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Yield performance and stability evaluation of *Striga*-resistant sorghum (*Sorghum bicolor* [L.] Moench)

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Sorghum is one of the most important cereal crops in Ethiopia. However, the productivity of this important crop is low owing to different factors, of which *Striga* is most detrimental. Multi-environment performance evaluation was carried out consisting of 11 sorghum genotypes. The objective was to select better performing, *Striga*-resistant and stable sorghum lines. The trial was conducted at three *Striga* prone areas of North-east Ethiopia for two years. The result of combined analysis of variance across locations over the years showed that genotype × location × year of interaction significantly affected all traits except days to heading, which indicate the inconsistency of the genotypes in different locations and cropping seasons. All the genotypes supported significantly lower number of *Striga* than the susceptible and local checks. Log transformed value of *Striga* count ranged from 1.41 for G5 to 2.71 for G10. The performance of the genotypes on individual locations showed that G7 was the highest yielding genotype, followed by G9 on environment Kobo 03. The additive main effect and multiplicative interaction (AMMI) analysis of variance showed that the total G×E variance was explained by three significant interactions principal component axes (IPCAs), which contributed 95.8% in total, while the genotype and genotype by environment (GGE) explained 90.18% of the G×E variance. Based on *Striga* resistance, agronomic performance and yield stability of genotypes, G7, G8 and G9 were found to be better sorghum genotypes for the area under consideration. Genotype G9 is a brown seeded and short-stalked released variety; whereas G8 (Gambella1107 × P-9403), as it was preferred by farmers, has been released by the name *Gedo* for production in the *Striga* prone areas of North-eastern part of Ethiopia. The three genotypes could be used as sources of *Striga*-resistance in future crossing programs.

Key words: Additive main-effect and multiplicative interaction (AMMI), desirable genotype, genotype and genotype by environment (GGE), interaction principal component axes (IPCAs), *Striga hermonthica.*

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is the most important crop for smallholder farmers of the semi-arid tropics, where rainfall is unpredictable and the temperature is variable (Bantilan et al., 2004). In Ethiopia generally, and in Northeast Ethiopia in particular, sorghum is very important and has a multitude of uses. The grain is used for food preparations like *injera*, porridge and local beverages like *tella* and *araki*. The stalk is used for

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Table 1. Global position and climatic information of the study locations.

Location	Altitude (m)	Soil type	Rainfall (mm)	Temperature		Global position	
				Min (°C)	Max (°C)	Latitude	Longitude
Kobo	1450	*Eutric fluvisol*	637	15.8	29.1	12°8'21''	$39^0$18'21''
Gobye	1670	*NA*	NA	NA	NA	11°53'06''	$39^0$42'00''
Sirinka	1850	*Eutric vertisol*	945	13.6	27.3	11°45' 00''	39^o36'36"

NA= not available.

livestock feed, fire wood and construction of simple traditional houses. As a result, high-yielding tall cultivars are preferred by farmers. In 2018, about 5 million tons of sorghum was produced on 1829662.39 ha of land by 4739613 producers (CSA, 2019).

However, the productivity of this important crop is low owing to different production limiting factors, of which *Striga* (*Striga hermonthica*) play a momentous role. *Striga*, also known as witch-weed, is the most detrimental weed in Northeast Ethiopia, causing sizable yield losses in sorghum.

Striga is an obligate parasite that needs a suitable host plant for its survival; as high as 200,000 very small seeds can be produced by a single *Striga* plant under ideal conditions (Hearne, 2009). In some countries, 20 to 80% yield loss have been documented (Atera and Itoh, 2011). Some agronomic practices (Udom et al., 2007), water and soil fertility management methods (Ayongwa et al., 2006; Reda and Verkleij, 2007; Jamil et al., 2011) and trap crops (Schulz et al., 2003) have been recommended for *Striga* control. However, it had limited success due to its less convenience, need of medium to high level of investment and training (Oswald, 2005). Common weed control methods, although able to reduce the *Striga* seed bank, are ineffective in improvement of sorghum productivity as the witch-weed causes significant damage before it emerges above ground (Ejeta et al., 1991).

The use of resistant varieties is more practical, reliable and economically feasible means of *Striga* control, it also has no adverse effect on the environment as chemicals are not involved. Low production of *striga* germination stimulant by host plants is one of the known mechanisms for *Striga* resistance (Vogler et al., 1996). The presence of ample variability for low *Striga* germination stimulant has been reported in sorghum (Yohannes et al., 2016).

Sorghum varieties with consistent resistance were identified and released in Ethiopia. However, some of these varieties had poor grain qualities (brown colored and covered by glumes) and were less preferred by farmers. As a result, identifying *Striga*-resistant sorghum varieties, which are better in productivity and grain quality characteristics than the existing cultivars, has been one of the main research priorities in the country.

Therefore, the objective of the experiment was to identify desirable *Striga*-resistant sorghum genotypes for moisture deficit and *Striga* prone areas of North-eastern Ethiopia.

MATERIALS AND METHODS

The experiment was carried out in different locations that represent sorghum production areas of North-east Ethiopia where *Striga* infestation is a serious problem. *Striga* sick plots at Sirinka, Kobo and Gobye were used to test genotypes (Table 1).

The materials include eight test entries, a susceptible check (KNE # 8574), a farmers' cultivar (*Jigurti*) and an improved *Striga* resistant variety (*Birhan*) cumulating eleven sorghum genotypes. The eight entries and the susceptible check were received from the national sorghum research program of Ethiopia. *Birhan*, KNE # 8574 and *Jigurti* were used as checks for comparison in all cases. The experiment was arranged in randomized complete block design (RCBD) with three replications. Planting was done from the end of June to the beginning of July, at the onset of the rain both in 2003 and 2004 cropping seasons. The materials were planted in 5 m × 3.75 m plot using 75 cm and 15 cm spacing between rows and plants, respectively. Fertilizers were added at the rates of 41 kg ha^{-1} N and 46 kg ha^{-1} of P_2O_5, weeding of other weed than *Striga*, were done uniformly as required.

The relevant data were collected for days to heading and maturity, plant height (cm), number of *Striga* emerged, 1000-seed weight (g) and grain yield (t ha^{-1}). Analysis of variance for number of *striga* emerged was performed after logarithmic [log (X+1)] transformation as outlined by Sokal and Rohlf (1995). The model suggested by Crossa et al. (1990) was used to implement Additive Main-effect and Multiplicative Interaction (AMMI) analysis. The procedure of Yan et al. (2000) was employed to analyze genotype plus genotype-environment interaction (GGE). To compute AMMI stability value (ASV), the formula forwarded by Purchase et al. (2000) was adopted. Ecovalence (W_i), the squared sum of G×E effects for each genotype across environments, was computed as per Wricke (1962). The estimates of mean ranks of genotypes was based on Nassar and Hüehn (1987). Combined analysis of variance across locations and over years, and all the stability parameters were computed using GenStat (16th edition) software.

RESULTS AND DISCUSSION

ANOVA and performance of genotypes

Combined analysis of variance across locations and over years showed significant ($p < 0.01$) differences among genotypes for all traits investigated, including *Striga* count. The result is in harmony with the findings of Ayana et al. (2019) and Mamo et al. (2020) who reported differences of sorghum genotypes in number of *Striga* supported in Ethiopia. Except for days to heading, genotype (G) × location (L) × year (Y) interaction showed significant differences for all traits, which indicate the

Table 2. Mean grain yield, *Striga* count and agronomic data of sorghum genotypes combined across three locations and over two years.

Genotype	Days to heading	Days to maturity	Plant height (cm)	*Striga* count[1]	1000-seed weight (gm)	Grain yield (t ha^{-1})
99MI 5008 P#2	82	125	112.78	1.64	27.78	1.418
99MI 5018 P#5	85	131	114.22	1.55	29.44	1.068
99MI 5142 P#42	80	126	110.28	1.46	32.22	1.551
2000 MW 6040 P#35	83	128	114.11	1.50	30.94	1.254
2000 MW 6081 P#38	82	127	133.39	1.41	30.61	1.597
SR P#4 SRSON 2001	81	127	114.22	1.59	30.89	1.540
ICSV-1112BF × SRN-39	79	124	111.5	1.70	28.83	1.789
Gambella1107 × P-9403	78	125	113.17	1.88	32.17	1.576
Birhan (Key#8566)	85	124	106.44	1.60	29.39	1.750
KNE # 8574	76	135	113.83	2.71	20.44	0.508
Jigurti	91	130	206.89	2.53	33.06	1.282
Mean	82	127	122.8	1.78	29.61	1.394
G	**	**	**	**	**	**
G×L×Y	NS	**	**	NS	**	**
LSD (5%)	2.31	1.3	7.31	0.24	1.56	0.216
CV (%)	4.28	1.54	9.02	23.01	7.96	23.47

G×L×Y = Genotype-location-year interaction, **= significant at 1% probability level, NS= nonsignificant. [1] log transformed value.

inconsistency of the genotypes in different locations and cropping seasons (Table 2). Similar results were reported in sorghum under non-infested condition (Worede et al., 2021, 2022). The significant G×L×Y interaction in the present study is an indication to further analyze the data set to assess the extent of genotype-environment interaction (G×E) by employing AMMI and GGE models.

Days to heading ranged from 76 for KNE # 8574 to 91 for farmers' variety *Jigurti*. Days to maturity varied from 124 for *Birhan* and ICSV-1112BF × SRN-39 to 135 for KNE # 8574. The finding indicates that KNE # 8574 was the earliest to head but very late to mature. Plant height varied from 106.44 for *Birhan* to 206.89 cm for *Jigurti*. *Striga* count also ranged from 1.41 for 2000 MW 6081 P#38 to 2.71 for KNE # 8574 (susceptible check). All the genotypes support significantly lower number of *Striga* than the susceptible and local checks. Thousand seed weight ranged from 27.78 g for 99MI 5008 P#2 to 33.06 g for *Jigurti*. Genotypes G3 and G8 were significantly higher than the standard check (*Birhan*) in thousand-seed weight but not from that of *Jigurti*. Grain yield varied from 0.508 t ha^{-1} for KNE # 8574 to 1.789 t ha^{-1} for ICSV-1112BF × SRN-39 with a mean of 1.394 t ha^{-1}. Comparatively, ICSV-1112BF × SRN-39 was the highest-yielding genotype followed by *Birhan*, 2000MW6081 P#38 and Gambella1107 × P-9403; the difference between them was not statistically significant, however (Table 2). The grain yield is lower than the one reported by Belay et al. (2020) based on the mean of five locations.

The performance of the sorghum genotypes on individual locations showed that G7 (3.426 t ha^{-1}) was the highest yielding genotype followed by G9 (3.064 t ha^{-1}) on Kobo03. In relative terms, Gobye04 and Kobo03 were highest-yielding environments; however, Gobye03 was the lowest-yielding environment (Table 3).

AMMI analysis

The AMMI analysis of variance of the eleven genotypes showed that G, E and G×E significantly affected sorghum grain yield. Belay et al. (2020) and Worede et al. (2021) also reported significant ($P<0.001$ and $P<0.01$) effects of the three terms on yield of *Striga*-resistant and malt sorghums using multi-location data. The result of the present investigation also showed that most of the treatment variance was explained by E (64.59%) followed by G (20.82%). The total G×E variance was explained by three significant IPCAs, of which IPCA1, IPCA2 and IPCA3 contributed 62.12, 25.08 and 8.60%, respectively (Table 4). The result corresponds with that of Human et al. (2011) who explained 88.61% of the G×E by three significant IPCAs. Belay et al. (2020) also explained 90.2% of the G×E by two IPCAs using multi-location data set of *Striga*-resistant sorghum.

The AMMI1 biplot showed that genotypes G7, G9 and G5 were higher-yilding genotypes in that order of importance; whereas G11, G4, G2 and G10 were genotypes with below average performance. Genotypes G2, G7, G9 and G10 had higher interaction scores, as a result they are reactive to environmental changes; G3 and G4 on the contrary had near zero interaction as a result they are stable in their performance (Figure 1).

Table 3. Mean grain yield (t ha^{-1}) of 11 sorghum genotypes grown on six environments.

Genotype		**Environment**					
Identification	**Code**	**Sirinka03**	**Kobo03**	**Gobye03**	**Kobo04**	**Sirinka04**	**Gobye04**
99MI 5008 P#2	G1	1.076	1.957	1.284	0.823	1.092	2.273
99MI 5018 P#5	G2	1.135	0.995	0.467	0.677	1.410	1.724
99MI 5142 P#42	G3	1.208	2.333	1.300	0.464	1.211	2.790
2000 MW 6040 P#35	G4	1.045	2.027	0.697	0.564	0.991	2.198
2000 MW 6081 P#38	G5	1.241	2.666	0.769	0.965	1.500	2.443
SR P#4 SRSON 2001	G6	1.248	2.451	0.597	0.795	1.556	2.589
ICSV-1112BF × SRN-39	G7	1.521	3.426	0.656	1.081	1.592	2.456
Gambella1107 × P-9403	G8	1.194	2.150	0.834	1.022	1.870	2.386
Birhan (Key#8566)	G9	1.308	3.064	0.515	1.271	1.623	2.721
KNE # 8574	G10	0.711	0.675	0.085	0.163	0.529	0.886
Jigurti	G11	1.077	2.427	0.382	0.717	1.265	1.824
Genotype mean		1.160	2.197	0.690	0.777	1.331	2.208

Table 4. AMMI analysis of variance for grain yield of 11 sorghum genotypes.

Source	**df**	**SS**	**MS**	**Variance explained (%)**	**G×E explained (%)**
Treatments	65	38.214	0.5879		
Genotypes	10	7.958	0.7958**	20.82	
Environments	5	24.684	4.9367**	64.59	
G×E Interactions	50	5.572	0.1114**	14.58	
IPCA 1	14	3.4611	0.2472**		62.12
IPCA 2	12	1.3977	0.1165**		25.08
IPCA 3	10	0.479	0.0479*		8.60
Residuals	14	0.234	0.0167		

**,*= significant at 0.01 and 0.05 probability levels, respectively.

By the same fashion, Kobo 03 and Gobye 04 were comparatively high yielding environments, while the rest were low yielding. The environment Kobo 03 exerted the highest interaction followed by Gobye 03 while the remaining environments had intermediate interaction effects (Figure 1).

The vector length of environments in AMMI2 biplot signifies magnitude of interaction imposed on the genotypes (Fan et al., 2001) while the vector of the genotypes indicates the response of genotypes to different environments (Purchase et al., 2000). Hence, Kobo 03 and Gobye 03 exerted higher effect to the G×E variance as a result these environments are highly discriminating; the rest had intermediate effects. Similarly, G3 followed by G1 had higher interaction effects; as a result they are specifically adapted to certain environments. Genotypes G6, G4, G5 and G8 had relatively small interaction; consequently they are better adapted to all the environments considered in the study (Figure 2). In agreement to the present finding, Worede *et al.* (2020, 2021) reported three and six stable early cycle sorghum genotypes, respectively, adapted to Northeast Ethiopia.

GGE analysis

About 90.18% of the GGE variance was explained by the first two PC axes (Figure 3). The value is higher than that of Worede et al. (2021, 2022) who reported 75.11 and 78.28% in early-maturing and malt sorghums, respectively. The finding is in ageement with Assefa et al. (2020) who reported that the first two IPCAs explained 93.01% of the GGE variance. As stated by Yan and Tinker (2006), the arrowed line (Figure 3) points to higher mean grain yield across environments. Hence, genotypes G7, G9, G3 and G8 were high-yielding genotypes; G1 had grain yield a little bit higher than the grand mean. Nevertheless, G11, G4, G2 and G10 were below average performing in terms of grain yield. The GGE agrees with AMMI1 analysis with this regard. Genotypes G7 and G10 were the highest and lowest yielding genotypes, respectively; which is in agreement with the AMMI1 analysis. The line perpendicular to the arrowed line, in

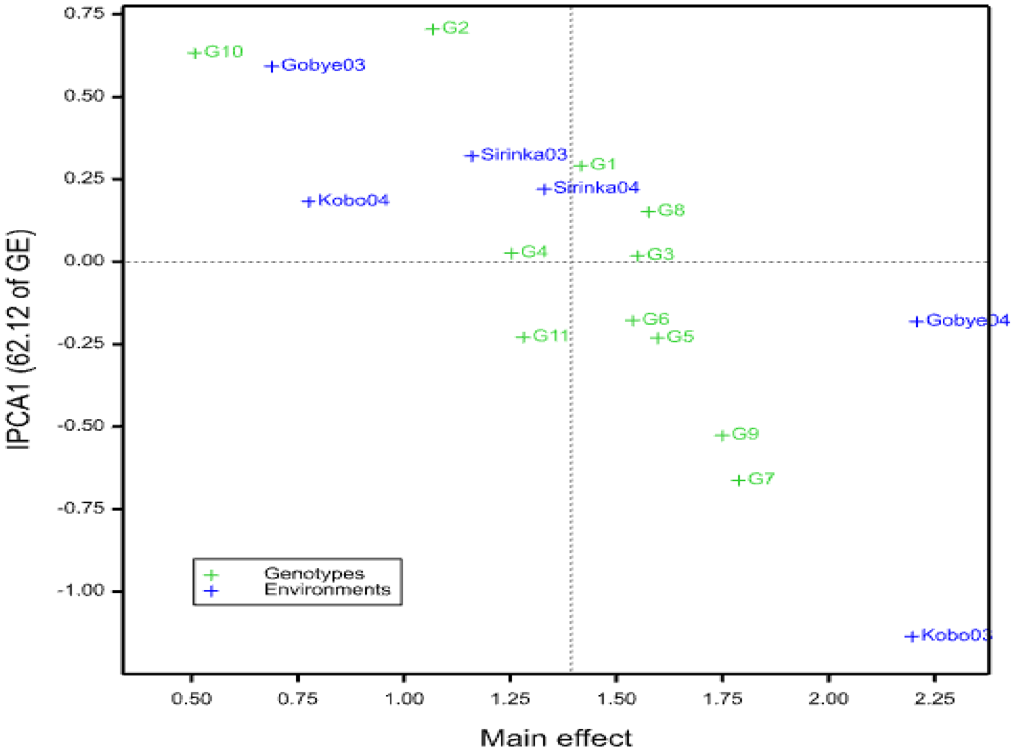

Figure 1. AMMI1 biplot of 11 sorghum genotypes and six environments plotted against mean grain yield and IPCA1. Genotype codes are as listed in Table 3.

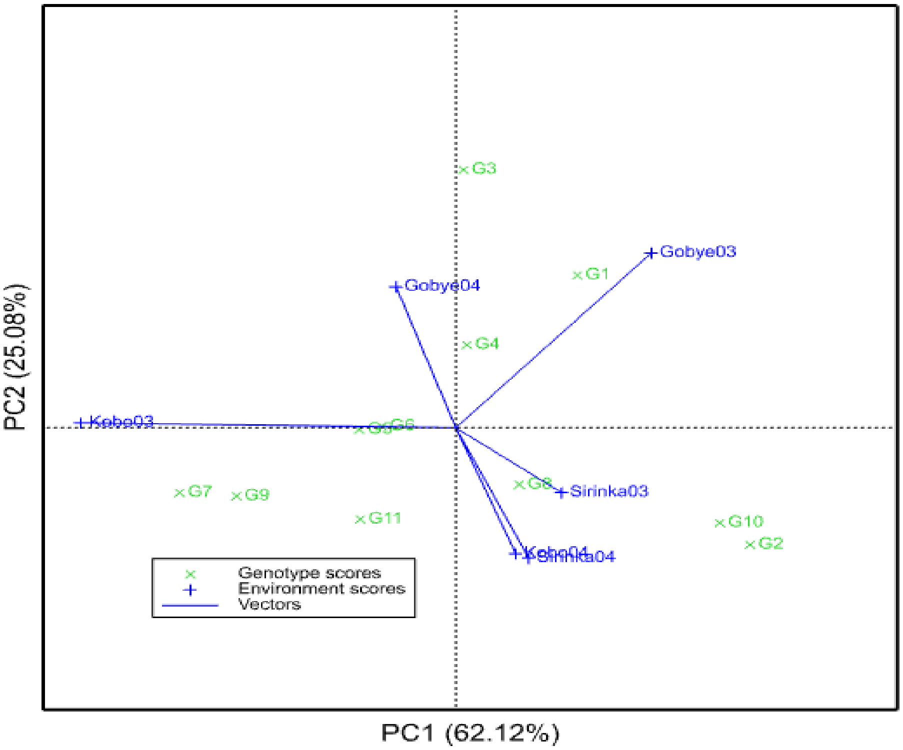

Figure 2. AMMI2 biplot of 11 sorghum genotypes and six environments plotted against IPCA1 and IPCA2. Genotype codes are as listed in Table 3.

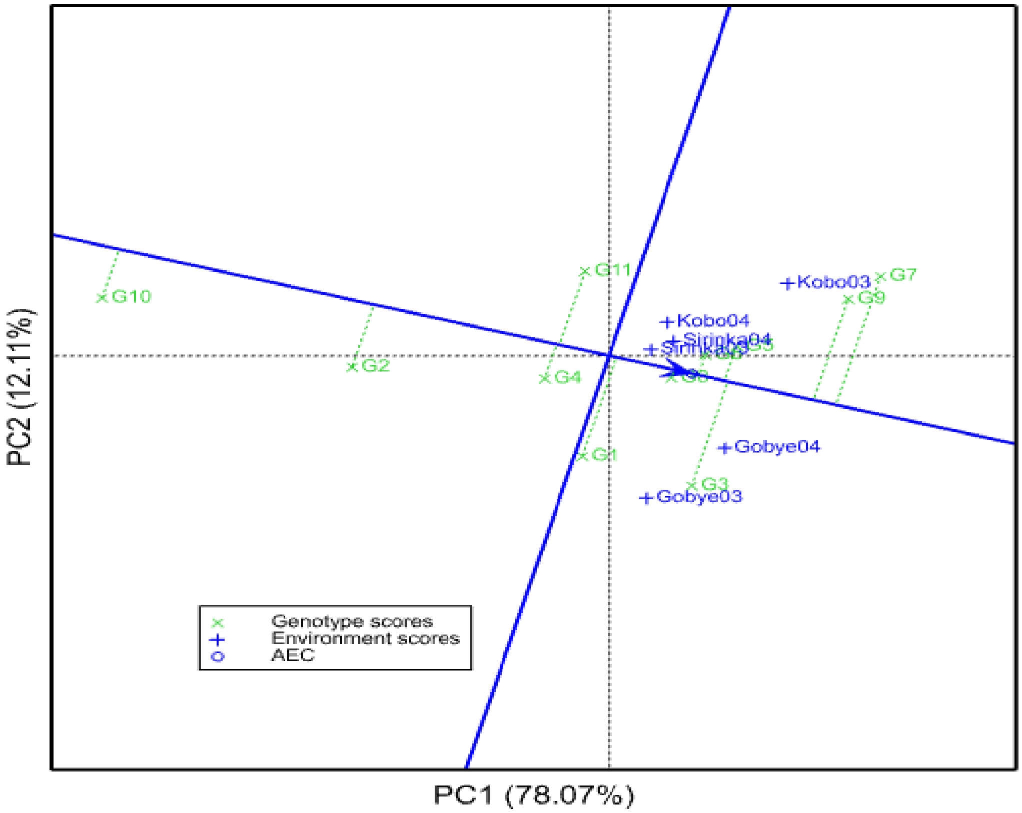

Figure 3. The average-environment coordination view showing the mean performance and stability of the 11 sorghum genotypes. Genotype codes are as listed in Table 3.

either direction, points to higher variability of performance (Yan and Tinker, 2006). Hence, the genotype G8, which lied on the abscissa of the AEC, was the most stable genotype; G4, G5, G6 and Gb10 were also better in terms of yield stability. In agreement with the present finding, Worede et al. (2021) reported four stable early cycle sorghum genotype identified by the same technique. However, stable genotypes are desirable only when they have high mean performance (Yan and Tinker, 2006). Figure 4 showes the desirability of genotypes across environments. In the figure, the ideal genotype is pointed by an arrow at the center of the concentric circles; genotypes placed closer to this genotype are assumed to be desirable (Yan and Tinker, 2006). Accordingly, G9, G7, G8, G6 and G5 are desirable genotypes. The result is in general agreement with the findings of Belay et al. (2020). Worede et al. (2021) also identified four genotypes by employing AEC view of mean performance and stability of GGE biplot.

Stability analyses

Basically, AMMI stability value (ASV) is the distance from zero in a two-dimensional plot of IPCA1 and IPCA2 scores; a genotype with a smallest ASV is assumed to be the most stable (Purchase et al., 2000). Based on ASV, G4, G8, G6 and G5 were the first four stable genotypes in that order of importance (Table 5). Chala et al. (2019) and Worede et al. (2022) recommended two sorghum genotypes using ASV of multi-location trials of sorghum in Ethiopia. In the present study, the GGE stability biplot and ASV were in agreement in identifying similar stable sorghum genotypes. Rakshit et al. (2017) also reported such correspondence in a study of post-rainy sorghum in India.

According to Wricke (1962), a genotype with zero ecovalence is considered as stable. In relation to Wricke's ecovalence values, genotypes G4, G5, G6 and G8 were better in stability in that order of importance (Table 4). Using the same stability statistic, Worede et al. (2022) reported three most stable sorghum genotypes under *Striga* non-infested condition.

Genotypes with lower values of mean ranks are regarded as stable (Nassar and Hüehn, 1987). Hence, G7 and G9 were equally important and were the best genotypes according to mean ranks stability coefficient. Genotypes G5 and G8 were the third and fourth important genotypes (Table 5). The finding agrees with that of Worede et al. (2022) who reported three stable

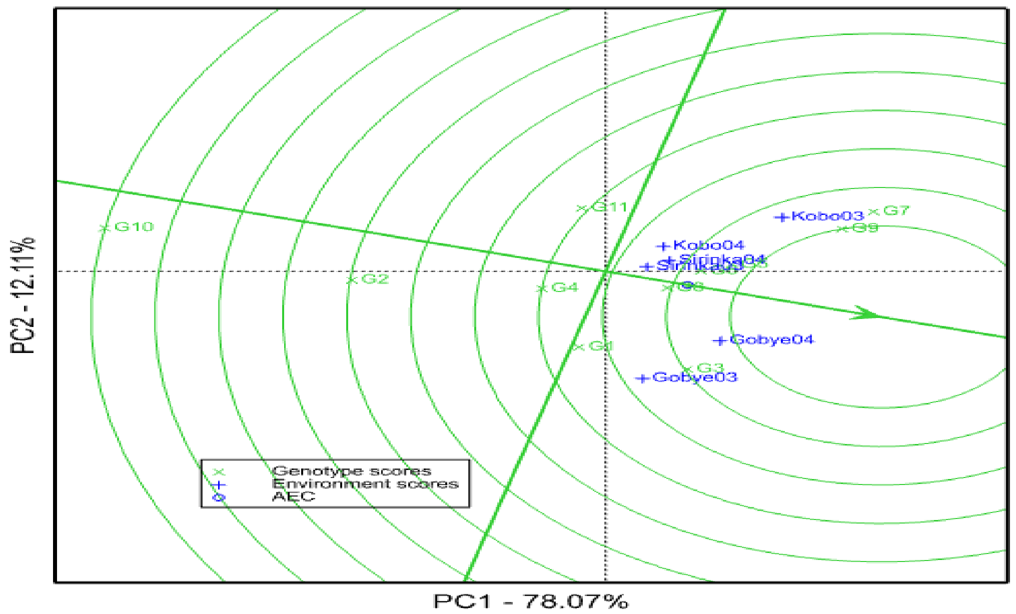

Figure 4. The average-environment coordination view of ranking the 11 sorghum genotypes relative to an ideal genotype. Genotype codes are as listed in Table 3.

Table 5. Grain yield, interaction principal component axes (IPCAs) and stability coefficients of sorghum genotypes for grain yield on six environments.

Genotype		Mean grain yield (t ha^{-1})		IPCA1		IPCA2		ASV		Wricke's covalence		Mean ranks	
Identification	**Code**	**Value**	**Rank**	**Value**	**Rank**	**Value**	**Rank**	**Value**	**Rank**	**Value**	**Rank**	**Value**	**Rank**
99MI 5008 P#2	G1	1.418	7	0.292	9	-0.444	2	0.847	7	0.479	6	6.833	7
99MI 5018 P#5	G2	1.068	10	0.706	11	0.340	11	1.780	11	1.109	11	8.333	9.5
99MI 5142 P#42	G3	1.551	5	0.019	6	-0.750	1	0.752	6	0.695	8	5.167	6
2000 MW 6040 P#35	G4	1.254	9	0.026	7	-0.241	3	0.249	1	0.085	1	8.333	9.5
2000 MW 6081 P#38	G5	1.597	3	-0.231	3	0.005	5	0.572	4	0.103	2	4.167	3
SR P#4 SRSON 2001	G6	1.540	6	-0.178	5	-0.005	4	0.440	3	0.150	3	4.500	5
ICSV-1112BF × SRN-39	G7	1.789	1	-0.662	1	0.189	7	1.650	10	0.928	9	2.833	1.5
Gambella1107 × P-9403	G8	1.576	4	0.152	8	0.165	6	0.410	2	0.208	4	4.333	4
Birhan (Key#8566)	G9	1.750	2	-0.526	2	0.198	8	1.318	8	0.634	7	2.833	1.5
KNE # 8574	G10	0.508	11	0.633	10	0.277	10	1.591	9	0.947	10	11.000	11
Jigurti	G11	1.282	8	-0.229	4	0.266	9	0.626	5	0.235	5	7.667	8

ASV= AMMI stability value.

malt-sorghum genotypes in Northeast Ethiopia.

The present investigation demonstrated that G7, G8 and G9 are better genotypes for the area in question. They could be utilized as parents in future sorghum improvement programs for *Striga* resistance. The three genotypes had comparable yield and *Striga* resistance level. However, G9 is brown colored and short-stalked, hence less preferred by farmers than the other two genotypes. From the other two, farmers preferred G8 as it had bold seeds.

Based on performance data and field evaluation result both on-station and on-farm, the National Variety Release Committee approved the release of G8 (Gambella1107×P-9403) in 2007 to be grown in *Striga* prone areas of Northeast Ethiopia. The variety is given a local name called *Gedo.* It is a line derived from the crossing of two released varieties. One of the parents, Gambella1107, is a collection from Ethiopia and released in several East and Central African countries (Obilana, 2004). The other parent, P-9403 (also called *Abshir*), is a *Striga* resistant variety adapted to Northern part of Ethiopia. *Gedo* is as early as the standard check (*Birhan*) and earlier than the farmers' cultivar (*Jigurti).* It has a comparatively taller stalk than *Birhan* and shorter than *Jigurti*. The seed is bold and pale yellow colored. It supports minimum number of *Striga* than the farmers' cultivar. By using the variety, farmers in the area can harvest acceptable sorghum grain while reducing the *Striga* seed bank in the soil which would be a sustainable witch-weed management practice.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interests.

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REFERENCES

Assefa A, Bezabih A, Girmay G, Alemayehu T, Lakew A (2020). Evaluation of sorghum (*Sorghum bicolor* (L.) Moench) variety performance in the lowlands area of Wag-Lasta, northeastern Ethiopia. Cogent Food and Agriculture 6(1):1778603.

Atera E, Itoh K (2011). Evaluation of ecologies and severity of *Striga* weed on rice in sub-Saharan Africa. Agriculture and Biology Journal of North America 2:752-760.

Ayana TT, Bantte K, Tadesse T (2019). Evaluation of Ethiopian sorghum [*Sorghum bicolor* (L.) Moench] landraces: low germination stimulant genotypes for *Striga hermonthica* resistance under field condition. Advances in Crop Science and Technology 7:444. doi: 10.4172/2329-8863.1000444

Ayongwa GC, Stomph TJ, Emechebe AM, Kuyper TW (2006). Root nitrogen concentration of sorghum above 2% produces least *Striga hermonthica* Stimulation. Annals of Applied Biology 149(3):255-262.

Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB, Evenso RE (2004). Introduction. In: Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB and Evenson RE (eds.). Sorghum genetic enhancement: research process, dissemination and impacts. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics pp. 5-18.

Belay F, Mekbib F, Tadesse T (2020). Genotype by environment interaction and grain yield stability of *Striga* resistant sorghum [*Sorghum bicolor* (L.) Moench] genotypes in Ethiopia. Ethiopian Journal of Crop Science 8(2):79-99.

Chala G, Tesso B, Lule D, Dessalegn K (2019). Additive Main Effect and Multiplicative Interactions (AMMI) and regression analysis in sorghum [*Sorghum bicolor* (L). Moench] varieties. Journal of Applied Biosciences 136:13868-13876.

Crossa J, Gauch Jr HG, Zobel RW(1990). Additive main effects and multiplicative interaction analysis of two international maize cultivar trials. Crop Science 30(3):493-500. https://doi.org/10.2135/cropsci1990.0011183X003000030003x

Central Statistical Authority (CSA) (2019). Agricultural Sample Survey: Report on area and production for major crops. Statistical Bulletin 589. Addis Ababa, Ethiopia.

Ejeta G, Butler LG, Babiker AG (1991). New Approaches to the Control of *Striga*: *Striga* Research at Purdue University. Perdue University Agricultural Experiment Station, Research Bulletin RB-991, p. 27.

Fan LJ, Hu BM, Shi CH, Wu JG (2001). A method of choosing locations based on genotype environment interaction for regional trials of rice. Plant Breeding 120(2):139-142. DOI: 10.1046/j.1439-0523.2001.00564.x

Hearne SJ (2009). Control - the striga conundrum. Pest Management Science 65(5):603-614.

Human S, Andreani S, Sihono, Indriatama WM (2011). Stability test for sorghum mutant lines derived from induced mutations with gamma-ray irradiation. Atom Indonesia 37(3):102-106.

Jamil M, Charnikhova T, Cardoso C (2011). Quantification of the relationship between strigolactones and *Striga hermonthica* infection in rice under varying levels of nitrogen and phosphorus. Weed Research 51:373-385.

Mamo M, Worede F, Bantayehu M (2020). Evaluation of sorghum (*Sorghum bicolour* (L.) Moench) genotypes for *Striga* resistance and yield and yield related traits. Black Sea Journal of Agriculture 3(2):85-95.

Nassar R, Hüehn M (1987). Studies on estimation of phenotypic stability: Test of significance for non-parametric measures of phenotypic stability. Biometrics 43:45-53. DOI: 10.2307/2531947

Obilana AB (2004). Sorghum breeding research in Africa. *In*: Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB and Evenson RE (eds.), Sorghum genetic enhancement: research process, dissemination and impacts. ICRISAT, Patancheru 502 324, Andhra Pradesh, India. pp. 105-136.

Oswald A (2005). Striga control-technologies and their dissemination. Crop Protection 24(4):333-342.

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 African Journal of Plant and Soil 17(3):101-107. DOI: 10.1080/02571862.2000.10634878

Rakshit S, Ganapathy KN, Gomashe SS, Dhandapani A, Swapna M, Mehtre SP, Gadakh SR, Ghorade RB, Kamatar MY, Jadhav BD, Das IK, Prabhakar (2017). Analysis of Indian post-rainy sorghum multi-location trial data reveals complexity of genotype × environment interaction. Journal of Agricultural Science 155(1):44-59.

Reda F, Verkleij JA (2007). Cultural and cropping systems approach for *Striga* management – a low-cost alternative option in subsistence farming. *In*: Ejeta G and Gressel J (eds.). Integrating new technologies for *Striga* control: towards ending the witch-hunt. World Scientific Publishing Co., Singapore pp. 229-240.

Schulz S, Hussaini MA, Kling JG, Berner DK, Ikie FO (2003). Evaluation of integrated *Striga hermonthica* control technologies under farmer management. Journal of Experimental Agriculture International 39:99-108.

Sokal RR, Rohlf FJ (1995). Biometry: The principles and practice of statistics in biological research. 3rd Edition, W.H. Freeman and Co., New York.

Udom GN, Babatunde FE, Tenebe VA (2007). Suppression of witch-weed (*Striga hermonthica*) in sorghum: cowpea mixture as affected by cowpea varieties and planting patterns. International Journal of Agricultural Research 2(3):268-274.

Vogler RK, Ejeta G, Butler LG (1996). Inheritance of low production of striga germination stimulant in sorghum. Crop Science 36(5):1185-1191. https://doi.org/10.2135/cropsci1996.0011183X003600050020x

Worede F, Tarekegn F, Teshome K (2021). Simultaneous selection for grain yield and stability of sorghum [*Sorghum bicolor* (L.) Moench] genotypes in Northeast Ethiopia. African Journal of Agricultural Research 17(10):1316-1323.

Worede F, Mamo M, Assefa S, Gebremariam T, Beze Y(2020). Yield stability and adaptability of lowland sorghum (*Sorghum bicolor* (L.) Moench) in moisture-deficit areas of Northeast Ethiopia. Cogent Food and Agriculture 6(1):1736865. https://doi.org/10.1080/23311932.2020.1736865

Worede F, Assefa S, Mamo M, Gebremariam T (2022). Multi-environment evaluation of malt sorghum in semi-arid areas of Northeast Ethiopia. Journal of Innovative Agriculture 9(2):50-56.

Wricke G (1962). Method of understanding the biological diversity in field research. Pfianzenzuchtg 47(1):92-146.

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

Yan W, Tinker NA (2006). Biplot analysis of multi-environment trial data: Principles and applications. Canadian Journal of Plant Science 86(3):623-645. https://doi.org/10.4141/P05-169

Yohannes T, Ngugi K, Ariga E, Abraha T, Yao N, Asami P, Ahonsi M(2016). Genotypic variation for low *striga* germination stimulation in sorghum (*Sorghum bicolor* (L.) Moench) landraces from Eritrea. American Journal of Plant Sciences 7:2470-2482. doi: 10.4236/ajps.2016.717215.