GMR
The Original by FUNPEC-RP

Adaptability and stability parameters for grain production in pigeonpea lines in the Brazilian semiarid region

A.E. da S. Costa[1] and C.A.F. Santos[2]

[1] Programa de Pós-Graduação em Agronomia, Melhoramento Genético de Plantas, Universidade Federal Rural de Pernambuco, Recife, PE, Brasil
[2] Embrapa Semiárido, Petrolina, PE, Brasil

Corresponding author: C.A.F. Santos
E-mail: carlos-fernandes.santos@embrapa.br

Genet. Mol. Res. 21 (4): gmr19066
Received May 24, 2022
Accepted September 19, 2022
Published October 25, 2022
DOI http://dx.doi.org/10.4238/gmr19066

ABSTRACT. Pigeonpea is a multipurpose species and can be used for grain, forage production, and as a soil improver. In Brazil, the scarcity of productive cultivars adapted to various growing conditions contribute to the underutilization of this legume crop. The genotype × environment (G×E) interaction is one of the main challenges to the development and recommendation of cultivars. Estimates of adaptability and stability parameters make it possible to predict the behavior and effects of the G×E interaction to reduce possible inconsistencies in cultivar recommendation. From this perspective, we assessed the adaptability and stability parameters for grain yield of 21 pigeonpea lines developed in the breeding program of this pulse at Embrapa Semiárido, Petrolina, PE, Brazil, and the variety 'guandu Petrolina' (control), in order to recommend new cultivars for general use. The genotypes were evaluated in eight environments, with experiments conducted in five irrigated and three rainfed environments using a randomized complete block design with three replications. Grain yield was corrected by covariance based on the average plant stand. The Eberhart and Russel, AMMI, and GGE Biplot methods were used in this study. The coefficient of variation for the experiments was 12.41%, with data transformed to square root. The effects of genotypes, the environments, and the genotype-by-environment interaction were highly significant ($p < 0.01$). The mean grain yield of the genotypes was 1,516 kg ha^{-1}. Lines 87, 100, and 158 simultaneously showed wide adaptability and good predictability according to the three methods, with mean yields of 1,530, 1,701, and 1,812 kg ha^{-1}, respectively, and reaching yields of up to 2,725, 2,928, and 2,955 kg ha^{-1} in some environments. These lines are indicated for recommendation as new pigeonpea cultivars for the semi-arid region of Brazil.

Key words: AMMI; *Cajanus cajan*; Eberhart and Russell; GGE biplot; G×E interaction; Multi-environment trials

INTRODUCTION

A species of Indian origin (Fuller and Harvey, 2006), the pigeonpea (*Cajanus cajan*) is an important source of protein for populations of low-income countries (Waldman et al., 2017). However, the low yield of this crop is the main challenge for producers in order to meet the ever-growing demand for grains (Bohra et al., 2020). Therefore, the development of high-yield pigeonpea cultivars is the objective of breeding programs conducted by institutions of different countries, such as India, the main producer and consumer (Muñoz et al., 2017). Pigeonpea is a crop with the potential for diversifying grain and forage production systems, especially in semi-arid areas of Brazil (Santos et al., 2000).

The possible superiority of new genotypes in relation to those already cultivated for commercial purposes is assessed in competition field trials, based on the responses of genotypes to diversified environments, a phenomenon known as genotype x environment interaction (G×E) (Piepho, 1996). According to Cruz et al. (2012), in order to minimize the effects of the G×E interaction, it is essential to identify genotypes with predictable behavior (stability) and satisfactory responses to environmental variations under specific and general conditions (adaptability).

In this scenario, several methods are commonly used to study adaptability and stability, classified according to the statistical approach employed, e.g., methods based on analysis of variance, regression, non-parametric tests, and multivariate analysis (Bornhofen et al., 2017). Methods based on regression analysis have been usually adopted in adaptability and stability studies with pigeonpea genotypes, e.g., Eberhart and Russell (1966), in addition to multivariate methods, including AMMI (Zobel et al., 1988) and GGE biplot (Yan et al., 2000). The AMMI and GGE Biplot methods were used by Yohane et al. (2021) to study the adaptability and stability of 81 pigeonpea genotypes evaluated in three environments in Malawi over two crop seasons, from which the authors selected five for recommendation as cultivars. Reddy et al. (2011) evaluated ten pigeonpea genotypes over three years under rainfed conditions using the Eberhart and Russell method to select those with good stability for grain yield, number of pods, and seed size. In another study, Kumar et al. (2021) recommended two out of 28 genotypes evaluated under rainfed conditions in ten locations using AMMI and GGE biplot analyses.

There are no published adaptability and stability studies in Brazil on pigeonpea lines developed by local breeding programs. According to Santos et al. (2000) pigeonpea is a species with appropriate characteristics and potential for cultivation in semi-arid areas of Brazil due to its resilience to soil fertility limitations and water stress, although cultivated in limited areas in the states of Bahia, Pernambuco, and Ceará. The development of pigeon pea cultivars with good yield performance, wide adaptability, and good stability, in addition to early harvesting, can contribute to expanding its cultivation to producing regions beyond those already present in the Brazilian semi-arid.

From this perspective, we examined the adaptability and stability parameters for grain yield in 21 pigeonpea lines using three methods through experiments conducted in five irrigated and three rainfed environments in order to recommend and release new cultivars of this legume for the semi-arid region of Brazil.

MATERIAL AND METHODS

Plant material and evaluation environments

Twenty-two pigeonpea genotypes were evaluated, comprising 21 lines developed by the breeding program of Embrapa Semiárido and the control cultivar ‘guandu Petrolina’,, recommended by the same institution. In Petrolina, PE, Brazil and Juazeiro, BA, Brazil six experiments were conducted at the experimental fields Caatinga (CEC) and Mandacaru (CEM), respectively. Four experiments were carried out in irrigated environments with sowing in October 2019 (CEC I and CEM I) and October 2021 (CECIII and CEM III), and two were carried out in a rainfed regime (CEC II and CEM II), with sowing in February 2020 (Table 1). Two experiments were carried out in the Experimental Field of Barbalha da Embrapa Algodão (CEB) in Barbalha, CE, Brazil, the first under irrigated conditions and sowing in October 2019 (CEB I), and the second under rainfed conditions with sowing in February 2019 (CEB II) (Table 1). Each experiment was considered as an independent environment. Both municipalities are located in the northeastern semi-arid region.The experiments were set up in plots with two planting rows measuring 2.4 x 2.5 m, between-row spacing of 1.2 m, and between-plant spacing of 0.5 m, with two plants per hole and a randomized complete block design with three replications. The plants were irrigated only in the second semester and received crop management practices whenever necessary during the experiment (Saxena et al., 2019). None of the environments received fertilizers.

Table 1. Locations, sowing dates, elevation, latitude, longitude, mean grain yield ($\bar{Y}_{\mathrm{i}}$), degrees of freedom of the residuals (DF_R), coefficients of variation (CV), and mean square of the residuals MS_R in experiments with 21 pigeonpea lines plus the control variety ‘guandu Petrolina’ conducted at the Barbalha Experimental Field (CEB), Barbalha, CE, Brazil; Caatinga Experimental Field (CEC), Petrolina, PE, Brazil; and Mandacaru Experimental Field (CEM), Juazeiro, BA, Brazil.

Environments	Locations	Sowing	Elevation (m)	Latitude (S)	Longitude (W)	$\bar{Y}_j$ kg ha^{-1}	DF$_R$	Coefficient of variation		MS$_R$	
								Original	Transformed*	Original	Transformed *
1	CEB I^1	October 17, 2019	402	07º17'	39º16'	1,648	38	18.79	9.79	97,423.04	15.28
2	CEB II^2	February 7, 2020	388	07º17'	39º16'	1,804	37	19.48	10.32	122,131.64	18.55
3	CEC I^1	October 9, 2019	376	09º04'	40º19'	954	33	35.73	19.84	115,560.41	34.47
4	CEC II^2	February 7, 2020	376	09º04'	40º19'	720	36	17.49	8.88	15,898.42	5.61
5	CEC III^1	October, 28, 2021	376	09º04'	40º19'	2,586	36	20.91	10.9	281,545.39	29.43
6	CEM I^1	October 3, 2019	379	09º23'	40º24'	2,097	36	19.9	9.72	175,871.02	19.14
7	CEM II^2	February 11, 2020	379	09º23'	40º24'	278	31	75.96	34.42	42,844.08	28.70
8	CEM III^1	November 11, 2021	379	09º23'	40º24'	2,043	36	19.76	9.6	165,296.51	18.73
Mean						1,516					

* Square root transformation; ^{1}Experiment conducted under irrigated conditions; ^{2}Experiment conducted under rainfed conditions.

Variables measured and analyses of variance for grain yield

Manual harvest was performed after at least 50% of the pods reached maturity, with a brownish color typical of mature pods. The harvest was divided into two moments, the first after the mentioned stage, and the second harvest 20 days later. The days to maturity were counted from sowing. Plant height at maturity was measured from the base of the plant to the tip of the main stem. To determine the grain production, the pods were harvested and processed with subsequent weighing of the seeds per plot.

After verifying that there was no significant effect for the final stand by the F test at 1% probability, grain yield (kg ha^{-1}) per plot in each experiment was adjusted by the covariance method considering the average plant stand of each experiment according to the statistical procedure described by Vencovsky and Barriga (1992) and using a script developed for the SAS PROC GLM procedure of SAS (Statistical Analysis System, v.9.4, Cary, NC).

Yield data were submitted to analysis of variance, an individual analysis was initially performed, followed by a joint analysis after assessing the homogeneity of residual variances of the experiments (MS_R), considering the ratio between the highest and lowest MS_R values. In the presence of heteroscedasticity, the data were transformed to square root ($\sqrt{x}$). For the joint analysis, the effects of the genotypes were considered fixed, while those related to the environment were considered random. All analyses were performed using the SAS PROC GLM procedure and the Lsmeans option (Statistical Analysis System, v.9.4, Cary, NC).

Adaptability and stability analyses

The adaptability and stability analyses were performed by the following methods: 1) regression model of Eberhart and Russell (1966); 2) AMMI (additive main effects and multiplicative interaction (Zobel et al., 1988); and 3) GGE biplot (genotype and genotype-environment interaction) (Yan et al., 2000) through the site regression model or SREG according to the model of Burgueño et al. (2003).

In the model proposed by Eberhart and Russell the parameters are classified according to the regression coefficient: β_{1i}=1 means that the genotype has wide adaptability, $\beta_{1i} > 1$ implies adaptability to favorable environments, and $\beta_{1i} < 1$ means adaptability to unfavorable environments. The variance of the regression deviations $\delta_{ij} = 0$ defines a stable genotype. This analysis was performed with the statistical software Genes (Cruz 2013).

In the graphic representation generated by the model of the AMMI methods (Zobel et al., 1988), AMMI1, the abscissa axis represents the main effects, i.e., those referring to the means of the genotypes and environments, whereas the ordinates express the scores of the genotypes and environments referring to the first component of the interaction, IPCA1. The genotypes and environments with lower scores are the most stable since they show a lower contribution to the interaction. On the other hand, adaptability is evaluated by observing the scores for each pair of genotypes and environments: genotypes and environments whose scores have the same sign tend to interact positively, an indicative aspect to be used in selection. In contrast, pairs of genotypes and environments with opposite signs should interact negatively, indicating an unfavorable combination between genotype and environment (Duarte and Vencovsky, 1999). The graphic representations obtained result in the mean × IPCA1 graphic (AMMI1), which indicates the contribution of each genotype and environment to the interaction, and a second graph, in which only the effects of the IPCA1 × IPCA2 interaction are considered (AMMI2). In that case, the most stable genotypes and environments are located close to the origin of the IPCA2 axis (Duarte and Vencovsky, 1999).

For the analyses by the GGE biplot method, the SREGs or regression sites were estimated using the software SAS (Statistical Analysis System, v.9.4, Cary, NC) according to the procedures proposed by Vargas-Hernandez and Crossa (2000) and modified by Burgueño et al. (2003). The interpretation of the graphic representation of the GGE biplot model is similar to that of the AMMI model: genotypes and environments close to the origins of the IPCA2 axis are the most stable (Yan et., 2000). The difference between the two methods lies in the early stage of analysis since the GGE Biplot model directly analyzes the effect of the genotype plus the effect of the G×E interaction, whereas the AMMI separates G from the G×E interaction to join them again in the final stage of analysis, forming the biplot graphs.

RESULTS AND DISCUSSION

The transformation to square root effectively eliminated heteroscedasticity, reducing the ratio between the highest and the lowest mean square of residuals from 17.71 in the analysis with original data to 6.14 in the analysis with transformed data (Table 1). The variances are considered homogeneous when the ratio is lower than 7.0 (Cruz et al., 2012). The genotypes (G), environments (E), and the G×E interaction were highly significant by the F-test ($P < 0.01$) in the joint analysis of variance for grain yield data (Table 2). The genotypes × environments interaction is one of the main complicators for the selection phase and the recommendation of cultivars. From this perspective, adaptability and stability studies are alternatives to mitigate or take advantage of interaction effects (Cruz et al., 2012). This stage is especially important for improving quantitative and complex traits, e.g., grain yield.

The mean yield of the genotypes was 1,516 kg ha^{-1}, ranging from 278 kg ha^{-1} in the rainfed environment Mandacaru (CEM II) to 2,586 kg ha^{-1} in the irrigated environment Petrolina (CEC III), (Table 1). The coefficient of variation of the experiments was 12.41%, with data transformed to square root. The highest mean yield was achieved by genotype 106, with 1,916 kg ha^{-1}, whereas the lowest yield was achieved with the control treatment, ‘guandu Petrolina’, with 1,016 kg ha^{-1} (Table 2).

Mean plant height was 141 cm, ranging from 96 cm in line 126 to 175 cm in line 45 (Table 2). In lines 126 and 130, the height was lower than 100 cm; genotypes 159, 90, 184, and ‘guandu Petrolina’ showed mean heights lower than 130 cm; 12 lines (110, 129, 96, 106, 179, 87, 162, 102, 182, 183, 158, and 100) showed heights of up to 160 cm. In contrast, lines 181, 190, 186, and 45 showed values higher than 166 cm. The average number of days to the first harvest was 128 days: 13 lines showed maturity before this period, ranging from 118 days in line 129 to 127 days in line 87. Lines 159, 186, 179, ‘guandu Petrolina’, 45, 181, 182, and 190 showed values above the overall mean, ranging from 129 to 151 days to at least 50% pod maturity.

Table 2. Parents and estimates of the stability and adaptability parameters for grain yield and joint ANOVA for 21 pigeonpea lines plus the control variety ‘guandu Petrolina’, evaluated in eight environments, three rainfed and five irrigated using the Eberhart and Russell method.

Treatment	Parents	Mean (kg ha^{-1})	β_{1i}	σd_{ii}	R^2	NDF (days)	PH (cm)
183	ICPL900053 × Anagé	1,590	0.93^{NS}	14.65^{**}	86.43	124	150
162	ICPL89027 × D3 Type	1,609	0.81^{*}	8.46^{*}	87.04	122	147
190	UW 10 × D3 Type	1,517	0.88^{NS}	82.80^{**}	57.43	151	169
130	ICPL89027 × UW 10	1,413	1.02^{NS}	2.26^{NS}	94.71	122	99
110	ICPL90045 × UW 10	1,218	0.81^{*}	27.54^{**}	75.00	122	134
181	ICPL900053 × Anagé	1,916	1.56^{**}	67.14^{**}	83.83	138	166
106	ICPL90045 × UW 10	1,871	1.11^{NS}	17.67^{**}	88.84	126	143
186	ICPL900053 × Anagé	1,455	1.00^{NS}	24.81^{**}	83.31	132	172
100	ICPL90045 × ICPL89027	1,701	1.05^{NS}	8.94^{*}	91.63	124	153
179	ICPL900053 × Anagé	1,521	1.21^{*}	18.26^{**}	90.11	132	145
96	ICPL90045 × ICPL89027	1,728	0.82^{*}	37.72^{**}	70.32	126	140
87	ICPL90053 × D2 Type	1,530	1.15^{NS}	-3.62^{NS}	98.41	127	147
126	ICPL89027 × UW 10	1,334	0.77^{**}	5.06^{NS}	88.48	122	96
129	ICPL89027 × UW 10	1,095	0.92^{NS}	45.86^{**}	71.47	118	135
159	ICPL89027 × D3 Type	1,352	0.81^{*}	26.84^{**}	75.31	131	109
90	ICPL90053 × D3 Type	1,523	1.15^{NS}	-0.47^{NS}	96.96	129	120
182	ICPL900053 × Anagé	1,715	0.94^{NS}	28.61^{**}	79.54	139	149
184	ICPL900053 × Anagé	1,464	0.97^{NS}	3.53^{NS}	93.41	122	129
158	ICPL89027 × D3 Type	1,812	1.14^{NS}	17.05^{**}	89.46	124	151
102	ICPL90045 × ICPL89027	1,583	1.15^{NS}	24.14^{**}	87.07	124	148
45	ICPL89020 × D3 Type	1,396	0.97^{NS}	113.8^{**}	55.05	133	175
‘Guandu Petrolina'	UW 10	1,016	0.85^{NS}	70.43^{**}	59.33	132	130
Mean		1,516				128	141
CV (%)		12.41					
MS Block		156.16^{*}					
MS Genotypes (G)		182.32^{**}					
MS Environments (E)		$7,436.22^{**}$					
MS G×E		91.51^{**}					
MS Residual		21.03					

Significance level by the F-test: * = $P < 0.01$, ** = $P < 0.05$, and NS = $P > 0.05$; NDF: number of days to the first harvest; PH: plant height; CV: coefficient of variation; MS: mean square

Eberhart and Russell method

The regression coefficients of 15 genotypes were statistically equal to 1, indicating wide adaptability (Table 2). For stability, five of the evaluated genotypes were classified with high predictability ($\sigma^2_{di} = 0$) (Table 2). Four genotypes were classified concomitantly with wide adaptability and good stability: 130, 87, 90, and 184 (Table 2), of which 87 and 90 also had yields higher than the overall mean of the experiments, with 1,516 kg ha^{-1}. Lines 100 and 158, despite $\sigma^2_{di} \neq 0$, showed $R^2 \geq 90\%$ (Table 2), with this parameter indicating good yield stability in the tested environments. According to Cruz et al. (2012) these lines should not be discarded as with low stability since the R^2 can be used for additional inference in genotype stability, which, when ≥ 90%, indicates good stability even with a significant σ^2_{di}. Of these four lines, 158, 87, and 100 were classified among the ten most productive lines. Through this method, the agreement between good yield performance and stability was low. However, it was high for adaptability since, among the 12 lines with above-average yield performance, nine showed wide adaptation to the evaluated environments (Table 2). Using this method, Reddy et al. (2011) reported the occurrence of pigeonpea genotypes with wide adaptability and good stability among high-yield genotypes, differing from the results of the present study.

Genotypes 181 and 179 were classified as adapted to favorable environments, $\beta_{1i}>1$, with unpredictable behavior, $\sigma^2_{di}\neq 0$ (Table 2). The parameters of genotypes 162, 110, 96, 126, and 159 indicate adaptability to unfavorable environments, $\beta_{1i}<1$, and unpredictability in the tested environments, $\sigma^2_{di}\neq 0$, except genotype 126. Genotypes 183, 190, 106, 186, 100, 129, 182, 158, 102, 45, and 'guandu Petrolina' showed unpredictability in the tested environments, $\sigma^2_{di}\neq 0$, despite their wide adaptability, $\beta_{1i}=1$.

Although the method of Eberhart and Russell is widely used, according to Scapim et al. (2000) it shows some limitations, e.g., the fact that the mean of all cultivars in each environment is taken as a measure of the environmental index and used as an independent variable in the regression. Therefore, there is no independence between variables, especially when working with a few cultivars (under 15). Another limitation highlighted by these authors lies in the variation of the regression coefficient estimates, which is usually low and complicates the classification of the genotype for stability and adaptability. Therefore, this analysis is more reliable to analyze studies that involve a few environments with low or high performance since the adjustment of the genotype can be broadly determined by its performance in some extreme environments, producing misleading results (Fasahat et al., 2015).

AMMI method

In the AMMI analysis, the contributions of the first two principal axes, IPCA1 and IPCA2, were significant ($P < 0.05$) (Table 3). The patterns associated with the interaction, explained by the IPCA1 and IPCA2 axes, correspond to 32.47% and 26.99%, respectively, with a cumulative contribution of 59.46% for the G×E interaction (Table 3).

Table 3. Stability and adaptability according to the AMMI method and result of the Gollob test for the SREG analysis (GGE biplot), with the interaction rate for each main axis for 21 pigeonpea genotypes and the control variety 'guandu Petrolina' evaluated in eight environments, three rainfed and fiver under irrigated conditions.

AMMI	**Eigenvalues**			
	%Explained	**%Cumulative**	**DF**	**MS**
IPCA1	32.47	32.47	27.00	65.54^{*}
IPCA2	26.99	59.46	25.00	58.84^{*}
IPCA3	18.47	77.93	23.00	43.79^{NS}
IPCA4	13.17	91.10	21.00	34.17^{NS}
IPCA5	4.59	95.69	19.00	13.17^{NS}
IPCA6	3.06	98.75	17.00	9.81^{NS}
IPCA7	1.25	100.00	15.00	4.53^{NS}
GGE BIPLOT				
IPCA1	39.17	39.17	27.00	301.55^{**}
IPCA2	21.28	60.45	25.00	176.97^{**}
IPCA3	16.90	77.35	23.00	152.75^{**}
IPCA4	11.26	88.61	21.00	111.41^{**}
IPCA5	4.93	93.54	19.00	53.92^{**}
IPCA6	3.52	97.05	17.00	43.00^{**}
IPCA7	2.23	99.28	15.00	30.90^{NS}
IPCA8	0.72	100.00	13.00	11.48^{NS}

Significance level by the F-test: * = $P < 0.01$, ** = $P < 0.05$, and NS = $P > 0.05$; DF: degrees of freedom; MS: sum of squares

The Mandacaru 3 environment showed the lowest contribution to the G×E interaction, followed by the Mandacaru 2 and Caatinga 1 environments (Figure 1A). The genotypes that least contributed to the interaction were 87, 183, 126, and 186, the last two with mean yields lower than 1,500 kg ha^{-1}. Conversely, genotypes 183 and 87 stood out with the eighth and tenth highest mean values, 1,590 and 1,530 kg ha^{-1}, respectively.

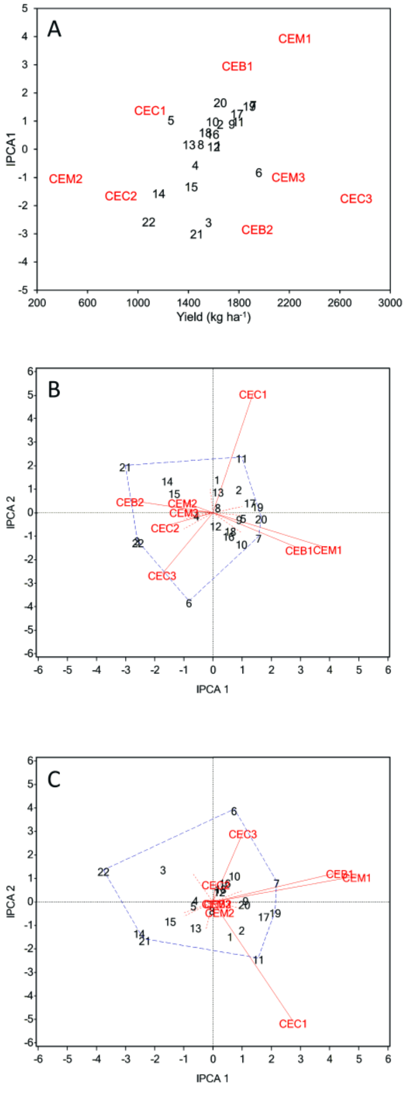

Figure 1. AMMI biplot using the means the first two principal component (A), and the first two principal components corresponding (B) and GGE biplot (C) corresponding to 21 pigeonpea genotypes plus the control variety ‘guandu Petrolina’ evaluated for grain yield in eight environments. Treatments: 1= 183, 2= 162, 3= 190, 4= 130, 5= 110, 6= 181, 7= 106, 8= 186, 9= 100, 10= 179, 11= 96, 12= 87, 13= 126, 14= 129, 15= 159, 16= 90, 17= 182, 18= 184, 19= 158, 20= 102, 21= 45, and 22= guandu Petrolina. Tested environments: Experimental Field of Embrapa Algodão in Barbalha, CE, Brazil: CEB1 (irrigated) and CEB2 (rainfed); Caatinga Experimental Field of Embrapa Semiárido in Petrolina, PE, Brazil CEC1 (irrigated), CEC2 (rainfed), and CEC3 (irrigated); and Mandacaru Experimental Field of Embrapa in Juazeiro, BA, Brazil: CEM1 (irrigated), CEM2 (rainfed), and CEM3 (irrigated).

In the second AMMI graph (Figure 1B), considering only the effects of the interaction, the IPCA1 × IPCA2 representation retained 59.46% of the sum of squares, confirming the stabilities of genotypes 186 and 87, especially the first one. Good predictability was also confirmed for the Mandacaru 3 environment, followed by Mandacaru 2 and Caatinga 2.

Among the ten most productive genotypes (Table 2), 102, 100, 158, 182, and 87 were the most stable in this analysis (Figure 1B). With the best yield, genotype 181 showed adaptability to the Caatinga 3 environment, whereas genotype 106, with the second-best productive performance, showed the best adaptability to the Barbalha 1 and Mandacaru 1 environments. Genotype 190 showed adaptability to the Caatinga 2 and Caatinga 3 environments and indicates adaptability to the Mandacaru 2 and 3 and Barbalha 2 environments, similar to genotype 159.

The genotypes that contributed the most to the interaction were 45, 190, ‘guandu Petrolina’, 102, and 129 (Figure 1A); consequently, these genotypes were the least stable according to the AMMI method (Figure 1B). With regard to the environments, those that most contributed to the interaction were the first trial conducted in Mandacaru, the two trials conducted in Barbalha, and the first trial conducted in Barbalha (Figures 1A and 1B).

GGE biplot analysis

The components were highly significant by the Gollob test ($P < 0.01$) for the first six axes, ICPA1, ICPA2, ICPA3, ICPA4, ICPA5, and ICPA6 (Table 3). According to the GGE biplot analysis, the ten genotypes with superior stability were 102, 110, 100, 130, 186, 158, 87, 182, 184, and 159. Considering the studied environments, the assays conducted in the Mandacaru 1 and 2 environments were the most stable, followed by Barbalha 2 and Caatinga 2 (Figure 1C).

The genotypes that most contributed to the G×E interaction by the GGE biplot analysis were 181, 96, 45, 190, 183, and ‘guandu Petrolina’ (Figure 1C), showing, therefore, lower predictability. The environments with the highest calculated vectors, indicating lower stability, were observed in the first and third trials conducted in the Caatinga, followed by the first trials conducted in Barbalha and Mandacaru (Figure 1C).

Among the ten lines with yields higher than the overall mean, lines 102, 100, 158, 87, and 182 were classified among those with greater stability, the same genotypes classified by the AMMI method, only differing for the classification of genotype 87, here with a stability value greater than 182. Although with lower yields than the overall mean, the other treatments with good predictability were lines 110, 130, 186, 184, and 159.

Comparison of parameters and line selection by the three methods

The selection of lines using the AMMI and GGE Biplot methods converged with the selection by the Eberhart and Russell method for lines 87, 100, and 158 (Table 4). Since it considers the main effects of the genotypes and the effect of the G×E interaction, SREG analysis is considered superior to the AMMI method, which estimates them as additive effects (Yan, 2000). SREG analysis incorporates the effect of the genotype and, in most cases, tends to be highly correlated with the scores of the first principal component, allowing the graphic evaluation of the effect of the genotype.

Table 4. Stability and adaptability, yield, number of days to the first harvest (NDF), and plant height (PH) of selected lines among 21 pigeonpea lines evaluated in eight environments according to the Eberhart and Russell, AMMI, and GGE biplot methods.

	Lines	**Yield (kg ha^{-1})**			**Eberhart and Russel**		**AMMI**		**GGE biplot**		**NDF**	**ALP**
		Mean	**Highest**	**Lowest**	**β_{1i}**	**σd_{ii}**	**IPCA1**	**IPCA2**	**IPCA1**	**IPCA2**	**(days)**	**(cm)**
Eberhart and Russel	158	1,812 $^{(3)}$	2,955 $^{(5)}$	240 $^{(10)}$	1.14$^{NS\,(11)}$	17.05$^{**\,(9)}$	1.53 $^{(16)}$	0.31 $^{(6)}$	2.13 $^{(5)}$	-0.40 $^{(6)}$	124 $^{(7)}$	151 $^{(17)}$
	100	1,701 $^{(6)}$	2,928 $^{(7)}$	396 $^{(5)}$	1.05$^{NS\,(5)}$	8.94$^{*\,(7)}$	0.89 $^{(10)}$	-0.23 $^{(4)}$	1.12 $^{(10)}$	0.12 $^{(3)}$	124 $^{(7)}$	153 $^{(18)}$
	87	1,530 $^{(10)}$	2,725 $^{(11)}$	187 $^{(14)}$	1.15$^{NS\,(14)}$	-3.62$^{NS\,(4)}$	0.09 $^{(1)}$	-0.49 $^{(8)}$	0.22 $^{(21)}$	0.49 $^{(7)}$	127 $^{(13)}$	147 $^{(12)}$
	90	1,523 $^{(11)}$	2,709 $^{(12)}$	138 $^{(16)}$	1.15$^{NS\,(12)}$	-0.47$^{NS\,(1)}$	0.53 $^{(5)}$	-0.94 $^{(11)}$	0.41 $^{(19)}$	0.86 $^{(11)}$	127 $^{(13)}$	147 $^{(12)}$
AMMI	158	1,812 $^{(3)}$	2,955 $^{(5)}$	240 $^{(10)}$	1.14$^{NS\,(11)}$	17.05$^{**\,(9)}$	1.53 $^{(16)}$	0.31 $^{(6)}$	2.13 $^{(5)}$	-0.40 $^{(6)}$	124 $^{(7)}$	151 $^{(17)}$
	182	1,715 $^{(5)}$	2,671 $^{(14)}$	306 $^{(9)}$	0.94$^{NS\,(6)}$	28.61$^{**\,(16)}$	1.26 $^{(14)}$	0.48 $^{(7)}$	1.74 $^{(6)}$	-0.56 $^{(8)}$	139 $^{(21)}$	149 $^{(15)}$
	100	1,701 $^{(6)}$	2,928 $^{(7)}$	395 $^{(5)}$	1.05$^{NS\,(5)}$	8.94$^{*\,(7)}$	0.89 $^{(10)}$	-0.23 $^{(4)}$	1.12 $^{(10)}$	0.12 $^{(3)}$	124 $^{(7)}$	153 $^{(18)}$
	102	1,583 $^{(9)}$	2,946 $^{(6)}$	116 $^{(19)}$	1.15$^{NS\,(13)}$	24.14$^{**\,(12)}$	1.66 $^{(19)}$	-0.19 $^{(3)}$	1.07 $^{(11)}$	-0.04 $^{(1)}$	124 $^{(7)}$	148 $^{(14)}$
	87	1,530 $^{(10)}$	2,725 $^{(11)}$	187 $^{(14)}$	1.15$^{NS\,(14)}$	-3.62$^{NS\,(4)}$	0.09 $^{(1)}$	-0.49 $^{(8)}$	0.22 $^{(21)}$	0.49 $^{(7)}$	127 $^{(13)}$	147 $^{(12)}$
GGE biplot	158	1,812 $^{(3)}$	2,955 $^{(5)}$	240 $^{(10)}$	1.14$^{NS\,(11)}$	17.05$^{**\,(9)}$	1.53 $^{(16)}$	0.31 $^{(6)}$	2.13 $^{(5)}$	-0.40 $^{(6)}$	124 $^{(7)}$	151 $^{(17)}$
	182	1,715 $^{(5)}$	2,671 $^{(14)}$	306 $^{(9)}$	0.94$^{NS\,(6)}$	28.61$^{**\,(16)}$	1.26 $^{(14)}$	0.48 $^{(7)}$	1.74 $^{(6)}$	-0.56 $^{(8)}$	139 $^{(21)}$	149 $^{(15)}$
	100	1,701 $^{(6)}$	2,928 $^{(7)}$	395 $^{(5)}$	1.05$^{NS\,(5)}$	8.94$^{*\,(7)}$	0.89 $^{(10)}$	-0.23 $^{(4)}$	1.12 $^{(10)}$	0.12 $^{(3)}$	124 $^{(7)}$	153 $^{(18)}$
	102	1,583 $^{(9)}$	2,946 $^{(6)}$	116 $^{(19)}$	1.15$^{NS\,(13)}$	24.14$^{**\,(12)}$	1.66 $^{(19)}$	-0.19 $^{(3)}$	1.07 $^{(11)}$	-0.04 $^{(1)}$	124 $^{(7)}$	148 $^{(14)}$
	87	1,530 $^{(10)}$	2,725 $^{(11)}$	187 $^{(14)}$	1.15$^{NS\,(14)}$	-3.62$^{NS\,(4)}$	0.09 $^{(1)}$	-0.49 $^{(8)}$	0.22 $^{(21)}$	0.49 $^{(7)}$	127 $^{(13)}$	147 $^{(12)}$
Control	‘guandu Petrolina’	1,016	1,016 $^{(22)}$	2,560 $^{(17)}$	116.72 $^{(18)}$	0.85$^{NS\,(15)}$	70.43$^{**\,(20)}$	-2.58 $^{(20)}$	-1.21 $^{(16)}$	-3.76 $^{(1)}$	132 $^{(16)}$	130 $^{(17)}$
Overall mean		1,516	2,848	255							128	141

$^{()}$ Order of classification of the lines for each parameter evaluated; Significance level by the F-test: * = $P < 0.01$, ** = $P < 0.05$, and NS = $P > 0.05$

For Rezende et al. (2020), the Eberhart and Russell, and AMMI methods are complementary: while the first evaluates the responsivity of each genotype to improvements in the environment, the AMMI estimates include the contribution of the genotype to the noise-free GE interaction (Silva and Duarte, 2006) since the initial eigenvalues of the PCA component of the AMMI model selectively recover the interaction pattern (Gauch and Zobel, 1988).

In already published studies on the adaptability and stability of pigeonpea, the most used methods are those of Eberhart and Russell (1966), AMMI (Zobel et al., 1988), and, more recently, the GGE biplot method (Yan et al., 2000). In the classification performed by Flores et al. (1998), the method of Eberhart and Russell is grouped among those in which the statistical approach satisfactorily associates genotypic performance with stability and adaptability, but with little correlation with yield. Therefore, the genotypes with the best performance with regard to the parameters adopted by this method are not always those with the best yield performance. Moreover, according to this classification, the AMMI and GGE biplot methods are grouped among those in which the stability and yield parameters are simultaneously considered in order to reduce the effect of the genotype × environment interaction.

Lines 126 and 130 showed the lowest mean heights, <100 cm, in relation to the remainder. However, the lower yield compared to the overall mean of the lines and the stability and/or adaptability parameters estimated by the three methods limit its wide recommendation. For Santos et al. (2000), low plant heights are desirable in grain pigeonpea as this parameter facilitates harvest, especially when using semi-mechanized practices.

The lines selected by the tree methods result from crosses performed in the pigeonpea breeding program of Embrapa Semiárido (Table 1), with parents defined based on an early harvest, small plant size, high yield, more grains per pod, and large grain sizes (Santos et al., 2000). The crosses used parents of different origins among accessions collected in expeditions to northeastern Brazil and others introduced from different countries, e.g., India. The Indian accessions showed early harvest, small plant size, and low grain yield as their main characteristics, whereas the Brazilian accessions showed larger grains, pods, and plants (Santos et al., 2000).

Lines 87, 100, and 158 showed high grain yields, above the overall mean of the experiments, 1,504 kg ha^{-1}, in addition to good stability and wide adaptability to the evaluated environments, according to the analyses with the Eberhart and Russell (Table 2), AMMI (Figs. 1A and 1B), and GGE biplot (Figure 1C) methods. These lines showed mean yields of 1,530 kg ha^{-1}, 1,701 kg ha^{-1}, and 1,812 kg ha^{-1}, reaching up to 2,725, 2,928, and 2,955 kg ha^{-1}, respectively, in some environments (Table 4). These lines show a cycle shorter than the average (Table 4), denoting precocity, a trait of interest to rainfed grain producers given the short rainy periods, with the potential for evaluation in macro-plots aiming at their recommendation for pigeonpea cultivation in the semi-arid region of Brazil.

With a neglected and little-explored potential in Brazil with regard to improvement actions, pigeonpea is a crop of significant importance in several developing countries for supplying the protein requirements of low-income populations (Yohane et al., 2021). In the last few years, the expansion of pigeonpea yield areas has surpassed that of soybean, cowpea, and peanut in some countries (Gumma et al., 2019). To date, there are no published studies in Brazil on the adaptability and stability of pigeonpea lines developed for semi-arid conditions. The present study reports lines with good yield performance and appropriate adaptability and stability for this vast region, with the possibility of being selected and recommended to producers. This pioneering study can directly contribute to expanding pigeonpea cultivation in Brazil, an activity traditionally performed by small producers in regions of transition from the semi-arid to wetter areas, e.g., the Agreste region of northeastern Brazil. And in the future with the establishment of this exploration in more regions of the country, perhaps an option for the legume export market.

CONCLUSIONS

A significant genotype × environment interaction was observed in 21 pigeonpea lines plus the control variety ‘guandu Petrolina’ evaluated for grain yield in eight environments of the semi-arid region of northeastern Brazil.

Lines 87, 100, and 158 showed wide adaptability and good predictability by the Eberhart and Russell, AMMI, and GGE biplot methods, in addition to above-average yields in the various studied environments. Therefore, these lines are recommended for release as new pigeonpea cultivars for the semi-arid region of Brazil.

ACKNOWLEDGMENTS

The authors would like to thank the Research supported by Coordination for the Improvement of Higher Education Personnel (CAPES) for the A.E.S. Costa scholarship and National Council for Scientific and Technological Development (CNPq) because C.A.F. Santos is also a CNPq productivity researcher.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Bohra A, Saxena KB, Varshney RK and Saxena RK (2020). Genomics-assisted breeding for pigeonpea improvement. *Theor. Appl. Genet.* 133(5): 1721-1737. https://doi.org/10.1007/s00122-020-03563-7.

Bornhofen E, Benin G, Storck L, Woyann LG, et al. (2017). Statistical methods to study adaptability and stability of wheat genotypes. *Bragantia.* 76(1): 1-10. https://doi.org/10.1590/1678-4499.557.

Burgueño J, Crossa J and Vargas M (2003). SAS programs for Graphing GE and GGE Biplots. In: Handbook of formulas and software for plant geneticists and breeders (Kang MS, ed.). Haworth Reference Press, Binghamton.

Cruz CD (2013). Genes: a software package for analysis in experimental statistics and quantitative genetics. *Acta Sci. Agron.* 35(3): 271-276. https://doi.org/10.4025/actasciagron.v35i3.21251.

Cruz CD, Regazzi AJ and Carneiro PCS (2012). Modelos biométricos aplicados ao melhoramento genético. 4th ed. UFV, Viçosa.

Duarte JB and Vencovsky R (1999). Interação genótipos x ambientes: uma introdução a análise "AMMI". Sociedade Brasileira de Genética, Ribeirão Preto.

Eberhart SA and Russell WA (1966). Stability parameters for comparing varieties. *Crop Sci.* 6(1): 36-40. https://doi.org/10.2135/cropsci1966.0011183X000600010011x.

Fasahat P, Rajabi A, Mahmoudi SB, Noghabi MA, et al. (2015). An overview on the use of stability parameters in plant breeding. *Biom. Biostat. Int. J.* 2(5): 00043. https://doi.org/10.15406/bbij.2015.02.00043.

Flores F, Moreno MT and Cubero JI (1998). A comparison of univariate and multivariate methods to analyze G×E interaction. *Field Crops Res.* 56(3): 271-286.

Fuller DQ and Harvey EL (2006). The archaeobotany of Indian pulses: identification processing and evidence for cultivation. *Environ. archaeol.* 11(2): 219-246. https://doi.org/10.1179/174963106x123232.

Gauch HG and Zobel RW (1988). Predictive and postdictive success of statistical analyses of yield trials. *Theor. Appl. Genet.* 76(1): 1-10. https://doi.org/10.1007/BF00288824.

Gumma MK, Tsusaka TW, Mohammed I, Chavula G, et al. (2019). Monitoring changes in the cultivation of pigeonpea and groundnut in Malawi using time series satellite imagery for sustainable food systems. *Remote Sens.* 11(12): 1475. https://doi.org/10.3390/rs11121475.

Kumar MN, Ramya V, Sameer Kumar CV, Raju T, et al. (2021). Identification of pigeonpea genotypes with wider adaptability to rainfed environments through AMMI and GGE biplot analyses. *Indian J. Genet. Plant Breed.* 81(1): 63-73.

Muñoz N, Liu A, Kan L, Li MW, et al. (2017). Potential uses of wild germplasms of grain legumes for crop improvement. *Int. J. M. Sci.* 18(2): 328. https://doi.org/10.3390/ijms18020328.

Piepho HP (1996). Analysis of genotype-by-environment interaction and phenotypic stability. In: Genotype-by-environment interaction (Kang MS, Gauch HG, eds.). CRC Press, Boca Raton.

Pimentel-Gomes F and Garcia CH (2002). Estatística aplicada a experimentos agronômicos e florestais: exposição com exemplos e orientações para uso de aplicativos. FEALQ, Piracicaba.

Reddy D, Venkateswarlu O, Obaiah MC and Jyothi GL (2011). Genotype x environment interaction for grain yield and its components in redgram [*Cajanus cajan* (L.) Millsp]. *Legume Res*. 34(4): 288-291.

Rezende WS, Cruz CD, Borém A and Rosado RDS (2020). Half a century of studying adaptability and stability in maize and soybean in Brazil. *Sci. Agric.* 78(3): e20190197. https://doi.org/10.1590/1678-992X-2019-0197.

Santos CAF, Araújo FP and Menezes EA (2000). Avaliação de genótipos de guandu de diferentes ciclos e portes no sertão pernambucano. *Magistra.* 12(1): 31-40.

Saxena RK, Saxena KB and Varshney RK (2019). Pigeonpea (*Cajanus cajan* L. Millsp.): An Ideal Crop for Sustainable Agriculture. In: Advances in Plant Breeding Strategies: Legumes (Al-Khayri J, Jain S, Johnson D, eds.). Springer, Cham.

Scapim CA, Oliveira VR, Braccini ADL, Cruz CD, et al. (2000). Yield stability in maize (*Zea mays* L.) and correlations among the parameters of the Eberhart and Russell, Lin and Binns and Huehn models. *Genet. Mol. Biol.* 23(2): 387-393. https://doi.org/10.1590/S1415-47572000000200025.

Silva WCJ and Duarte JB (2006). Métodos estatísticos para estudo de adaptabilidade e estabilidade fenotípica em soja. *Pesqui. Agropecu. Bras.* 41(1): 23-30. https://doi.org/10.1590/S0100-204X2006000100004.

Vargas-Hernández M and Crossa J (2000). The AMMI analysis and graphing the biplot. CIMMYT, Mexico.

Vencovsky R and Barriga P (1992). Genética biométrica no fitomelhoramento. Sociedade Brasileira de Genética, Ribeirão Preto.

Waldman KB, Ortega DL, Richardson, RB and Snapp SS (2017). Estimating demand for perennial pigeon pea in Malawi using choice experiments. *Ecol. Econ.* 131: 222-230. https://doi.org/10.1016/j.ecolecon.2016.09.006.

Yan W, Hunt L, Sheng Q and Szlavnics Z (2000). Cultivar evaluation and mega-environment investigation based on the GGE biplot. *Crop Sci.* 40(3): 597-605. https://doi.org/10.2135/cropsci2000.403597x.

Yohane EN, Shimelis H, Laing M, Mathew I, et al. (2021). Genotype-by-environment interaction and stability analyses of grain yield in pigeonpea [*Cajanus cajan* (L.) Millspaugh]. *Acta Agric. Scand. B.* 71(3): 145-155. https://doi.org/10.1080/09064710.2020.1859608.

Zobel RW, Wright MJ and Gauch HG (1988). Statistical analysis of a yield trial. *Agron J.* 80: 388-393. https://doi.org/10.2134/agronj1988.00021962008000030002x.