Original Research Article

Genotype × environment interaction and stability of *Sorghum bicolor* lines for some agronomic and yield traits in Egypt

ABSTRACT

Developing high performing and stable sorghum genotypes across different environments is of utmost importance to plant breeders. This study was conducted to compare relative stability of 25 grain sorghum B-lines under Egyptian conditions for some agronomic and yield traits. Six experiments with 25 sorghum B-lines were conducted at two locations in Egypt (Giza and Shandaweel) in two years and two planting dates in one location (Giza). A randomized complete block design was used in each environment with three replications. The three evaluation parameters used were mean performance, regression coefficient and the deviation from regression. Stability analysis was performed for five traits, namely days to flowering (DTF), plant height (PH), 1000-grain weight (TGW), grains/plant (GPP) and grain yield/plant (GYPP). The top five high yielding lines (G1, G3, G10, G12 and G25) displayed regression coefficient much lower than unity, indicating their adaptability to poor environments. The genotypes G12 and G20 exhibited significant deviation from regression for GYPP, indicating that they are unstable. The most responsive genotype for GYPP was G9 followed by G2 and G20; they are adapted to high-yielding environments. The three lines G11 (ICS-8001), G21 (BTX-407) and G24 (BTX -631) displayed above average grain yield/plant (GYPP), regression coefficient (b_i) value near unity (1.07 and 1.05) and small and non-significant deviation from regression (S^2_d), indicating that these genotypes are stable and widely adapted to different environments. The most stable genotypes were G17, G19 and G6 for days to flowering, G1, G4, G22, G24 and G16 for plant height, G8, G17, G19 and G16 for grains/plant and G14 and G22 for 1000-grain weight. These B-lines can be utilized as parental lines for the development of grain sorghum hybrids in view of their stability for the respective traits.

Key words: Grain sorghum, Responsiveness, Regression coefficient, Deviation from regression, Adaptability

1. INTRODUCTION

Grain sorghum (*Sorghum bicolor* L. (Moench)) is the fourth major cereal crop in Egypt in terms of area and production next to wheat (*Triticum aestivum* L.) rice (*Oriza sativa* L.) and maize (*Zea mays* L.). In 2014 season, the cultivated area of grain sorghum in Egypt was about 353,346 feddan (148,456 ha), producing about 804,000 tons with an average productivity of 16.25 ardab/fed (5.42 ton/ha) according to FAOSTAT [1]. Most of grain sorghum cultivated area in Egypt is concentrated in Assiut and Sohag governorates (Upper Egypt), where the atmospheric temperature during the growing season is high, since grain sorghum is more tolerant to high temperature than maize [2-6]. A major challenge of sorghum production in these parts of the country is lack of stable varieties. For the last decades, a number of hybrid sorghum varieties were developed and released for growing in these areas. The parental lines of these single cross hybrids should be stable and tolerant to high temperature.

Developing high yielding and stable sorghum hybrids is of utmost importance to plant breeders. The success of a hybrid depends as much on its stable performance over varied environments as well as on its inherent yielding ability. The desired hybrid is one that would be adapted to a wide range of growing conditions in a given production area, with above average yields and below average variances across environment. That is to say, sorghum growers need cultivars that are dependable and consistent across a wide array of stress conditions and yet have high yield potential that may be expressed when production conditions become more favorable. In this respect, Allard and Bradshaw [7] suggested that, while developing cultivars with specific adaptation to predictable specific environments, plant breeders should aim to produce cultivars that are adapted to withstand unpredictable transient environmental variations. In addition, evidence for enhanced hybrid stability would facilitate wider acceptance of sorghum hybrids by growers throughout the region. Fortunately, the possibility exists to find or develop stable and high-yielding genotypes (fit genotypes) for different environments [8].

One of the early attempts to obtain measurement of the stability of individual lines was made by Plaisted and Peterson [9] who estimated the variance component of cultivars x location interaction for each of the possible pairs of cultivars tested. The average of the estimates of all combinations using common cultivars was considered paramount for stability measurements. This method becomes cumbersome when a large number of genotypes are tested. Furthermore, this model lacks a dynamic estimate of stability and adaptability. Finlay and Wilkinson [10] developed a different model. This model is based on linear regression; for each variety, a linear regression of individual yields on the mean of all varieties for each environment is computed. The main feature of this model is the use of average yields of all varieties to describe the environment, so that the complexities of defining the interacting edaphic and seasonal factors are avoided. It provides two measures of the genotypic changes to environment: the regression coefficient (bi) and the variety mean. In the experiment upon which this model was developed, it was found that 70% of the genotype x environment (G x E) was attributed to linear regression. However, this model does not take into account the non-linear component. To address this limitation, Eberhart and Russell [11] developed a stability model based on computing two stability parameters: linear regression and deviation from regression. In effect, this model divides the genotype x environment interaction into two aspects: (i) deviation due to the response of the variety to varying environmental indexes (linear) and (ii) the unexplained deviations from the regression on the environmental index (non-linear). These estimates of linear and non-linear parameters provide an adequate account of the dynamic response of genotypes to changing environment and are used with mean performance to assess the potentialities of different genotypes. Plant breeders on various crops [12-16] have extensively used this approach. In Egypt, however, no such studies have been conducted to establish the stability of sorghum B-lines.

Development of a stable variety is one of the major objectives of all breeding programs. Phenotypically stable varieties are usefully sought for commercial production of crop plants. In any breeding program, it is necessary to screen and identify phenotypically stable genotypes, which could perform more or less uniformly under different environmental conditions. Several models have been proposed for stability analysis; the most important is Eberhart and Russell's model. The stability analysis may be more meaningful when the material is tested under various environments. In the present study, a set of 25 B-lines were evaluated under six environments. The performance of different genotypes in respect to various characters were studied for estimating stability and significance of genotype × environment interactions. This study was thus, conducted to compare relative stability of 25 grain sorghum B-lines under Egyptian conditions for grain yield and its components. The three evaluation parameters used were mean, regression coefficient and the deviation from regression.

2. MATERIALS AND METHODS

The fieldwork of this study was carried out at two locations, namely Giza and Shandaweel Research Stations of the Agricultural Research Center, Egypt in 2012 and 2013 growing seasons of grain sorghum.

Breeding materials

Twenty-five grain sorghum maintainer lines (B-lines) kindly provided by Grain Sorghum Res. Dept. of Agric. Res. Center (ARC), Egypt were used as breeding material of this study. Designation, name and origin of these lines are presented in Table (1).

Table 1. Designation, name and origin of grain sorghum maintainer lines (B-lines) used in this study.

Genotype No.	Name	Origin	Genotype No.	Name	Origin
G1	**ICSB -1**	ICRISAT- India	**G14**	**ICSB -8005**	ICRISAT- India
G2	**ICSB -11**	ICRISAT- India	**G15**	**ICSB -30**	ICRISAT- India
G3	**ICSB -14**	ICRISAT- India	**G16**	**ICSB-8010**	ICRISAT- India
G4	**ICSB -20**	ICRISAT- India	**G17**	**ICS B -015**	ICRISAT- India
G5	**ICSB -37**	ICRISAT- India	**G18**	**ICSB -0001**	ICRISAT- India
G6	**ICSB -70**	ICRISAT- India	**G19**	**ICSB -1003**	ICRISAT- India
G7	**ICSB -102**	ICRISAT- India	**G20**	**BTX 2-1**	Texas- USA
G8	**ICSB -122**	ICRISAT- India	**G21**	**BTX -407**	Texas- USA
G9	**ICSB -155**	ICRISAT- India	**G22**	**BTX -409**	Texas- USA
G10	**ICSB -1808**	ICRISAT- India	**G23**	**BTX -630**	Texas- USA
G11	**ICSB -8001**	ICRISAT- India	**G24**	**BTX -631**	Texas- USA
G12	**ICSB -8003**	ICRISAT- India	**G25**	**BTX TSC-20**	Texas- USA
G13	ICSA -88004	ICRISAT- India			

Source: Grain sorghum Res. Department, Field Crops Res. Institute, Agric. Res. Center, Egypt.

Field experiments

Six field experiments represented different environments (E1, E2, E3, E4, E5 and E6) were carried out; four of them (E1 through E4) at Giza (two planting dates x two seasons) and two (E5 and E6) at Shandaweel (one planting date x two seasons). The two planting dates at Giza were on 1^{st} of June and 1^{st} of July in both growing seasons (2012 and 2013). The planting date at Shandaweel was on 1^{st} July in both seasons (2012 and 2013). Characterization of the six environments used in this study is presented in Tables (2 and 3).

Table 2. Location, latitude, longitude, altitude, planting date, air temperature and relative humidity (RH) of the six tested environments (E1 to E6).

Environ-ment	Location	Latitude	Longitude	Altitude	Planting date	Temperature (^{o}C)			RH%
						Max.	Aver.	Min.	
E1	Giza	30^{o} 02` N	31^{o} 13`E	22.5 masl	1/6/2012	37.6	29.6	24.8	64.0
E2	Giza	30^{o} 02` N	31^{o} 13`E	22.5 masl	1/7/2012	37.7	29.4	24.8	58.7
E3	Giza	30^{o} 02` N	31^{o} 13`E	22.5 masl	1/6/2013	35.2	28.8	22.4	60.4
E4	Giza	30^{o} 02` N	31^{o} 13`E	22.5 masl	1/7/2013	37.2	30.3	23.7	60.7
E5	Shandaweel	26^{o} 33` N	31^{o} 41`E	67.0 masl	1/7/2012	41.1	30.5	26.2	33.7
E6	Shandaweel	26^{o} 33` N	31^{o} 41`E	67.0 masl	1/7/2013	40.8	33.6	25.5	32.2

masl = meter above sea level.

Table 3. Soil analysis at 0-30 cm depth in the experimental fields at Giza and Shandaweel in 2012 and 2013 growing seasons.

Soil characteristics	Season 2012	Season 2013	Season 2012	Season 2013
	Giza		Shandaweel	
Physical Analysis				
Coarse sand %	3.68	5.80	13.30	12.26
Fine sand %	19.52	9.00	21.70	18.38
Silt %	26.55	38.30	31.84	24.26
Clay %	50.25	46.90	33.16	45.15
Texture	Clay	Clay	Clay loam	Clay
Chemical analysis				
pH (paste extract)	8.25	8.09	7.40	7.70
EC (dS/m)	3.21	1.78	0.80	0.67
Organic matter %	1.86	1.7	1.89	1.32

Experimental design

A randomized complete block design in three replications was used in each of the six experiments. Each experimental plot consisted of one ridge of five meters length and 0.7 meter widths. Therefore, the experimental plot area for each B-line was 3.5 m^2. Seeds were sown in hills at 20 cm apart, thereafter (before the first irrigation) were thinned to two plants/hill to achieve a plant density of 60,000 plants/fed (142,800 plants/ha).

Cultural practices

Flood irrigation was given at planting, the first irrigation after 21 days and the next irrigations at 10-15 day intervals depending on the requirement of plants. Nitrogen fertilizer was added at the rate of 100 kg N/fed (238 kg/ha) as Urea (46.5 % N) in two equal doses; the first dose before the first irrigation and the second before the second irrigation. Calcium Superphosphate fertilizer (15% P_2O_5) was added at the rate of 30 kg P_2O_5/fed as soil application before sowing during preparation of the soil for planting. Potassium fertilizer at the rate of 24 kg K_2O/fed was added as soil application before the second irrigation as Potasium Sulfate (48% K_2O). Other cultural practices were carried out following the recommendations of ARC, Egypt. Weed control was performed chemically with Stomp herbicide (active constituent: 455 g/l Pendimethalin; manufactured by BASF, Australia) before the planting irrigation and just after sowing and manually by hoeing twice, the first before the first irrigation and the second before the second irrigation. Pest control was performed when required by spraying plants with Lannate (Methomyl) 90% (manufactured by DuPont, USA) against borers.

Data recorded

1. **Days to flowering (DTF)** measured as the number of days from the date of emergence to the date at which about 50% of the plants in a plot showed blooming.
2. **Plant height (PH)** in cm measured on 10 guarded plants $plot^{-1}$ as the average height from the ground level to the tip of the panicle at the time of harvesting.
3. **Number of grains/plant (GPP)** measured on five guarded plants/plot.
4. **1000-grain weight (TGW)** in g measured on five samples/plot adjusted at 14% grain moisture.
5. **Grain yield/plant (GYPP)** in g estimated on 10-guarded plants/plot as the average weight of grain yield/plant adjusted at 14% grain moisture.

Biometrical analyses

Analysis of variance of the randomized complete block design (RCBD) was performed for each of the six environments on the basis of individual plot observation using the DSAASTAT Version 1.1 (Update: 18/03/2011). Combined analysis of variance across the six environments was also performed if the homogeneity test was non-significant. Least significant difference (LSD) values were calculated to test the significance of differences between means according to Steel *et al.* [17].

Stability analysis

Stability analysis of the 25 grain sorghum lines was carried out for characters under study. Stability parameters were estimated for grain yields by using the model described by Eberhart and Russell [11]. This model utilizes the deviations from the grand mean of the yield over the various environments as production indexes of the environments. It provides regression response indexes (b values) and mean squares for deviations from regression minus pooled error (S^2d values) as indexes of production response and stability, respectively. The performance of a variety is then defined by the equation:

$$Y_{ij} = \mu_i + \beta_i I_j + \delta_{ij}$$

Where Y_{ij} is the mean grain yield of the i^{th} genotype in the j^{th} environment, μ_i is the mean of the i^{th} genotype, β_i the coefficient which measures the regression of the i^{th} genotype on different environments (linear response predictive), δ_{ij} is the deviation from regression of the genotype in the j^{th} environment, and I_j is the environmental index calculated as the mean of all genotype at the j^{th} environment less the grand mean over all environments.

Since the sum of I_j over all environments is zero, the yield of a variety in a given environment can be predicted as follows: $Y_{ij} = x_i + b_i I_j$. Where x_i and b_i are estimates of μ_i and β_i, respectively. The mean squares due to deviations from regression (S^2_d) indicate the degree of reliance that can be placed upon linear regression. In fact, S^2_d reveals a non-linear response of varieties (non-predictive). When the deviations are significant, the genotype stability is specified by a joint consideration of both μ and β.

The significance of means squares was tested against the pooled error. The t-test based on the standard error of regression value was used to test the significant deviation of b from 1.0. To determine whether deviations from regression were significantly different from zero, the F-test was employed (i.e., comparing the mean squares due to deviations from regression with pooled error mean squares). In addition, a separate analysis for parental lines was conducted to test for heterogeneity of the slopes among entries of the two genotypic groups. The entries x environment (linear) mean square estimates were tested separately for parental lines using the respective deviation mean squares.

If the regression coefficient was close to one ($b_i = 1.0$), the genotype was adapted in all environments, genotypes with $b_i > 1.0$ were more responsive or adapted to high yielding environments, whereas any genotype with b_i significantly lower than 1.0 was adapted to low yielding environments [11]. Analysis of Eberhart and Russell's stability was performed using the Genestat-17.1.13780 software program. According to Eberhart and Russell's [11] model, a stable variety is one, which has above average mean yield, a regression coefficient of unity (b_i=1) and non-significant mean square deviations from regression (S^2_{di}=0). The high value of regression (b_i >1) indicates that the variety is more responsive for input rich environment, while, low value of regression (b_i<1) is an indication that the variety may be adopted in poor environment.

3. RESULTS AND DISCUSSION

3.1. Analysis of variance

The pooled analysis of variance provides an estimate of genotype × environment interaction, which measures changes in rank and magnitude of fluctuations about the mean of different environments. The mean squares due to environments and genotypes were significant (P<0.01) for all studied traits (Table 4). The mean squares due to genotype × environment interaction were significant for all the traits. Thus, stability analysis was carried out for all the traits.

Analysis of variance for stability (Table 4) revealed the existence of substantial variability among the genotypes for all studied traits showing that genotypic differences were highly significant for these traits. Significance of genotype × environmental interaction was found for all characters revealing that genotypes interacted significantly with environments. The presence of significant environment by genotype interaction showed the inconsistency of performance of grain sorghum parental lines across the test environments. A similar result was reported on sorghum [2-6, 18-20].

As shown in Table 4, partitioning of genotype by environment into linear and non-linear portions for studied traits indicated that both were vital. Genotype by environment (linear) and pooled deviations were significant when tested against pooled mean squares, revealing that both linear and non-linear components accounted for genotype by genotype x environment variance. The large significant genotype by environment variance suggests that the component was most important in contributing to differences in performance of genotypes across the test environments. The relatively large proportion of environment variance when compared with genotype as main effect suggests the large influence of environment on performance of grain sorghum lines. These findings were in accordance with several investigators [21-23].

Table 4. Analysis of variance (mean squares) of phenotypic stability for studied traits of 25-grain sorghum parental lines.

SOV	df	Days to flowering	Plant height	1000-Grain weight	Grains /plant	Grain yield /plant
Environment (E)	5	1230.3**	8751.3**	527.9**	12003248**	7224.8**
Genotype (G)	24	94.8**	1504.7**	60.6**	465056*	362.3**
GxE	120	28.8**	222.2**	14.3**	246720**	123.6**
Env.+(Gen. x Env.)	125	76.8**	563.3**	34.8**	716981**	407.6**
Env.(Linear)	1	6151.6**	43756.5**	2639.6**	60016242**	36124.2**
GxE (linear)	24	22.1**	153.8**	11.6**	345516**	193**
Pooled Deviation	100	29.21	229.7	14.3	213140	101.9

***, ** Significant at P≤ 0.05 and P≤ 0.01, respectively.**

Understanding the relationship among testing environments is important if plant breeders are to target germplasm better adapted to different production environments or regions [24]. The estimates of environmental index (Table 5) showed that E5 (Shandaweel, 2013) was the best performing environment for grain yield/plant, grains/plant and 1000-grain weight, i.e. all studied yield attributes, but produced the latest flowering plants. The environment E1 (Giza, 1st planting date, 2012) was the poorest in 1000-grain weight and grains/plant, and performed the shortest plants. The environment E6 (Shandaweel, 2013) produced the tallest plants and E3 (Giza, 1st planting date, 2013) was the poorest in grain yield/plant.

Table 5. Estimates of environmental index.

Env.	Days to flowering	Plant height	Grains/ plant	1000-Grain weight	Grain yield /plant
E1	-3.81	-17.6	-298	-3.81	-7.66
E2	-2.26	-4.6	-96	-2.26	-1.66
E3	-3.26	4.3	-153	-3.26	-9.6
E4	4.57	8.6	-27	4.57	-1.73
E5	5.51	-3.1	793	5.51	17.79
E6	-0.77	12.3	-222	-0.77	2.87

This variation in the environmental index showed that the performance of the genotypes varied from location to location, from planting date to another and from year to year. Shandaweel location 2nd year (E5) was therefore the most favorable environment for realizing the yield potential of grain sorghum parental lines with the location possessing favorable environmental resources, particularly better soil variables. Although most genotypes were adapted to E5 environment, some genotypes demonstrated specific adaptation to poorer environments, suggesting other climatic conditions were the determining factors for the performance of grain sorghum genotype and confer either broad or specific adaptation to such environments.

3.2. Stability for individual characters

Two stability parameters consisting of regression coefficient "b_i" and deviation from regression "S^2_{di}" were used to evaluate 25 parental B-lines as shown in Table (6). A genotype with a unit value for regression coefficient and minimum deviation from regression is considered stable [11].

Table 6. Estimates of stability parameters for studied characters of grain sorghum lines evaluated across six environments.

Genotype No.	B-Line Name	Mean	b_i	S^2_d	Mean	b_i	S^2_d
		Days to flowering			Plant height (cm)		
G1	**ICSB -1**	67.73	1.18	25.35	117.0	1.03	23.18
G2	**ICSB -11**	66.67	0.84	1.04	116.6	0.99	137.84
G3	**ICSB -14**	67.78	1.19	57.04	140.8	1.45	287.57
G4	**ICSB -20**	66.27	0.71	15.02	119.7	1.02	238.56
G5	**ICSB -37**	63.17	0.95	64.74	122.0	0.61	140.00
G6	**ICSB -70**	65.12	1.02	5.94	115.7	1.45	176.26
G7	**ICSB -102**	61.05	1.55	18.26	100.8	1.25	614.45

G8	**ICSB -122**	65.90	0.62	38.31	109.7	1.13	922.80*
G9	**ICSB -155**	61.78	1.62	38.63	96.5	1.24	263.81
G10	**ICSB -1808**	67.85	1.25	34.16	120.8	0.63	145.69
G11	**ICSB -8001**	68.23	1.36	13.15	109.6	1.10	112.38
G12	**ICSB -8003**	67.50	1.29	24.51	113.0	1.61	118.01
G13	**ICSB -8004**	70.00	0.81	36.80	119.3	0.68	59.83
G14	**ICSB -8005**	69.27	0.57	8.16	120.1	1.21	109.22
G15	**ICSB -30**	65.68	1.11	42.17	110.2	0.92	193.89
G16	**ICSB-8010**	70.88	0.52	40.14	126. 7	1.00	471.21
G17	**ICS B -015**	67.50	0.96	6.33	116.4	0.92	117.60
G18	**ICSB -0001**	67.22	0.81	13.77	105.8	0.60	266.11
G19	**ICSB -1003**	68.62	0.97	41.99	105.3	0.43	424.68
G20	**BTX 2-1**	65.07	0.67	17.10	108.3	0.58*	38.67
G21	**BTX -407**	66.33	1.10	1.65	122.6	1.20	176.99
G22	**BTX -409**	67.52	1.20	2.97	115.7	1.03	46.51
G23	**BTX -630**	65.65	1.25	110.11*	126.8	0.86	162.26
G24	**BTX -631**	68.07	0.65	8.79	116.0	1.02	95.90
G25	**BTX TSC-20**	67.67	0.82	61.61	114.3	1.08	402.99
			1000-Grain weight (g)			**Grains/plant**	
G1	**ICSB -1**	28.00	1.24	6.90	1857.77	0.72	117093
G2	**ICSB -11**	25.40	1.15	26.11	1895.95	1.45	206277
G3	**ICSB -14**	27.55	0.93	5.53	1930.93	0.67	847902*
G4	**ICSB -20**	24.68	0.70	16.73	1803.77	0.45	121686
G5	**ICSB -37**	26.02	1.70	11.97	1677.85	0.59	204618
G6	**ICSB -70**	28.53	0.32*	4.66	1745.35	0.22	261746
G7	**ICSB -102**	24.62	1.58	12.74	1604.55	1.20	68301
G8	**ICSB -122**	25.48	1.27	6.50	1808.68	1.02	110253
G9	**ICSB -155**	24.12	0.75	14.18	1925.78	1.12	1200524*
G10	**ICSB -1808**	26.87	1.06	3.91	2044.05	1.15	131716
G11	**ICSB -8001**	29.03	0.86	26.78	1705.57	1.52*	81751
G12	**ICSB -8003**	25.87	1.22	15.65	2171.23	0.56	289859
G13	**ICSB -8004**	28.13	0.85	19.96	1694.55	1.58	141407
G14	**ICSB -8005**	29.35	0.97	17.64	1697.50	1.15	28053
G15	**ICSB -30**	27.63	0.91	25.25	1660.78	1.18	111058
G16	**ICSB-8010**	27.57	1.28	13.42	1723.68	0.98	167500
G17	**ICS B -015**	25.45	0.85	8.40	1841.83	1.03	74847
G18	**ICSB -0001**	23.73	1.06	19.17	1917.72	0.74	76570
G19	**ICSB -1003**	23.97	1.10	2.97	1873.35	0.99	147150
G20	**BTX 2-1**	23.52	0.51	13.93	1938.47	1.66	259572
G21	**BTX -407**	25.55	1.15	11.90	1939.4	1.10	89369
G22	**BTX -409**	24.93	0.99	13.04	1791.72	1.26	49284
G23	**BTX -630**	28.28	0.38	7.69	1639.02	1.12	170836
G24	**BTX -631**	29.27	1.35	36.41	1743.43	1.17	116208
G25	**BTX TSC-20**	26.03	0.80	17.42	2256.17	0.35	254784
			Grain yield/plant (g)				
G1	**ICSB -1**	51.28	0.58	68.32			
G2	**ICSB -11**	47.28	1.60	77.16			
G3	**ICSB -14**	51.53	0.41	479.86*			
G4	**ICSB -20**	44.43	0.83	101.80			
G5	**ICSB -37**	42.73	0.60	49.67			
G6	**ICSB -70**	47.82	0.51	182.54			
G7	**ICSB -102**	40.50	1.26	65.44			
G8	**ICSB -122**	46.22	1.28	113.83			
G9	**ICSB -155**	37.98	1.75**	16.34			
G10	**ICSB -1808**	54.40	0.72	110.02			
G11	**ICSB -8001**	48.37	1.07	3.73			
G12	**ICSB -8003**	55.45	0.64	408.55*			
G13	**ICSB -8004**	46.07	1.21	89.07			
G14	**ICSB -8005**	47.87	0.72	24.61			
G15	**ICSB -30**	43.00	1.11	105.13			

G16	**ICSB-8010**	46.87	1.00	79.85
G17	**ICS B -015**	45.55	1.13	44.39
G18	**ICSB -0001**	45.17	1.04	9.21
G19	**ICSB -1003**	45.17	1.22	77.09
G20	**BTX 2-1**	45.20	1.57	209.25*
G21	**BTX -407**	47.92	1.05	5.25
G22	**BTX -409**	44.32	1.32	84.76
G23	**BTX -630**	45.53	1.02	60.53
G24	**BTX -631**	48.90	0.95	60.85
G25	**BTX TSC-20**	58.10	0.41**	23.13

b_i= Regression coefficient and S^2_{di} = Deviation from regression. *, ** Significant at P ≤ 0.05 and P≤ 0.01, respectively.

3.2.1. Days to flowering

For number of days to flowering, the genotype G23 (BTX-630) had a significant deviation from linear regression (Table 6), implying that this genotype was unstable across the environments for days to flowering. Out of the six latest flowering genotypes (G11, G13, G14, G16, G19 and G24), one genotype (G11) had average responsiveness (b_i> 1.0), implying that this genotype produced their late plants under favorable environments (Table 6 and Fig. 1). The other genotypes G13, G14, G16, and G24 were considered late flowering under poor environments with predictable performance as they exhibited high performance for days to flowering along with below average responsiveness (b_i<1) and non-significant deviation from regression line.

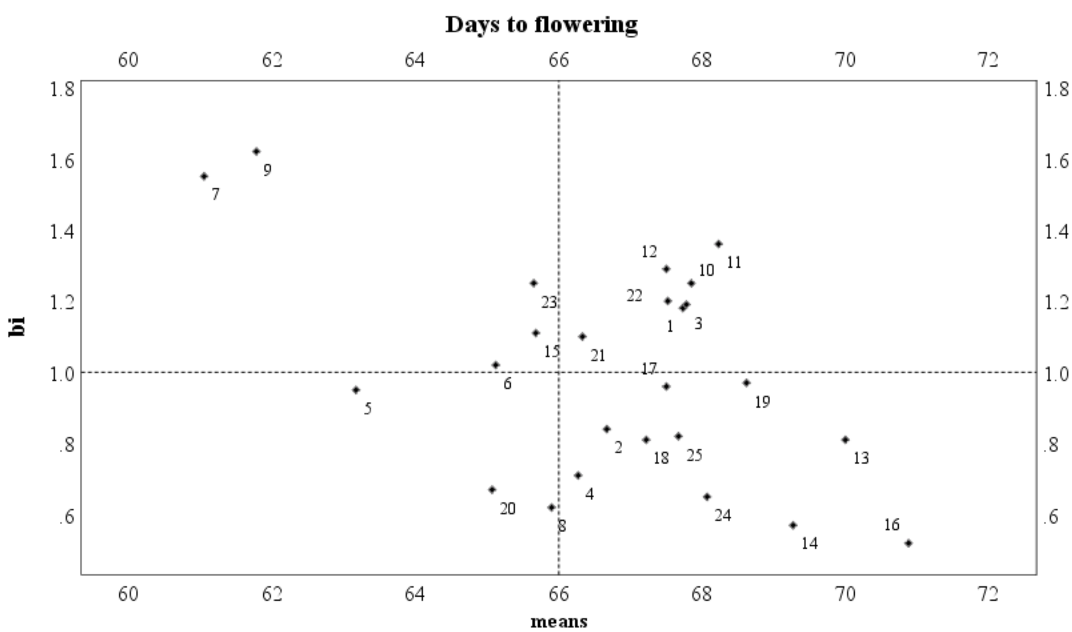

Fig. 1. Relationship between mean number of days to flowering of 25 grain sorghum parental lines and regression coefficient across six environments.

Parental lines G7 and G9 were found responsive for favorable conditions (rich environments) with predictable performance as they showed low performance for days to flowering along with above average responsiveness (b_i>1.0) and non-significant deviation from the regression line. The two lines G17 (ICSB-015) and G19 (BTX-2-1) displayed above average performance and the line G6 (ICSB-70) displayed below average performance; for days to flowering, the regression coefficient value near unity and non-significant deviation from regression, indicating that these three genotypes are stable and widely adapted. These three lines can be utilized as parental lines for the development of single cross hybrids in view of their stability. Regression coefficient for days to flowering across locations ranged from 0.57 (G14) to 1.62 (G9). The results further showed that 12 out of 25 grain sorghum lines gave regression coefficient value (b_i) ≥ 1, indicating that these lines responded to favorable environment and can produce later flowering plants when provided with suitable environments. On the other hand, the rest 13 lines with regression coefficient less than one (b_i< 1) can produce later flowering plants under poor environments; i.e. earlier flowering plants under rich environments. Sujay *et al.* [25] also reported significant G x E interactions for days to flowering of sorghum.

3.2.2. Plant height

For plant height, the genotype G8 (ICSB -122) had a significant deviation from linear regression (Table 6), implying that this genotype was unstable across the environments. Out of the top six tall plant genotypes (G3, G5, G10, G14, 21 and G23), three genotypes (G3, 21 and G14) were found suitable for favorable conditions (rich environments) with predictable performance as they showed high performance for plant height along with above average responsiveness (b_i> 1.0) and non-significant deviation from regression line and (Table 6 and Fig. 2). The other three genotypes G5, G10 and G23, were considered suitable for poor environments with predictable performance as they exhibited high performance for plant height (tallness) along with below average responsiveness (b_i<1) and non-significant deviation from regression line. Four lines (G1, G4, G22 and G24) displayed near average performance for plant height, regression coefficient value near unity and non-significant deviation from regression, indicating that these genotypes are stable and widely adapted. Moreover, the genotype G16 (ICSB-8010) displayed the lowest performance for plant height (shortness) with regression coefficient value near unity and non-significant deviation from regression, indicating that this genotype is stable and widely adapted. The latter five lines can be utilized as parental lines for the development of single cross hybrids of grain sorghum in view of their stability for plant height.

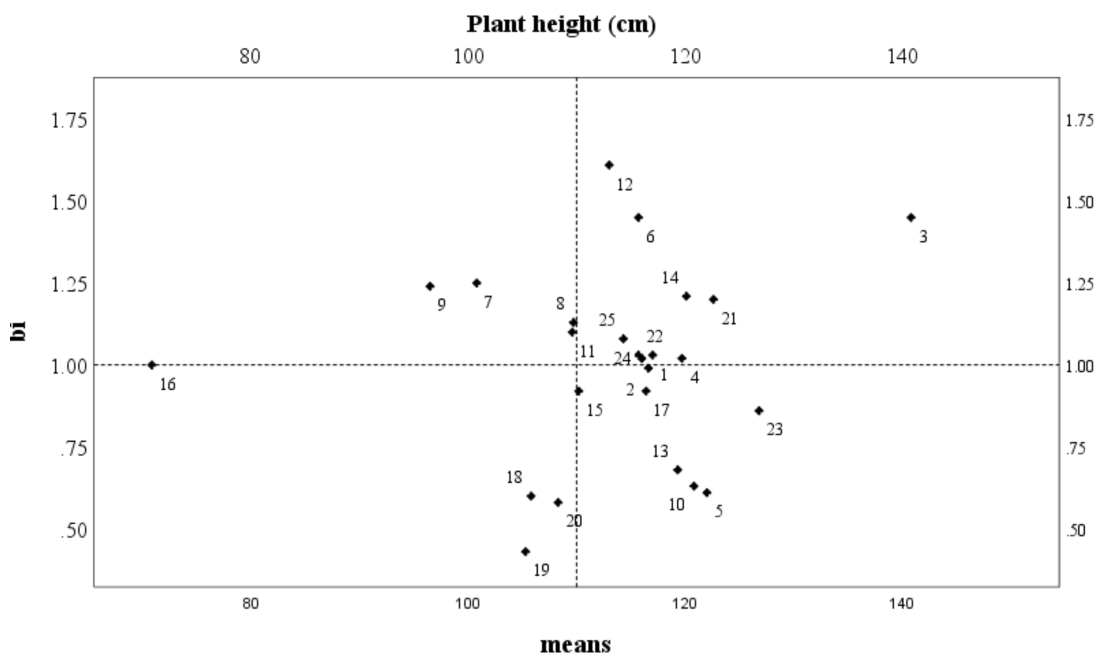

Fig. 2. Relationship between mean plant height of 25 grain sorghum parental lines and regression coefficient across six environments.

Regression coefficient for plant height across locations ranged from 0.43 (G19) to 1.61 (G12). The results further showed that 15 out of 25 grain sorghum lines gave regression coefficient value (b_i) ≥ 1, indicating that these lines responded to favorable environment and can produce taller plants when provided with suitable environments. On the other hand, the 10 lines (G2, G5, G10, G13, G15, G17, G18, G19, G20 and G23) with regression coefficient less than unity (b_i< 1) can produce taller yields under poor environments or shorter plants under rich environments. Significant G x E interactions for plant height of sorghum was also reported by other investigators [2-6, 19, 20, 25].

3.2.3. Grains/plant

For number of grains/plant, two genotypes (G3 and G9) had a significant deviation from linear regression (Table 6), implying that these two genotypes were unstable across the environments, based on S^2_{di} parameter. Out of the top eight lines in grains/plant (G25,G12, G10,G20, G21,G9, G3 and G18), the lines G9, G10, G20 and G21 were found suitable for favorable conditions with predictable performance as they showed high number of grains/plant along with above average responsiveness (b_i> 1.0) and non-significant deviation from regression line (Table 6 and Fig.3). The other four genotypes (G25, G12, G3 and G18), were considered suitable for poor environments with predictable performance as they exhibited high and above average performance for number of grains/plant along with below average responsiveness (b_i<1) and non-significant deviation from regression line. The four genotypes (G25, G12, G3 and G18) displayed high mean number of grains/plant, regression coefficient value of less than unity and non-significant deviation from the regression line. Four lines (G8, G17, G19 and G16) displayed below average mean number of grains/plant, regression coefficient value near unit and non-significant deviation from regression, indicating that these four genotypes are stable and widely adapted. These four lines can be utilized as parental lines for the development of single cross hybrids of grain sorghum in view of their stability for grains/plant. Regression coefficient for number of grains/plant across environments ranged from 0.22 (G6) to 1.66 (G20) .

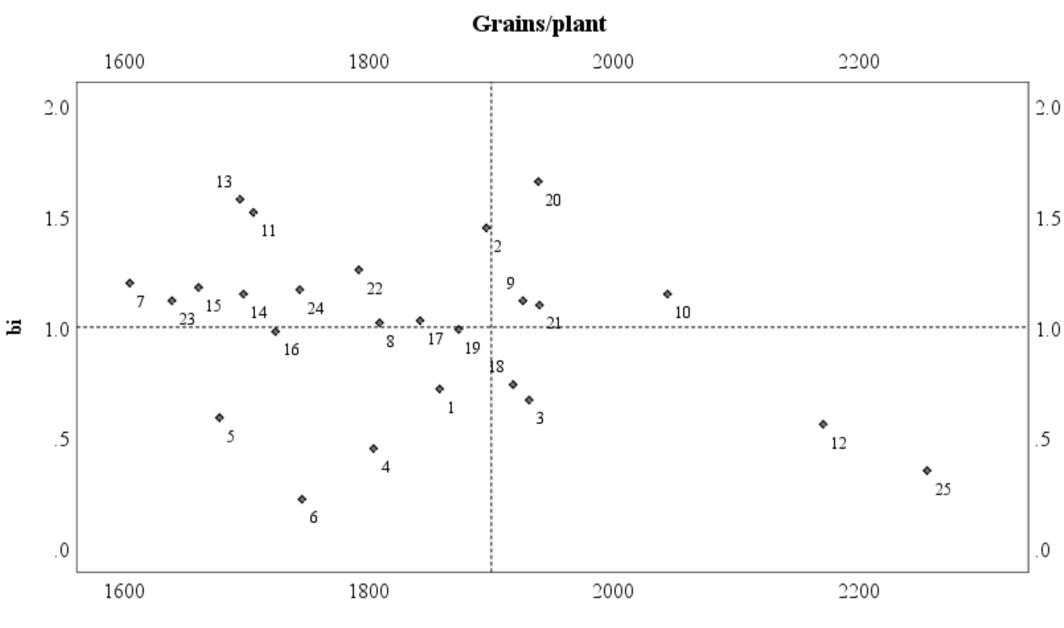

Fig. 3. Relationship between mean number of grains/plant of 25 grain sorghum parental lines and regression coefficient across six environments.

The results further showed that 15 out of 25 grain sorghum lines gave regression coefficient value greater than one, indicating that these lines responded to favorable environment and can produce higher number of grains/plant when provided with suitable environments. On the other hand, the 10 lines with regression coefficient less than one responded to all environments and possess wider adaptation to varying environmental conditions. Significant G x E interactions for grains/plant of sorghum was also reported by other investigators [2-6, 19, 20, 25].

3.2.4. 1000-Grain weight

For 1000-grain weight, all genotypes had non-significant deviation from linear regression (Table 6), implying that all genotypes were stable across the environments for this trait, based on parameter of stability (S^2_{bi}). Out of the top seven heaviest seed lines (G14, G24, G11, G6, G23, G13 and G1), two lines (G1 and G24) were found suitable for favorable conditions with predictable performance as they showed high mean 1000-grain weight along with above average responsiveness ($b_i > 1.0$) and non-significant deviation from regression line (Table 6 and Fig.4). The other five genotypes (G14, G6, G11, G13 and G23), were considered suitable for poor environments with predictable performance as they exhibited high performance for 1000-grain weight along with below average responsiveness ($b_i<1$) and non-significant deviation from regression line. Out of the top three genotypes for 1000-grain weight (G11, G14 and G24), the genotype G24 (BTX-631) displayed high mean value of 1000-grain weight, regression coefficient value of high than unity and non-significant deviation from the regression line and so it is considered responsive to favorable conditions. The genotype G14 displayed the highest mean grain weight, regression coefficient value near unit (0.97) and non-significant deviation from regression, indicating that this genotype is stable; widely adapted. This line can be utilized as a parental line for the development of single cross hybrids of sorghum in view of stability and high mean values for 1000-grain weight. The line G22 displayed below average mean grain weight, regression coefficient value near unity (0.99) and non-significant deviation from regression, indicating that this genotype is stable and widely adapted for light grain weight.

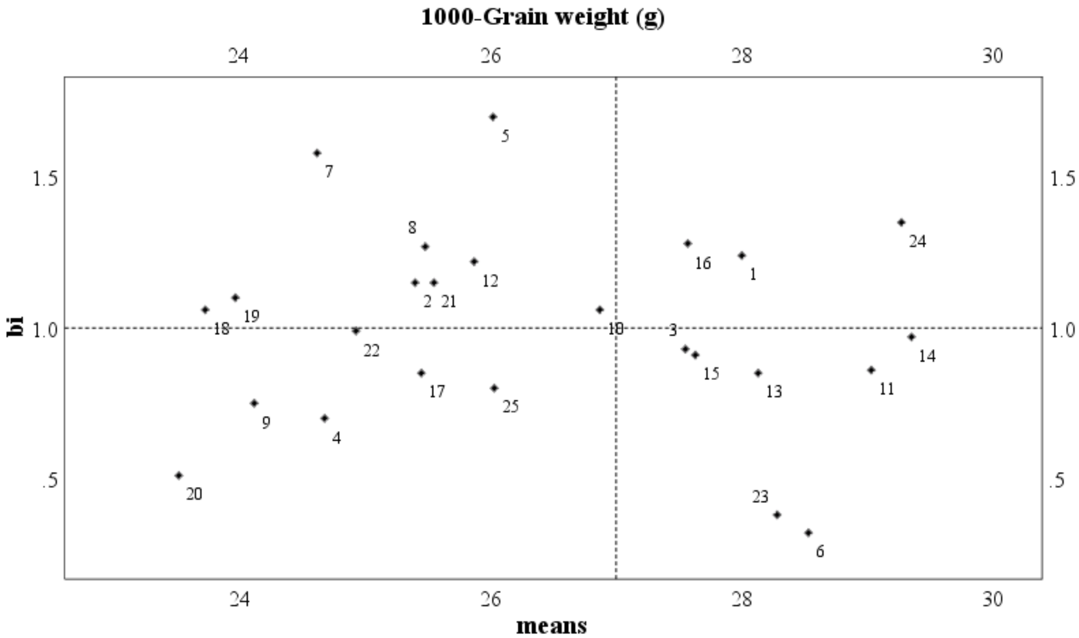

Fig. 4. Relationship between mean 1000-grain weight of 25 grain sorghum parental lines and regression coefficient across six environments.

Regression coefficient for 1000-grain weight across locations ranged from 0.32 (G6) to 1.70 (G5). The results further showed that 11 out of 25 grain sorghum lines gave regression coefficient value (b_i) ≥ 1, indicating that these lines responded to favorable environment and can produce heavy grain weight when provided with suitable environments. On the other hand, the 14 lines (G3, G4, G6, G9, G11, G13, G14, G15, G17, G20, G22, G23 and G25) with regression coefficient less than unity (b_i< 1) can produce heavy grain weight under poor environments. Sujay *et al.* [2-6] and Al-Naggar *et al.* [2-6, 19, 20] also reported significant G x E interactions for 1000-grain weight of sorghum.

3.2.5. Grain yield/plant

For grain yield, three genotypes (G3, G12 and G20) had a significant deviation from linear regression (Table 6), implying that these three parental lines were unstable across the environments. The five highest yielding lines G25, G12, G10, G3 and G1 were found suitable for poor environments, as they showed below average responsiveness (b_i < 1.0) (Table 6 and Fig.5). Out of these high yielding five genotypes, two lines (G3 and G12) have unpredictable performance due to their significant deviation from the regression line, while three genotypes (G25, G10 and G1) displayed high mean grain yield, regression coefficient value of less than unity (suitable for poor environments) and non-significant deviation from the regression line.

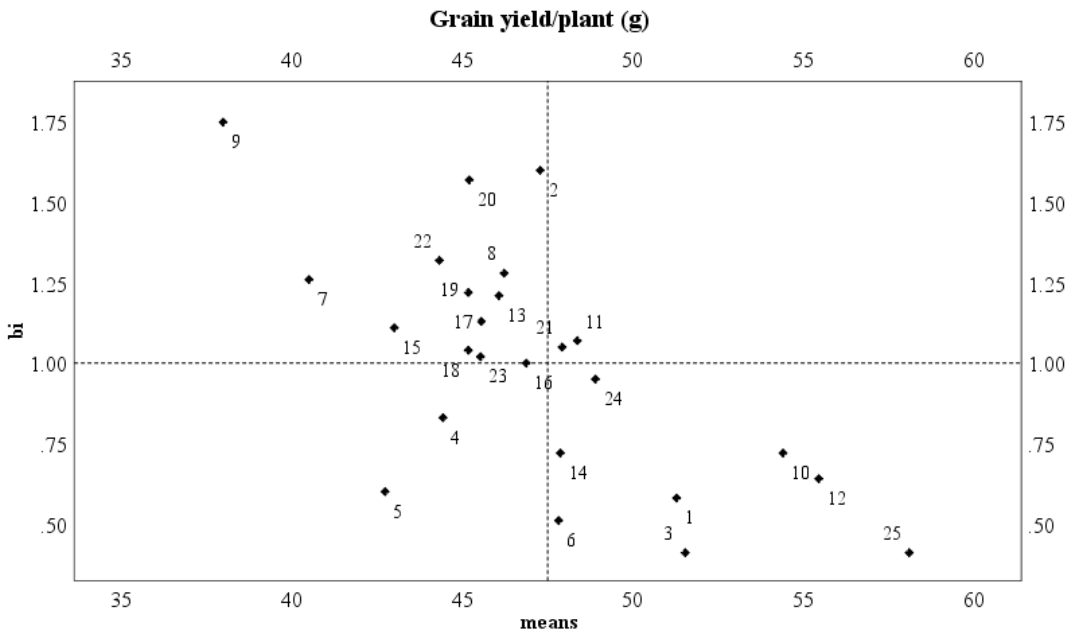

Fig. 5. Relationship between mean grain yield/plant of 25 grain sorghum parental lines and regression coefficient across six environments.

The three lines G11, G21 and G24 displayed above average mean yield, regression coefficient value near unity (1.07, 1.05 and 0.95) and small and non-significant deviation from regression, indicating that these three genotypes are stable and widely adapted. These three lines can be utilized as parental lines for the development of single cross hybrids of sorghum in view of their stability and high mean values for grain yield. The lines G16, G23 and G18 were also stable (b_i near unity and non- significant deviation from linear regression), but displayed below average grain yield/plant. High yielding genotypes can differ in yield stability; high grain yield and yield stability are not mutually exclusive [26].

Regression coefficients for grain yield across locations ranged from 0.41 (G3) to 1.75 (G9). The results further showed that 15 out of 25 grain sorghum lines gave regression coefficient value greater than one, indicating that these lines responded to favorable environment and can produce higher yields when provided with suitable environments. On the other hand, the 10 lines with regression coefficient less than one responded to all environments and possess wider adaptation to varying environmental conditions.

On the contrary, the genotypes G9 and G7 (displaying b_i higher than unity, i.e. adapted to good environments) and G5 (displaying b_i lower than unity, i.e. adapted to poor environments) were the lowest yielders.

Toolnar and Lee [26] reported significant differences among high yielding maize hybrids for their yield stability. Sujay *et al.* [2-6] and Al-Naggar *et al.* [2-6, 19, 20] also reported significant G x E interactions for grain yield of sorghum. Gama and Hallauer [27] detected significant hybrid x environment interaction for maize hybrids, while some were reported to be stable when both stability parameters were considered. Kang and Gorman [28] and Vulchinokova [29] also reported significant G x E interactions for different traits of maize.

4. CONCLUSION

Significance of genotype × environment interaction was found for all characters revealing that genotypes interacted significantly with environments. The presence of significant environment by genotype interaction showed the inconsistency of performance of grain sorghum parental lines across the test environments. Stable genotypes differed from trait to trait. Two of the five top most yielding genotypes (G3 and G12) were not stable based on deviation from regression and the three genotypes (G25, G10 and G1) were also not stable based on regression coefficient parameter; all of them were considered suitable for poor environments with predictable performance as they exhibited high performance for grain yield along with below average responsiveness (b_i<1). The three lines G11 (ICS-8001), G21 (BTX-407) and G24 (BTX -631) displayed above average grain yield/plant (GYPP), regression coefficient (b_i) value near unity and small and non-significant deviation from regression (S^2_d), indicating that these three genotypes are stable and widely adapted to different environments. For other studied traits, the most stable genotypes were G17, G19 and G6 for days to flowering, G1, G4, G22, G24 and G16 for plant height, G8, G17, G19 and G16 for grains/plant and G14 and G22 for 1000-grain weight. In the future, these B-lines can be utilized as parental lines for the development of grain sorghum hybrids in view of their stability for the respective traits.

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