academicJournals

Vol. 8(3) pp. 30-37, October 2017
DOI: 10.5897/IJBMBR2017.0281
Article Number: 181ADDF66508
ISSN 2141-2154

http:// www.academicjournals.org/IJBMBR

International Journal of Biotechnology and Molecular Biology Research

Full Length Research Paper

Genotype by environment interactions and grain yield stability of released and advanced Desi type chickpea (*Cicer arietinum* L.) genotypes in western Ethiopia

Biru Alemu[1,3]*, Kassahun Tesfaye[2,3,4], Teklehaimanot Haileselassie[4] and Dagnachew Lule[5]

[1]Haro Sabu Agricultural Research Center, P. O. Box 010, Haro Sabu, Ethiopia.
[2]Ethiopian Institute of Biotechnology, Addis Ababa, Ethiopia.
[3]Department of Microbial, Cellular and Molecular Biology, Addis Ababa University, Ethiopia.
[4]Institute of Biotechnology, Addis Ababa University, Ethiopia.
[5]Oromia Agricultural Research Institute, Addis Ababa, Ethiopia.

Received 1 August, 2017; Accepted 14 October, 2017

Genotype by environment interaction (G×E) obstructs breeding by persuading variations in genotype performance in different environments and thereby complicating selection. The aim of the present study was to determine the stability and yield performance of desi type chickpea varieties and advanced lines at multiple growing environments of western Ethiopia, using genotype-by-environment interaction (GGE) biplot analysis and AMMI model to find stable high yielding cultivar(s) and ratify for wider production. The experiment was laid out in a randomized complete block design with three replicates. The analysis of variance (ANOVA) indicated highly significant differences ($P \leq 0.01$) for environments, genotypes and importantly genotype by environment interaction (G×E). Additive main effects and multiplicative interactions (AMMI) and GGE biplot, AMMI Stability Value (ASV) and Genotype Selection Index (GSI) indices indicate that Natoli (G8) variety and DZ-2012-CK-20113-2-0042 (G16) advanced lines showed better grain yield with better stability across environments and thus are recommended for wider production in test locations and similarly agro-ecologies in Ethiopia.

Key words: Chickpea (*Cicer arietinum* L.), genotype-by-environment interaction (GGE) biplot, Additive main effects and multiplicative interactions (AMMI), AMMI stability value (ASV), genotype selection index (GSI), stability.

INTRODUCTION

Population growth, dwindling agricultural land, and climate change present increasing risks to crop production. The impact of these factors can simply be sensed in a country like Ethiopia where the overall economic growth is heavily dependent on the success of th agriculture sector. Particularly, the importance of pulses such as chickpea (*Cicer arietinum* L.) cannot be overstated because of their significant role in sustaining food security, balancing ecosystem, and generating revenue (Getachew et al., 2015). Socioeconomically,

---

*Corresponding author. E-mail: birrollee@gmail.com. Tel: +251917096447.

chickpea is an essential staple crop in Ethiopia. It is the main food legume in the northern and central highlands of Ethiopia (Keneni et al., 2012). The country is a major producer and consumer of this legume next to Haricot bean. Annual production of 10.8464 tons has been recorded for 2015/2016 growing season of which 77.27% is used for home consumption (CSA, 2015).

The development of superior varieties in terms of grain yield, quality, stress resistance, and yield stability is an important consideration in plant breeding programs. Chickpea breeding programs in Ethiopia have been focused mainly on major abiotic and biotic stresses that adversely affect the yield of chickpea. However, genotype and environment interaction (G×E) hampers breeding by inducing variations in genotype performance in diverse environments and affecting selection (Zobel, 1990).

Different crops including chickpea are sensitive to environmental variations and hence the development of stable genotypes fixed with improved yield has become one of the alternatives to mitigate the effects of genotype by environment interaction (G×E), and making the recommendation of cultivars with such attributes more reliable (Zobel, 1990). Adaptability of any genotype is the product of the inherent capacity of genotype, the environmental factor in which a given genotype is raised and the interplay between the environment and genotype. Thus, the assessment of adaptability and stability parameters supports to define the response of genotypes to environmental variations, sketch realistic conclusion and solidifying the recommendation of new cultivars (Zobel, 1990). Consequently, multi- environmental yield trials are critical to detect adaptable high yielding cultivars and discover sites that best represent the target environment.

Through a series of time, various statistical models have been engaged in examining the adaptability and stability of genotypes over environments. However, traditional statistical models such as analysis of variance (ANOVA) flop to detect a significant interaction component, and principal component flops to detect and separate the significant effects of genotype by environment interactions (Flores et al., 1996). The linear regression model accounts only for a small portion of the interaction sum square (Yau, 1995).

Therefore, by indicating these deficits of traditional models, some authors suggested a model that integrates the analysis of variance and principal component analysis into an incorporated method (Gauch and Zobel, 1988; Crossa et al*.,* 1990). In this regards, two multivariate models *viz.,* additive main effects and multiplicative interaction models (AMMI) and the genotype plus genotype by environment interaction effect (G×E) model, is the most widely used analytical and statistical tools to determine the pattern of genotypic responses across diverse environments using different crops (Smith and Smith, 1992; Yan and Kang, 2002).

The aim of the present study was, therefore, to determine the stability and yield performance of advanced Desi type chickpea varieties and advanced lines at multiple locations using GGE biplot analysis and AMMI model in order to identify stable high yielding cultivar(s) recommended for wider production in the test environments and similar agro-ecologies in Ethiopia.

MATERIALS AND METHODS

The experiment was conducted under field condition at five locations *viz.,* Shambu, Hawa Galan, Mata, Alaku Belle and Badesso, western Ethiopia, during the 2016/17 main cropping season. A total of 16 desi type chickpea varieties *viz.,* 8 cultivars released over three decades, 1 local variety and 7 advanced lines collected from Debre Zeit Agricultural Research Center (DZARC) were used (Table 1).

The experiment was laid out in a randomized complete block design with three replicates and plot size of 3 m length and 1.8 m width. All other crop management practices and recommendations were applied uniformly to all varieties as recommended for the crop.

Statistical analysis

Analyses of variance (ANOVA) was done for each environment and combined across environments using SAS (SAS Inc., 2002). The presence or absence of genotype by environment interactions (G×E) was determined from the combined analysis of variance (ANOVA) table. Bartlett's test of homogeneity was used to check the homogeneity of variances between environments before performing combined analyses of variance. Total variation attributed due to an environment, genotype, and genotype by environment interaction (G×E) was calculated from the sums squares of the analysis of variance (ANOVA) table.

Additive Main Effects and Multiplicative Interaction Model (AMMI) which help to envisage relationships among genotypes and environments by demonstrating both main and interaction effects was investigated using GenStat software (GenStat, 2012). Integrating biplot display and genotypic stability statistics allow genotypes to be grouped grounded on the similarity of a performance of each genotype across diverse environments.

AMMI method as described in Zobel et al. (1988) was used to analyze adaptability and phenotypic stability using the following statistical model:

$$y_{ij} = \mu + gi + e_j + \sum_{k=n}^{n} \lambda_k \alpha_{ik} y_{ij} + r_{ij} + \varepsilon_{i_j}$$

Where, Y_{ij} is the yield of the i^{th} genotype in the j^{th} environment; μ is the grand mean; g_i and e_j are the genotype and environment deviations from the grand mean, respectively; λ_k is the eigenvalue of the PCA analysis axis k; α_{ik} and γ_{ij} are the genotypes and environment principal component scores for axis k; n is the number of principal components retained in the model and ε_{ij} is the error term.

AMMI stability value was used to determine stability value and rank of each genotype as given below (Purchase et al., 2000).

AMMI Stability Value (ASV)

$$= \sqrt{\left[\left(\frac{IPCA1SS}{IPCA2SS}\right)(IPCA1\ Score)\right]2 + (IPCA2\ Score\ )2}$$

Stability was not merely selection parameter and therefore,

Table 1. Passport description of the Desi type chickpea varieties and advanced lines evaluated at multi-locations.

Genotype code	Genotype names	Status	Year of release
G1	Akaki	Released	1995
G2	Dalota	Released	2013
G3	Dimtu	Released	2012
G4	Dubie	Released	1978
G5	Local	Local variety	-
G6	Mariye	Released	1985
G7	Minjar	Released	2010
G8	Natoli	Released	2007
G9	Teketay	Released	2013
G10	DZ-2012-CK-0032	Advanced line	-
G11	DZ-2012-CK-0034	Advanced line	-
G12	DZ-2012-CK-0233	Advanced line	-
G13	DZ-2012-CK-0237	Advanced line	-
G14	DZ-2012-CK-0312	Advanced line	-
G15	DZ-2012-CK-0313	Advanced line	-
G16	DZ-2012-CK-20113-2-0042	Advanced line	-

Table 2. Partitioning of the Explained Sum of square (SS) and Mean of square (MS) from AMMI analysis of variance for grain yield of 16 chickpea varieties evaluated at five environments.

Source of variation	DF	SS	Explained % SS	MS
Total	239	143.45	100	0.6
Treatments	79	113.08	78.83	1.43***
Genotypes	15	15.89	11.08	1.06***
Environments	4	79.62	55.50	19.9***
Block	10	10.62	7.40	1.06***
Interactions	60	17.56	12.25	0.29***
IPCA1	18	11.15	63.49	0.62***
IPCA2	16	3.41	19.40	0.21ns
Residuals	26	3.01	17.11	0.12
Pooled error	150	19.76		0.13

Genotype Selection Index (GSI) which combines both mean yield and stability in a single index has been introduced (Magari and Kang, 1993; Mohammadi et al., 2007; Mohammadi and Amri, 2008; Farshadfar, 2008). Genotype Selection Index (GSI) was calculated as:

$$GSI = RASV + RY$$

Whereas RASV is the rank of AMMI stability value and RY is the rank of mean grain yield of genotypes across environments.

GGE biplot was first coined by Gabriel (1971) and subsequently improved by (Zobel et al., 1988). The reason that makes GGE biplot preferred by plant breeders is that it can accommodate genotype and genotype by environment interaction concurrently to make meaningful decisions. Therefore, GGE biplot which is mostly useful for cultivar evaluation of the multi- environmental trial was computed as suggested by Yan and Kang (2002) as follows:

$$\hat{y}_{ij} = \mu + \alpha_i + \beta_i + \phi_{ij}$$

Whereas, $\hat{y}_{ij}$ is the expected yield of genotype *i* in environment *j*, μ is the grand mean of all observations, α_i *is* the main effect of genotype *i*, β*j* is the main effect of environment *j*, and Φ*ij is* the interaction between genotype *i* and environment *j*.

RESULTS AND DISCUSSION

AMMI analysis of variance (ANOVA) with the appropriate AMMI model was indicated in Table 2. The analysis of variance (ANOVA) indicated highly significant differences ($P \leq 0.01$) for environments, genotypes and importantly

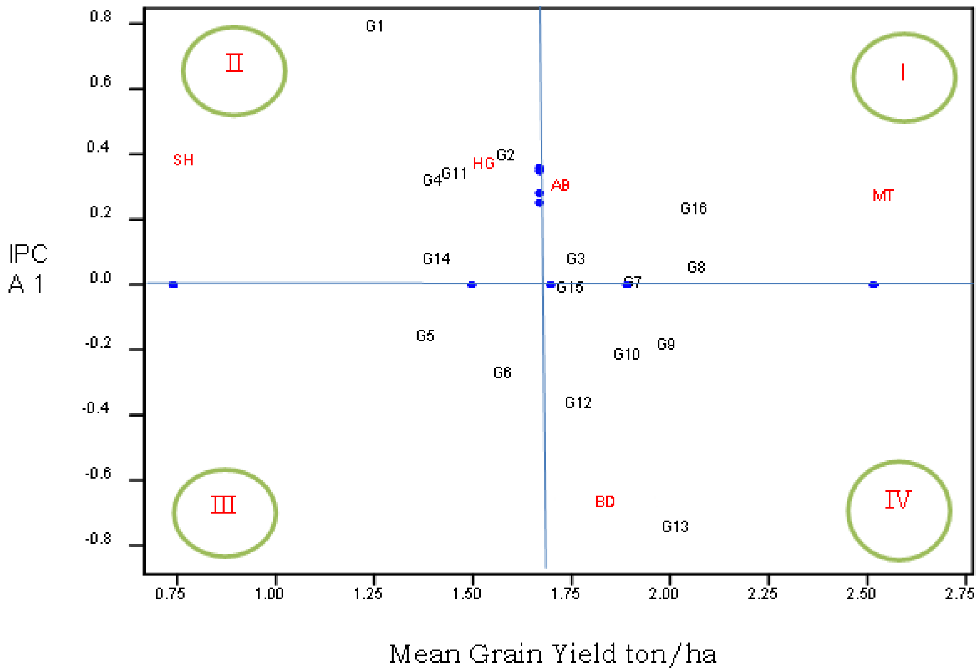

Figure 1. Biplot of interaction principal component axis (IPCA-1) against mean yield of chickpea varieties evaluated across five environments.

genotype by environment interaction (G×E).

The IPCA-1 axis of genotype by environment interaction (G×E) was also highly significant (P ≤ 0.01). The first principal component managed over 63% of the genotype by environment interaction (G×E) sum squares while the second principal component revealed 19% of the interaction, and the remaining 17% is due to residual (noise) and it is difficult to interpret and thus need to be discarded. Different authors suggest the importance of apprehending most of the genotype by environment interaction (G×E) sum squares in the first axis, to attain accurate information (Gauch and Zobel, 1988; Zobel et al., 1988; Crossa et al., 1990; Purchase et al., 2000).

The most striking piece of AMMI analysis is the construction of biplot graphs, by combining the analysis of variance with multivariate analysis through principal component analysis. There is two basic AMMI biplot, that is, AMMI 1 biplot, which is the main effect (Genotype and Environment means) and IPCA-1 scores which are plotted against each other, and AMMI 2 biplot where scores of IPCA-1 and IPCA-2 are plotted against each other (Shafii et al., 1992). Only the first IPCA-1 explaining 63% of the total genotype by environment interaction (G×E) was significant in the AMMI analysis of variance, demonstrating that the AMMI model-1 was the best fit for this data set. Stability of genotypes over environments is foretold by IPCA scores of a genotype in the AMMI analysis.

The greater and lesser the IPCA scores of the genotypes to the origin of the axis, the more designated are the instability of genotype and stability of genotype, respectively. That is the more the IPCA scores approximate to zero, the more stable the genotype is all over the environments sampled (Purchase et al., 2000). In another word, the ideal genotype is one with high productivity and IPCA-1 values close to zero and undesirable genotype has low stability associated with low productivity (Kempton, 1984; Gauch and Zobel, 1988). In the AMMI-1 biplot display, genotypes or environments that fall on a perpendicular and horizontal line of the graph had similar mean yield and similar interaction, respectively. On the other hand, genotypes or environments on the left and right-hand side of the midpoint line have less and higher yield than the grand mean, respectively. The score and sign of IPCA-1 reflect the magnitude of the contribution of both genotypes and environments to genotype by environment interaction (G×E), where scores near zero are the characteristic of stability and a higher score (absolute value) designate instability and specific adaptation to a certain environment (Gollob, 1968).

The characterization of each promising lines (genotypes) to mean grain yield and contribution to genotype by environment interaction (G×E) by mean of IPCA-1 indicated that genotypes Natoli (G8), and DZ-2012-CK-20113-2-0042 (G16) were specifically adapted to high yielding environments Mata (MT) and Alaku Belle (AB) having a grain yield more than grand mean yield (Figure 1). But with respect to their contribution to genotype by environment interaction (G×E) (the IPCA-1

Score, that is, stability), DZ-2012-CK-20113-2-0042 (G16) and Natoli (G8) were intermediately stable genotypes. However, Minjar (G7) and DZ-2012-CK-0237 (G15) were shown to have a higher stability for yield than any other genotypes because these genotypes were positioned near the origin of the biplot (Figure 1).

However, any genotype to be considered as best genotype should be able to combine good grain yield and stable performance across a range of production environments. In this regard, Natoli (G8) and DZ-2012-CK-20113-2-0042 (G16) were relatively high yielding and stable variety and pipeline genotype, respectively. On the other hand, Dalota (G2), Dubie (G4), DZ-2012-CK-0034 (G11) and DZ-2012-CK-0312 (G14) were adapted to the low-yielding environment and unstable. Local material (G5) and Mariye (G6) were poor yielder genotypes and also phenotypically unstable. Akaki (G1) and DZ-2012-CK-0237 (G13) were the most unstable genotypes but, the latter showed specific adaptation to Badesso (Figure 1).

Genotypes and environments positioned close to each other in the biplot have positive associations which enable us to create agronomic zones with relative ease. For instance, DZ-2012-CK-0237 (G13) had a peculiar adaptation to Badesso (BD) environment whereas G1 (Akaki) was comparatively better adapted to Shambu (SH) and Hawa Galan (HG) areas. The current results indicated that, even under very heterogeneous environments (be it due to soil character and other agro-ecological condition) cultivars with wide geographic adaptation and high productivity (> 2-ton ha^{-1}) were identified. Besides, suitable growing environments with better productivity were also identified for each variety and genotype tested in the present study.

The environments showed considerable variability in both additive main effects and interactions (Table 2). In AMMI biplot, environments are more dispersed than the genotypes demonstrating that variability due to environments is higher than the variation among the tested chickpea materials. This is fully in agreement with the analysis of variance indicated in Table 2. The contribution of the environments to the interaction is high for Badeso (BD) and intermediate for others. The average yield in environments Mata (MT), Alaku Belle (AB) and Badeso (BD) exceeded the grand mean (1.67-ton ha^{-1}).

The most potential environment Mata (MT) having positive IPCA-1 score showed a differential performance of genotypes for grain yield. The lowest yielding environment was Shambu (SH) with positive IPCA-1 score suggesting that, though all the genotypes poorly performed under this environment has a significant role in differentiating genotypes.

AMMI stability value (ASV) and genotype selection index (GSI)

AMMI stability value was also computed to determine a stability of the genotypes. Stability was not merely selection parameter and therefore, Genotype Selection Index (GSI) which combine both mean yield and stability in a single index (Mohammadi et al., 2007; Mohammadi and Amri, 2008) have been introduced to further detect high yielding genotypes with unswerving yield performance, through diverse growing environments.

In AMMI model, a genotype with least ASV score was seen as the most stable. Accordingly, genotypes Minjar (G7), DZ-2012-CK-0312 (G14), Dimtu (G3), Local variety (G5), Natoli (G8), Teketay (G9) and DZ-2012-CK-20113-2-0042 (G16) had general adaptation, while genotypes Akaki (G1), Dalota (G2), DZ-2012-CK-0233 (G12) and DZ-2012-CK-0237 (G13) were the most unstable and/or they are specifically adapted to certain environments (Table 3). This result was consistent with that of AMMI biplot.

Nevertheless, stable genotypes would not inevitably provide the best yield performance and hence identifying genotypes with high grain yield coupled with consistent stability across growing environments has paramount importance. In this regard, Genotype Selection Index (GSI) was utilized to further identify stable genotypes with better yield performance. Accordingly, Minjar (G7), Natoli (G8), DZ-2012-CK-20113-2-0042 (G16), Teketay (G9), and Dimtu (G3) were considered as most stable genotypes, whereas, Akaki (G1), Dalota (G2), Dubie (G4), Local variety (G5), Mariye (G6), DZ-2012-CK-0034 (G11), DZ-2012-CK-0233 (G12), and DZ-2012-CK-0237 (G13) were the least stable genotypes.

Genotype and Genotype by Environment interaction (GGE) biplot analysis

Environments and genotypes that fall in the central (concentric) circle are considered as an ideal environments and stable genotypes, respectively (Yan and Kang, 2002). In the present study, Mata (MT) was the most stable environment where variability between genotypes was minimum followed by Alaku Belle (AB) (Figure 3). Genotype-focused scaling biplot comparison revealed that Natoli (G8) fell in the central circle indicating its high yield potential and stability compared to the rest of the varieties and advanced lines evaluated in this study (Figure 2).

Besides, DZ-2012-CK-20113-2-0042 (G16), Teketay (G9) and Minjar (G7) are on the brink of the ideal cultivar and are, therefore, most desirable of all the other tested

Table 3. AMMI stability Value, Genotype selection index, yield rank and principal component axis.

Genotypes name	Mean	R. Yield	ASV	R. ASV	GSI	IPCA-1	IPCA-2
Akaki(G1)	1.23	15	2.52	16	31	0.77	0.04
Dalota(G2)	1.56	10	1.23	13	23	0.38	-0.08
Dimtu(G3)	1.74	7	0.28	3	10	0.06	-0.20
Dubie(G4)	1.38	12	1.02	11	23	0.30	0.33
Local variety(G5)	1.36	14	0.60	6	20	-0.18	0.10
Mariye(G6)	1.55	11	0.97	10	21	-0.30	-0.06
Minjar(G7)	1.88	5	0.21	1	6	-0.01	-0.20
Natoli(G8)	2.04	1	0.48	5	6	0.03	-0.47
Teketay(G9)	1.97	3	0.69	7	10	-0.20	0.16
DZ-2012-CK-0032(G10)	1.85	6	0.93	9	15	-0.24	0.51
DZ-2012-CK-0034(G11)	1.42	13	1.04	12	25	0.32	0.08
DZ-2012-CK-0233(G12)	1.73	8	1.26	14	22	-0.39	-0.02
DZ-2012-CK-0237(G13)	1.91	4	2.51	15	19	-0.76	-0.19
DZ-2012-CK-0312(G14)	1.37	13	0.25	2	15	0.06	0.17
DZ-2012-CK-0313(G15)	1.71	9	0.30	4	13	-0.03	0.28
DZ-2012-CK-20113-2-0042(G16)	2.02	2	0.82	8	10	0.21	-0.45

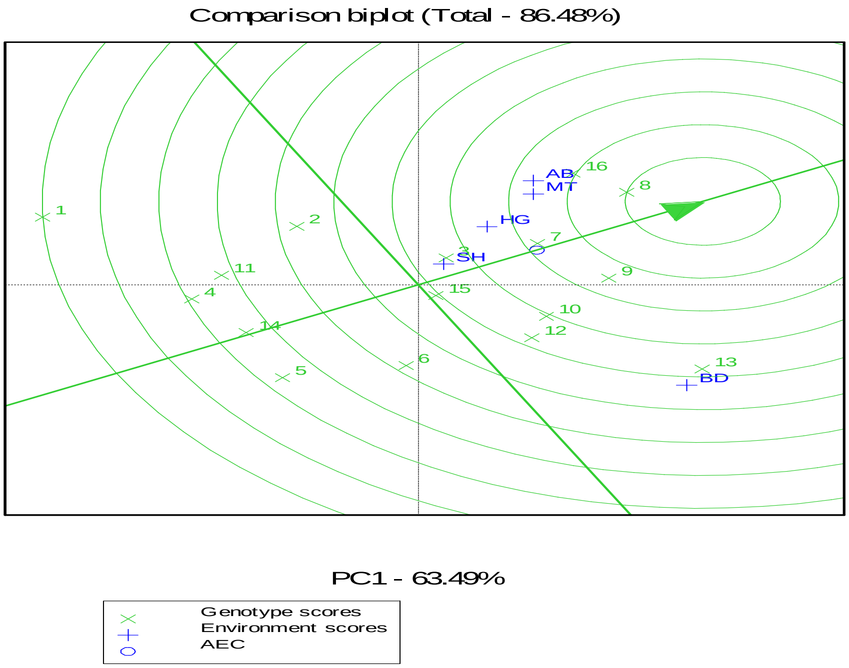

Figure 2. GGE biplot based on genotype-focused scaling for comparison of chickpea materials for their yield potential and stability.

cultivars. Most importantly, the genotype-focused scaling pattern of GGE biplot indicates that advanced pipeline genotype DZ-2012-CK-20113-2-0042 (G16) was desirable genotype in that, it has broad adaptability. This result agrees with that of AMMI biplot. The scenario is parallel to the environments too. An environment is desirable and discriminating when positioned nearer to the center circle or nearer to an ideal environment in environment-focused GGE biplot (Dabessa et al., 2016). This study clearly discloses that Mata (MT), as the ideal environment and Alaku Belle (AB) and Hawa Galan (HG) as desirable environments discriminating and representative environment. On the other hand, Badesso (BD) was positioned distant from centric circle and

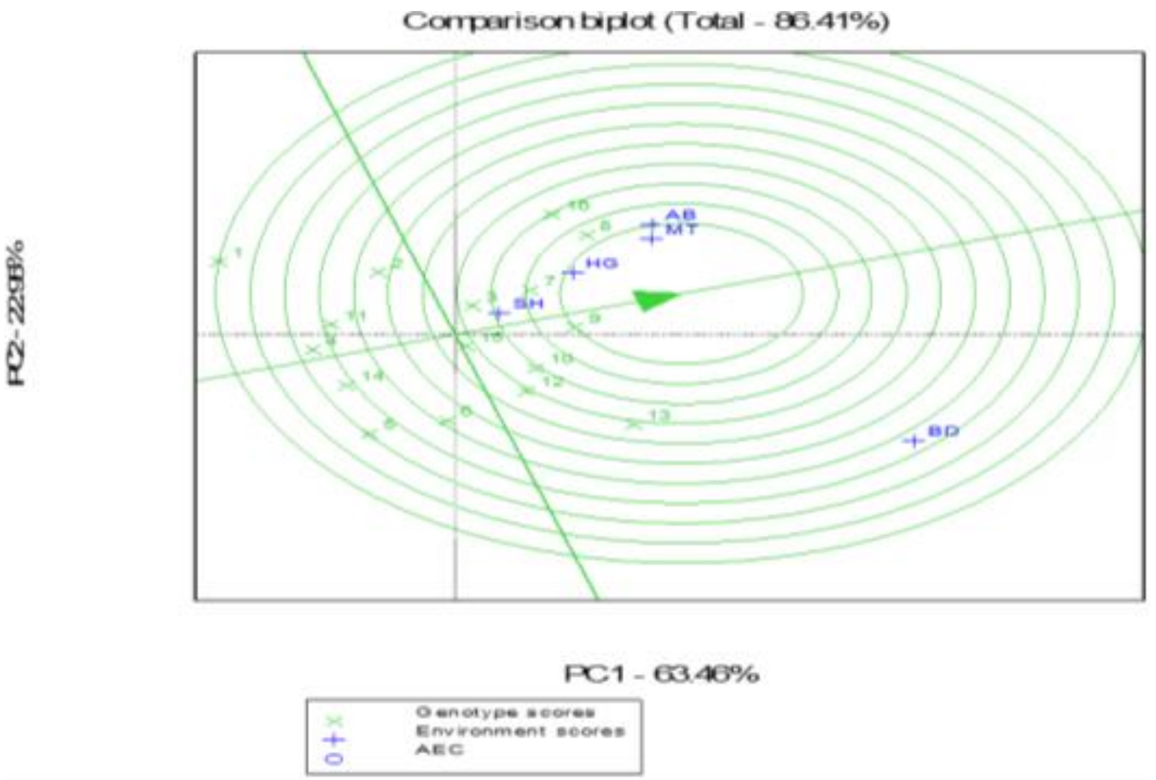

Figure 3. GGE biplot based on environment-focused scaling for comparison of test environment.

therefore, it is not an ideal environment.

Conclusion

The AMMI model analysis of variance (ANOVA) for grain yield displayed that genotypes, environments, genotype by environment interaction (G×E), and interaction principal component axis (IPCA-1) were significant. Thus, grain yield and the first principal component axis were used to construct a biplot graphs because of its significant contribution to the genotype by environment interaction (G×E). A graphical interpretation of the AMMI analysis, GGE biplot and GSI index incorporating with the ASV and the yield capacity of the different genotypes in a single non-parametric index, were useful for discriminating genotypes with superior and stable grain yield.

Generally, the current results indicated that, based on yield performance, AMMI and GGE biplot, ASV and GSI indices DZ-2012-CK-20113-2-0042 (G16) and Natoli (G8) variety showed better grain yield with better stability across environments and thus are recommended for wider production in test locations and similar agro-ecologies. To sum up both yields, stability should be considered concurrently to recommend any varieties for wider production and thus reducing the impact of genotype by environment interaction (G×E) and drawing a realistic conclusion for growers.

CONFLICTS OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

The authors would like to thank PEER grant scheme (USAID) project for financial support and collaborators at Bako and Haro Sabu Agricultural Research Center, who contributed greatly during the carrying out of the research and exceptionally, our thanks are due to Merara Gidisa, field assistant of Bako Agricultural Research Center (BARC), at Shambu. We are grateful to Debre Zeit Agricultural Research Center (DZARC) for the provision of testing germplasms.

REFERENCES

Crossa J, Gauch HG, Zobel RW (1990). Additive main effects and multiplicative interaction analysis of two international maize cultivar trials. Crop Sci. 30(3):493-500.

Central Statistical Agency (CSA) (2015). Crop and livestock product utilization. Statistical Bulletin. Central Statistical Agency (CSA), Addis Ababa, Ethiopia.

Dabessa A, Alemu B, Abebe Z, Lule D (2016). Genotype by Environment

Interaction and Kernel Yield Stability of Groundnut (*Arachis hypogaea* L.) Varieties in Western Oromia, Ethiopia. J. Agric. Crops 2(11):113-120.

Farshadfar E (2008). Incorporation of AMMI stability value and grain yield in a single non-parametric index (GSI) in bread wheat. Pak. J. Biol. Sci. 11(14):1791.

Flores F, Moreno MT, Martinez A, Cubero JI (1996). Genotype-environment interaction in Faba Bean: Comparison of AMMI and principal coordinate models. Field Crops Res. 47(23):117-127.

Gabriel KR (1971). The biplot graphic display of matrices with application to principal component analysis. Biometrika 58(3):453-467.

Gauch HG, Zobel RW (1988). Predictive and postdictive success of statistical analyses of yield trials. Theor. Appl. Genet. 76(1):1-10.

GENSTAT (2012). GenStat Statistical Software, version 15.01. GenStat CO, UK.

Getachew T, Firew M, Asnake F, Million E (2015). Genotype x environment interaction and stability analysis for yield and yield related traits of Kabuli-type Chickpea (*Cicer arietinum* L.) in Ethiopia. Afr. J. Biotechnol. 14(18):1564-1575.

Gollob HF (1968). A statistical model which combines features of factor analytic and analysis of variance techniques. Psychometrika 33(1):73-115.

Kempton RA (1984). The use of biplots in interpreting variety by environment interactions. J. Agric. Sci. 103(1):123-135.

Keneni G, Bekele E, Imtiaz M, Dagne K, Getu E, Assefa F (2012). Genetic diversity and population structure of Ethiopian chickpea (*Cicer arietinum* L.) germplasm accessions from different geographical origins as revealed by microsatellite markers. Plant Mol. Biol. Report. 30(3):654-665.

Magari R, Kang MS (1993). Genotype selection via a new yield-stability statistic in maize yield trials. Euphytica 70(1):105-111.

Mohammadi R, Abdulahi A, Haghparast R, Aghaee M, Rostaee M (2007). Nonparametric methods for evaluating of winter wheat genotypes in multi-environment trials. World J. Agric. Sci. 3(2):137-242.

Mohammadi R, Amri A (2008). Comparison of parametric and non-parametric methods for selecting stable and adapted durum wheat genotypes in variable environments. Euphytica 159(3):419-432.

Purchase JL, Hatting H, Van Deventer CS (2000). Genotype× environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: II. Stability analysis of yield performance. South Afr. J. Plant Soil 17(3):101-107.

SAS Institute (2002). SAS/STAT guide for personal computers, version 9.0 edition. SAS Institute Inc., Cary, NC, USA.

Shafii B, Mahler KA, Price WJ, Auld DL (1992). Genotype✕ Environment Interaction Effects on Winter Rapeseed Yield and Oil Content. Crop Sci. 32(4):922-927.

Smith MF, Smith A (1992). The success of the AMMI model in predicting Lucerne yields for cultivars with differing dormancy characteristics. South Afr. J. Plant Soil 9(4):180-185.

Yan W, Kang MS (2002). GGE Biplot Analysis: A graphical tool for breeders, geneticists, and agronomists. CRC press.

Yau SK (1995). Regression and AMMI analyses of genotype× environment interactions: An empirical comparison. Agron. J. 87(1):121-126.

Zobel RW, Wright MJ, Gauch HG (1988). Statistical analysis of a yield trial. Agron. J. 80(3):388-393.

Zobel RW (1990). A powerful statistical model for understanding genotype by environment interaction. Genotype-by-Environment Interaction and Plant Breeding (MS Kang, ed.). pp. 126-140.