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Adaptive Response of Chickpea Varieties with Diverse Breeding Pathways Across Six Contrasting Semi-arid Environments using AMMI and GGE Biplot Analysis

Fatiha Zine-Zikara[1,2], Fatma Zohra Bouras[2], Wahiba Tiliouine[1], Samia Hamdi-Daoud[1], Amar Haireche[3], Oussama Baghdadli[3], Rabah Rahim[3], Mohamed Réda Bououlcis[3], Meriem Laouar[2]

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ABSTRACT

Background: This study aimed to evaluate the variety × environment interaction for high grain yields and stability of chickpea varieties with different breeding pathways, across six contrasting semi-arid environments.

Methods: During one cropping season, trials were conducted at the farmers' fields. Ten genotypes were evaluated in a completely randomized block design, with three replicates in six semi-arid contrasting environments. Analysis of variance, AMMI and GGE biplot models were used.

Result: Genetic variability of grain yield was strongly influenced by the environment that explained almost 26% of the total variance, whereas the G×E interaction explained 16%, highlighting the importance of genotype-specific adaptation. Two discriminating environments, E5 and E4 were selected. The introduced variety G8-IV showed excellent stability and high yield (1.32 t-ha^{-1}), demonstrating its plasticity. Similarly, participatory variety G4-PS showed high stability despite its selection in a specific terroir, demonstrating a wider-than-expected capacity for adaptation. Conversely, some local varieties, such as G1-LV, showed narrower adaptation limited to environments such as E3. These elements allow breeding to be oriented towards the greater resilience of farming systems in the face of climatic variability.

Key words: Additive main effects and multiplicative interaction (AMMI), Chickpea, Genotype plus genotype-by-environment interaction biplot (GGE), Semi-arid, Varieties pathway, Yield stability.

INTRODUCTION

Chickpea (*Cicer arietinum* L.) is a globally important food legume and a major source of protein in human diets (Baite *et al*., 2017). It contributes substantially to soil fertility through biological nitrogen fixation, making it an ideal rotational crop in sustainable cereal-based systems (Saraf *et al*., 1998).

Chickpea is cultivated under rainfed systems in semi-arid Mediterranean environments (Bouri *et al*., 2019). It requires relatively low water (300-400 mm), but its production is increasingly constrained by irregular rainfall, terminal drought during flowering and pod filling (Street *et al*., 2016) and high temperatures. In fact, terminal drought can potentially reduce yields by 58-95% compared to irrigated conditions (Farooq *et al*., 2017).

The semi-arid Algerian environments are broadly representative of Mediterranean rainfed systems (Djellouli, 2025), where water scarcity is increasingly critical from eastern to western regions (Alrteimei *et al*., 2022).

Developing varieties with drought tolerance and adaptation to variable rainfall is crucial to sustain productivity and food security under climate variability (Arriagada *et al*., 2022). Chickpea breeding pathways include: (i) pure (bred) varieties, genetically homogeneous; (ii) participatory selection varieties, co-developed with farmers to enhance local adaptation and adoption; and (iii) heterogeneous local varieties, maintained by farmers and characterized by high intra-population diversity and resilience under marginal rainfed conditions (Raggi *et al*., 2019).

Expanding the genetic base enhances chickpea resilience to drought and heat stress while improving productivity (Kharrat *et al*., 2023). Nevertheless, some self-

[1]INRAA, National Institute of Agronomic Research of Algeria, Biotechnology and Plant Breeding Division, Algiers, Algeria.
[2]ENSA, National Higher School of Agronomy-El Harrach, Laboratory of Integrated Improvement of Plant Productions (C2711100), Algiers, Algeria.
[3]OAIC, Algerian Inter professional Cereals Office, Algeria.

Corresponding Author: Fatiha Zine-Zikara, Meriem Laouar; INRAA, National Institute of Agronomic Research of Algeria, Biotechnology and Plant Breeding Division, Algiers, Algeria; ENSA, National Higher School of Agronomy-El Harrach, Laboratory of Integrated Improvement of Plant Productions (C2711100), Algiers, Algeria.
Email: fatiha.zine.zikara@gmail.com; meriem.laouar@edu.ensa.dz

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pollinating homogeneous varieties retain notable tolerance to abiotic stresses (Panigrahi *et al*., 2024). In the context of increasing climatic variability and a limited genetic pool (Varshney *et al*., 2024), it is therefore important to determine not only the best-adapted genotypes but also the most appropriate type of classical selection to adoptto maximize productivity for long-term resilience.

Understanding genotype × environment is critical for guiding varietal selection toward yield stability and resilience under variable semi-arid conditions. While multi-year trials are ideal, evaluating varieties across contrasting environments within a single year can provide robust insights into stability and adaptation, as demonstrated in recent studies (Khan *et al*., 2024).

To capture these interactions, this study employs Additive Main Effects and Multiplicative Interaction (AMMI) and Genotype plus Genotype × Environment (GGE) biplot analyses, integrating robust statistical modeling with visual interpretation (Laxuman *et al*., 2025; Shekhawat *et al*., 2024; Annicchiarico, 2020; Zobel *et al*., 1988).

The specific objectives of this study are to: (i) evaluate the performance of chickpea varieties differing by breeding pathway across six contrasting Algerian environments; (ii) quantify G×E interactions for grain yield and stability; and (iii) identify varieties most stable and adapted for rainfed semi-arid conditions, provid guidance for sustainable varietal deployment.

MATERIALS AND METHODS

Genetic material

Ten varieties of chickpea were obtained through different selection methods; their pedigree, origins and supplying institutes are listed in Table 1. They correspond to local varieties (LV), participatory selected varieties (PS) and introduced varieties (IV) selected by ICARDA.

Experimental sites and environmental variability

Six sites, favorable for chickpea cultivation, with contrasting conditions (climatic and edaphic) were selected for the study and are illustrated in Fig 1 (S1 to S6).

Multiple Factor Analysis was carried out using climatic data (Algerian National Office of Meteorology) for twenty-three years (2000 to 2022) and soil analysis (2021-2022). This enabled us to confirm the environmental variability of the sites along the axes 1-2-3.

For each site, we assigned a code to the corresponding environment by identifying its most distinctive characteristics (Table 2).

Trial setup

The experiments were conducted during the 2021-2022 season on a farmer's field. The climatic and edaphic characteristics of each experiment by site are presented in Table 2.

Climatic data for 2021-2022 (Fig 2) indicate higher or stable rainfall from March to May (early spring) compared to the 23-year average, but reduced precipitation from December to February (winter) and after May. This atypical winter deficit contrasts with the usual spring water stress in these semi-arid regions and aligns with recent reports of declining winter rainfall, shorter wet seasons and greater variability in northern Algeria (Bessaoud and Montaigne, 2009; Meddi *et al*., 2010; Djellouli and Laborde, 2022). Mean temperatures remained close to the historical average.

Experimental design and recorded traits

The experiment was laid out as a completely randomized block design with three replicates. Elementary plots

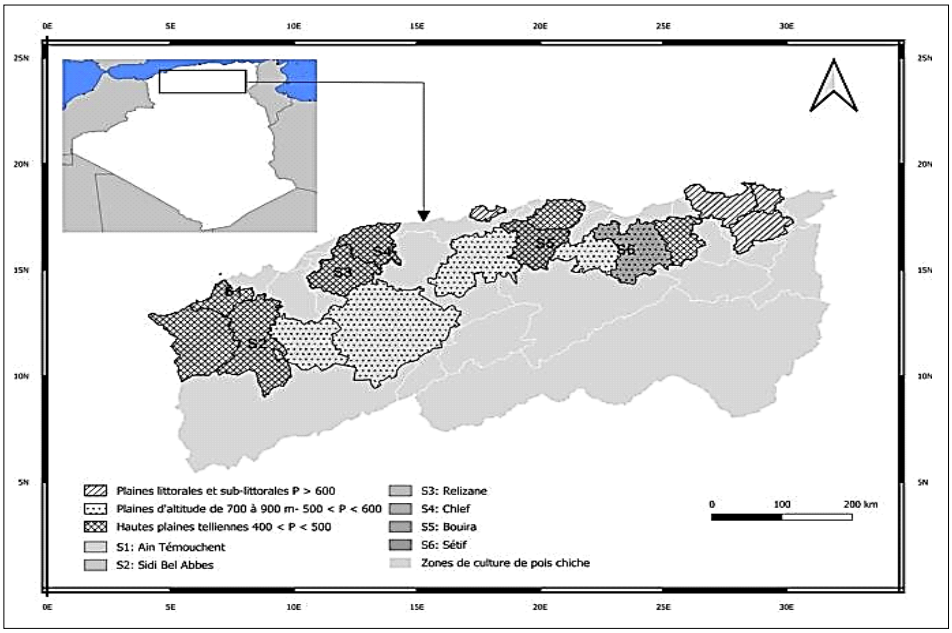


Fig 1: Algerian production chickpea areas and location of study sites.

Table 1: Breeding pathway, codes, names, pedigrees, origins, source and target environments of ten chickpea varieties.

Breeding pathway	Code	Variety	Pedigree	Origin	Source	Selection purpose
Local variety (LV)	G1-LV	Tadjena	Not available	Farmer/Chlef	OAIC	Large grain
	G2-LV	Rabat		Farmer/Skikda		
	G3-LV	Bouazza		Farmer/SBA	INRAA	
Participatory selected variety (PS)	G4-PS	F10-5*		Not available		Height plant, medium grain size, anthracnose tolerance
	G5-PS	F10-49*				Large grain size, drought resistance
	G6-PS	F4-82*				Large grain, tolerant to anthracnose
Introduced variety (IV)	G7-IV	ILC 32-79	Line	ICARDA		Height plant, upright habit, productive, very resistant to disease.
	G8-IV	Ghab4 (FLIP 93-93c)	X89TH258/ (flip85-122CX flip82- 150C) /flip86-77C			Height plant, disease tolerance, stable yield.
	G9-IV	Flip 90-13C	X87TH317/ (PI.Se.Be.81-40X ILC195)Xflip84-46C			Anthracnose tolerance
	G10-IV	Flip 05-153C	X2001TH16/ (Flip97- 25CXS98588) XS99481			Large grain

*: Selected by Dr. Labdi M. and Mrs. Hamdi S., at National Institute of Agronomic Research of Algeria, INRAA, OAIC: Algerian Inter professional Cereals Office, ICARDA: International center for agricultural research in the dry areas.

measured 6 m × 1.8 m and consisted of four rows sown at 20 seeds m^{-1} (150 kg ha^{-1}) with a thousand-seed weight of 340 g. The crop cycle was between December and June for all sites except site 1 (sowing in February).

Six agronomic traits were selected based on their relevance to the yield, plant architecture and adaptation to environmental constraints (Singh *et al*., 2020): grain yield, plant height, number of primary branches, stem length to the first pod, 100-seed weight and the harvest index.

Statistical analysis

Analysis of variance (ANOVA) was conducted to assess yield differences among varieties within each environment, aiming to test the variety effect and to classify the ten cultivars individually or according to their breeding pathways. In addition, a factorial ANOVA was applied to several agronomic traits measured in the six environments, considering the main effects of the selection pathway, environment and their interaction. Analyses were carried out using RStudio software (version 2023.12.0+369) Multiple comparisons of the means were performed using Tukey's test.

Statistical analyses of the Additive Main Effects and Multiplicative Interaction (AMMI) Zobel *et al*. (1988) and genotypic main effect + genotype-by-environment interaction (GGE) biplot models (Ponsiva *et al*., 2024) were performed using the "metan" package in RStudio software version 12.0. AMMI models were applied to study the G×E interaction, adaptation and stability of varieties across the six environments.

According to Gauch *et al*. (2008), the display of nominal variety yields (AMMI-1) clearly describes the winning varieties and adaptive responses.

RESULTS AND DISCUSSION

Grain yield performance across environments

ANOVA for grain yield revealed significant differences (1.01 t·ha^{-1} to 2.18 t·ha^{-1}) among varieties across most environments, except for E1 (Table 3).

Participatory selection varieties showed the most consistent yields across environments, performing best under moderately productive conditions. Local varieties were well adapted to favorable environments, particularly under adequate spring rainfall and exhibited moderate stability. In contrast, introduced varieties displayed the highest variability, occasionally achieving high yields but often underperforming, indicating greater sensitivity to environmental conditions.

Effects of breeding pathways, environment and their interaction on morpho-agronomic traits

The environment had a highly significant effect on all traits, except Number of primary branches (Table 4), highlighting the major role of local conditions in shaping phenotypic expression. The pathway × environment interaction was especially pronounced for 100-grain weight.

Table 2: Climatic and soil variations of the six study sites.

Site/Code	S1/E1	S2/E2	S3/E3	S4E4	S5/E5	S6/E6
Average rainfall (mm)_Year	495.79	499.08	464.76	426.6	508.8	574.44
Average rainfall (mm)_cycle culture	299.10	380.26	225.07	294.13	292.21	259.37
MinT (°C)/month	5.41/January	7.66/January	6.54/January	8.68/January	6.96/January	0.51/January
MaxT (°C)/month	34.39/July	33.76/August	35.52/August	31.43/August	37.10/July	33.90/July
Soil texture	Silty	Silty clay	Silty clay	Silty	Clayey silt	Silty clay
Soil-EC (ds/m)	0.14	0.13	0.16	0.38	0.11	0.24
Soil-TAL (%)	10.07	2.65	4.5	6.64	5.36	3.15
Soil-OM (%)	2.79	1.29	1.32	0.44	1.84	3.27
Soil-P_2O_5 (ppm)	4.87	4.26	4.56	6.39	3.64	11.25
Soil-K_2O (mg/kg)	0.27	0.24	0.25	0.24	0.63	3.09
Characteristics	Dry, with calcareous and nutrient-richsoil	Intermediate	Intermediate	Hot, withlow rainfall and saline soil	Moderately rainy	Cold and rainy, with fertile/rich soil

EC: Electrical conductivity, TAL: Total active limestone, OM: Organic matter.

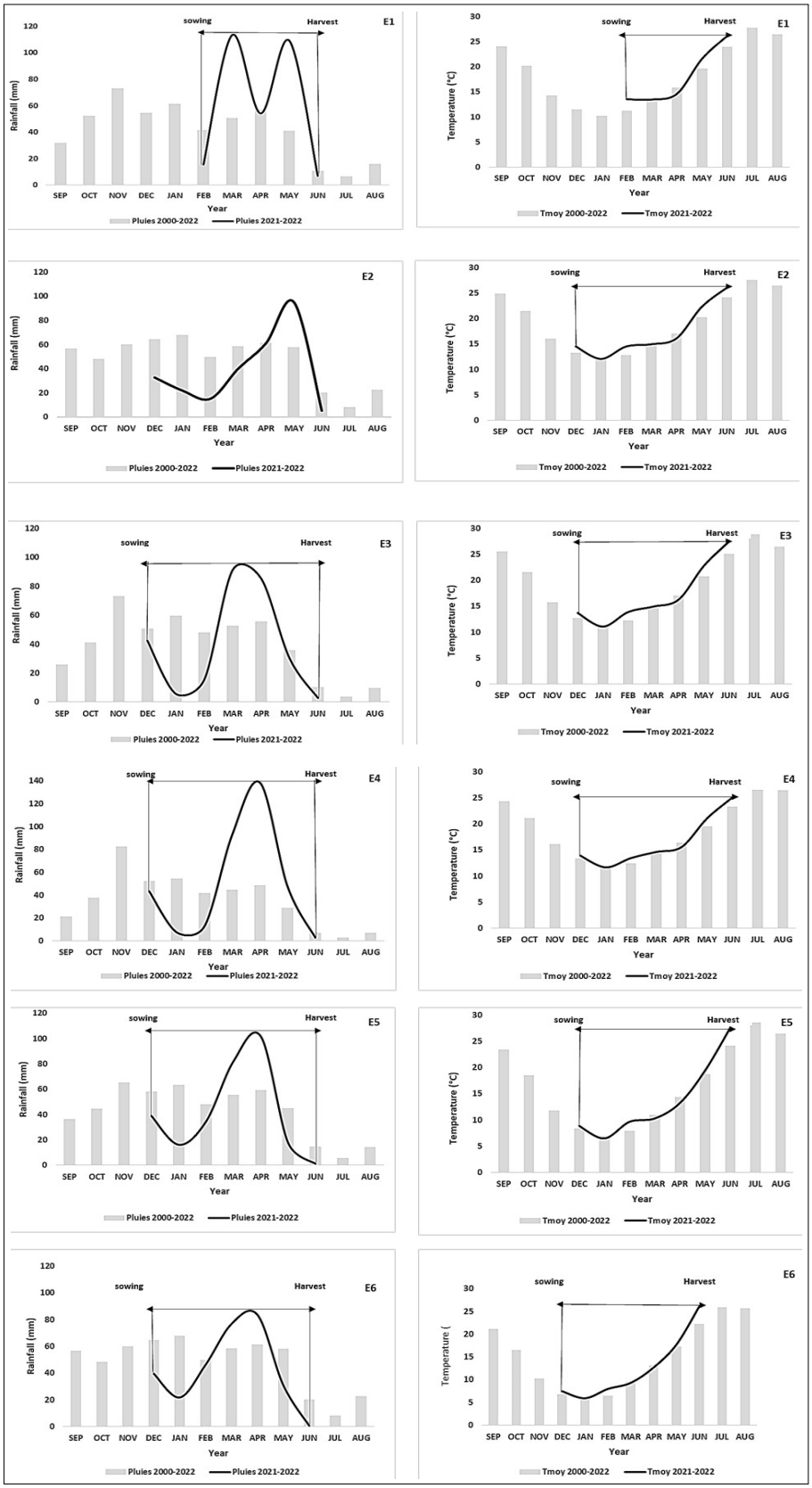


Fig 2: Monthly temperatures and precipitation over the 2021-2022 growing season and inter annual monthly mean values recorded over the period 2000-2022 at the six environments (E1 to E6).

The results indicate that the selection method influences the genetic response of the lines depending on the environment, emphasizing the importance of evaluating varieties under diverse conditions to fully capture their potential.

AMMI and GGE analyses and multivariate exploration of yield stability and genotype × environment interaction

Analysis of variance (Table 5) revealed significant effects of genotype and environment, as well as a highly significant

Table 3: Analysis of variance (ANOVA) for grain yield (t ha^{-1}) of ten varieties corresponding to three selection types across six environments, with hierarchical mean comparison using the LSD test.

Nature of breeding pathway	Varieties	Environment				
		E2	E3	E4	E5	E6
Local varieties (LV)	G1	0.92^{cde}	0.59^{d}	1.83^{c}	1.64^{a}	0.74^{d}
	G2	0.74^{de}	1.01^{bc}	2.31^{bc}	1.43^{ab}	1^{bcd}
	G3	1.36^{abc}	1.13^{ab}	1.86^{c}	0.90^{bcd}	1.33^{ab}
	Mean	1.01^{b}	0.91^{b}	2.00	1.33^{a}	1.02^{b}
Participative selection varieties (PS)	G4	1.19^{abcd}	0.87^{bcd}	2.15^{bc}	1.20^{abc}	1.42^{a}
	G5	1.27^{abc}	1.47^{a}	0.89^{d}	1.20^{abc}	1.16^{abc}
	G6	1.50^{ab}	1.08^{abc}	3.15^{a}	0.84^{cd}	1.24^{ab}
	Mean	1.32^{a}	1.14^{a}	2.07	1.08^{ab}	1.27^{a}
Introduced varieties (IV)	G7	1.01^{bcde}	0.73^{cd}	1.93^{c}	1.08^{abcd}	1.05^{abcd}
	G8	1.68^{a}	0.98^{bcd}	2.16^{bc}	0.94^{bcd}	0.97^{bcd}
	G9	0.66^{e}	1.28^{ab}	2.44^{abc}	0.77^{cd}	0.83^{cd}
	G10	0.73^{de}	0.96^{bcd}	2.97^{ab}	0.57^{d}	1.00^{abcd}
	Mean	1.02^{b}	0.99^{ab}	2.38	0.85^{b}	0.96^{b}
LSD (P<0.05)_type of selection		***	*	NS	*	*
LSD (P<0.05)_varieties		***	**	***	**	**
Total mean		1.11	1.01	2.18	1.08	1.08

*P<0.05, **P<0.01 and*** P<0.001, NS: Not significant; LSD: Least significant difference.

Table 4: Analysis of variance morpho-agronomic traits of three breeding pathways (ten chickpea varieties) across six environments.

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-test
Line	**Plant height (cm)**			
Breeding pathways (BP)	2	243.31	121.66	***
Environment (E)	5	2134.33	426.87	***
BP × E	10	498.43	49.84	***
Trait	**Number of primary branches**			
Breeding pathways (BP)	2	1.45	0.72	*
Environment (E)	5	15.32	3	***
BP × E	10	2.97	0.29	NS
Line	**Stem length to the first pod (cm)**			
Breeding pathways (BP)	2	239.82	119.91	***
Environment (E)	5	1831.77	366.35	***
BP × E	10	167.8	16.78	**
Trait	**100-seed weight (g)**			
Breeding pathways (BP)	2	5686.5	2843.24	***
Environment (E)	5	2457	491.4	***
BP × E	10	2055	205.5	***
Line	**Grain yield (t.ha^{-1})**			
Breeding pathways (BP)	2	0.27	0.13	NS
Environment (E)	5	26.08	5.21	***
BP × E	10	3.24	0.32	*
Trait	**Harvest index**			
Breeding pathways (BP)	2	0.00893	0.004466	NS
Environment (E)	5	0.48	0.096822	***
BP × E	10	0.4	0.040322	***

*P<0.05,**P<0.01,***P<0.001 significance.

G×E interaction. The first principal component (PC1) explained 60.3% of the interaction variance, reflecting a clear environmental gradient and well-structured response.

The AMMI analysis identified G6-PS, G8-IV and G2-LV as the most productive varieties. G8-IV, G4-PS and G7-LV exhibited the highest stability values (Table 6). Considering both high yield and low instability, the introduced variety G8-IV emerged as the best-performing and most broadly adapted genotype, followed by G4-PS and G2-LV.

Regarding environments, E4 was clearly separated along the negative side of PC1, reflecting specific conditions highlighting the performance of certain varieties (Fig 3). E2, E5 and E6 were positioned on the positive side of PC1, representing moderately differentiated environments favorable to other genotypic profiles. E1 and E3, near the center of PC1, generated fewer G×E interactions and represented average environmental conditions.

The nominal stability plot (Fig 4) provided complementary insight: varieties with steep slopes (G6-PS, G10-IV, G5-PS) exhibited strong specific interactions, whereas G8-IV, G2-LV and G4-PS displayed more regular responses indicative of stability.

Fig 4 also highlighted significant environmental differences. E4 generated pronounced variation among varieties, reflecting strong specific interactions, while E1 and E3 elicited more homogeneous responses, identifying them as reference environments. E2, E5 and E6 showed intermediate structuring, differentiating certain varieties while maintaining overall consistency.

Finally, the GGE biplot (Fig 5) illustrated environmental structure. E5, with a long vector, was the most discriminating environment.

The evaluation of performance and stability of chickpea genotypes derived from different selection methods under contrasting environments is essential for identifying varieties with high resilience potential. AMMI and GGE biplot analyses proved effective in characterizing genotype × environment (G×E) interactions, facilitating the selection of varieties that combine high productivity and stability, key traits for adaptation to semi-arid conditions with increasingly irregular and limited rainfall. Environmental factors accounted for the largest portion of variation (over 25% of total variation), followed by G×E interactions and genotypic differences, a pattern reported in recent studies (Istanbuli *et al*., 2025; Eskezia *et al*., 2025). This confirms the predominant influence of the environment on chickpea grain yield, with GEI playing a secondary but significant role. These findings align with Din *et al*. (2024), who emphasized the contribution of both environmental and G×E effects to the stability and adaptation of Desichickpeagenotypes.

The contrasting performance of both homogeneous and heterogeneous varieties across environments suggests that stability is not solely determined by genetic background. Local varieties, often heterogeneous and co-

Table 5: Analysis of variance of main effect and genotype × environment interactions for chickpea grain yield (t-ha-^{1}).

Source of variation	Degrees of freedom (df)	Sum of squares (SS)	Mean squares (MS)	F value (F)	Probability (>F)	Proportion (%)
ENV	5	92.52	18.50	63.77	***	-
REP(ENV)	12	3.48	0.29	0.75	NS	-
GEN	9	7.51	0.83	2.18	*	-
GEN:ENV	45	57.18	1.27	3.32	***	-
PC1	13	11.48	0.88	2.31	**	60.3
Residuals	468	178.87	0.38	-	-	-
Total	584	358.63	0.61	-	-	-

*P<0.05, **P<0.01 and ***P<0.001, NS: Not significant; LSD: Least significant difference; ENV: Environment; GEN: Genotype (variety).

Table 6: Mean chickpea grain yield and AMMI analysis of the ten varieties tested across six environments.

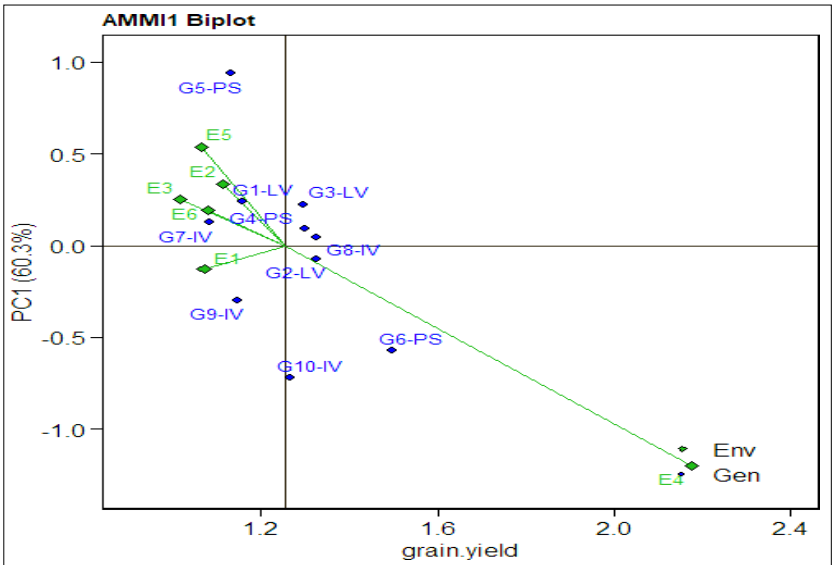
Varieties	Type of selection	Mean grain yield (t.ha^{-1})	ASV	rASV	YSI	rYSI	GSI
G8	IV	1.32	0.30	2	4	2	4
G4	PS	1.29	0.27	1	5	4	5
G2	LV	1.32	0.58	4	7	3	7
G6	PS	1.49	1.72	8	9	1	9
G3	LV	1.29	0.73	5	10	5	10
G7	IV	1.08	0.37	3	13	10	13
G1	LV	1.15	0.99	7	14	7	14
G9	IV	1.14	0.88	6	14	8	14
G10	IV	1.26	2.13	9	15	6	15
G5	PS	1.12	2.79	10	19	9	19

ASV: AMMI stability value; rASV: Rank of each genotype according to AMMI stability value; YSI: Yield stability index; rYSI: Rank of each genotype according to yield stability index; GSI: Genotype stability index.

adapted, continue to evolve under local conditions, whereas introduced varieties, developed through intensive breeding in foreign environments, display distinct morphological and agronomic traits.

The analysis across six experimental sites confirmed significant genetic variability and underscored the importance of G×E interactions in chickpea agronomic performance (Jagan *et al*., 2023; Ligarreto-Moreno and Pimentel-Ladino, 2022). Environments E1, E4 and E5 were the most discriminating, but only E4 and E5 displayed high productive potential, supporting the relevance of current chickpea zoning and multi-location breeding strategies (Pérez *et al*., 2005). This highlights the need to consider agro-climatic specificity rather than generalizing performance across apparently similar zones (Srivastava *et al*., 2024).

Contrary to commonassumptions, varieties introduced through international programs such as ICARDA are not inherently less plastic than local varieties. For instance, G8 (FLIP 93-93C, Ghab 4), selected in the WANA region, exhibited both high yield and stability, confirming its adaptation to Algeria's diverse semi-arid conditions. This observation agreeswith Meddi *et al*. (2010); Annicchiarico (2017) and Dhuria and Babbar (2019), demonstrating that varieties developed for Mediterranean arid zones can combine high yield potential with broad adaptation. Similarly, the locally participatory-selected variety G4 displayed substantial plasticity across environments,



The different G represent the different varieties (see Table 1). E1 to E6 indicate the six environments identified by the AFM; Env: Environment; Gen: Genotypes (varieties).

Fig 3: AMMI1 biplot for 10 chickpea varieties across six environments for grain yield.

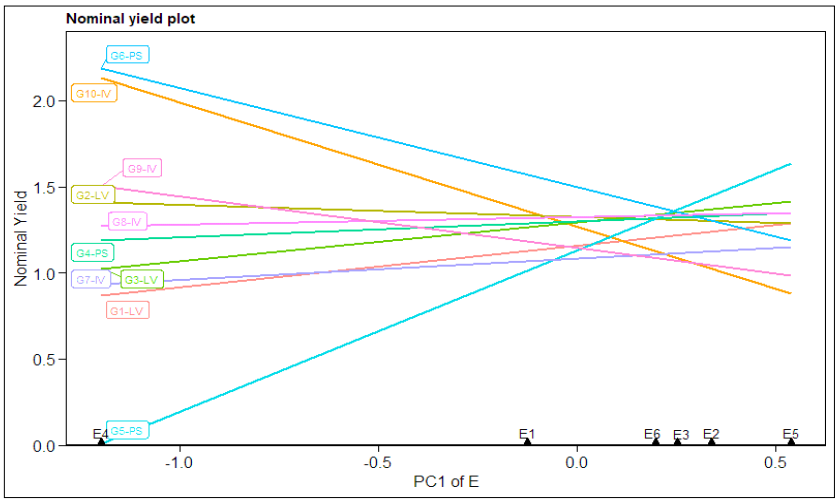


Fig 4: Nominal yield plot based on AMMI1 scores and mean grain yield of chickpea varieties.

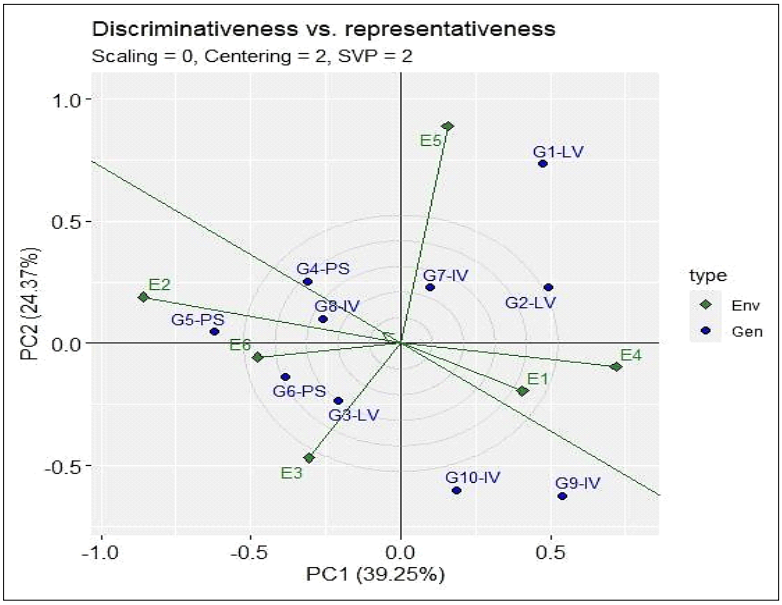


Fig 5: PCA Biplot of grain yield performance of ten chickpea varieties across six environments.

challenging the traditional dichotomy between plastic local varieties and specialized improved varieties.

Selecting genotypes such as G8-IV, G4-PS and G2-LV, which perform stably across most environments, provides a strong foundation for breeding broadly adapted varieties. These genotypes represent valuable resources for addressing climate change challenges, including drought, salinity and increasing precipitation variability (Bessah *et al*., 2023; Djellouli and Laborde, 2022; Khoshro and Maleki, 2025).

Joint AMMI and GGE analyses revealed that no single site encompassed the full range of constraints and opportunities in semi-arid zones. Environments E5 and E4 proved strategic for selection, offering a balanced compromise between experimental efficiency and representativeness by capturing both general and specific adaptations of chickpea varieties (Yan and Rajcan, 2002). Other sites showing redundancy or low discriminatory power could be excluded in an optimized experimental design (Gauch and Zobel, 1997).

CONCLUSION

Promising candidates, G8-IV, G4-PS and G2-LV, appear to be for direct use by farmers or breeding stocks in selection programmes. Their contrasting profiles, derived from different breeding methods, underscore the importance of diversifying the genetic sources for chickpea breeding. Multi-environment analysis showed that the E5 and E4 environments are particularly informative for breeding. These elements reinforce the relevance of flexible agro-ecological zoning for chickpeas in Algeria, enabling breeding to be oriented towards greater resilience of farming systems in the face of climatic variability.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All the experimental procedures and handling techniques were approved by the National Higher School of Agronomy (ENSA), Laboratory of Integrated Improvement of Plant Production.

Conflict of interest

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