.50	1.50	0.43	0.43	0.86
BK	12.82	28.8	44.7	16.1	4.21	1	5.00	12.5	2.50	0.71	0.71	1.43
BALITSA	10.04	<b>6.13</b>	5.12	1.22	12.29	0	5.00	4.50	2.50	0.45	0.45	0.91
GYPSY	10.37	11.9	3.15	0.48	10.6	0	3.00	12.5	1.50	0.33	0.33	0.67

Note: Y: Yield, CV: Coefficient of Variation,  $W^2i$ : The Ecovalence value of Wricke,  $\sigma^2$ : The stability variance of Shukla, Pi: Superiority index, Fox: Frequency top in stratum,  $Si^{(1)}$  and  $Si^{(2)}$ : Nassar and Hühn measures of stability,  $N^{(1)}$ ,  $N^{(2)}$ ,  $N^{(3)}$ ,  $N^{(4)}$ : Thennarasu measures of stability

**Table 4.** Parametric and nonparametric stability ranks on yield

Genotypes	Y	CV	W <sup>2</sup> i	$\sigma^2$	Pi	Fox	Si <sup>(1)</sup>	Si <sup>(2)</sup>	N <sup>(1)</sup>	N <sup>(2)</sup>	N <sup>(3)</sup>	N <sup>(4)</sup>	Overall rank
AB	2	4	3	1	2	1	1	1	1	1	1	1	1
AK	1	3	2	2	1	1	1	1	1	2	2	2	2
BB	3	5	1	4	3	2	2	2	2	3	3	3	3
BK	4	6	6	6	4	2	3	3	3	5	5	5	6
BALITSA	6	1	5	5	6	3	2	2	3	4	4	4	5
GYPSY	5	2	4	3	5	3	3	3	2	2	2	2	4

Note: Y: Yield, CV: Coefficient of Variation, W<sup>2</sup>i: The ecovalence value of Wricke,  $\sigma^2$ : The stability variance of Shukla, Pi: Superiority index, Fox: Frequency top in stratum, Si<sup>(1)</sup> and Si<sup>(2)</sup>: Nassar and Hühn measures of stability, N<sup>(1)</sup>, N<sup>(2)</sup>, N<sup>(3)</sup>, N<sup>(4)</sup>: Thennarasu measures of stability

The nonparametric results support the parametric results. According to superiority index method, a lower Pi value indicates a closer distance to the maximum yield, so that genotype is considered as the best genotype. The Pi value also indicates the superiority of the genotype in terms of its broad adaptability. The analysis results show that AK had the lowest superiority index (Pi = 0.46), indicating that its results are closest to the optimal genotype in each environment. Meanwhile, Balitsa and Gypsy obtained high Pi values, which indicate low stability. Fox revealed that AB and AK were most often in the highest yield group in each location. A significant Fox value indicates that the genotype often performs well, confirming its ability to maintain high yields even when environmental conditions change. Balitsa and Gypsy had a TOP = 0, indicating consistently low rank across environments. Nassar Hühn and Thennarasu indices likewise ranked AB and AK as the most stable genotypes.

Based on various approaches, each approach interprets stable genotypes differently and each stability index has been converted into a ranking to inform final genotype recommendations (Table 4). Based on the overall approach, AB and AK genotypes are superior in the overall ranking. AK had the highest mean yield (14.19 t ha<sup>-1</sup>), the lowest superiority index (Pi = 0.46), the highest Fox values, and the lowest Nassar Hühn and Thennarasu stability index, indicating it is the best performing genotype across environment. AB showed the smallest Shukla's stability variance ( $\sigma^2 = 0.11$ ), suggesting minimal contribution to G × E interaction, the highest Fox values, and the lowest Nassar Hühn and Thennarasu stability index. Based on overall rank, indicating that both genotypes had the highest yield and stability.

Overall, each stability method captures different aspects of genotype performance and is based on distinct assumptions. Parametric methods emphasize variance components and statistical structure, whereas nonparametric methods prioritize ranking consistency across environments. The ideal genotype can maintain high yield values with low CV, W<sup>2</sup>i,  $\sigma^2$ , Pi, Si<sup>(1)</sup>, Si<sup>(2)</sup>, N<sup>(1)</sup>, N<sup>(2)</sup>, N<sup>(3)</sup>, N<sup>(4)</sup>, and high FOX values. Thus, the combination of parametric and nonparametric identify AB and AK as the best candidates for broad adaptation. This comprehensive approach provides a strong scientific basis for selecting genotypes that are resistant to agroclimatic diversity.

## GGE biplot

### Mean vs. stability

GGE biplot was used to visualize genotype performance and stability across environments. It projects genotypes and environments onto two principal components. The first Principal Component (PC1) accounted for 73.24% of the G+GE variation, while the second Principal Component (PC2) explained 26.77%, indicating that the two-dimensional biplot captures all of the genotype plus G × E signal present in the data. PC1 represents the average genotype performance across environments, and PC2 represents relative stability. The mean vs. stability model shows the yield variability and stability of six bush-type common bean genotypes tested in two environments (Figure 1). The Average Environment Axis (AEA) represents the direction of the average environment; the position of a genotype along the AEA indicates its average performance level, while the perpendicular distance from the AEA measures the degree of instability. Genotypes whose projections lie closer to the AEA have a higher average yield, while stability is assessed by the perpendicular distance from the AEA, the closer a genotype is to the AEA line, the more stable it is across environments.

Genotypes AK and AB are located close to the AEA, indicating high average yields with moderate stability in both environments. Genotype BB is slightly further away but still close to the AEA, indicating relatively high yields and good stability. Meanwhile, Balitsa and Gypsy are further away from the AEA, indicating low yields in both environments. BK is slightly closer to the AEA but far from the AEA line, indicating high yield potential but relatively lower stability. The placement of these genotypes shows differences in adaptation. AK and AB are broadly adapted, BB is a moderate alternative, and BK is environment-specific.

### Which-won-where

GGE biplot with the which-won-where model displays specific genotype patterns in specific environments and provides recommendations for potential genotypes (Figure 2). The identification of genotypes based on polygon sectors is important for understanding the relative advantages of each genotype and its relationship with the test environment. E1 and E2 occupy different sectors confirming environmental contrast. Genotypes that are within the polygon, but not at the peak of the polygon line,

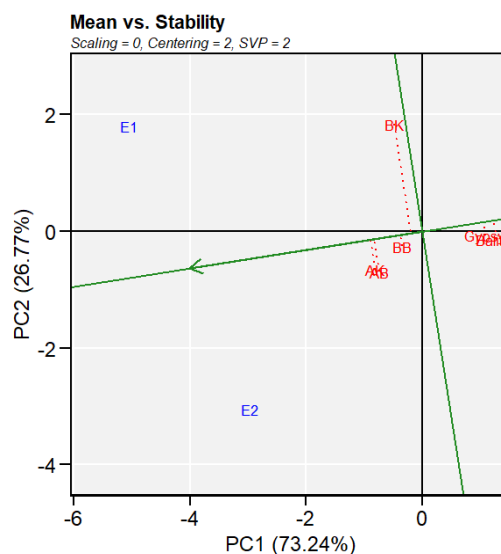
such as BB, indicate low responsiveness to  $G \times E$  and tend to be stable across environments.

BK is closest to the E1, indicating that this genotype has specific adaptations to high-altitude areas. BK can be recommended as a potential genotype for specific environment. Meanwhile, AB, AK, and BB are located closer to the centre of biplot, these genotypes tend to be stable in both environments. Meanwhile, the two check varieties performed poorly in both environments because they were far from the environmental vectors. To strengthen the interpretation of the GGE biplot, the visual patterns were supported with quantitative stability indices. The classification of AB and AK as the most stable genotypes was consistent with their low Wricke ecovalence, low Shukla variance, low Pi values, and the lowest Huehn and Thennarasu ranks, indicating small contribution to  $G \times E$  interactions. Conversely, the poor stability of Balitsa and Gypsy shown in the biplot was confirmed by their high  $W^2_i$ ,  $\sigma_i^2$ , and Pi values. The consistency between the results of multivariate stability analysis with GGE biplot and univariate stability analysis with numerical indices of parametric and nonparametric provides statistical validation of stability conclusions.

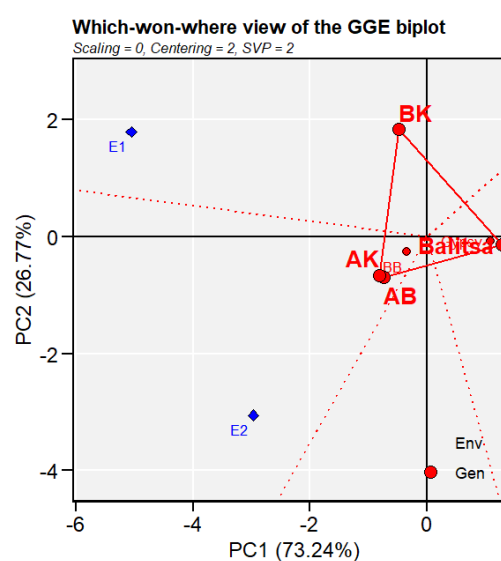
## Discussion

The two different test locations in elevation and microclimate influenced plant growth and productivity. The high-altitude area (Bumiaji, 1,060 m asl.) had lower temperatures (20.8-22.1°C), more stable rainfall (84-100 mm), and higher humidity (88%), whereas the mid-altitude area (Singosari, 520 m asl.) was characterized by higher temperatures (22.9-24°C, reaching maximum temperatures nearly 29°C in August), more variable rainfall (4-113 mm), and lower humidity (77%). According to Khotimah et al. (2022), an increase in altitude of approximately 100 m can reduce air temperature by 0.61°C, which explains the observed thermal differences between the two locations. These environmental conditions at both locations were generally within the suitable range for common bean cultivation. However, variations in temperatures and rainfall distribution significantly influenced plant performance. Temperature differences played a critical role in determining plant physiological responses. The optimal temperature of common bean growth is approximately 20-25°C. In Bumiaji, temperatures were closer to this optimum range, supporting balanced vegetative and reproductive development. In contrast, higher temperatures in Singosari likely increased respiration rates relatively to photosynthesis, reducing assimilates availability for pod filling and potentially resulting in lower yield. Temperature differences between the two environments influence genotype responses, with medium-altitude areas known to have days to flowering that are 3-4 days earlier compared to high-altitude areas. Furthermore, high temperatures may reduce pollen viability and disrupt anther dehiscence, leading to impaired fertilization and pod formation (Rose et al. 2023; Adireddy et al. 2024). Conversely, temperatures below 20°C can perform slow metabolic processes and limit photosynthesis, although they may allow more extended pod-filling periods (Suárez et al. 2020). These findings are

in line with Rinaldi et al. (2023), which reported that higher temperatures at lower altitudes consistently accelerate flowering in yardlong beans. Plant phenology is generally also influenced by environmental conditions, especially temperature and sunlight intensity, so that environmental changes cause acceleration or deceleration of the growth phase. This indicates that the reproductive development of each genotype is sensitive to environmental conditions, particularly the interaction between temperature and photoperiod (González et al. 2021).



**Figure 1.** GGE biplot (mean vs. stability) for yield performance of six common bean genotypes showing mean performance and yield stability as estimated using the AEC across the two test environments (E1: Bumiaji, high altitude, E2: Singosari, mid altitude)



**Figure 2.** GGE biplot (which-won-where) for illustrating the specific yield adaptability of six common bean genotypes across two environments (E1: Bumiaji, high altitude, E2: Singosari, mid altitude)

Common bean requires approximately 1,500-2,500 mm of annual rainfall or 250-450 mm per month. Rainfall in Bumiaji was relatively stable, while in Singosari experienced highly uneven rainfall distribution, with very low precipitation in July followed by a sharp increase in August. Such fluctuations, combined with lower humidity, may increase transpiration rates and disrupt plant water balance, leading to accelerated phenological development and reduced flower and pod formation. Irregular rainfall patterns can negatively affect flowering and seed-filling stages, potentially reducing yield by up to 60% (Papathanasiou et al. 2022). On the other hand, excessive rainfall and high humidity may promote fungal disease development (Kusumiyati et al. 2015). Therefore, more stable rainfall patterns as observed in Bumiaji, are generally more favorable for common bean production. Environmental factors representing differences in altitude and climatic conditions, such as medium altitude (Singosari) and high altitude (Bumiaji), can modify physiological processes such as photosynthesis rate, transpiration, assimilate distribution, and reproductive development, thereby affecting pod filling and biomass accumulation (Adireddy et al. 2024; Amongi et al. 2025).

Combined ANOVA showed that genotype, environment, and  $G \times E$  interaction explained significant variation for most traits (Abera et al. 2022; Demessie et al. 2024; Amongi et al. 2025). The presence of significant  $G \times E$  interactions indicates that genotypes respond inconsistently to different conditions at both high and medium altitudes. Thus, the overall data confirm that differences in elevation and microclimate can increase crop productivity variability and this pattern is important as a basis for assessing adaptability, as the test environment represents contrasting agroecological conditions (Bouchetat et al. 2023). Significant differences in yield between genotypes at the study site indicate that the environment can modulate genetic expression and that genetic traits are not always expressed equally under all environmental conditions and also can determine yield and yield components (Ashango and Alamerew 2017; Mondo et al. 2019).  $G \times E$  interactions were found in plant height, number of pods per plant, pod weight per plant, and yield. The presence of  $G \times E$  interactions indicates that genotype rankings differ between locations, reflecting different physiological responses to location conditions (Molosiwa et al. 2019). The presence of  $G \times E$  further emphasizes the importance of testing at multiple locations to identify stable genotypes (Demessie et al. 2024). The presence of  $G \times E$  interactions on traits related to yield and yield components is in line with Gelete et al. (2022), which reported that plant height, number of pods per plant, and 100-seed weight grown in five environments were influenced by genotype, environment, and their interaction, which were influenced by differences in altitude and climatic conditions, particularly temperature, rainfall, and soil type. Traits related, such as number of pods per plant is one of the determinants of crop yield, which is influenced by environmental factors such as environmental stress, competition for resources, and plant population density (Seo et al. 2024).

Meanwhile, no significant  $G \times E$  interactions were found for the number of leaves, days to flowering, days to fresh pod harvest, pod length, and pod diameter. Non-significant genotype-environment interactions were found in traits related to plant phenology associated with the timing of growth and development phases, as well as traits related to pod size, such as pod length and diameter. Meanwhile, the absence of  $G \times E$  interactions indicates that genotypes respond similarly across different environments (Suárez et al. 2020). Traits related to pod size are strongly influenced by genotype. This shows that genotype is a major factor, so that environmental changes at different altitudes are not strong enough to alter phenotypic expression. Pod length is strongly influenced by genetic factors, with each genotype having different size potentials. This indicates that the genetic potential of the genotype determines pod length, so that pod length remains relatively uniform at various altitudes and climatic conditions, as long as environmental stress is not extreme (Nath and Dasgupta 2013). These findings are in line with Dhakal et al. (2020), which states that genotype has a very significant effect on pod length, indicating that each genotype maintains its pod length pattern even when grown in different environments. Pod diameter, which assesses pod thickness, is largely genetically controlled. In line with Seo et al. (2024), pod thickness is caused by genetic differences determined by the number of cell layers and cell wall thickness, which are genetically regulated from the early stages of pod formation. Understanding genotype-environment interactions determines selection strategies for recommending varieties with broad or location-specific adaptability (Rezene 2019).

Stability analysis was performed to evaluate the consistency of genotype performance across the tested environments. The results revealed that AB and AK were able to maintain high and stable yields despite facing significant differences between high and medium altitudes. AB and AK had the highest mean yields and small fluctuations between sites. This stability was evidenced by low coefficients of variation, low Wricke's ecovalence and Shukla's stability variance, low superiority and nonparametric stability statistics model, along with consistently high performance based on frequency-based ranking. These indicators confirm the strong yield stability of both genotypes across environments. These findings suggest a broad adaptive capacity to stabilize physiological processes in response to varying environmental conditions, as evidenced by the consistency of growth and relatively stable yields at both test locations (Pour-Aboughadareh et al. 2022). To further complement and provide a visual interpretation of the univariate stability results, GGE biplot analysis was also performed.

GGE biplot was used to visualize genotype performance and stability across environments and to complement univariate stability statistics (de Souza et al. 2023). The mean vs. stability model helps breeders assess two main priorities, which are the average performance of genotypes and the stability or consistency of genotype performance across all test environments. In this model, stability is indicated by the perpendicular distance from the average environment, which exhibit both high productivity and

consistent performance (da Cruz et al. 2020; Parkina et al. 2024). Both genotypes, AB and AK, maintained vigorous growth with high biomass and number of pods under both high- and med- altitude area, effectively buffered environmental stress and likely maintained stable photosynthetic activity and efficient assimilate partitioning under fluctuating temperature and moisture. With their ability to withstand extreme environmental differences, both genotypes align with the breeding objective of producing superior varieties that can withstand climate variability. AB and AK can be recommended as widely adaptable superior varieties for common bean farmers in Indonesia because farmers face inconsistent rainfall, high pest pressure at mid-altitudes, and frequent temperature spikes associated with climate change. These constraints often reduce pod filling and shorten reproductive periods, which explains why genotypes with broad adaptability, such as AB and AK are needed to buffer yield loss across seasons and regions.

GGE biplot with the which-won-where model displays specific genotype patterns in specific environments and provides recommendations for potential genotypes to maximize productivity (Rezene 2019). The red polygon line connects genotypes that are furthest from the origin of the biplot, which represent potential winners in each biplot (Mare et al. 2020). Genotypes that are within the polygon but not at the peak of the polygon line indicate low responsiveness to  $G \times E$  and tend to be stable across environments (Baraki et al. 2024). BK is in a separate sector specifically E1, indicating that BK can be recommended as a potential genotype for specific environment in high-altitude area. This pattern resembles to Prado-García et al. (2025) that Andean common bean types are adapted to cooler climates and lose vigor at higher temperatures and often reduce yield under warm conditions due to disrupted pollen and pod development. This response suggests that BK performs optimally only within a narrower environmental range. It is valuable for specific environments in cooler conditions to maximize pod set and filling, so it is less suitable for broad recommendations. Meanwhile, AB, AK, and BB are located closer to the centre of biplot, these genotypes tend to be stable in both environments. Meanwhile, the two check varieties performed poorly in both environments because they were far from the environmental vectors. The identification of genotypes based on polygon sectors is important for understanding the relative advantages of each genotype and its relationship with the test environment (da Cruz et al. 2020).

The ability of genotypes AB and AK to maintain stable yields across environments highlights the role of genetic adaptability in buffering environmental variation. In line with our findings, Gelete et al. (2022) reported that several common bean genotypes in East Africa were capable of maintaining competitive yields across environments, demonstrating that climate conditions do not necessarily reduce productivity. Moreover, Djuariah et al. (2016) showed that several common bean genotypes exhibited promising adaptability at medium altitude in Indonesia, supporting the present evidence that well-selected genotypes such as AB and AK can perform strongly not

only in high altitudes but also in medium altitudes. Prado-García et al. (2025) identified two genotypes with high yields ( $1,800 \text{ kg ha}^{-1}$ ) under high temperature conditions, highlighting specific physiological mechanisms enabling tolerance, and differences in physiological response patterns are influenced by the genetics of each genotype. These studies reinforce the conclusion that the broad adaptability observed in AB and AK aligns with existing evidence from previous research. The high stability of AB and AK is likely associated with their ability to maintain consistent physiological performance under variable environmental conditions. In many stable common bean genotypes, yield consistency is often linked to traits such as efficient photosynthetic activity, stable flowering duration, and the ability to maintain pod filling even when exposed to thermal fluctuations.

The evaluation of genotype responses to different environments can be conducted using both univariate and multivariate approaches. To strengthen the interpretation of stability results, it is important to acknowledge that parametric methods rely on assumptions of normality and homogeneous variances, whereas nonparametric methods based on a ranking procedures (Subaşı and Başalma 2021). Therefore, combining multiple stability analyses with stability indices to provide numeric statistical confirmation and biplot to offer intuitive visualization of adaptability and stability reduce sensitivity to distributional biases (de Souza et al. 2023). The convergence of conclusions across these complementary approaches increases confidence in identifying AB and AK as broadly adapted genotypes, while BK showed specific adaptation. Nevertheless, this study has limitations with two locations so the results should be interpreted cautiously and future multi-season or multilocation trials are recommended to validate genotype stability across wider agroecological conditions.

In conclusion, this study demonstrated the presence of  $G \times E$  interactions affecting yield and related traits of bush-type common bean genotypes across contrasting altitudes. Stability analysis consistently identified genotypes AB and AK as high-yielding with broad adaptability, as reflected by their consistent stable performance across environments. In contrast, genotype BK had specific adaptability to high-altitude area, indicating its suitability for targeted environments. These findings provide important implications for breeding programs, where AB and AK can be utilized as parental lines for developing widely adapted cultivars, while BK can be recommended for high-altitude areas. The integration of multi-environment testing and complementary stability analyses was effective in identifying stable and high-performing genotypes, and can serve as a useful framework for common bean improvement in tropical regions with diverse agroecological conditions.

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