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Research paper

Multi-environment evaluation of malt sorghum in semi-arid areas of Northeast Ethiopia

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Multi-environment trials are important to identify desirable genotypes. A field experiment was carried out at four locations for two years to evaluate thirteen malt-sorghum genotypes together with two checks so as to identify stable and high-yielding genotypes. The trial was laid out in a three-time replicated randomized complete block design. Data were collected on seven agronomic and yield-related traits. The results of the combined analyses of variance over years and across locations showed significant ($p<0.01$) differences among the sorghum genotypes for all the seven traits considered. Both the genotype × location ($p<0.05$) and genotype × location × year ($p<0.01$) interactions significantly affected grain yield. The genotype G4 (SDSL89473) gave the highest (4.663 t ha^{-1}) grain yield as compared to the farmers' variety (3.489 t ha^{-1}). The average-environment coordination view of Genotype main effect plus Genotype-Environment interaction biplot ranked G4 (SDSL89473) as the most desirable (high-yielder and stable) genotype, followed by G7 and G13. Most of the stability statistics including cultivar superiority, mean ranks, mean absolute differences of pairs of ranks and variance of ranks were also identified SDSL89473 as the most stable malt-sorghum genotype. The genotype SDSL89473 could, therefore, be recommended for production in dry low-altitude areas of Northeast Ethiopia. It could also be used as a parent in future malt-sorghum improvement program as a possible parent for crossing.

Key words: *GGE, malt-sorghum, moisture stress, multi-environment, stability*

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is among the most important crops of the world. Mostly, farmers dwelling in the semi-arid tropics, where rainfall and temperature are variable, produce the crop (Bantilan et al., 2004). Sorghum is the third most important crop in Ethiopia in terms of both area overage and total production (CSA, 2019). The Northeastern part of Ethiopia is one of the major producers of sorghum. In Northeast Ethiopia, mid and lowland parts of Eastern Amhara region in particular, many landraces of sorghum were identified (Tesfahun et al., 2007) and a great deal of variability of sorghum was documented (Benor & Sisay, 2003; Desmae et al., 2016; Derese et al., 2018). In the intermediate altitude sorghum growing areas, farmers prefer to grow the tall, high-yielding, compact-headed and late maturing sorghum landrace called *Degalit*. This variety, however, needs extended growing period. Due to the decline of rainy days in the growing period as a result of climate change, farmers are forced to grow short-cycle sorghum cultivars.

Some early maturing sorghum improved varieties like *Teshale* (3443-2-OP), *Miskir* (PGRC/E#69441 × P-9401) and *Girana-1* (CR:35×DJ1195×N-13) have been identified and released for this moisture-deficit area (MoANR, 2016; Worede et al., 2020a; Worede et al., 2021). Although the stalk is used for livestock feed, fire-wood and simple construction of traditional houses, the grain is mostly used for food and traditional beverage preparations. Beverages like *tella* and *araki* are the common alcoholic drinks prepared from sorghum in Ethiopia. Though most of the breweries in Ethiopia use malt barley, the demand for malt has never been satisfied. A few breweries introduced malt-sorghum into beer production in Ethiopia; this should be promoted as utilization of malt sorghum not only satisfy the demand of malt factories, but also minimize the foreign currency expenditure, and increase the income of the farmers. So far only three malt-sorghum varieties have been released and/or registered in Ethiopia (MoANR, 2016; Seyoum et al., 2019). However, no malt-sorghum variety is under production by farmers of Northeast Ethiopia. It is, therefore, imperative to identify malt-sorghum varieties that fulfill the yield requirements of farmers and quality standards of brewing industries. The objective of this research was to identify stable and high yielding malt-sorghum varieties adapted to the moisture-deficit areas of Northeast Ethiopia.

MATERIALS AND METHODS

The experiment was conducted at Jari, Chefa and Kobo during the main rainy season of 2007 and 2008. The locations represent the main sorghum growing lowland areas of Northeast Ethiopia; descriptions of the locations are displayed in Table 1. The test materials include 13 white malt-sorghum genotypes supplied by the national sorghum research program of Ethiopia, situated at Melkassa, standard (*Abuare*) and local (*Jigurti*) checks. The malt-sorghum genotypes were previously introduced from ICRISAT Zimbabwe, Bulawayo. The experiment was laid out in a three-times replicated randomized complete block design (RCBD). The sorghum genotypes were planted on plots of 5 m × 3.75 m; each plot contained five rows spaced 75 cm, and 15 cm spacing between plants was maintained. Fertilizer was applied at the rate of 41 and 46 kg ha^{-1} N and P_2O_5, respectively. Half of the N was applied at planting and the rest was applied at knee-height stage, while the full dose of P_2O_5 was applied at planting. Weeding was done three times, before the critical stages of weed competition, uniformly to all plots.

Table 1. The geographic and climatic descriptions of the study areas

Location	Altitude (m)	Soil type	Rainfall (mm)	Temperature		Global position	
				Min (^{0}c)	Max (^{0}c)	Latitude	Longitude
Kobo	1450	*Eutric fluvisol*	637	15.8	29.1	12^{0}8’21”	39^{0}18’21”
Jari	1680	*Vertisol*	NA	NA	NA	11^{0}21′	39^{0}38’
Chefa	1600	*Vertisol*	850	11.6	30.4	10^{0}57’	39^{0}47’

NA – Not available

Observations were taken from the central three rows to avoid boarder effect. Data were collected on days to heading, days to maturity, plant height (cm), head weight (t ha^{-1}), thousand-seed weight (g) and grain yield (t ha^{-1}). The grain yield data over six environments (combinations of three locations and two years) were used for analyses of Additive Main-effect and Multiplicative Interaction (AMMI), and Genotype main effect plus Genotype-Environment interaction (GGE). The models proposed by Crossa et al. (1990) and Yan et al. (2000) were employed to work out AMMI and GGE analyses, respectively. AMMI Stability Value (ASV) was computed following the formula forwarded by Purchase et al. (2000). The procedure of Lin and Binns (1988) was employed to compute cultivar superiority of sorghum genotypes. Variance of a genotype across environments was used to measure static stability; in this case, desirable genotype will have smaller environmental variance (Becker and Leon, 1988). Ecovalence (W_i) was computed according to Wricke (1962). The methodologies of Nassar & Huehn (1987) were used to measure mean and variance of the ranks of each genotype, and the absolute differences of pairs of ranks. Rank-order correlation coefficient (r_s) of Spearman was determined as per Steel and Torrie (1980). Variance, AMMI, GGE and stability analyses were computed by using GenStat (16th edition) software.

RESULTS AND DISCUSSION

Analysis of variance

The combined analyses of variance across locations and over years (three-way ANOVA) are presented in Table 2. The result of the analyses showed highly significant ($p<0.01$) differences among sorghum genotypes for all the traits considered. The result agrees with that reported by Worede et al. (2020a). The genotype × location interaction significantly ($p<0.05$) affected plant height, head weight, 1000-seed weight and grain yield. The genotype × year interaction was significant ($p<0.01$) for head weight and 1000-seed weight. The genotype × location × year mean square was also significant ($p<0.01$) for plant height, head weight, 1000-seed weight and grain yield (Table 2). This shows differential responses of the genotypes from location to location and from year to year.

Performance of genotypes

The performance of the malt-sorghum genotypes is depicted in Table 2. It showed that the genotype Dwarf Wonder was the

Table 2. Mean grain yield and yield related traits of sorghum genotypes combined across locations (Jari, Chefa and Kobo) and over years (2007 and 2008)

Genotype	DH	DM	PH (cm)	HW (t ha^{-1})	TSW (g)	GY (t ha^{-1})
SDSR91050	72.4	122.9	159.4	4.983	25.56	3.867
AMH1190	73.3	120.3	158.5	4.425	23.60	3.271
LARSVYT19	78.4	129.5	120.1	3.580	21.52	2.183
SDSL89473	75.9	124.7	187.9	5.965	33.77	4.663
MRS13	74.4	121.7	193.8	4.963	29.64	3.623
R8602	73.9	123.8	169.8	5.590	22.56	3.604
AHM658	74.8	125.3	198.8	5.803	26.33	4.071
SDSR91011	75.9	123.4	161.5	4.750	27.76	3.128
SDSL89420	80.6	129.7	148.2	3.852	23.94	2.523
SDSL90007	76.6	133.2	149.8	5.185	22.49	3.886
Dwarf Wonder	73.1	118.8	118.7	5.417	19.27	3.518
SDSL90177	75.0	124.5	139.2	4.983	30.08	3.485
SDSR91054	78.4	127.3	190.3	5.561	32.68	3.966
Abuare	75.4	124.4	155.8	4.572	24.72	3.027
Jigurti	79.7	129.4	299.3	5.467	32.81	3.489
Mean	75.9	125.3	170.1	5.006	26.45	3.487
Genotype (G)	**	**	**	**	**	**
Location (L)	**	NS	NS	*	**	NS
Year (Y)	NS	**	**	NS	*	NS
G×L	NS	NS	*	*	*	*
G×Y	NS	NS	NS	**	**	NS
L×Y	*	NS	NS	**	*	NS
G×L×Y	NS	NS	**	**	*	**
CV (%)	5.1	5.3	11.1	16.1	12.2	0.021

DH= days to heading, DM= days to maturity, PH= plant height, HW= head weight, TSW= 1000-seed weight, GY= grain yield, NS= non-significant, *and **= Significant at 0.05 and 0.01 probability levels

earliest (118.8 days) and *Jigurti* was very late (129.4 days) to mature. However, the genotype SDSL89473 was as early as the standard check, *Abuare* (both took 124 days to mature). Moreover, Dwarf Wonder (118.7 cm) and *Jigurti* (299.3 cm) were the shortest and the tallest genotypes, respectively. The highest head weight was recorded for the genotype SDSL89473 (5.965 t ha^{-1}) followed by AHM658 (5.803 t ha^{-1}). The highest mean grain yield recorded was 4.663 t ha^{-1} for SDSL89473 followed by 4.071 t ha^{-1} for AHM658. In agreement to this finding, Seyoum et al. (2019) reported the highest mean grain yield of 4.78 t ha^{-1}.

Environment mean grain yield was ranged from 2.804 t ha^{-1} for Jari07 to 5.129 t ha^{-1} for Kobo07; as a result, Jari07 and Kobo07 are regarded as the lowest and the highest yielding environments, respectively. The highest mean genotypic yield recorded was 6.99 t ha^{-1} for SDSL89473 (G4) followed by 6.232 t ha^{-1} for SDSR91054 (G13) and 6.226 for R8602 (G6), all from the highest yielding environment (Table 3). The sorghum genotype SDSL89473 ranked first in four out of the six environments in terms of grain yield.

GGE analyses

The GGE analyses showed that 57.51% and 20.77% (78.28%) of the GGE variance were captured by the first and the second significant PCAs (Figure 1 and 2). The finding is in harmony with other researchers who reported GGE variance ranging from 74.7% up to 76.59% contributed by the first two PCAs (Mare et al., 2017; Worede et al., 2020a, 2021).

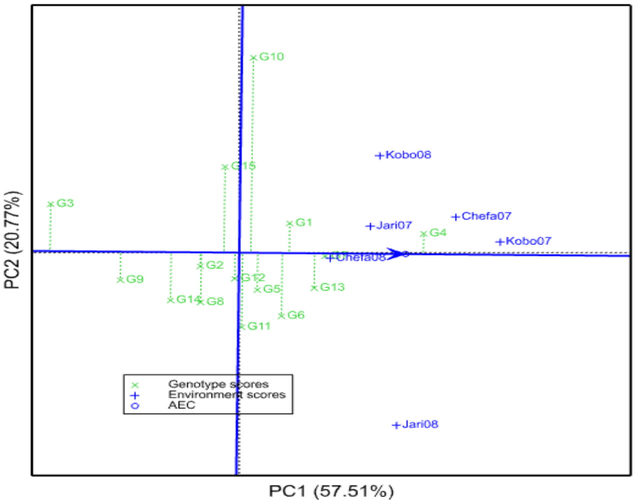

Figure 1. The average-environment coordination view showing the mean performance and stability of the 15 sorghum genotypes. Genotype codes are as listed in Table 3.

The arrowed line passing through the origin of the Figure 1 points towards the high yielding genotypes, and projections from this line (genotypic vectors) indicate the responsiveness (stability) of the genotypes (Yan and Tinker, 2006). Accordingly, genotype G4 was the highest yielding genotype followed by G7 and G13; while G3 was the poorest. As far as the stability is concerned, G7 was the most stable followed by G2, G4 and G12; although, G2 had below average performance.

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

Genotype		Environment					
Identification	**Code**	**Jari07**	**Chefa07**	**Kobo07**	**Jari08**	**Chefa08**	**Kobo08**
SDSR91050	G1	3.168	3.125	5.542	3.214	3.757	**4.681**
AMH1190	G2	2.384	2.747	5.095	2.635	3.695	2.892
LARSVYT19	G3	1.851	1.908	3.614	0.877	3.137	2.029
SDSL89473	G4	3.409	**5.157**	**6.99**	**3.802**	**4.365**	4.511
MRS13	G5	2.678	4.205	5.001	3.353	3.368	2.900
R8602	G6	3.119	3.517	6.226	3.592	2.861	2.586
AHM658	G7	3.564	4.433	5.779	3.438	3.551	3.565
SDSR91011	G8	2.268	2.821	4.803	3.214	3.445	2.963
SDSL89420	G9	1.915	2.533	3.553	2.635	2.987	2.849
SDSL90007	G10	3.655	3.86	5.342	0.877	3.148	4.597
Dwarf Wonder	G11	3.047	2.566	5.006	**3.802**	4.173	3.241
SDSL90177	G12	**3.674**	3.2	4.717	3.353	2.712	3.299
SDSR91054	G13	2.693	3.718	6.232	3.592	4.236	3.464
Abuare	G14	2.404	2.65	3.912	3.438	2.594	3.495
Jigurti	G15	2.230	3.384	5.116	1.985	3.404	4.215
Environment mean		2.804	3.322	5.129	2.920	3.429	3.419

Table 4. Stability coefficients of sorghum grain yield for genotype by environment data

Genotype		**Grain yield (t ha^{-1})**		**Cultivar superiority**		**Static stability**		**Wricke's ecovalence**		**Mean ranks**		**MADPR**		**Variances of ranks**		**ASV**	
Identification	Code	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
SDSR91050	G1	3.915	4	0.600	4	0.986	9	1.116	6	5.583	4	3.833	9	10.24	9	1.340	5
AMH1190	G2	3.241	12	1.340	11	1.022	10	0.525	1	9.750	11	3.033	6	7.38	7	0.621	2
LARSVYT19	G3	2.236	15	3.531	15	0.971	8	1.750	10	14.083	15	1.567	2	2.44	4	1.868	9
SDSL89473	G4	4.706	1	0.008	1	1.615	13	1.378	8	1.917	1	1.433	1	1.64	1	1.226	4
MRS13	G5	3.584	7	0.852	5	0.756	5	1.234	7	8.250	8	3.167	8	7.97	8	1.587	8
R8602	G6	3.650	5	0.856	6	1.739	14	2.681	14	7.583	7	5.567	14	22.64	14	2.707	12
AHM658	G7	4.055	2	0.337	2	0.846	7	0.717	3	4.250	2	1.900	4	2.38	3	0.418	1
SDSR91011	G8	3.252	11	1.363	12	0.736	4	0.559	2	9.917	12	1.967	5	2.84	5	2.180	10
SDSL89420	G9	2.745	14	2.367	14	0.294	1	1.045	4	13.250	14	1.633	3	1.77	2	1.428	6
SDSL90007	G10	3.580	8	1.204	10	2.343	15	6.667	15	6.417	5	5.900	15	24.64	15	8.365	15
Dwarf Wonder	G11	3.639	6	1.096	7	0.768	6	1.898	12	7.083	6	5.167	12	18.04	12	3.267	13
SDSL90177	G12	3.492	9	1.153	9	0.457	3	1.656	9	8.417	9	5.233	13	20.04	13	1.127	3
SDSR91054	G13	3.989	3	0.429	3	1.456	12	1.078	5	4.583	3	3.100	7	6.44	6	1.445	7
Abuare	G14	3.082	13	1.837	13	0.374	2	1.995	13	10.250	13	4.700	11	14.78	11	2.212	11
Jigurti	G15	3.389	10	1.099	8	1.396	11	1.764	11	8.667	10	4.267	10	13.07	10	3.659	14

MADPR = Mean absolute differences of pairs of ranks, ASV= AMMI Stability Value. Genotypes ranked according to the stability coefficient in the previous column (running downwards from 1 = best)

However, G10 was the least stable genotype (Figure 1). In agreement with the present finding, Worede et al. (2021) reported four stable sorghum genotypes, of which one was with poor grain yield. The average-environment coordination (AEC) view of ranking genotypes (Figure 2) helps visualize the placement of genotypes relative to the ideal genotype (the arrow at the concentric circles).

Genotypes closer to the ideal genotype are expected to be high-yielding and stable or desirable (Yan and Tinker, 2006). Therefore, G4 was the most desirable genotype, while G7 and G13 were the next desirable genotypes. Genotype G3 was the least desirable as it is farthest from the ideal genotype. The result agrees with the one reported by Worede et al. (2021) who identified two desirable sorghum genotypes adapted to the moisture-deficit areas of Northeast Ethiopia using the same methodology.

Stability analyses

Seven stability statistics were used to compare the 15 sorghum genotypes. The results of the stability analyses are presented in Table 4. Lin and Binns (1988) stated that cultivars with lower values are assumed to be stable. Accordingly, genotype G4, G7 and G13 were more important, in that order, in terms of cultivar superiority as they had relatively smaller coefficients. Genotypes with smaller static stability statistic are assumed to be stable (Becker and Leon, 1988). As a result, G9 was the most stable genotype followed by G14 (*Abuare*) and G12 based on this stability concept; in contrast, G10 was unstable. According to Wricke (1962), a genotype with W_i= 0 is considered as stable. Wricke's ecovalence, therefore, identified G2, G8 and G7 as the first, second and third stable genotypes; nevertheless, G10 was the least stable. In concurrence with the present finding, Worede *et al*. (2020a) identified two sorghum genotypes with low

Table 5. Correlation of stability coefficients for genotype by environment data of 15 sorghum genotypes

Stability statistics	Grain yield	Cultivar superiority	Static stability	Wricke's ecovalence	Mean ranks	MADPR	Variances of ranks	ASV
Grain yield	1.0							
Cultivar superiority	0.971**	1.0						
Static stability	-0.496	-0.454	1.0					
Wricke's ecovalence	0.014	0.089	0.296	1.0				
Mean ranks	0.971**	0.929**	-0.561*	-0.018	1.0			
MADPR	-0.061	0.007	0.175	0.671**	-0.096	1.0		
Variances of ranks	0.021	0.086	0.196	0.704**	-0.018	0.986**	1.0	
ASV	0.229	0.296	0.221	0.732**	0.211	0.546*	0.568*	1.0

** and * = significant at the 0.01 and 0.05 levels (2-tailed). MADPR= Mean absolute differences of pairs of ranks, ASV= AMMI stability value.

values of ecovalence (higher stability). Genotypes with smaller values of mean ranks such as G4, G7 and G13, in that order, were more stable genotypes. Genotype G4, G3 and G9 were the first three most stable sorghum lines based on mean absolute differences of pairs of ranks (MADPR) as they had smaller stability coefficients; G10 was the least stable. Based on variance of ranks, G4 was the most stable followed by G9 and G7 whereas G10 was the least stable sorghum genotype. AMMI Stability Values (ASVs) are assumed to be the distance from the central point (origin) in a biplot of the first two significant IPCA scores (Purchase et al., 2000). According to ASV, G7 was ranked first while G2, G12 and G4 were ranked second, third and fourth; however, G10 was the least stable according to this stability concept.

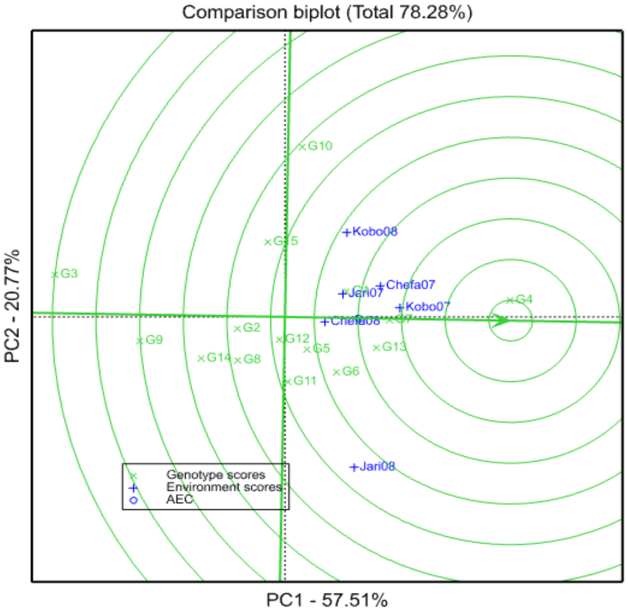

Figure 2. The average-environment coordination view of ranking the 15 sorghum genotypes relative to an ideal genotype. Genotype codes are as listed in Table 3.

The stability analyses showed that G4 (SDSL89473) was ranked first based on cultivar superiority, mean ranks, mean absolute differences of pairs of ranks and variance of ranks. Besides, this genotype was found to be the highest yielder. Nevertheless, static stability statistic, Wricke's ecovalence, MADPR, variance of ranks and ASV identified G10 as the least stable malt-sorghum genotype.

Association of the stability statistics considered

The result of rank-order correlation (r_s) analysis of Spearman is depicted in Table 5. Mean ranks was significantly correlated with grain yield (0.971**), cultivar superiority (0.929**) and static stability (-0.561*); its correlation with the first two was positive while with the last one was negative (Table 5). The result demonstrates that mean ranks and cultivar superiority stability statistics could be used in selection of stable and high-yielding sorghum varieties. The finding agrees with that of Worede et al. (2020b) who reported positively significant correlation of mean ranks with grain yield (0.971**) and cultivar superiority (0.929**) in tef. Similarly, positive and significant association of grain yield and cultivar superiority were reported in sunflower (Noruzi & Ebadi, 2015) and faba bean (Temesgen et al., 2015).

ASV was positively and significantly correlated with Wi (0.732**), MADPR (0.546*) and variances of ranks (0.568*); these stability statistics may measure similar stability aspects. As a result, either one of these measures may suffice to identify stable sorghum genotypes. The present finding is in line with Abate *et al.* (2015). Moreover, in wheat, Purchase *et al.* (2000) also observed positively significant association of ASV with *Wi*.

CONCLUSION

The GGE biplot identified G4 (SDSL89473) as the most desirable (stable and high-yielding) malt-sorghum genotype. Moreover, stability statistics such as cultivar superiority, mean ranks, mean absolute differences of pairs of ranks and variance of ranks also ranked SDSL89473 first in terms of stability. In addition to its desirability, SDSL89473 is white seeded, which makes it preferable for food preparations. It out-yielded the other malt-sorghum genotypes, the standard check (*Abuare*) and the farmers' variety (*Jigurti*). Furthermore, the genotype has relatively higher head weight which is one of the most important sorghum selection criteria of farmers. This variety could be recommended for the semi-arid areas of Northeast Ethiopia and could be utilized in future malt-sorghum improvement programs as a parent for crossing.

AUTHOR CONTRIBUTIONS

FW; initiated the research idea, suggested the research methods, analyzed and interpreted the result and wrote the manuscript. SA; initiated the research idea, suggested the research methods, and reviewed the manuscript. MM and TG; implemented the research, collected and encoded the data.

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COMPETING INTERESTS

The authors declare that they have no competing interests.

ETHICS APPROVAL

Not applicable

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