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 (2017). 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 (Al-Naggar *et* 2002 a, b, c and 2007 a, b). 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 (1964) 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 (Gauch and Zobel 1997).

One of the early attempts to obtain measurement of the stability of individual lines was made by Plaisted and Peterson (1959) 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 a 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. A different model was developed by Finlay and Wilkinson (1963). 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

71   x environment (G x E) was attributed to linear regression. However, this model does not take
72   into account the non-linear component. To address this limitation, Eberhart and Russell
73   (1966) developed a stability model based on computing two stability parameters: linear
74   regression and deviation from regression. In effect, this model divides the genotype x
75   environment interaction into two aspects: (i) deviation due to the response of the variety to
76   varying environmental indexes (linear) and (ii) the unexplained deviations from the
77   regression on the environmental index (non-linear). These estimates of linear and non-linear
78   parameters provide an adequate account of the dynamic response of genotypes to changing
79   environment and are used with mean performance to assess the potentialities of different
80   genotypes. This approach has been extensively used by plant breeders on various crops (Virk
81   *et al*., 1985; Becker and Leon, 1988; Gupta and Ndoye, 1991; Pettonee-Saino *et al*., 1993;
82   Ezeaku *et al*. 2014). In Egypt, however, no such studies have been conducted to establish the
83   stability of sorghum B-lines.

84   This study was thus, conducted to compare relative stability of 25 grain sorghum B-
85   lines under Egyptian conditions for grain yield and its components. The three evaluation
86   parameters used were mean, regression coefficient and the deviation from regression.

2. MATERIALS AND METHODS

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

91   **Breeding materials**

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

96   **Table 1. Designation, name and origin of grain sorghum male sterile lines (A-lines) used**
97   **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

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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 represent 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 1st of June and 1st of July in both growing seasons (2012 and 2013). The planting date at Shandaweel was on 1st 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° 02` N	31° 13`E	22.5 masl	1/6/2012	37.6	29.6	24.8	64.0
E2	Giza	30° 02` N	31° 13`E	22.5 masl	1/7/2012	37.7	29.4	24.8	58.7
E3	Giza	30° 02` N	31° 13`E	22.5 masl	1/6/2013	35.2	28.8	22.4	60.4
E4	Giza	30° 02` N	31° 13`E	22.5 masl	1/7/2013	37.2	30.3	23.7	60.7
E5	Shandaweel	26° 33` N	31° 41`E	67.0 masl	1/7/2012	41.1	30.5	26.2	33.7
E6	Shandaweel	26° 33` N	31° 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				

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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

112 **Experimental design**

113 A randomized complete block design in three replications was used in each of the

114 six experiments. Each experimental plot consisted of one ridge of five meters length and 0.7

115 widths. Therefore, the experimental plot area for each B-line was 3.5 m^2. Seeds were sown in

116 hills at 20 cm apart, thereafter (before the first irrigation) were thinned to two plants/hill to

117 achieve a plant density of 60,000 plants/fed (142,800 plants/ha).

118 **Cultural practices**

119 Flood irrigation was given at planting, the first irrigation after 21 days and the next

120 irrigations at 10-15 day intervals depending on the requirement of plants. Nitrogen fertilizer

121 was added at the rate of 100 kg N/fed (238 kg/ha) as Urea (46.5 % N) in two equal doses; the

122 first dose before the first irrigation and the second before the second irrigation. Calcium

123 Superphosphate fertilizer (15% P_2O_5) was added at the rate of 30 kg P_2O_5/fed as soil

124 application before sowing during preparation of the soil for planting. Potassium fertilizer at

125 the rate of 24 kg K_2O/fed was added as soil application before the second irrigation as

126 Potasium Sulfate (48% K_2O). Other cultural practices were carried out following the

127 recommendations of ARC, Egypt. Weed control was performed chemically with Stomp

128 herbicide (active constituent: 455 g/l Pendimethalin; manufactured by BASF, Australia)

129 before the planting irrigation and just after sowing and manually by hoeing twice, the first

130 before the first irrigation and the second before the second irrigation. Pest control was

131 performed when required by spraying plants with Lannate (Methomyl) 90% (manufactured

132 by DuPont, USA) against borers.

133 **Data recorded**

134 1. **Days to flowering (DTF)** measured as the number of days from the date of

135 emergence to the date at which about 50% of the plants in a plot showed blooming.

136 2. **Plant height (PH)** in cm measured on 10 guarded plants $plot^{-1}$ as the average height

137 from the ground level to the tip of the panicle at the time of harvesting.

138 3. **Number of grains/plant (GPP)** measured on five guarded plants/plot.

139 4. **1000-grain weight (TGW)** in g measured on five samples/plot adjusted at 14% grain

140 moisture.

141   **5. Grain yield/plant (GYPP)** in g estimated on 10 guarded plants/plot as the average
142   weight of grain yield/plant adjusted at 14% grain moisture.

Biometrical analyses

144   Analysis of variance of the randomized complete block design (RCBD) was
145   performed for each of the six environments on the basis of individual plot observation using
146   the DSAASTAT Version 1.1 (Update: 18/03/2011). Combined analysis of variance across
147   the six environments was also performed if the homogeneity test was non-significant. Least
148   significant difference (LSD) values were calculated to test the significance of differences
149   between means according to Steel *et al.* (1997).

Stability analysis

151   Stability analysis of the 25 grain sorghum lines was carried out for characters under study.
152   Stability parameters were estimated for grain yields by using the model described by Eberhart
153   and Russell (1966). This model utilizes the deviations from the grand mean of the yield over
154   the various environments as production indexes of the environments. It provides regression
155   response indexes (b values) and mean squares for deviations from regression minus pooled
156   error (S^2d values) as indexes of production response and stability, respectively. The
157   performance of a variety is then defined by the equation:

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

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

164   Since the sum of I_j over all environments is zero, the yield of a variety in a given
165   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
166   and β_i, respectively. The mean squares due to deviations from regression (S^2_d) indicate the
167   degree of reliance that can be placed upon linear regression. In fact, S^2_d reveals a non-linear
168   response of varieties (non-predictive). When the deviations are significant, the genotype
169   stability is specified by a joint consideration of both μ and β.

170   The significance of means squares was tested against the pooled error. The t-test
171   based on the standard error of regression value was used to test the significant deviation of b

172 from 1.0. To determine whether deviations from regression were significantly different from
173 zero, the F-test was employed (i.e., comparing the mean squares due to deviations from
174 regression with pooled error mean squares). In addition, a separate analysis for parental lines
175 was conducted to test for heterogeneity of the slopes among entries of the two genotypic
176 groups. The entries x environment (linear) mean square estimates were tested separately for
177 parental lines using the respective deviation mean squares.

178 If the regression coefficient close to one ($b_i = 1.0$), the genotype was adapted in
179 all environments, genotypes with $b_i > 1.0$ were more responsive or adapted to high yielding
180 environments, whereas any genotype with b_i significantly lower than 1.0 was adapted to low
181 yielding environments (Eberhart and Russell, 1966). Analysis of Eberhart and Russell's
182 stability was performed using the Genestat-17.1.13780 software program.

183 **3. RESULTS AND DISCUSSION**

184 Development of a stable variety is one of the major objectives of all
185 breeding programs. Phenotypically stable varieties are usefully sought for commercial
186 production of crop plants. In any breeding program, it is necessary to screen and
187 identify phenotypically stable genotypes, which could perform more or less uniformly
188 under different environmental conditions. Several models have been proposed for stability
189 analysis; the most important is Eberhart and Russell's model.

190 According to Eberhart and Russell's (1966) model, a stable variety is one, which
191 has above average mean yield, a regression coefficient of unity ($b_i=1$) and non-
192 significant mean square deviations from regression ($S^2_{di}=0$). The high value of
193 regression ($b_i >1$) indicates that the variety is more responsive for input rich
194 environment, while, low value of regression ($b_i<1$) is an indication that the variety may
195 be adopted in poor environment.

196 The stability analysis may be more meaningful when the material is tested under
197 various environments. In the present study, a set of 25 B-lines were evaluated under six
198 environments. The performance of different genotypes in respect to various characters
199 were studied for estimating stability and significance of genotype × environment
200 interactions.

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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 highly 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 (Abebe *et al*. 1984; Al-Naggar *et al*. 2002 a, b, c, d, 2006 and 2007 a, b).

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 (Kang 2002, Kenga et al. 2003 and Abubuche 2013).

Table 4. Analysis of variance (mean squares) of phenotypic stability for studied characters 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**

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| Pooled Deviation | 100 | 29.21 | 229.7 | 14.3 | 213140 | 101.9 |

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

230   Understanding the relationship among testing environments is important if plant
231 breeders are to target germplasm better adapted to different production environments or
232 regions (Trethowan *et al*., 2001). The estimates of environmental index (Table 5) showed that
233 E5 (Shandaweel, 2013) was the best performing environment for grain yield/plant,
234 grains/plant and 1000-grain weight, i.e. all studied yield attributes, but produced the latest
235 flowering plants. The environment E1 (Giza, 1st planting date, 2012) was the poorest in 1000-
236 grain weight and grains/plant, and performed the shortest plants. The environment E6
237 (Shandaweel, 2013) produced the tallest plants and E3 (Giza, 1st planting date, 2013) was the
238 poorest in grain yield/plant.

239 **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

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

249 **3.2. Stability for individual characters**

250   Two stability parameters consisting of regression coefficient "b_i" and deviation
251 from regression "S^2_{di}" were used to evaluate 25 parental B-lines as shown in Table (6). A
252 genotype with a unit value for regression coefficient and minimum deviation from regression
253 is considered to be stable (Eberhart and Russell, 1966).

254

255 **Table 6. Estimates of stability parameters for studied characters of grain sorghum lines**
256 **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			

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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 $P \leq 0.05$ and $P \leq 0.01$, 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 was produced their latest plants under the favorable environments (Table 6 and Fig. 1). The other five 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.
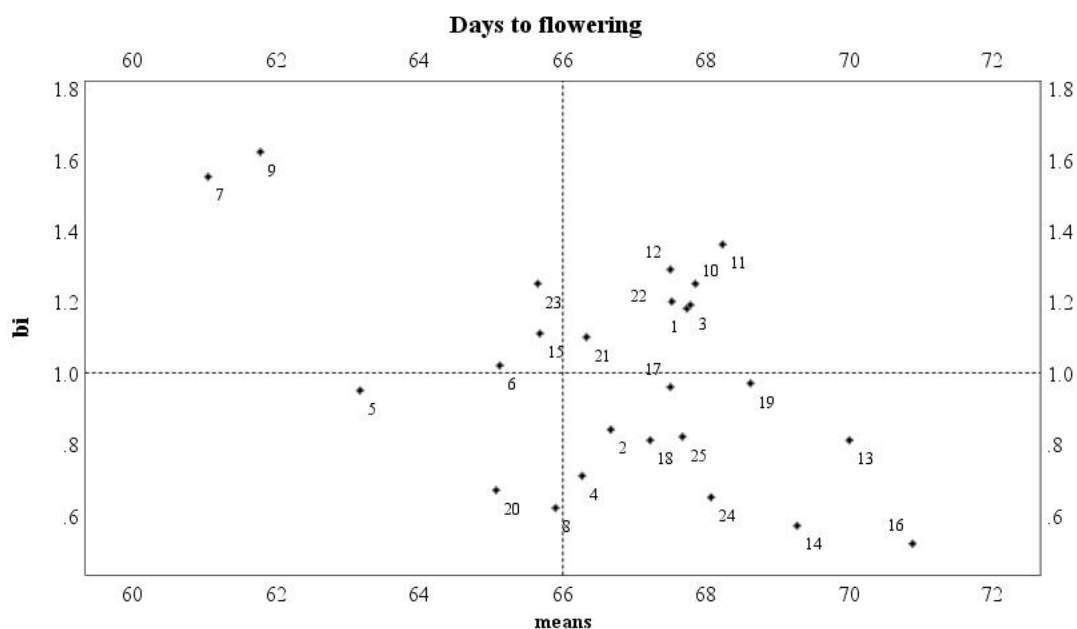
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Days to flowering

270

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

273   Parental lines G7 and G9 were found responsive for favorable conditions
274 (rich environments) with predictable performance as they showed low performance
275 for days to flowering along with above average responsiveness ($b_i > 1.0$) and non-
276 significant deviation from regression line. The two lines G17 (ICS B -015) and G19
277 (BTX 2-1) displayed above average performance and the line G6 (ICSB -70)
278 displayed below average performance, for days to flowering, regression coefficient
279 value near unity and non-significant deviation from regression, indicating that these
280 three genotypes are stable and widely adapted. These three lines can be utilized as
281 parental lines for the development of single cross hybrids in view of their stability.
282 Regression coefficient for days to flowering across locations ranged from 0.57 (G14)
283 to 1.62 (G9). The results further showed that 12 out of 25 grain sorghum lines gave
284 regression coefficient value (b_i) ≥ 1, indicating that these lines responded to favorable
285 environment and can produce later flowering plants when provided with suitable
286 environments. On the other hand, the rest 13 lines with regression coefficient less than
287 one ($b_i < 1$) can produce later flowering plants under poor environments; i.e. earlier
288 flowering plants under rich environments. Sujay *et al*. (2012) also reported significant
289 G x E interactions for days to flowering of sorghum.

12

3.2.2. Plant height

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291   For plant height, the genotype G8 (ICSB -122) had a significant deviation from
292 linear regression (Table 6), implying that this genotype was unstable across the environments.
293 Out of the top six tall plant genotypes (G3, G5, G10, G14, 21 and G23), three genotypes (G3,
294 21 and G14) were found suitable for favorable conditions (rich environments) with
295 predictable performance as they showed high performance for plant height along with above
296 average responsiveness (b_i> 1.0) and non-significant deviation from regression line and
297 (Table 6 and Fig. 2). The other three genotypes G5, G10 and G23, were considered suitable
298 for poor environments with predictable performance as they exhibited high performance for
299 plant height (tallness) along with below average responsiveness (b_i<1) and non-significant
300 deviation from regression line. Four lines (G1, G4, G22 and G24) displayed near average
301 performance for plant height, regression coefficient value near unity and non-significant
302 deviation from regression, indicating that these genotypes are stable and widely adapted.
303 Moreover, the genotype G16 (ICSB-8010) displayed the lowest performance for plant height
304 (shortness) with regression coefficient value near unity and non-significant deviation from
305 regression, indicating that this genotype is stable and widely adapted. The latter five lines can
306 be utilized as parental lines for the development of single cross hybrids of grain sorghum in
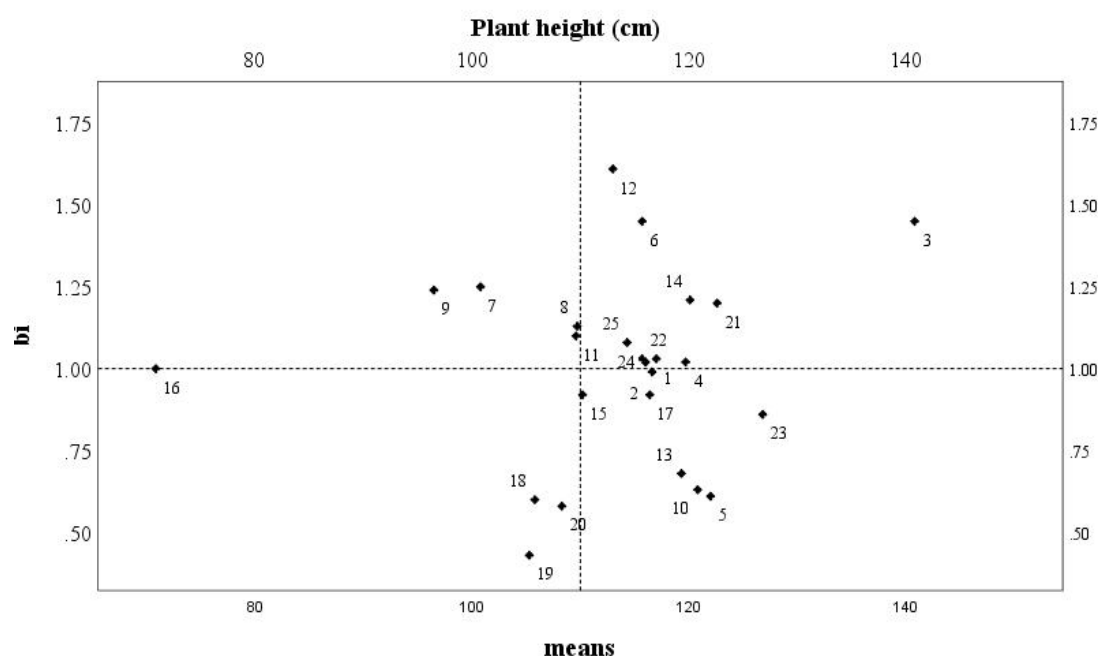307 view of their stability for plant height.

308

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

311   Regression coefficient for plant height across locations ranged from 0.43 (G19) to
312 1.61 (G12). The results further showed that 15 out of 25 grain sorghum lines gave regression
313 coefficient value (b_i) $\geq$ 1, indicating that these lines responded to favorable environment and
314 can produce taller plants when provided with suitable environments. On the other hand, the
315 rest 10 lines (G2, G5, G10, G13, G15, G17, G18, G19, G20 and G23) with regression
316 coefficient less than unit (b_i< 1) can produce taller yields under poor environments or shorter
317 plants under rich environments. Sujay et al. (2012) and Al-Naggar et al. 2002 a, b, c, d, 2006
318 and 2007 a, b) also reported significant G x E interactions for plant height of sorghum.

319 **3.2.3. Grains/plant**
320   For number of grains/plant, two genotypes (G3 and G9) had a significant deviation
321 from linear regression (Table 6), implying that these two genotypes were unstable across the
322 environments, based on S^2_{di} parameter. Out of the top eight lines in grains/plant (G25,G12,
323 G10,G20, G21,G9, G3 and G18), the lines G9, G10, G20 and G21 were found suitable for
324 favorable conditions with predictable performance as they showed high number of
325 grains/plant along with above average responsiveness (bi> 1.0) and non-significant deviation
326 from regression line (Table 6 and Fig.3). The other four genotypes (G25, G12, G3 and G18),
327 were considered suitable for poor environments with predictable performance as they
328 exhibited high and above average performance for number of grains/plant along with below
329 average responsiveness (bi<1) and non-significant deviation from regression line. The four
330 genotypes (G25, G12, G3 and G18) displayed high mean number of grains/plant, regression
331 coefficient value of less than unity and non-significant deviation from regression line. Four
332 lines (G8, G17, G19 and G16) displayed below average mean number of grains/plant,
333 regression coefficient value near unit and non-significant deviation from regression,
334 indicating that these four genotypes are stable and widely adapted. These four lines can be
335 utilized as parental lines for the development of single cross hybrids of grain sorghum in
336 view of their stability for grains/plant. Regression coefficient for number of grains/plant
337 across environments ranged from 0.22 (G6) to 1.66 (G20) .
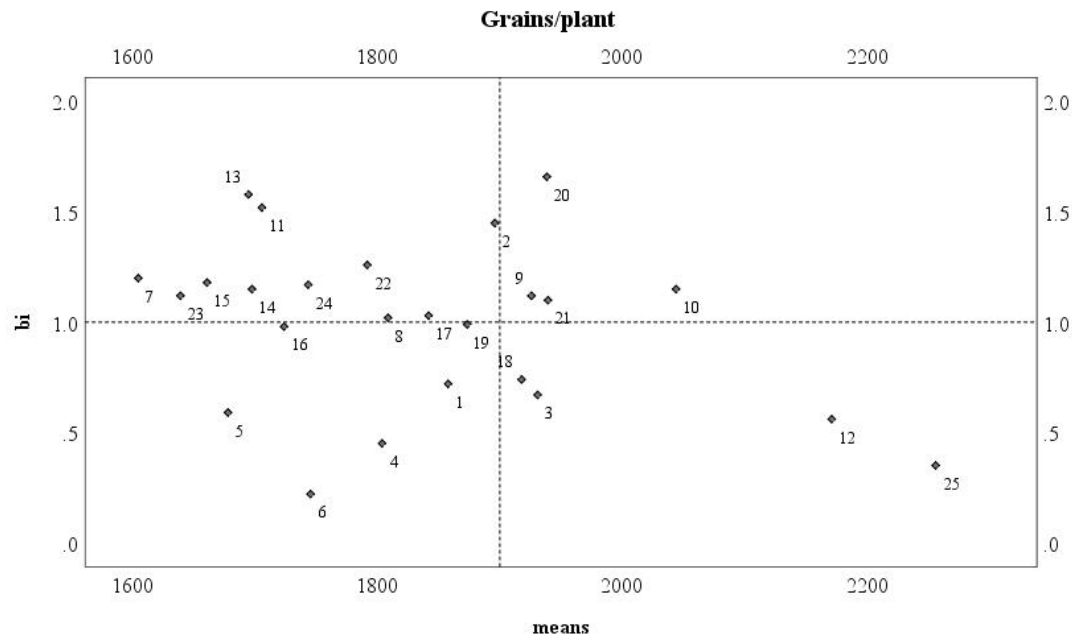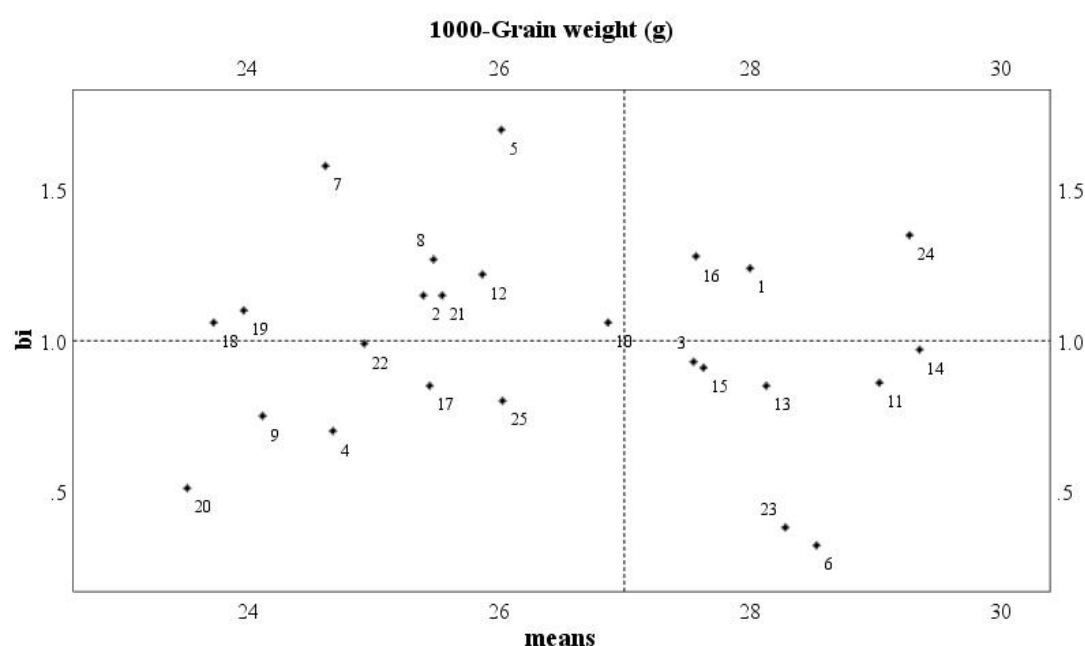
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Fig. 3. Relationship between mean number of grains/plant of 25 grain sorghum parental lines and regression coefficient across six environments.

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 rest 10 lines with regression coefficient less than one responded to all environments and possess wider adaptation to varying environmental conditions. Sujay *et al*. (2012) and Al-Naggar et al. (2002 a, b, c, d, 2006 and 2007 a, b) also reported significant G x E interactions for grains/plant of sorghum.

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 this 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

15

358   non-significant deviation from regression line. Out of the top three genotypes for 1000-grain

359   weight (G11, G14 and G24), the genotype G24 (BTX-631) displayed high mean value of

360   1000-grain weight, regression coefficient value of high than unity and non-significant

361   deviation from regression line and so it is considered responsive to favorable conditions. The

362   genotype G14 displayed the highest mean grain weight, regression coefficient value near unit

363   (0.97) and non-significant deviation from regression, indicating that this genotype is stable,

364   widely adapted. This line can be utilized as parental line for the development of single cross

365   hybrids of sorghum in view of their stability and high mean values for 1000-grain weight.

366   The line G22 displayed below average mean grain weight, regression coefficient value near

367   unit (0.99) and non-significant deviation from regression, indicating that this genotype is

368   stable and widely adapted for light grain weight.

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

372   Regression coefficient for 1000-grain weight across locations ranged from 0.32

373   (G6) to 1.70 (G5). The results further showed that 11 out of 25 grain sorghum lines gave

374   regression coefficient value (b_i) $\geq$ 1, indicating that these lines responded to favorable

375   environment and can produce heavy grain weight when provided with suitable environments.

376   On the other hand, the rest 14 lines (G3, G4, G6, G9, G11, G13, G14, G15, G17, G20, G22,

377   G23 and G25) with regression coefficient less than unit (b_i< 1) can produce heavy grain

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378   weight under poor environments. Sujay *et al.* (2012) and Al-Naggar et al. 2002 a, b, c, d,

379   2006 and 2007 a, b) also reported significant G x E interactions for 100- grain weight of

380   sorghum.

381   **3.2.5. Grain yield/plant**

382   For grain yield, three genotypes (G3, G12 and G20) had a significant deviation from

383   linear regression (Table 6), implying that these three parental lines were unstable across the

384   environments. The five highest yielding lines G25, G12, G10, G3 and G1 were found suitable

385   for poor environments, as they showed below average responsiveness (b_i < 1.0) (Table 6 and

386   Fig.5).   Out of these high yielding five genotypes, two lines (G3 and G12) have

387   unpredictable performance due to their significant deviation from regression line, while three

388   genotypes (G25, G10 and G1) displayed high mean grain yield, regression coefficient value

389   of less than unity (suitable for poor environments) and non-significant deviation from
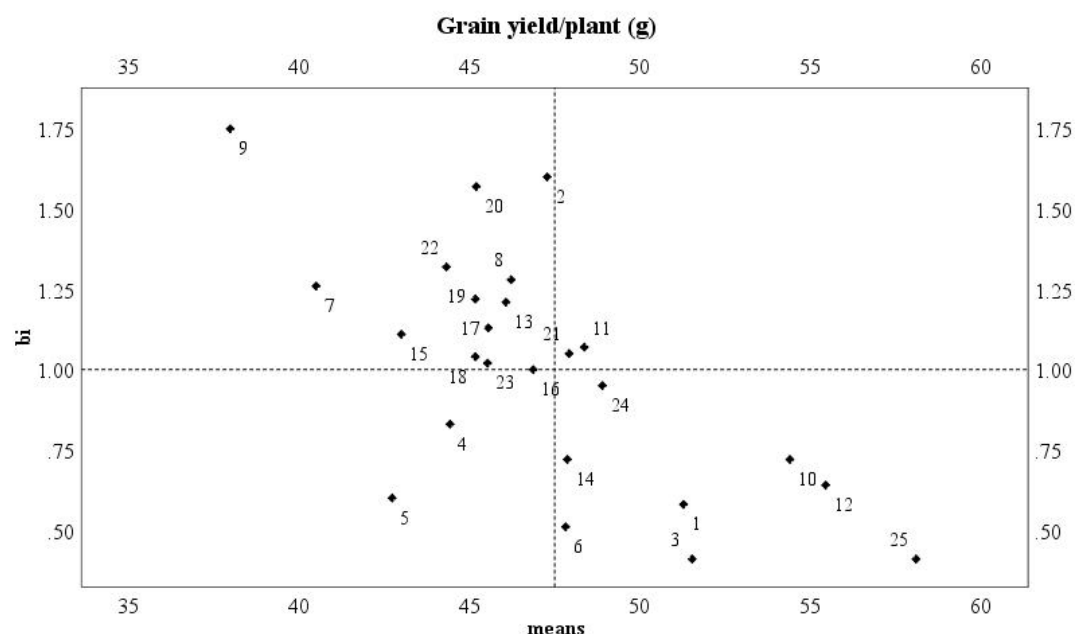
390   regression line.

391

392   **Fig. 5. Relationship between mean grain yield/plant of 25 grain sorghum parental lines**

393   **and regression coefficient across six environments.**

394   The three lines G11, G21 and G24 displayed above average mean yield, regression

395   coefficient value near unity (1.07, 1.05 and 0.95) and small and non-significant deviation

396   from regression, indicating that these three genotypes are stable and widely adapted. These

397   three lines can be utilized as parental lines for the development of single cross hybrids of

17

398   sorghum in view of their stability and high mean values for grain yield. The lines G16, G23

399   and G18 were also stable (b_i near unity and non- significant deviation from linear regression),

400   but displayed below average grain yield/plant. High yielding genotypes can differ in yield

401   stability and that yield stability and high grain yield are not mutually exclusive (Tollenaar and

402   Lee, 2002).

403   Regression coefficient for grain yield across locations ranged from 0.41 (G3) to

404   1.75 (G9). The results further showed that 15 out of 25 grain sorghum lines gave regression

405   coefficient value greater than one, indicating that these lines responded to favorable

406   environment and can produce higher yields when provided with suitable environments. On

407   the other hand, the rest 10 lines with regression coefficient less than one responded to all

408   environments and possess wider adaptation to varying environmental conditions.

409   On the contrary, the genotypes G9 and G7 (displaying b_i higher than unity, i.e.

410   adapted to good environments) and G5 (displaying b_i lower than unity, i.e. adapted to poor

411   environments) were the lowest yielders.

412   Toolnar and Lee (2002) reported significant differences among high yielding maize

413   hybrids for their yield stability. Sujay *et al*. (2012) and Al-Naggar et al. 2002 a, b, c, d, 2006

414   and 2007 a, b) also reported significant G x E interactions for grain yield of sorghum. Gama

415   and Hallauer (1980) detected significant hybrid x environment interaction for maize hybrids,

416   while some were reported to be stable when both stability parameters were considered. Kang

417   and Gorman (1989) and Vulchinokova (1990) also reported significant G x E interactions for

418   different traits of maize.

4. CONCLUSION

420   Significance of genotype × environment interaction was found for all characters

421   revealing that genotypes interacted significantly with environments. The presence of

422   significant environment by genotype interaction showed the inconsistency of performance of

423   grain sorghum parental lines across the test environments. Stable genotypes differed from

424   trait to trait. Two of the five top most yielding genotypes (G3 and G12) were not stable based

425   on deviation from regression and the rest three genotypes (G25, G10 and G1) were also not

426   stable based on regression coefficient parameter; all of them were considered suitable for

427   poor environments with predictable performance as they exhibited high performance for

428   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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