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RESEARCH ARTICLE

Genotype × environment interaction and phenotypic stability analysis in niger (*Guizotia abyssinica* (L.f.) Cass) breeding lines using Eberhart-Russell and AMMI models

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Abstract

Niger (*Guizotia abyssinica* (L.f.) Cass), an important oilseed crop primarily grown in marginal regions of India, faces significant challenges in production due to environmental fluctuations and a limited genetic base. This study analysed 42 niger genotypes, including two checks, across three sowing settings using the Eberhart-Russell and AMMI (additive main effects and multiplicative interaction) models to measure genotype × environment interaction (GEI) and phenotypic stability. The field experiments were conducted in a randomized block design during the 2021 and 2022 *kharif* seasons at the zonal agricultural research station, Jawaharlal Nehru Krishi Vishwavidyalaya, Chhindwara, Madhya Pradesh. The analysis of variance demonstrated remarkably significant differences across genotypes, environments and GEI for important agronomic and quality factors. The Eberhart-Russell model revealed genotypes such as JCN-1 and JCN-27 as highly stable and extensively adaptable, based on the regression coefficient (*bi* = 1) and minimal deviation from regression (σ^2di). Genotypes including JCN -3 and JCN-11 revealed great responsiveness to favorable situations, whereas JCN-9 and JCN-20 showed specific adaptability to stress-prone environments. AMMI1 biplot indicated high-yielding genotypes like JCN-1 and JCN-16, whereas AMMI2 identified JCN-15, JCN-30 and JCN-31 as widely adapted and stable. Genotypes JCN-20 and JCN-28 were particularly adapted to favorable surroundings, whereas JCN-3 and JCN-21 suited marginal environments. The merging of both stability models proved useful in finding genotypes with extensive and specific adaptation. These results give useful insights for breeders attempting to increase yield stability and adaptation in niger under varied agro-ecological situations.

Keywords: AMMI analysis; Eberhart-Russell model; genotype × environment interaction (GEI); niger (*Guizotia abyssinica* (L.f.) Cass); phenotypic stability

Introduction

The Asteraceae family includes the oilseed crop niger (*Guizotia abyssinica* (L.f.) Cass.), which is often valued for its high linoleic acid concentration as well as use in the culinary, medicinal and industrial sectors. Predominantly grown in marginal and tribal areas of India, niger has emerged as an important export commodity. The export of niger seeds continued to increase. India leads in area, production and total exports for niger globally, with the USA, Europe and East Africa as key destinations (1). Regarding nutritional aspects, niger seed contains approximately 40 % edible oil, which is composed of 75-80 % linoleic acid, 7-8 % palmitic and stearic acids and 5-8 % oleic acid. The Indian types of niger contains 25 % oleic and 55 % linoleic acid (2). However, its yield potential remains underexploited, largely due to environmental fluctuations and a narrow genetic base in improved cultivars.

In oilseed breeding programs, yield stability is as crucial as yield potential. The relationship between genotype and environment (GEI) is crucial in plant breeding, especially for crops that hold considerable agricultural and economic importance, like niger. The interplay between genotype and environment often results in varying levels of performance, making the selection of genotypes for wide adaptation a complex task. Multi-environment trials and robust statistical models are essential to quantify GEI and identify stable genotypes. Niger crop growers require varieties that are reliable and stable across environments as well as have high yield potential under favorable conditions. However, the response of different genotypes under different environments can vary. This might be due to the fluctuation of rainfall pattern during the cropping season, emerging and remerging disease, as well as insects and abiotic factors like different soil status, drought and other stresses (3). Consequently, a variety that performs well in one environment during one season may not perform in different testing sites. This showed that GEI impede superior genotypes across environments (4).

As the demand for resilient and high-yielding cultivars intensifies in the face of climate variations, understanding the responsiveness of different genotypes to diverse environmental conditions becomes increasingly crucial. The Eberhart and Russell stability model and the AMMI model are widely employed to dissect GEI components. This research focuses on the phenotypic stability of various niger breeding lines, utilizing both the Eberhart-Russell and AMMI models for a comprehensive analysis of GEI. The outcomes of this analysis not only deepen our understanding of the stability and adaptability of niger lines but also provide essential insights for breeders aiming to enhance crop resilience, ultimately contributing to the sustainability of agricultural practices in changing climates. By employing these statistics, the study aims to characterize stability in 42 breeding lines of niger using the Eberhart and Russell along with AMMI model, thereby enhancing the understanding of environmental responsiveness and aiding in selection for stable performance thereby informing and optimizing breeding strategies.

Materials and Methods

Experimental setup

The study was conducted at the Zonal Agricultural Research Station, AICRP on niger, Jawaharlal Nehru Krishi Vishwavidyalaya (JNKVV), Chhindwara, Madhya Pradesh, during the 2021 and 2022 *kharif* seasons under three environments (EI: 5 Aug 2021 and 2022, EII: 20 Aug 2021 and 2022, EIII: 5 September 2021 and 2022). Forty-two niger genotypes, including two checks (JNS-9 and JNS-28), were evaluated in a randomized block design (RBD) with three replications across three sowing environments (early, mid and late planting). Each plot consisted of four rows, 1.5 m long, with 30 cm row-to-row and 10 cm plant-to-plant spacing. The experimental site, situated at 683 meters above sea level, is characterized by sandy loam soils and variable rainfall. Temperature and relative humidity varied significantly during the crop growth period, influencing genotype performance.

Data collection and statistical analysis

Eleven phenological and yield traits were recorded, including days to DF - days to 50 % flowering; DM - days to maturity; PH - plant height (cm); BP - branches per plant; CP - capitula per plant; SC - seeds per capitulum; TGW - thousand grain weight (g); BY - biological yield (g); HI - harvest index (%); Oil % - oil content and YP - seed yield per plant (g). Seed yield per plant (g) was the primary trait analyzed for stability. ANOVA (analysis of variance) was performed to test the significance of genotypes, environments and GEI. Stability analyses were conducted using R Studio software for AMMI and Eberhart and Russell calculations.

The Eberhart and Russell model was employed to partition GEI into linear and non-linear components. Stability assessment categorized genotypes as: *bi* = 1 (average stability), *bi* > 1 (responsive to favorable environments), or *bi* < 1 (stable in unfavorable conditions). Here *bi* is the regression coefficient used to quantify how a genotype responds to environmental variation. Significance was tested using F-tests and t-tests for *bi* deviation from unity. The AMMI model combined ANOVA and PCA (principal component analysis) to analyze GEI (5). Data curated from three distinct environments made up the environment-centered datasets. For the GGE (genotype + genotype × environment) biplot analysis, which incorporates both genotypic and G*E interaction effects, the first two principal component axes (interaction principal component axis - IPCA 1 and IPCA 2) were used. To illustrate stability and adaptation, AMMI1 and AMMI2 biplots were generated. Based on their percentage similarity, they were then put through cluster analysis to pinpoint the genotypes that reacted similarly to the surroundings (6).

Results and Discussion

The performance of the 42 niger genotypes across three environments revealed substantial genetic variability and strong GEI effects for most of the agronomic and quality traits.

Analysis of variance (ANOVA)

The ANOVA for all studied traits, including days to 50 % flowering, plant height, branches per plant, 1000-seed weight and seed yield per plant, indicated significant (p < 0.01) differences among genotypes, environments and their interactions (Table 1). The environmental variance contributed significantly to the total variability, emphasizing the influence of seasonal and climatic conditions on genotype performance. Particularly, traits like seed yield, oil content and plant height were highly influenced by environmental conditions, demonstrating the critical need for multi-environment testing in niger breeding programs. All traits, except for branches per plant, showed strong genotype × environment interactions, a hallmark of crops grown in heterogeneous environments. Traits like flowering time, maturity, plant height and reproductive traits (CP and SC) were particularly sensitive to environment quality, with large linear environmental effects, supporting the use of regression-based stability models. The presence of significant variety × environment (linear). For nearly all traits, this further justifies the application of the Eberhart and Russell model, as it effectively partitions GEI into predictable and unpredictable components, aiding in the selection of stable genotypes for multi-locational testing. Traits with low GEI (e.g., BP) may be prioritized for early generation selection, while those with high GEI (e.g., PH, CP, SC) should be selected using stability indices. The significance of GEI indicates differential genotypic responses under varying environmental conditions, necessitating stability analysis to identify widely adapted genotypes.

Eberhart and Russell's stability analysis

The model divides the G*E*I into two components: the linear regression (*bi*) representing the genotype's response to the environmental index and the deviation from regression (σ^2di), reflecting the unpredictability of that response. A stable genotype should possess three main characteristics: high mean performance (μ), a regression coefficient (*bi*) approaching unity and deviation from regression (σ^2di) near zero (7).

The seed yield per plant across three environments ranged from 6.23 g (JCN-38) to 2.81 g (JCN-29). The regression coefficients (*bi*) ranged from 2.16 to -0.43, while the deviations from regression (σ^2di) ranged from 2.79 to 0.03 (1, 8, 9).

Table 1. ANOVA for the stability model of Eberhart and Russell (1966) for seed yield and its attributing traits

Source of variation	Df	DF	DM	PH	BP	CP	SC
Rep within Env.	12	0.665	0.426	10.549	0.278	0.836	0.731
Varieties	41	3.734 **	14.740 **	94.166 ***	3.693 ***	27.279 ***	47.356 ***
Env. + (Var.* Env.)	210	47.192 ***	30.482 ***	48.171 ***	4.325 ***	38.547 ***	22.281 **
Environments	5	1859.078 ***	834.033 ***	716.595 ***	134.105 ***	1271.972 ***	147.723 ***
Var.* Env.	205	2.999 **	10.883 *	31.868 **	1.159	8.464	19.221 *
Environments (Lin.)	1	9295.389 ***	4170.167 ***	3582.972 ***	670.524 ***	6359.859 ***	738.613 ***
Var.* Env. (Lin.)	41	6.327 ***	19.815 ***	72.239 ***	1.874 **	11.183 *	35.798 ***
Pooled deviation	168	2.116 ***	8.444 ***	21.257 ***	0.957 ***	7.598 ***	14.718 ***
Pooled error	492	0.168	0.235	2.994	0.107	0.554	0.679
Total	251	40.093	27.91	55.684	4.221	36.707	26.377
Source of variation	**Df**	**TGW**	**BY**	**HI %**	**Oil %**	**YP**	
Rep within Env.	12	0.001	1.862	0.503	0.013	0.006	
Varieties	41	0.392 ***	104.214 ***	44.649 ***	89.655 ***	4.034 ***	
Env. + (Var.* Env.)	210	0.209 ***	51.124 ***	14.214 **	0.052 **	2.428 ***	
Environments	5	5.489 ***	1192.291 ***	90.009 ***	0.167 ***	61.888 ***	
Var.* Env.	205	0.080 **	23.291 *	12.365 *	0.049 *	0.978 *	
Environments (Lin.)	1	27.444 ***	5961.453 ***	450.044 ***	0.836 ***	309.442 ***	
Var.* Env. (Lin.)	41	0.194 ***	48.563 ***	24.307 ***	0.097 ***	1.886 ***	
Pooled deviation	168	0.051 ***	16.568 ***	9.157 ***	0.036 ***	0.733 ***	
Pooled error	492	0.004	2.395	0.696	0.014	0.01	
Total	251	0.239	59.796	19.185	14.688	2.691	

** significant at 5 % and *** significant at 1 % respectively.

Note: DF - days to 50 % flowering; DM - days to maturity; PH - plant height (cm); BP - branches per plant; CP - capitula per plant; SC - seeds per capitulum; TGW - thousand grain weight (g); BY - biological yield (g); HI - harvest index (%); Oil % - oil content; YP - seed yield per plant (g).

Genotypes JCN-1 (5.84 g), JCN-4 (5.48 g), JCN-10 (5.57 g), JCN-15 (5.16 g) and JCN-38 (6.23 g) recorded the highest mean yields. However, only JCN-1 combined high yield with ideal *bi* (0.98) and low σ^2di (0.09), suggesting general adaptability and stability. Genotype JCN-38, while having the highest mean yield (6.23 g), had *bi* = 1.20 and σ^2di = 0.39, indicating it was responsive to favorable environments but with moderate unpredictability. JCN-27 (μ = 3.39 g, *bi* = 1.00, σ^2di = 0.03) was the most stable genotype across all environments with perfect bi and negligible σ^2di. Though its mean yield was moderate, its predictability makes it suitable for regions with high environmental variability. JCN-13 had a moderate yield (3.21 g), *bi* < 1, indicating better performance under stress or poor environments. Genotypes such as JCN-3 (*bi* = 2.16), JCN-11 (*bi* = 1.98) and JCN-16 (*bi* = 1.92) showed high responsiveness (*bi* > 1) and moderate-to-high yields. These are suited for high-input or optimal conditions but are less stable across stress-prone environments. Genotypes like JCN-9 (*bi* = 0.26) and JCN-20 (*bi* = 0.41) had low regression coefficients, indicating specific adaptation to stress-prone areas, although they had low-to-moderate yield potential. These genotypes can be recommended for cultivation in marginal lands with minimal resource availability. These results corroborate the observations regarding genotype adaptation to stress conditions (10). High σ^2di values were observed in JCN-25 (2.79), JCN-22 (1.71) and JCN-7 (1.85), reflecting poor predictability across environments. JCN-3 and JCN-36, although having high *bi* values, also recorded high σ^2di, making them responsive but unreliable. JCN-15 had a negative *bi* (-0.43), suggesting an atypical response. Such a genotype may react inversely to favorable environments and is not recommended for breeding programs aimed at broad adaptability (Table 2). The present investigation identified significant variations in stability parameters among the 42 niger genotypes (11, 12).

The weight of 1000-seeds is considered an important component of yield. The values across genotypes ranged from 4.63 g to 3.49 g. The regression coefficients for this trait varied from 1.82 to -0.45 and the σ^2di ranged from 0.28 to 0.00. JCN-1 (μ = 4.62, *bi* = 0.66, σ^2di = 0.03) and JCN-4 (μ = 4.28, *bi* = 0.68, σ^2di = 0.04) exhibited low deviation from regression and *bi* < 1, suggesting suitability for low-input environments. JCN-11 (μ = 4.32, *bi* = 1.67, σ^2di = 0.00) and JCN-3 (μ = 4.20, *bi* = 1.78, σ^2 di = 0.00) showed positive linear responsiveness to favorable environments with excellent predictability. This makes JCN-11 an excellent candidate, particularly for areas with favorable conditions.

Oil content, a critical trait in niger, ranged from 30.13 % to 45.31 %, with a grand mean of 33.70 %, reflecting substantial genotypic and environmental variation, supporting the claims regarding the environmental stability of quality traits in niger (13). JCN-3 (μ = 45.31 %, *bi* = 2.49, σ^2di = 0.05) and JCN-4 (μ = 45.30 %, *bi* = 4.25, σ^2di = 0.01) showed excellent oil content but high *bi* values, suggesting specific adaptation to high-input environments. JCN-11 (μ = 30.14 %, *bi* = 0.98, σ^2di = -0.01) and JCN-13 (μ = 31.17 %, *bi* = -1.00, σ^2di = -0.01) had near-zero deviation, making them more predictable under varying conditions, though oil content was moderate. JCN-27 (μ = 39.25 %, *bi* = 2.01, σ^2di = 0.03) and JCN-36 (μ = 38.29 %, *bi* = -1.84, σ^2 di = 0.00) offer high oil content and predictable responses, with potential in environment-specific breeding.

These findings suggest that these genotypes can maintain consistent yield under varying climatic and soil conditions and may serve as promising candidates for varietal release or breeding programs focused on stability. These results are consistent with previous research by that emphasized the importance of genotype-specific responses in niger and the role of regression-based models in identifying stable varieties (14, 15).

Table 2. Niger genotypes identified for stability and adaptability

Character	Idea and stable (σ^2di ~0, *bi* ~1, Mean<GM)	Stable (σ^2di ~0, *bi* ~1, Mean>GM)	Below average stability (σ^2di ~0, *bi* >1, Mean>GM)	Above average stability (σ^2di ~0, *bi* <1, Mean>GM)
Days to 50 % flowering	JCN-7, JCN-11, JCN-26, JCN-27, JCN-33, JCN-36, JCN-28	JCN-40, JCN-34, JCN-15, JCN-29, JCN-24, JCN-5, JCN-13	JCN-16, JCN-40, JCN-24, JCN-34	JCN-12, JCN-31, JCN-5, JCN-13, JCN-29, JCN-10
Days to maturity	JCN-36, JCN-29	JCN-9	-	-
Plant height (cm)	-	-	JCN-3, JCN-21	JCN-09, JCN-22, JCN-10
Number of branches per plant	JCN-34, JCN-9, JCN-22, JCN-10, JCN-2, JCN-30	JCN-28	-	-
Capitula per plant	JCN-1, JCN-21, JCN-23	JCN-40	-	JCN-1, JCN-3, JCN-21, JCN-23
Number of seeds per capitula	JCN-40	-	-	JCN-10, JCN-27
1000 grain weight	-	JCN-7, JCN-2	JCN-11, JCN-26, JCN-27, JCN-33, JCN-36	-
Biological yield	-	JCN-20, JCN-35	-	JCN-40, JCN-27, JCN-4
Harvest index (%)	JCN-14	-	JCN-34, JCN-15, JCN-2	-
Oil (%)	JCN-11, JCN-18, JCN-30, JCN-37	JCN-38, JCN-39	JCN-25, JCN-40, JCN-27, JCN-4, JCN-3	-
Seed yield/ plant (g)	JCN-24, JCN-6, JCN-18	JCN-1	JCN-34	JCN-1, JCN-10

AMMI analysis

The AMMI model further dissected the GEI into principal components using PCA (Table 3). The first two IPCA1 and IPCA2 explained 56.3 % and 43.7 % of the GEI variance, respectively (Table 4). The AMMI biplots (AMMI1 and AMMI2) offered a graphical interpretation of genotypic stability and environmental discrimination (Fig. 1, 2) (16, 17).

Table 3. ANOVA for AMMI stability model

	DF	SS	MSS
ENV	2	67.32145	2.76342***
GEN	41	34.49831	0.84142**
ENV*GEN	82	22.34221	0.21376**
PC1	42	76.54371	4.32176***
PC2	40	23.64321	0.43840**
PC3	38	216.76416	1.07639**
Residuals	252	21.5968	0.0857**

** significant at 5 % and *** significant at 1 % respectively.

Note: DF - degree of freedom; SS - sum of squares; MSS - mean sum of squares; EVN- environment; GEN- genotype; PC - principal component

Table 4. Interaction principal component axis (IPCA) score and environmental index

Environment	Mean yield	PC1 score	PC2 score
E1	2541.848	6.703912	20.14949
E2	2517.672	15.23871	-15.5243
E3	2557.489	-21.9426	-4.62522

AMMI 1 biplot analysis

To investigate the main and interaction effects, the AMMI 1 biplot was created for seed yield (Fig. 1). IPCA1 scores are used to define the association between genotype and environment mean (main effect). The results depicted that the displacement of genotypes and the interaction effect indicated variations in an additive effect. The environments that cluster together have similar effects on the genotypes clustered in the same group for adaptation (15). X-axis (PC1) captures the main component of GEI, 56.3 % of GEI variation. Y-axis (mean seed yield) reflects the average performance of genotypes or environments across all locations (13).

Genotypic stability

Genotypes positioned close to the IPCA1 axis (PC1 ≈ 0), such as G1, G6, G12, G14 and G27, exhibited low interaction effects, indicating broad adaptability and phenotypic stability (10). Conversely, genotypes such as G9, G19 and G4 had high positive IPCA1 values, suggesting specific adaptation to favourable environments. In contrast, G3, G23 and G28, with strongly negative IPCA1 scores, were better suited to less favourable conditions (e.g., E3) (18).

Mean yield

Genotypes located higher along the Y-axis were associated with greater mean seed yield. Notably, G9, G19, G16, G1 and G36 exhibited the highest yields. Among these, G1 and G16 were particularly promising as they combined high productivity with low IPCA1, indicating both high performance and stability.

Environment-specific interaction

E1 and E2, both located on the right side of the biplot with positive IPCA1 values, interacted positively with genotypes such as G1, G4 and G32, suggesting their suitability under these environments. E3, positioned on the far left with a negative IPCA1 score, showed better interaction with genotypes such as G3, G28 and G21, indicating their potential for stress-prone environments.

AMMI 2 biplot analysis

The AMMI2 biplot, plotting PC1 against PC2, allowed further dissection of specific adaptation and stability based on both primary and secondary interaction effects (Fig. 2). The yields of advanced breeding lines that are grouped on the plot will be comparable in every year. Diverse genotypes exhibit distinct responses to their surroundings or vary in their yields. Environments and genotypes that belong to the same quarter interact favourably, whereas those that belong to other sectors interact poorly (19).

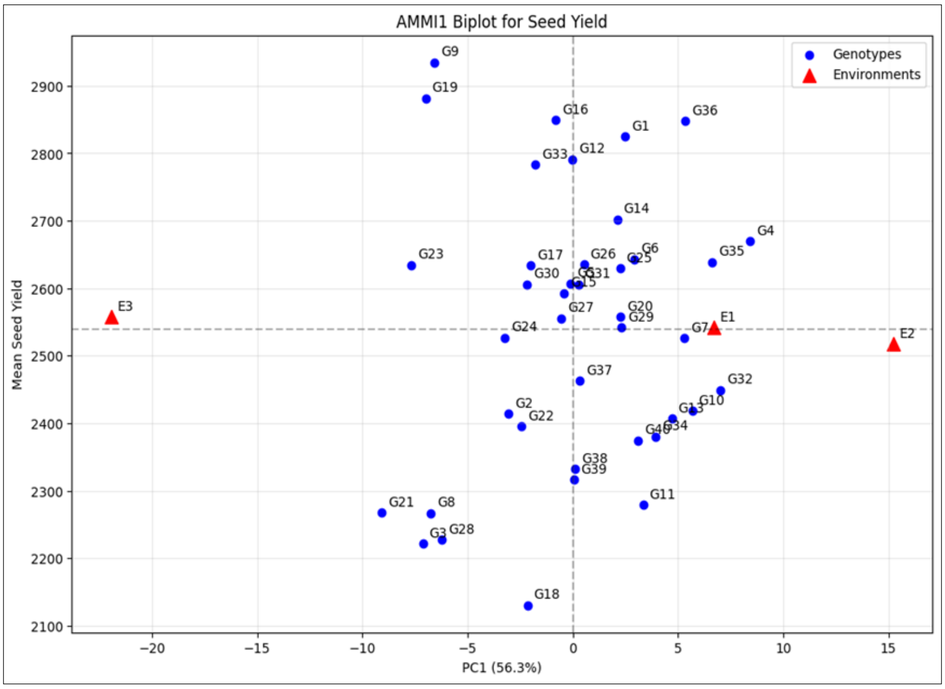

Fig. 1. AMMI biplot 1 for seed yield per plant.

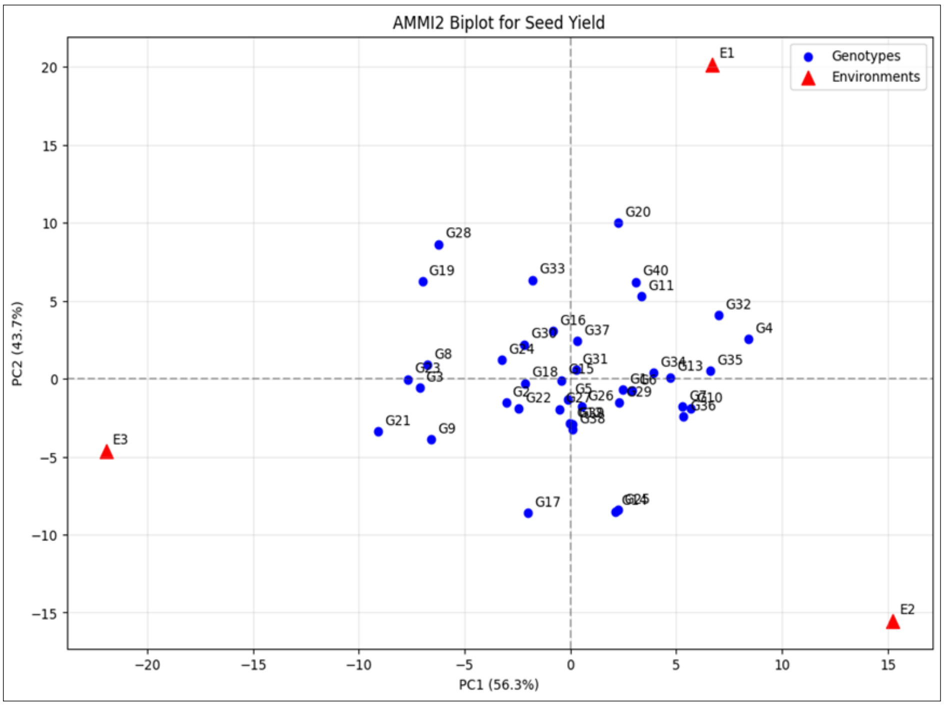

Fig. 2. AMMI biplot 2 for seed yield per plant.

Broadly adapted genotypes

Genotypes positioned near the origin (0,0), including G15, G26, G29, G30, G31 and G38, demonstrated minimal GEI, indicating high stability and wide adaptability across test environments. G15 was particularly noteworthy, exhibiting extremely low interaction scores for both PC1 and PC2, thus emerging as the most ideally stable genotype.

Specifically adapted genotypes

Genotypes situated far from the origin, such as G20, G28, G25, G17 and G21, exhibited high interaction effects, indicating specific adaptability to particular environments but poor overall stability (17). For instance, G20, positioned in the upper-right quadrant along with environment E1, was identified as genotypes with a strong positive interaction with E1, thereby making them suitable for high-input or favourable environments (20, 21). Similarly, G21, located near E3 (bottom-left), was specifically adapted to less favourable or stress-prone environments (Table 5) (9).

Table 5. The joint interpretation of AMMI1 and AMMI2 biplots

Genotype	Interpretation
G15	High stability; near-zero PC1 and PC2; broadly adapted
G1, G16	High yield; moderate GEI; suitable for general cultivation
G20	High GEI; specifically adapted to E1
G21	Low yield; adapted to E3
G9, G19	High yield but high GEI; suited to favourable, stable environments
G31, G30	Moderate yield; stable; candidates for wide-area trials

Conclusion

This research revealed a significant GEI yield and other agronomic traits in niger, thus emphasizing the importance of multi-environment and multilocation trials for identifying stable and high-performing genotypes. Seed yield, oil content and plant height were particularly influenced by the environment, which underlines the need to assess genotype stability under diverse conditions. Using the Eberhart-Russell model, genotypes such as JCN-1 and JCN-27 emerged as broadly adapted and phenotypically stable. JCN-11, JCN-3 and JCN-4 demonstrated superior performance for traits like 1000-seed weight and oil content, making them suitable for targeted breeding in favorable environments. Genotypes like JCN-36, JCN-38 and JCN-25 performed well under optimal conditions but exhibited higher GEI, suggesting limited adaptability. In contrast, JCN-9, JCN-20 and JCN-13 showed better performance in marginal environments and are candidates for resource-limited and stress-prone areas. The AMMI model further supported the results unravelled by the Eberhart and Russell model. AMMI1 biplot analysis identified JCN-1 and JCN-16 as high-yielding and stable, while AMMI2 confirmed the broad adaptability of JCN-15, JCN-30 and JCN-31, which had low interaction scores across both principal components. Genotypes like JCN-20 and JCN-28 exhibited specific adaptation to favorable environments (E1), while JCN-21 and JCN-3 were better suited for stress-prone areas (E3). Integrating both models facilitated the identification of reliable genotypes for varietal release and breeding. These findings can advance the development of resilient, high-yielding niger cultivars for diverse agro-ecological zones.

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Authors' contributions

ADA conceived and designed the experiment, conducted fieldwork, recorded and analyzed the data and led the manuscript writing and revision. RB supervised the research, provided technical guidance throughout the study and critically reviewed the manuscript for scientific content and accuracy. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

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