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Original Research Article

Analysis of Maize Yield Stability and Genotype by Environment Interaction Based on GGE Biplot Graphical Technique

Yidnekachew Marid[1*], Hailu lire[2]

[1]EIAR, Hawassa National Maize Research sub-Center, Hawassa-Ethiopia, PO box 198 Shashamane, Ethiopia
[2]Crop Research Process, Wondogenet Agricultural Research Center, Ethiopian Institute of Agricultural Research, Wondogenet, Ethiopia

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Abstract: Conducting multi-location trials along with the commercial varieties and genotype by environment (G x E) data analysis are vital to breeders to develop superior genotypes and to meet the challenges posed by environmental factors. This research was undertaken to evaluate maize hybrids for yield, to assess the effect of G x E on grain yield, and determine the yield stability of hybrids across major maize growing areas of Ethiopia. A total of 24 maize hybrids including standard checks (BH546, BH547, BH661 and Limu) were evaluated at six locations (Bako, Jimma, Pawe, Ambo Wendogenet and Asosa) in randomized complete block design (RCBD) with three replications during the 2020 cropping season. The hybrids had significant differences for grain yeild at all locations. The analysis of variance for mean squares for genotype, location and G x E were significant. The hybrids SXM1910007, WE3106 and WE7131 were the most stable and high yielding with mean grain yield of 8.68 t/ha, 8.06 t/ha and 7.98t/ha, respectively, which was higher than best commercial checks. Therefore identified as the best widely adapted hybrids across locations. In conclusion, the identified desirable maize hybrids could be used as candidate varieties for cultivation in major maize growing areas of Ethiopia. However, the identified hybrids need to be further evaluated under verification trial over many locations to be recommended as commercial varieties.

Keywords: GGE bi plot, Maize hybrids, Commercial check. multi-location, genotype by environment (G x E)

INTRODUCTION

Maize is the second most widely produced crop in the world and it is the most important cereals in Sub-Saharan Africa (SSA) and a staple food for an estimated 50% of the population (Badu-Apraku and Fakorede, 2017). Maize grain yields have doubled from around 1.6 t/ha in 1990 to 4 t/ha in recent years, which are the highest level in sub-Saharan Africa after South Africa (FAOSTAT, 2022). Maize is therefore an important cereal for the economic wellbeing and food security of hundreds of millions of households in SSA (Fisher *et al*., 2015). Despite its importance in the region, maize yields in SSA are still the lowest compared with other regions of the world (Masuka *et al*., 2017). In Ethiopia, maize ranks first among cereals in terms of total production and grain yield (4.18 t/ha), and second to teff (Eragrostis teff) in area of production among all the cereals (CSA, 2021). Ethiopia is a significant maize producer in Africa. The maize sector in Ethiopia has experienced a significant transformation over the past two decades. Important factors for the increased productivity include Increased availability and use of modern inputs (e.g. improved hybrid seeds and inorganic fertilizers), better extension services and increasing demand (Tesdeke Abate *et al*., 2015). Despite the recent progress, maize national average grain yield in Ethiopia is still very low relative to the potential of the crop and world's average due to lack of well-adapted and improved cultivars and due to genotype by environment (GE) interaction. (Legesse *et al.*, 2020). The national average yield of maize is higher than Africa's average (2.21 t/ ha), the figure is lower than the world's average yield (5.80 t/ha) (FAO, 2022).

Stability of performance is special importance in Ethiopia and similar countries where environmental conditions vary considerably and means of modifying the environment are far from adequate. In addition, low cultivar turnover and genotype environment interaction (GEI) predominantly contribute to low yield in small-scale farming systems (Demiselew et al., 2016, Legese *et.al* 2018). Analysis of GE interaction becomes indispensable for breeders and varietal experimentation. Each cultivar reacts specifically to changing climatic and soil conditions; some of them exhibit high GE interaction, while in others it is low. The estimation of G x E interaction and yield stability analysis of Ethiopian

***Corresponding Author:** Yidnekachew Marid
EIAR, Hawassa National Maize Research sub- Center, Hawassa-Ethiopia, PO box 198 Shashamane, Ethiopia.

maize has been addressed by other workers (Mosisa and Habtamu, 2008; Solomon et al., 2008 Demisew et al., 2016a; Legesse et al., 2018; Desalegn, 2019; Legesse et al., 2020, Mohammed, 2020). However, no information is available on the G x E interaction and stability in grain yield performance of these hybrids that are newly developed by the Bako national maize research. In these study tests of performance of new maize hybrids across a wide range of environments is conduced to reduce the effect of GEI and to ensure that the selected genotypes have a high and stable performance across several environments. With this the objectives of this study were to assess the effect of genotype by environment interaction on yield stability of maize hybrids and evaluate their performances for agronomic traits in maize growing areas in Ethiopia.

Description of Study Area

The experiment was conducted at six locations representing major maize-growing agro-ecologies of Ethiopia. These locations vary in altitude, temperature, total annual rainfall and soil types.

Table 1: Description of the study locations

Location	Altitude (m.a,s.l)	Soil type	Rainfall (mm)	Geographical position		Temperature	
				Latitude	Longitude	Maximum	Minimum
Bako	1650	Nitisol	1598	9° 06’	37°09’	29	12.78
Asosa	1547	Nitisol	1276.2	100° 02'	340° 31’	33	21
Jimma	1753	Nitosol	1561	7 0° 46’	360° 00’	23	18
Pawe	1120	Nitisol	1250	110°19’	36° 24’	32.6	16.5
Wondo Genet	1780	Alluvial	1128	7° 19’	38° 38’	26	11
Ambo	2175	Vertisol	1265.7	8º 57’	37º 51’	25.6	11.7

Source: Ethiopian institute of agricultural research (2020)

Planting Materials, Trial Management and Experimental Design

Twenty maize hybrids with four commercial cheacks (BH546 BH 547 BH661 and Limu) were across location in six representative sites. These hybrids were developed or adapted by the National Maize Research Program of the Ethiopian Institute of Agricultural Research (EIAR) based at Bako Agricultural Research Center (BARC). The trial was conducted during the 2020 main cropping season in randomized complete block design (RCBD) with three replications. Each hybrid was planted in a two-row plot of 5 m long with spacing of 0.75 m between rows and 0.25 m between plants within a row. Two seeds were sown per hill for each genotype and later thinned to one plant at three to four leaf stages to get the generally recommended total plant population of 53,000 plants per hectare. Planting was done immediately after the onset of the main rainy season after an adequate soil moisture level to ensure good germination and seedling development. The NPS fertilizer at the rate of 150 kg /ha was applied once at planting time at all locations as per the recommendation (MoA, 2018), while 200 kg/ha Urea at Ambo and Pawe and 250 kg/ ha Urea at Bako, Wendo Genet Jima and Asosa was applied in split, half at thinning and the remaining half at knee height.

Table 2: Maize hybrids tested across six locations in 2020 main growing season.

Entry	Hybrids	Pedigree	Source
1	WE6103	CKDHL0089/CML395//CKLTI0036-B-B	CIMMYT
2	WE7124	CKDHL0089/CKDHL0295//CKLTI0348-B-B	CIMMYT
3	CZH15568	CZH15568	CIMMYT
4	WE2108	CML312/CML442//CKDHL0411-B-B-B	CIMMYT
5	CZH15587	CZH15587	CIMMYT
6	WE7117	CKLTI0139/CKLMARSI0029//CKDHL120312-B-B-B	CIMMYT
7	BH 661	CML395/CML202//142-1-e	Bako
8	SXM1910008	BKL004/BKL003	Bako
9	BH 546	CML395/CML202/BKL001	Bako
10	BH 547	CML312BK/BKL002/BKL003	Bako
11	SXM1910173	SC22/124- b(113)	Bako
12	Limu	Limu	Pioneer
13	WE3105	CML444/CML442//CKDHL0295-B-B-B	CIMMTY
14	CZH15523	CZH15523	CIMMTY
15	3XM1900476	CML488/CML489/CML536	Bako
16	SXM1910007	CML444/CML536	Bako
17	WE3106	CML312/CML395//CKDHL0089-B-B-B	CIMMYT
18	WE7131	CKDHL0089/CKDHL0323//CKLTI0045-B-B	CIMMYT
19	WE7126	CML395/CML444//CKLTI0348-B-B	CIMMYT
20	WE7119	CKDHL0500/CKLTI0137//CKDHL120312-B-B-B	CIMMYT

Entry	Hybrids	Pedigree	Source
21	WE7128	CKDHL0089/CML395//CKLTI0368-B-B-B	CIMMYT
22	WE1101	CML395/CML444//CML539-B-B-B	CIMMYT
23	WE6105	CKDHL0089/CKDHL0295//CKLTI0344-B-B	CIMMYT
24	WE6106	CKDHL0089/CKDHL0323//CKLTI0200-B-B-B	CIMMYT

CIMMYT= International Maize and Wheat Improvement Center.

Data Analyses

Data of each location were subjected to analysis of variance separately (Table 3) and the combined analysis of variance was calculated as indicated in table 3. The homogeneity of error variances test was verified using Bartlett test for the trait evaluated and the combined analyses of the variance across locations were computed using R software 4.1 versions. The mean comparison of the hybrids was done by LSD test at 5% probability levels.

Table 3: Outline of analysis of variance for individual locations

Sources	DF	SS	MS	Expected MS
Replication (R)	(r - 1)	SSr	MSR	$\sigma^2e + g\sigma^2r$
Genotypes (G)	(g - 1)	SSg	MSG	$\sigma^2e + r\sigma 2g$
Error (e)	(r - 1) (g - 1)	SSe	Mse	σ^2e

SS_r =sum square of replication, SS_g = sum square of genotypes, SS_e= sum square of error, MS_e = mean squares due to error, MS_G = mean squares due to genotypes, MS_R = mean squares due to replications.

The statistical model for combined analysis of variance was as outlined by (Gomez and Gomez, 1984). $Yijk = \mu + Gi + Ej + GEij + Bk(j) + \epsilon ijk$ Where, Yijk, is the total variation of the response variable, μ the grand mean, Gi the treatment/genotype effect, Ej the location effect, Bk(j) the effect of the replication within location, GEij the interaction effect between genotype vs. location and ϵijk the residual.

Table 4: Combined Analysis of Variance Over location

Source	Df	MS	Expected MS	F- ratio
Total	ERG- 1			
Environment (E)	E – 1	MS_E	$\sigma^2e + g\sigma^2R(E) + RG\,\sigma^2E$	MSE/MSGE
Rep/ Env't (R)	E(R -1)	MSR	$\sigma^2e + g\sigma^2R(E)$	
Genotype (G)	(G - 1)	MSG	$\sigma^2e + g\sigma^2GE + ER\,\sigma^2G$	MSG/MSGE
G x E Interaction	(E- 1) (G - 1)	MSGE	$\sigma^2e + g\sigma^2GE$	MSGE/MSe
Pooled Error (e)	E (G - 1) (R-1)	MSe	σ^2e	

G = number of genotypes, E = number of environments, MSE = mean squares due to environments, MSR = mean squares due to block (locations), MSG = mean squares due to genotypes, MSGE = mean squares due to G x E and MSe = mean squares due to residual and R = number of replications.

GGE bi plot

Superior maize hybrids were selected using GGE biplot analysis. GGE (Genotype and Genotype by Environment) biplot was proposed by (yan *et.al.* 2000) to select high-yield varieties that are stable and adaptable to multi environment conditions. GGE biplot model was formulated as (Gauch, 2006).

$$Y_{hij} = \mu + E_h + G_i + GE_{hi} + B_{j(h)} + e_{hij},$$

Where μ is the population mean, Eh is the environmental effect, Gi is the genotypic effect, GE_{hi} is the genotype by environment effect, Bj(h) is the block effect, and eh_{ij} is the random error.

GGE biplots based on average environment coordination (AEC) was used to determine yield performance and stability of 24 Maize hybrids. Environment-focused scaling was used to test the relationship of the test environments. A GGE polygon view was also used to identify high yielding genotypes in specific environments through analysis of the "which won where pattern" (Yan *et al.*, 2000).

Analysis of Variance for grain yield across environments

The results of combined ANOVA showed that the mean squares of genotype, location and G x E were significant. The significant mean square of G x E showed the hybrids had differential performances over locations. The significance of GEI showed that the genotypes' performance varies from one location to another. As a result, grain performance stability should be examined. The hybrids with specific adaptability to each environment and hybrids with general adaptability were investigated and identified. Other workers Balestre *et al*. (2009), Warke *et al*., (2013), Lalise *et al*., (2015), Demisssew *et al*., (2016), Legesse *et al*., (2020), Gemechu *et al*., (2021), Seyed *et al*., (2021) also observed differential response for grain yield in improved maize hybrids when grown in different environments.

Table 5: Mean square from combined analysis of variance for grain yield and yield related traits of maize hybrids evaluated at six locations in Ethiopia during 2020 cropping season

Source of variation	Df	Mean square
Rep within Environment	12	2.81
Genotype	23	10.81 **
Environment	5	247.92**
GEI	115	4**
Error	276	0.50
CV (%)		9.3

ns,*and**, non-significant, significant at 5% and 1% probability level.

GGE Biplot

Mean Grain Yield and Yield Stability of hybrids

The GGE biplot is presented with two principal components explaining a total of 66.92% (PC1 = 44.07%, PC2 = 22.72 %,) of the maize grain performance variation, indicating the high relative validity of the biplot graph obtained from this study in explaining the G + GE changes. In the GGE bi plot (showed in figure 1) the hybrids were ranked along the average-tester axis (ATC abscissa), with the horizontal line based on their average performance across the six locations. The single-arrowed line is the average environment coordinate (AEC) abscissa (or AEA) and points to higher mean yield across environments (Figure1). Accordingly, in this study from this graph, hybrids, WE3105 (G13), 3XM1900476 (G15) SXM1910007 (G16), WE3106 (G17) and WE7131 (G18) were high yielding while SXM1910173 (G11) and WE7124 (G2) low yielding. The AEC ordinate separate hybrids that had below average grain yield from those showing higher grain yields than the average accordingly, hybrids SXM1910173 (G11), WE2108 (G4), WE7124 (G2), WE1101 (G22), WE7126 (G19), and BH 547 showed below-average mean grain yield and hybrids WE7131 (G18), WE3106 (G17), SXM1910007(G16), CZH15523(G14) and WE3105(G13) showed above-average mean. From the figure 1 the hybrids that had long distance from the AE abscissa in either direction indicates greater GE interaction and reduced stability. Thus Hybrids SXM1910008 (G8) and WE6103 (G24) are the highest yielding but most unstable hybrids, while CZH15587 (G5) and WE7117 (G6) are the lowest yielding but very stable. For selection, the ideal genotypes are those with both high mean yield and high stability. So those, hybrids SXM1910007 (G16), WE3106 (G17) and WE7131 (G18) were the high yielding and most stable and therefore identified as the best widely adapted hybrids across locations. In the present study, hybrids SXM1910173 (G11), WE2108 (G4), WE7124 (G2), CZH15587 (G5) and WE7117 (G6) was low yielding and not considered for production. In line with findings in this study, several researchers reported the relative contribution of stability and mean grain yield for the identification of desirable hybrid following the GGE bi-plot procedure (Yan *et al.*, 2007; Demisew *et al.*, 2016; Oral *et al.*, 2018 Legesse *et al.*, 2018).

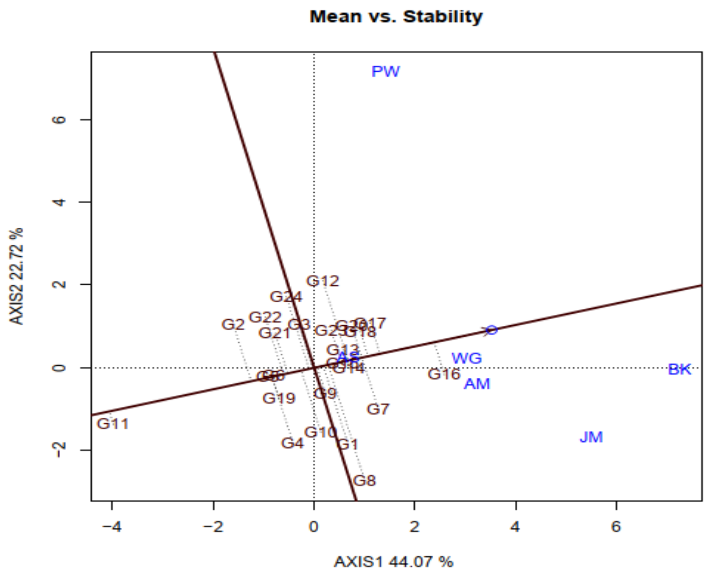

Figure 1: GGE biplot showing "mean vs. stability" of 24 maize hybrids across 6 environments

The hybrids, G1-G24 = recoded hybrids for easy of presentation in the thesis and locations are indicated by their identification names. Where BK=Bako, AM=Ambo, JM=Jimma PW=Pawe, WG=Wendogenet AS=Asosa,

"Which-Won-Where" Patterns

In the polygon there were six sectors. Accordingly, hybrids, Limu (G12), SXM1910007 (G16), SXM1910008 (G8) and SXM1910173 (G11), located at the corner of a polygon were vertex hybrids with longest vectors. vertex hybrids in each sector represents the highest yielding hybrids in the location that falls within that particular sector and in comparison to other, these hybrids were among the most responsive to the environments in their respective directions But the three hybrids, SXM1910173 (G11), WE7124 (G2) and WE2108 (G4), were the low-yielding and located far away from all the test locations, reflecting poorly yielded at all location. The hybrids within the polygon were less responsive to location than the corner hybrids. As shown in Figure 2, the rays of the two-line graphs divided the graph into six parts, with five environments appearing in one sector and the remaining environments appearing in another by identifying the existence of two mega-environments where SXM1910007(G16) hybrid was in winning environments (BK, JM, AM and WG), and limu(G12) winning environment (PW). Several authors who reported and identified mega-environments and possibility of selecting stable hybrids using GGE bi-plot models (Yan *et al*., 200; Yan *et al.*, 2007; Legesse *et al*., 2019; Abel *et al.*, 2019; Gemechu *et al.*, 2021).

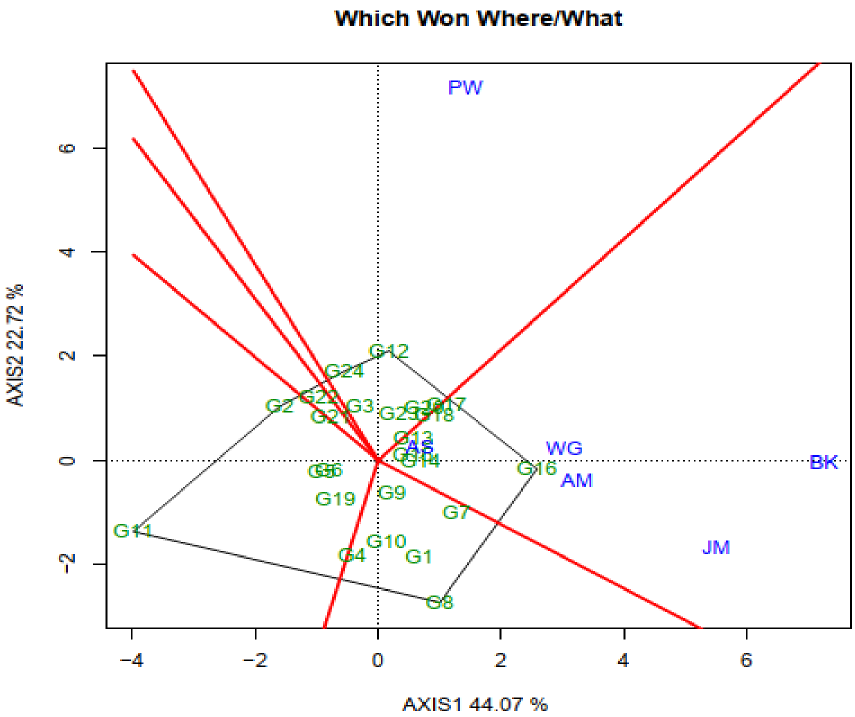

Figure 2: Which-won-where pattern of GGE biplot for 24 maize hybrids evaluated across six locations. The hybrids are indicated in block letter while the locations are indicated by their identification names. Where BK=Bako, AM=Ambo, JM=Jimma PW=Pawe, WG=Wendogenet AS=Asosa, AXIS1=PC1 AXIS2=PC2

Discriminating ability of testing location

The obtained result showed that among the six test environments (showed in figure 3) environments, Pawe, Jimma, and Bako were most discriminating or hold more information about hybrids while Asosa were less discriminating and consistently non-discriminating (non-informative) provide little information on the hybrids as it fall close to bi-plot origin and very short vector). Jimma and Pawe had long vectors and large angles with the AEC abscissa and this suggesting that they may not be used in picking superior hybrids, but may be used in culling unstable hybrids and selecting specifically adapted hybrids environment therefore this environment is discriminating but non-representative. Among environments Bako were more discriminating the hybrid and representative of the test environments and consequently are ideal for selecting superior hybrids so that is both discriminating and representative environments. Many authors (Dagnechew *et al*., 2014; Abel *et al*., 2019; Abel *et al*., 2019; Gemechu *et al.*, 2021) were used GGE biplot to identify high representativeness and discriminating test environments for genotypes of different crops.

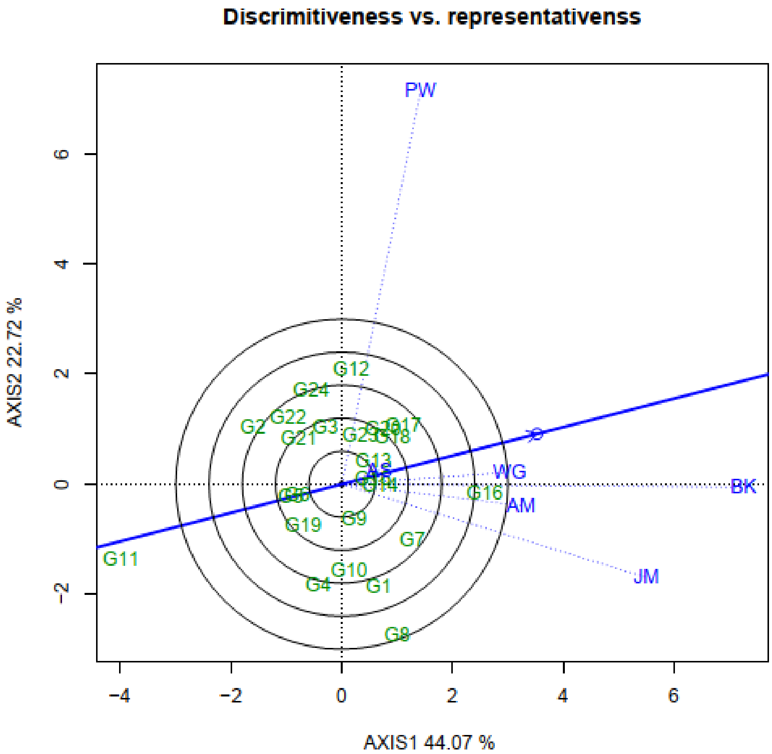

Figure 3: GGE biplot showing Rank of test locations based on both discriminating ability and representativeness. AXIS1=PC1, AXIS2= PC2, BK=Bako, AM=Ambo, JM=Jimma PW=Pawe, WG=Wendogenet AS=Asosa

CONCLUSIONS

The results of experiment indicated the presence of significant variations among the 24 maize hybrids. The results of combined ANOVA showed that the mean squares of genotype, location and G x E were significant. The SXM1910007 hybrid had the highest yielding of all genotype with mean grain yield of 8.68 t/ha. The two hybrids, WE3106 and WE7131 along with other two hybrids were identified as most stable hybrids for yield GGE bi plot. Among environments Bako had long vectors and small angles with the AEC abscissa this showed Bako is more discriminating the hybrid and representative of the test environments and consequently are ideal for selecting superior hybrids so that is both discriminating and representative environments. The identified desirable maize hybrids could be used as candidate varieties for cultivation in major maize growing areas of Ethiopia. However, the identified HYBRIDS need to be further evaluated under verification trial over many locations to be recommended as commercial varieties.

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