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Simultaneous selection for grain yield and stability of sorghum [*Sorghum bicolor* (L.) Moench] genotypes in Northeast Ethiopia

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Sorghum is an important crop in Ethiopia. However, its productivity is low owing to lack of farmer-preferred and stable improved varieties. To identify suitable cultivars, multi-environment evaluation of sorghum genotypes was carried out at four locations for two years. The result of AMMI ANOVA showed that genotype (G), environment (E) and genotype-environment interaction (G×E) significantly (*P<0.01*) affected sorghum grain yield. The G×E term was partitioned into two significant Interaction Principal Component Axes; where they captured 65.89% of the G×E variance. Genotypes G9, G10 and G12 are highly affected by environmental changes as they had higher G×E. Genotypes G1, G7, G2, G5, G11 and G8 had relatively low G×E, indicating lower influence of the environments on their performance. The GGE analysis showed that the first two PCAs explained 75.11% of the GGE variance. Genotypes G8 and G3 were the highest-yielding genotypes and significantly out yielded the checks. Genotypes G1, G12, G7 and G8 were stable genotypes. G8 was the most desirable genotype followed by G3, G7 and G6. G8 (PGRC/E#222878 × KAT-369-1) was officially released and given a local name called *Raya.* This white seeded variety is preferred by farmers for various food preparations (recipes), and it commands a premium price at the market. It can give high and stable yield in the unstable environmental conditions of Northeast Ethiopia. If used in its appropriate niche, the variety can contribute to the increase of sorghum productivity, and income of the cultivators.

Key words: AMMI, Desirable genotype, GGE, G×E, sorghum, stability

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is one of the most important food and feed grain crops in the world; in 2018, about 59.3 million tons of sorghum was produced on 42.1 million ha of land globally. It is the second main crop in Africa with total production of 29.7 million tons on 29.7 million ha of land (FAOSTAT, 2018). In Ethiopia, it ranks

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Table 1. Geographic, edaphic and climatic description 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°18'21''
Sirinka	1850	*Eutric vertisol*	945	13.6	27.3	11°45' 00''	39°36'36"
Mersa	1600	*NA*	NA	NA	NA	11°40'	39°39.5'
Chefa	1600	*Vertisol*	850	11.6	30.4	10°57'	39°47'

NA= not available.

third in total production and area coverage preceded by maize and tef (*Eragrostis tef* [Zucc.] Trotter). In 2018/19 cropping season, sorghum was produced by 4739613 producers on 1829662.39 ha of land with production of about 5 million tons and average productivity of 2.736 t ha^{-1} (CSA, 2019). The crop has a multitude of uses where the grain is used for food and local beverages, and the stalk is used for feed, fire wood and construction of traditional houses. Moreover, the stalks are used to a lesser extent as a confection (Gebrekidan, 1973). The folklore, songs and some of the local names given to varieties show the importance of sorghum in Ethiopia (Kebede, 1991).

Much of the crop is produced in the semi-arid tropics where rainfall and temperature are variable, mainly on smallholdings (Bantilan et al., 2004). Moisture deficit is the major constraint for crop production in Northeastern Ethiopia. Sometimes the rainfall is erratic, unpredictable and insufficient. Consequently, in almost all areas of Northeast Ethiopia, crops including sorghum, are prone to periodic drought. In an area stretching from Chefa ($10^0$57'N/$39^0$47'E) to Kobo ($12^0$8'21''N/$39^0$18'21''E), about 30 landraces have been identified differing in utilization, maturity, height, resistance to biotic and abiotic stress and other agronomic characteristics (Tesfahun et al., 2007). Stemler et al. (1975) also stated that durra sorghums are most important in the Eastern and Northern mid-elevation highlands of Ethiopia.

Farmers used to grow highly productive, late maturing sorghum landraces which are planted from mid-April to early May. Currently, due to absence of rainfall in April or May, late maturing varieties are marginalized and farmers are forced to grow early maturing landrace and improved sorghum varieties. That made identification of early or medium maturing genotypes stable in multiple-environments indispensable.

Understanding of the causes of G×E helps to reduce the cost of extensive genotype evaluation by using representative testing sites. The presence of a large G×E may necessitate establishment of additional testing sites (Kang, 1996), which is not affordable in developing countries. To this effect, identifying sorghum varieties that are better in productivity and stability than the existing cultivars has been one of the main research thematic areas for this part of Ethiopia. Therefore, the objectives of the experiment were to identify better sorghum genotypes for low- and mid-altitude and deficit moisture stress areas of Northeastern part of Ethiopia.

MATERIALS AND METHODS

The experiment was carried out at four trial sites of Sirinka agricultural research center that represent sorghum production areas of Northeast Ethiopia. Sirinka, Kobo, Mersa and Chefa were used for testing the sorghum genotypes. The distance between Chefa and Kobo is about 250 km; Mersa and Sirinka lie in between 170 and 188 km away from Chefa, respectively. The descriptions of the locations are listed in Table 1.

Twelve sorghum genotypes were used in the study. Ten of the genotypes were test lines which attained homozygosity originally introduced to Ethiopia through Eastern African Regional Sorghum and Millets (EARSAM) network and were received from the national sorghum research program of Ethiopia, located at Melkassa. Two checks, standard (*Yeju*) and local (*Jigurti*), were used for comparison. The genotypes were tested in randomized complete block design (RCBD) with three replications. The materials were planted in 5 m × 3.75 m plot using 75 and 15 cm spacing between rows and plants, respectively in 2003 and 2004 cropping seasons. Fertilizer rates of 50 kg ha^{-1} urea and 100 kg ha^{-1} DAP were used. All the DAP and half of the urea were applied at planting, whereas the other half of the urea was applied at knee height stage after thinning and weeding. All other cultural practices like thinning and weeding were done uniformly as required.

The genotypes were evaluated for days to flowering and maturity, plant height, 1000-seed weight and grain yield. While collecting data for plant height, five plants were randomly picked from the central four rows and the means were used for analysis. The data were subjected to combined analysis of variance across location and over years (three-way ANOVA) initially to see the statistical difference of genotypes for the traits considered as per Cochran and Cox (1992):

$$Y_{ijk}= \mu + G_i + L_j + S_k + GL_{ij} + GS_{ik} + LS_{jk} + GLS_{ijk} + e_{ijk}$$

Where Y_{ijk} is response of i^{th} genotype in the j^{th} location and k^{th} year; μ is the overall mean; G_i is the effect of the i^{th} genotype; L_j is the effect of the j^{th} location; S_k is the effect of k^{th} year; GL_{ij} is the effect of interaction of the i^{th} genotype with the j^{th} location; GS_{ik} is the interaction effect of the i^{th} genotype with the k^{th} year; LS_{jk} is the interaction effect of the j^{th} location with k^{th} year; GLS_{ijk} is the interaction effect of i^{th} genotype with the j^{th} location and k^{th} year; e_{ijk} is the effect of random error.

Location-year combinations were used to represent environments for Additive Main-effect and Multiplicative Interaction (AMMI), and Genotype main effect and Genotype-Environment interaction (GGE) analyses. AMMI analysis was performed according to Zobel et al. (1988) and GGE analysis was computed as per Yan et al. (2000). Combined analysis across locations and over years, AMMI and GGE analyses were computed by GenStat (16th edn.) software.

Table 2. Mean grain yield and agronomic data of sorghum genotypes combined across locations at Sirinka, Kobo, Mersa and Chefa and over years in 2003 and 2004.

Variety	Code	Days to flowering	Days to maturity	Plant height (cm)	1000 seed weight (gm)	Grain yield (t ha^{-1})
Local bulk white × P9404	G1	82.5	132.54	191.83	32.08	2.085
ICSV 1112 BF × P9403	G2	75.58	128.83	181.2	33.17	3.019
IS23453 × P9403	G3	76.87	127.12	193.37	31.08	3.704
3443-2-OP × ICSV1 × (T5 × 135/4/2/3/1)	G4	83.37	132.58	234.5	27.54	2.559
Acc.#69447 × ICSV1 KAT369-1	G5	85.37	133.95	213.2	28.58	2.942
3443-2-OP × 12 × 34/F4/3/E/1	G6	78.08	126.58	201.83	32	3.326
12 × 34/F4/3/E/1 × ICSV 708	G7	78.54	127.79	185.83	32.41	3.318
PGRC/E × 222878 × KAT369-1	G8	82.79	129.7	185.7	22.12	3.768
SDSL-8942-6	G9	84.08	129	176.75	27.45	2.972
SDSL-89422	G10	81.83	128.12	163.41	28.12	2.948
Yeju (ICSV 111 inc)	G11	72.37	123.17	194.25	31.2	3.259
Jigurti	G12	79.16	132.2	242.12	35.67	3.185
Mean		79.88	129.3	197	30.12	3.090
G (Genotype)		**	**	**	**	**
G×Y (Year)		**	**	NS	NS	NS
G×L (Location)		**	**	**	**	**
G×L×Y		**	**	**	**	**
LSD (5%)		1.9	1.37	15.1	2.07	0.517
CV (%)		2.96	1.85	9.52	8.54	2.75

**= significant at 0.01 probability level, NS= non-significant, LSD= least significant difference, CV= coefficient of variation.

RESULTS AND DISCUSSION

Analysis of variance

Combined analysis of variance across locations and over years indicated statistically significant ($P<0.01$) difference among genotypes for all characters considered. Genotype × year interactions were significant only for days to flowering and days to maturity (Table 2). Genotype × location, and genotype × location × year interactions were significant for all the traits considered indicating differential responses of the genotypes across locations and seasons. In line with the present finding, a number of researchers observed significant ($P<0.01$) effects of G and G×L on grain yield (Human et al., 2011; Filho et al., 2014; Teodoro et al., 2016; Mare et al., 2017).

Performance of genotypes

Days to flowering ranged from 72.37 for G11 to 85.37 for G5 with a mean of 79.88. Days to maturity also ranged from 123.17 for G11 to 133.95 for G5 with a mean of 129.3. Plant height varied from 163.41 cm for G10 to 242.12 cm for G12 (farmers' variety; *Jigurti*) with a mean of 197 cm. Thousand-seed weight also varied from 22.12 g for G8 to 35.67 g for G12 (*Jigurti*) with a mean of 30.12 g. Grain yield had a mean of 3.09 t ha^{-1} varying from 2.085 t ha^{-1} for G1 to 3.768 t ha^{-1} for G8. Only four genotypes, G8, G3, G6 and G7 out yielded the two checks. Genotypes G8 and G3 were the highest-yielding genotypes. The two genotypes significantly out yielded the checks (Table 2).

With regards to environments, the highest yield was recorded for G3 (5.279 t ha^{-1}) at Kobo03. Environments Kobo03 and Mersa04 were comparatively the highest and lowest yielding environments, respectively. Likewise, G3 (5.279 t ha^{-1}) and G10 (2.529 t ha^{-1}) were the highest yielding genotypes at the highest and lowest yielding environments (Table 3). Comparatively, Mersa (Mersa03 and Mersa04) was low-yielding environment as evidenced by grain yields of the genotypes. Environments of low-productivity are prone to large errors, less differentiation among genotypes, and less repeatability across seasons (Braun et al., 1992). Consequently, genotypes should be evaluated cautiously to minimize experimental errors in such environments.

AMMI analysis

Genotype (G), environment (E) and genotype-environment interaction (G×E) significantly (P<0.01) affect sorghum grain yield (Table 4). The results are in general agreement with the reports of Worede et al. (2020). Genotype, E and G×E explained 28.18, 41.70 and 30.13% of the treatment variance. The magnitude of

Table 3. Mean grain yield (t ha^{-1}) of 12 sorghum genotypes grown on eight environments of Northeast Ethiopia.

Genotype		Environment								Genotype mean
Code	Identification	Sirinka 03	Kobo 03	Mersa 03	Chefa 03	Kobo 04	Mersa 04	Sirinka 04	Chefa 04	
G1	Local bulk white × P9404	2.134	2.607	1.784	1.601	1.669	1.522	3.098	2.267	2.085
G2	ICSV 1112 BF × P9403	3.423	4.181	3.280	2.483	2.686	2.001	2.698	3.398	3.019
G3	IS23453 × P9403	4.776	5.279	3.301	2.742	3.253	2.471	3.339	4.470	3.704
G4	3443-2-OP × ICSV1 × (T5 × 135/4/2/3/1)	3.404	3.352	2.871	1.822	1.500	1.998	2.155	3.367	2.559
G5	Acc.#69447 × ICSV1 KAT369-1	3.623	4.345	2.664	2.399	2.476	1.860	2.977	3.195	2.942
G6	3443-2-OP × 12 × 34/F4/3/E/1	3.193	3.450	2.907	3.836	2.898	2.368	3.455	4.502	3.326
G7	12 × 34/F4/3/E/1 × ICSV 708	4.269	3.650	2.911	3.492	2.557	2.430	3.133	4.105	3.318
G8	PGRC/E × 222878 × KAT369-1	4.127	4.137	3.552	4.026	3.828	2.295	3.946	4.234	3.768
G9	SDSL-8942-6	3.764	2.441	3.008	3.787	2.316	1.945	3.863	2.652	2.972
G10	SDSL-89422	4.053	2.584	2.764	2.826	2.032	2.529	3.317	3.482	2.948
G11	*Yeju* (ICSV 111 inc)	3.218	4.051	2.768	2.327	3.277	2.480	3.572	4.380	3.259
G12	*Jigurti*	2.979	4.417	2.854	3.771	2.313	1.377	3.755	4.013	3.185
	Environment mean	3.580	3.708	2.889	2.926	2.567	2.106	3.276	3.672	

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

Source	df	SS	MS	Variance explained (%)	G×E explained (%)
Treatments	95	66.29	0.698		
Genotypes	11	18.68	1.698**	28.18	
Environments	7	27.64	3.949**	41.70	
Interactions (G×E)	77	19.97	0.259**	30.13	
IPCA 1	17	8.55	0.503**		42.81
IPCA 2	15	4.61	0.307*		23.08
Residuals	45	6.82	0.151		

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

the E term was the highest while that of the G term was the lowest. The finding was in harmony with the observations of previous workers in sorghum (Adugna, 2007; Admas and Tesfaye, 2017; Al-Naggar et al., 2018; Worede et al., 2020).

The G×E term was partitioned into two significant IPCAs; where IPCA1 (42.81%) and IPCA2 (23.08%) captured 65.89% of the G×E variance (Table 4). In agreement with the present finding, Adugna (2007) and Worede et al. (2020) explained 68.7 and 68.62% of the G×E variance by the first two IPCAs, respectively. Human et al. (2011), however, explained 88.61% of the G×E by three significant ($P<0.05$) IPCAs.

In the AMMI1 biplot (Figure 1), distances along the horizontal axis shows differences in grain yield (main effect); however, the vertical axis shows differences in interaction (G×E). Genotypes G8 and G3 were high performing whereas G1 was least performing genotypes in terms of grain yield. Genotypes G9 and G3 were highly affected by environmental changes (had high G×E) as a result they are not stable. Genotypes G12, G7, G1 and G8 had minimum G×E and hence they are adapted to all the environments considered in the study; G1 had the lowest yield, though. Genotypes G5, G9 and G10 had almost similar main effects (grain yield) as they are arranged vertically, only differing in interaction effects (Figure 1). Likewise, environment Kobo03, Chfa04, Sirinka03 and Sirinka04 had above average yield while the rest had below average grain yield. Environments Kobo03 and Mersa04 were the highest and the lowest yielding environments, respectively. Environments Kobo03 and Chefa03 exerted higher G×E; Sirinka04 had medium; Mersa03 followed by Mersa04, Sirinka03, Kobo04 and Chefa04 exerted low G×E (Figure 1). The results are in agreement with the observations of Worede et al. (2020).

The lengths of the vectors from the origin indicates the magnitudes of the G×E imposed by the environments on the genotypes (Fan et al., 2001). Hence, environment Chefa03 and Kobo03 had higher G×E (long spoke) and hence they are highly discriminating environments. Environments Sirinka03, Sirinka04 and Mersa04 had

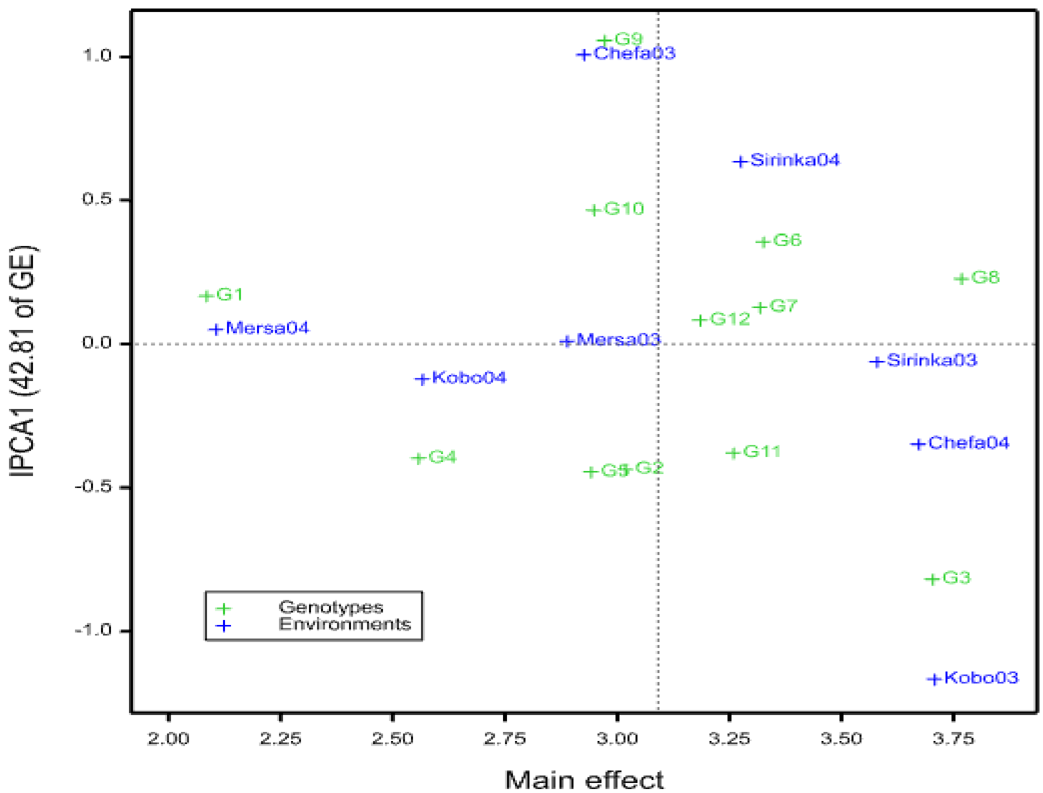

Figure 1. AMMI1 biplot of 12 sorghum genotypes and eight environments plotted against mean grain yield and IPCA1. Genotype codes are as listed in Table 2.

medium G×E. Whereas Mersa03, Chefa04 and Kobo04 had minimum G×E as a result these environments are least discriminating. Similarly, Genotypes G9, G10 and G12 are highly affected by environmental changes as they had long spokes (G×E). Genotypes G1, G7, G2, G5, G11 and G8 had relatively low G×E indicating lower influence of the environments on their performance (Figure 2). The results were in harmony with the observations of Al-Naggar et al. (2018) and Worede et al. (2020).

GGE analysis

GGE analysis showed that PCA1 and PCA2 explained 53.44% and 21.67% of the GGE variance, respectively (Figures 3 and 4). Figure 3 help visualize grain yield performance and stability of the genotypes. In such a figure, the average environment coordinate (AEC) passes through the biplot origin (Yan and Kang, 2003); its abscissa points towards higher grain yield, and its ordinate points to greater instability, in either direction (Yan and Tinker, 2006). Thus, G8 was the highest yielding genotype followed by G3 and G6, while G1 was the least. Lenghtes of the vectors from the AEC axis indicate responsiveness or stability of genotypes. Genotypes with large vectors are highly responsive (less stable) and those with small vectors are stable (Yan and Tinker, 2006). Accordingly, Genotypes G1, G12, G7 and G8 were stable genotypes; whereas G9 and G3 were least stable (Figure 3).

One of the important features of GGE biplot is the AEC view of ranking genotypes relative to an ideal genotype to identify desirable genotypes. Genotypes proximal to the arrow at the center of the concentric circles (ideal genotype) are assumed to be suitable (Yan and Tinker, 2006). Hence, G8 was the most desirable genotype followed by G3, G7 and G6. However, G1 is the least desirable followed by G4 (Figure 4). The result is in concurrence with that of Worede et al. (2020) and Assefa et al. (2020) who identified two desirable genotypes and a variety, respectively, using this methodology in Northeast Ethiopia. Moreover, a number of researchers identified high yielding and stable sorghum genotypes using a similar technique (Gasura et al., 2015; Mare et al., 2017; Al-Naggar et al., 2018).

During 2006 cropping season, genotypes IS234453 × P-9403 and PGRC/E#222878 × KAT-369-1, together with the checks, were sown on 10 m × 10 m plot both on-station and on-farm in all locations, and their performance was evaluated by farmers and the national variety release committee. In 2007, PGRC/E#222878 × KAT-369-1 (G8)

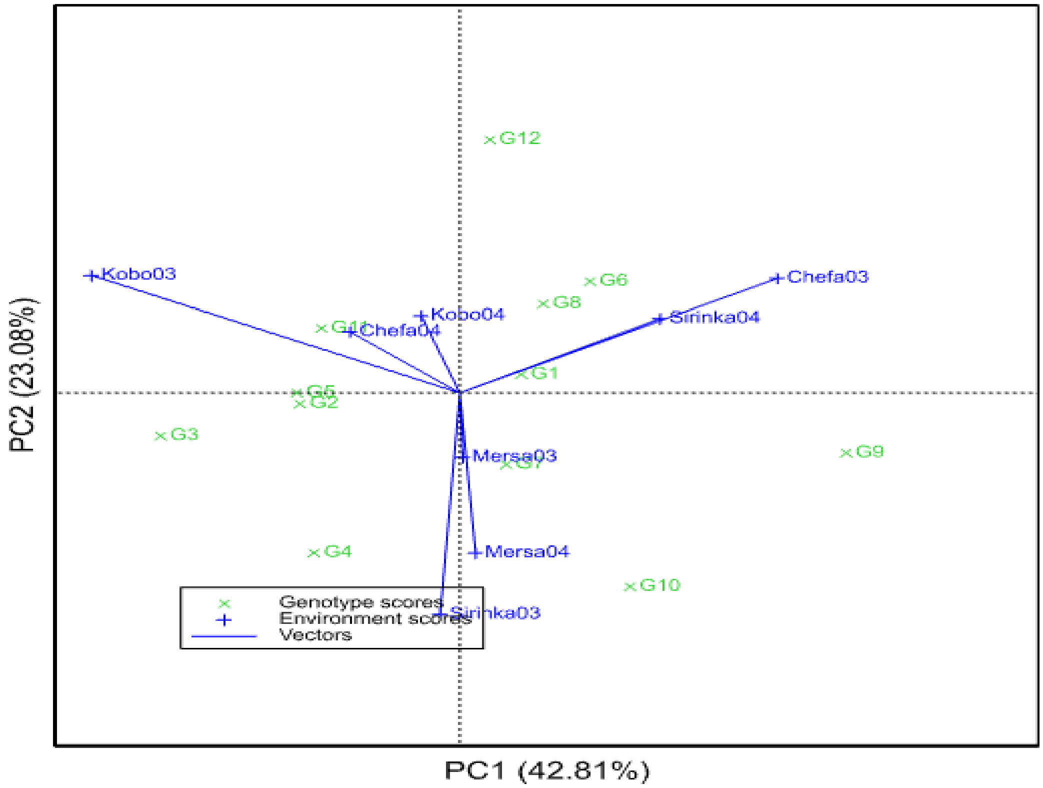

Figure 2. AMMI2 biplot of 12 sorghum genotypes and eight environments plotted against IPCA1 and IPCA2. Genotype codes are as listed in Table 2.

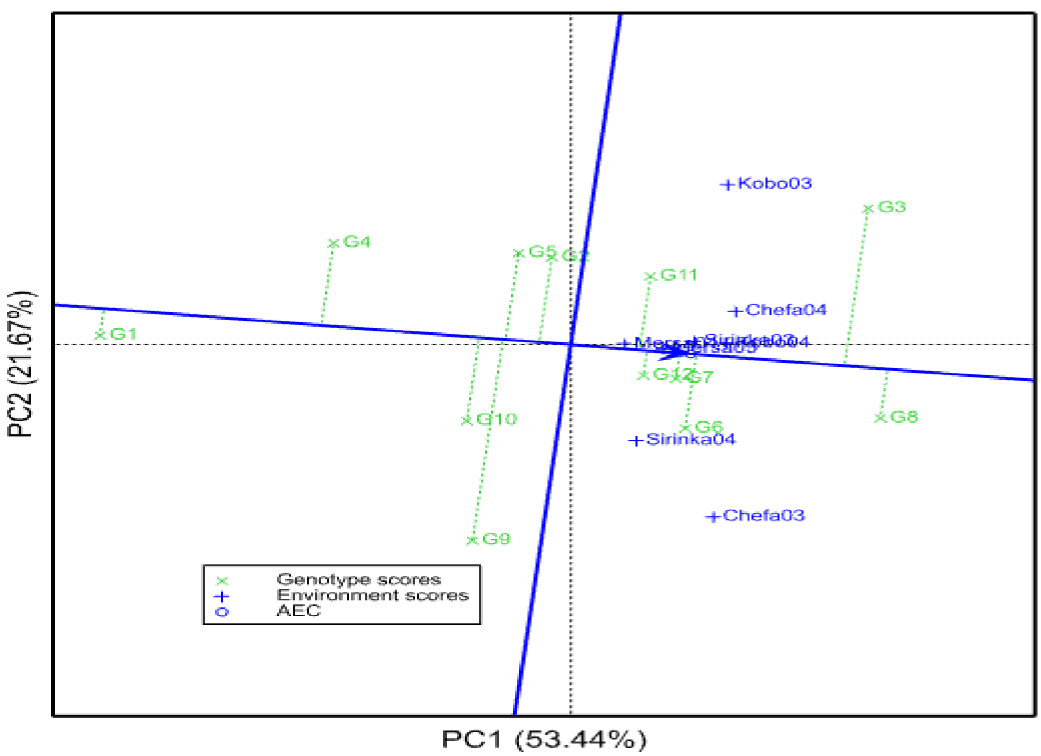

Figure 3. The average-environment coordination view showing the mean performance and stability of the 12 sorghum genotypes. Genotype codes are as listed in Table 2.

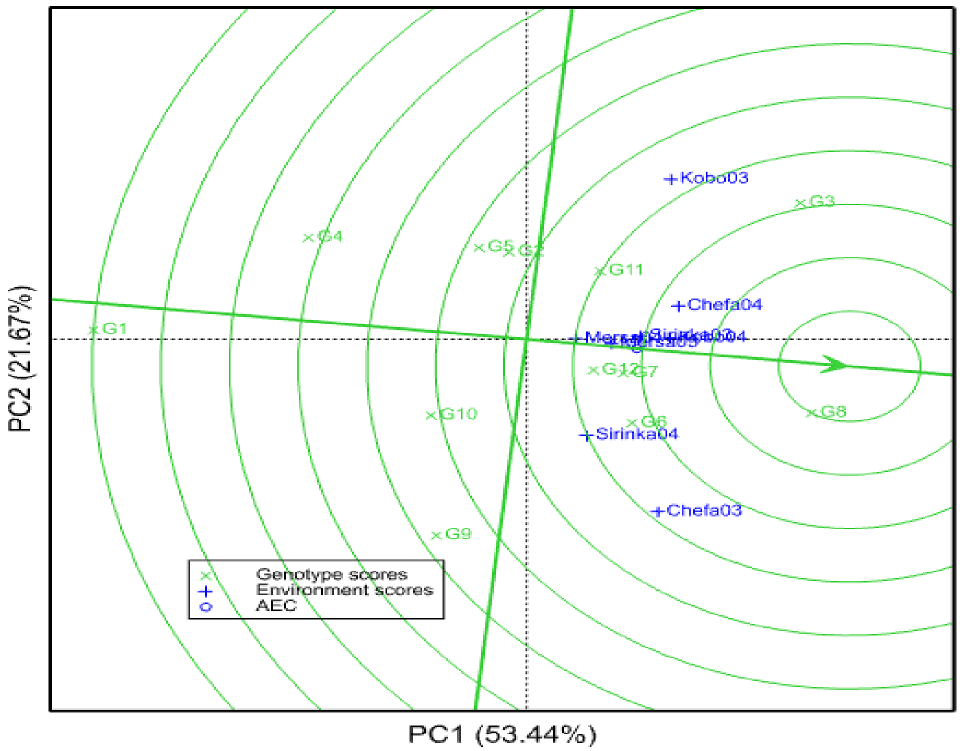

Figure 4. The average-environment coordination view of ranking the 12 sorghum genotypes relative to an ideal genotype. Genotype codes are as listed in Table 2.

was officially released for Northeast Ethiopia and similar areas with altitude as high as 1850 m.a.s.l. for the reason that G8 was better in yield stability; otherwise, there was no significant yield difference between the two candidates. The released variety is given a local name called *Raya. Raya* (PGRC/E#222878 × KAT-369-1) matures later than the standard check *Yeju* (ICSV 111 inc) but earlier than the local check (*Jigurti*). It has short stalk as compared to *Jigurti* but taller than *Yeju*. The variety is white seeded, and that made it preferred by farmers and consumers for various food preparations; it also commands a premium price at the market. If used with the optimum management practices, the variety can contribute to the increase of sorghum productivity in the area.

IS234453 × P-9403 (G3) is a progeny of one of the *Striga* resistant varieties (P-9403; *Abshir*) released in the same area. Evaluation of G3 for *Striga* resistance could be an area of future research. The genotype G3 is also tall and relatively bold seeded as compared to G8 and can be utilized in future sorghum improvement programs as a possible parent for crossing.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

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