

STABILITY AND ADAPTABILITY OF SORGHUM HYBRIDS ELUCIDATED WITH GENOTYPE–ENVIRONMENT INTERACTION BILOTS

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ABSTRACT

This study was conducted to compare the performance of ten sorghum hybrids at two locations (Maize and Millets Research Institute, Yusafwala, Sahiwal, MMRI) & Sorghum Research Sub-Station, Dera Gazi Khan, D.G. Khan) for two consecutive years (2015 and 2016), i.e. in a total of four environments (MMRI-15, MMRI-16, DG Khan-15 and DG Khan-16). The experiment was conducted in a Randomized Complete Block Design with a plot size of $4 \times 0.75 \times 2$ m. In all four environments the crop was sown in July and harvested in December. Five plants were selected randomly from each plot for data collection. The following ranges were determined in the investigated traits; grain yield (2858.34-5266.33 kg ha⁻¹), fodder yield (28663-45667 kg ha⁻¹), days to 50% anthesis (76-81 days) and Brix value (8.28 -18.42). Analysis of variance (ANOVA) estimates, generated by the biplot software were used for data interpretation. It was found that the influence of genotype, environment and G × E interaction was significant (P<0.05) for all traits in all environments. The data for all traits except Brix value were useful for further study. For grain yield and fodder yield, hybrid YSH-95 was the most suitable due to its higher yield and better stability. Sorghum Research Sub-Station Dera Gazi Khan (DG Khan), a non-discriminating location, were considered suitable for generally adapted hybrids and Maize and Millets Research Institute, Yusafwala, Sahiwal (MMRI), a more discriminating location, were considered best for specifically adapted hybrids. The results of which-won-where biplots showed that Lasani was the best general hybrid at both locations, whereas YSH-95 was the best hybrid for the specific environmental conditions at MMRI.

Keywords: Brix value, correlation, Maize and Millets Research Institute, stalks weight,

INTRODUCTION

The livestock sector is increasing in Pakistan, and grew from 191.3 Million in 2016-2017 to 196.5% Million in 2017-2018. Similarly, chicken production also increased from 32.67 Million in 2016-2017 to 32.91 Million in 2017-2018. The availability of fodder and feed seed was 61140 metric tons, of which 13400 metric tons were imported in 2017-2018, at considerable expense. The availability of seed is increasing with the increase in livestock and chicken production. Despite its large milk (5790 tons) and meat (4262 tons) production, Pakistan is still ranked number 4 in milk production, number 9 in beef production and 28th in chicken production in all over all world (FAOSTAT, USDA, Govt. of Pakistan, 2017-18). The reasons for this situation are low quality fodder and limited feed availability. Because of low quality fodder and feed, animals reach puberty later, and the inter-calving interval is shorter (Ali, 2011; Mumtaz et al., 2017b). This situation could be improved with increased

milk and meat productivity per animal, and increased chicken production, and targets could be achieved by increasing milk, meat and chicken production up to 100% with good quality fodder and feed availability. However, land area used for fodder crops is decreasing steadily due to urbanization (Government of Pakistan, 2017-18). In addition, the unavailability of *Trifolium alexandrinum* L. (barseem) in lean periods (Dec, Jan and June, July) is a major factor in the limited availability of fodder (FAOSTAT).

The total area devoted to fodder production in Pakistan is 2.04 million hectares, and production is 51.92 metric tons. Sorghum (*Sorghum bicolor*) is cultivated in a total area of 0.255 million hectares, with a production of 148000 tons. Sorghum for fodder production thus accounts for 11.11% of the total area used for fodder crops, which is second largest area after barseem (43.54%) (Pakistan Bureau of Statistics, 2017-18, Govt. of Pakistan, 2017-18). Because sorghum accounts for 15%–

20% of all poultry feed (PARC, 2017), this crop appears to be the best target for tackling these issues given that sorghum grain is used as a feed and the stalks are used as fodder.

Sorghum is an important coarse grain crop in rain-fed and arid zones. This crop is important as a grain as well as a summer fodder crop in Pakistan (Bibi et al., 2010). It ranks fifth among important cereal crops worldwide, after wheat, rice, maize and barley (Ritter et al., 2007; Motlhaodi et al., 2014). Its grain is used as poultry feed, and its fodder is used for livestock. Its importance is increasing with the expansion of the poultry industry. It is also gaining importance as a source of starch for textile industries, and is also used in gum manufacture (FAOSTAT). It is a good source of carbohydrates and protein (Selle, 2011), and is palatable to animals due to its sweetness (Cifuentes et al., 2014; Mumtaz et al., 2017a).

Insect damage by stem borers is a major challenge to sorghum crop production. Sorghum is also affected to some extent by rootstalk disease, white fly, midges and mites. Hydrogen cyanide (HCN) is present in sorghum fodders, which may be fatal to ruminants (Panhwar, 2005; Kumar and Devendra, 2010; PARC, 2017).

Genotype \times environment interactions ($G \times E$) can be described as the different ranking of genotypes in different environmental conditions (Sayar et al., 2013). In their efforts to improve genotype selection, plant breeders have turned their attention to genotype \times environment interactions ($G \times E$). In these models the superiority of a given variety can be estimated by relative ranking. However, evaluations based on $G \times E$ interactions in diverse environments can be challenging. Especially when the $G \times E$ interaction is significant ($P < 0.05$), care must be taken to consider its cause, nature and implication (Kang and Gorman, 1989). Different stability analyses have been used for $G \times E$ interaction such as multivariate analysis (Westcoff, 1987), cluster analysis (Crossa et al. 1991), regression analysis (Guach, 1988) and the additive main effects and multiplicative interaction (AMMI) model (Guach, 1992). However, the most powerful technique is

the $G \times E$ biplot technique owing to its visual presentation of interactions. The $G \times E$ biplot method with mega-environment analysis has been used for many crops such as barley (Dehghani et al., 2006), maize (Fan et al., 2007), lentils (Sabaghnia et al., 2008), wheat (Mohammadi et al., 2009, Ilker et al., 2011) and grasspea (Sayar and Han, 2015).

The aim of this study was to compare the performance (adaptability and stability) of sorghum hybrids in two consecutive years at two locations, and to recommend the best sorghum hybrids and best environments for sorghum crops.

MATERIALS AND METHODS

Ten hybrids including three check cultivars (YS-16, YSS-98 and Lasani) were evaluated at two locations: the Maize and Millets Research Institute, Yusafwala, Sahiwal, Pakistan (MMRI) and Sorghum Research Sub-Station Dera Gazi Khan (DG Khan). Crops were grown in two consecutive years (2015 and 2016) and in three replications, for a total of four tested environments: MMRI-15, MMRI-16, DG Khan-15, DG Khan-16. In all four environments the crop was sown in July and harvested in December. The experiment was conducted in a randomized complete block design with three replications. Each plot size in the experiments was 6 m² (4 row numbers, 0.75 m row spacing, 2 m row length). The seed rate used was 8 Kg ha⁻¹. All agronomic practices, i.e., irrigation, fertilizer application, pesticide application, hoeing and thinning, etc. were done at appropriate times. Five plants were selected randomly from each plot for data collection. The monthly climate data of MMRI and DG Khan is given in Table 1 & 2. There were continuous monsoon rains in July and August 2016 at MMRI which affected crop growth. A dry spell was observed in November, December in 2016 and 2017 in harvesting season of crop at DG Khan which was ideal for sorghum crop. The sorghum crop affected badly in November 2017 due to smog in the fields caused suffocation to the plants due to which plant growth of sorghum crop was affected badly in all Pakistan.

Table 1. Climate Data of Maize and Millets Research Institute, Yusafwala, Sahiwal, Pakistan

Sr.	Month	Average temperature °C				Rainfall (mm)	
		Maximum		Minimum			
No.		(2016)	(2017)	(2016)	(2017)	(2016)	(2017)
1	July	39.20	40.58	28.58	28.45	92.30	25.70
2	August	39.09	39.67	27.09	27.93	75.00	9.00
3	September	37.25	38.43	23.90	23.76	1.00	74.00
4	October	34.71	37.52	18.55	19.77	-	-
5	November	27.10	27.51	12.40	12.88	-	2.20
6	December	26.39	27.45	9.00	7.21	-	7.60
Total Rainfall						186.3	118.5

Table 2. Climate Data of Sorghum Research Sub-Station Dera Gazi Khan, Pakistan

Sr. No.	Month	Average Temperature °C				Rainfall (mm)	
		Maximum		Minimum		2016	2017
		2016	2017	2016	2017		
1	July	39.00	38.22	29.00	28.61	29.00	57.00
2	August	37.00	37.70	28.00	28.41	---	---
3	September	38.00	33.68	27.00	25.87	---	---
4	October	37.80	35.38	26.33	20.67	----	---
5	November	28.50	23.48	13.90	12.80	---	---
6	December	25.43	22.06	10.73	7.54	---	---
Total Rainfall						29.00	57.00

Data were collected for the following traits: grain yield, fodder yield, days to 50% anthesis and Brix value. Brix value was estimated with the help of refractometer. The GGE biplot model was applied according to Yan and Kang (2003) and Sabaghnia et al. (2008) with the help of GEA-R software. The multi-location trial (MLT) data were analyzed without scaling ('Scaling 0' option) to generate tester-centered (centering 2) $G \times E$ biplots as suggested by Yan and Tinker (2006). For $G \times E$ genotype evaluation, $G \times E$ genotype-focused singular value partitioning (SVP = 1) was used with the 'Mean versus stability' option of $G \times E$ biplot software, while for location evaluation, environment-focused singular value partitioning (SVP = 2) was used (Yan 2001) with the 'Relation among testers' option. The 'Which-won-where' option was used to identify which genotype was the winner in a given environment, and to identify mega-environments. Analysis of variance (ANOVA) estimates generated by the biplot software were used for interpretation.

RESULTS AND DISCUSSION

Statistical significance and proportion of variation

The results of ANOVA and the proportions of variance accounted for by $G \times E$ genotype (G), environment (E) and interaction ($G \times E$) are presented in Table 3. The effects of G, E and $G \times E$ were highly significant ($P < 0.01$) for all traits except $G \times E$ and Brix value, which were significant ($P < 0.05$) to a lesser degree. Environment was the largest source of variation in grain yield. For grain yield the environment contributed 37.25% of the variation, compared to G genotype (33.22%) and $G \times E$ interaction (29.52%). For days to 50% flowering, the contribution of $G \times E$ was 53.44% versus G genotype (21.96%) and environment (24.59%). For fodder yield, the contribution of $G \times E$ was 59.15% versus G genotype (26.40%) and environment (14.45%). For Brix value, the contribution of G genotype was 98.41% versus environment (1.01%) and $G \times E$ (0.57%) (Table 3).

Table 3. ANOVA and proportion of variation in G, E and $G \times E$

Trait		G	E	$G \times E$
Grain yield (Kg)	MS	6206744**	20876852**	1838546**
	Proportion of G + E + $G \times E$	33.22431	37.25083	29.52486
Fodder yield (Kg)	MS	257385289**	422549916**	192217418**
	Proportion of G + E + $G \times E$	26.40154	14.44782	59.15065
Days to 50% flowering	MS	54.92685**	184.5417**	44.56636**
	Proportion of G + E + $G \times E$	21.95846	24.5918*	53.44974
Brix value (%)	MS	243.0069**	7.53897**	0.4694*
	Proportion of G + E + $G \times E$	98.41201	1.0177	0.57029

G, Genotype; E, Environment; $G \times E$, Genotype \times Environment interaction; **Highly significant ($P < 0.01$); *Significant ($P < 0.05$)

In accordance with our research findings, many researchers in various crops reported that effect of environment was much greater than the effects of genotype and $G \times E$ in grain yield trait (Gauch and Zobel, 1997; Dehghani et al., 2006; Kaya et al., 2006; Kendal and Sayar, 2016). Additionally, in their study of peanut strains, Putto et al. (2008) observed that environment accounted for 15%-46%. They found a very low contribution by $G \times E$ (4%-5%). In another study of sorghum, Rakshit et al. (2012) found that location accounted for a large proportion (59.3%-89.9%) of variation, whereas $G \times E$ genotype explained a relatively

low proportion (3.9%-16.7%). In maize, Munawar et al. (2013) found that environment explained 79.22% of the variation, whereas $G \times E$ genotype explained only 9.52%. In comparison to these findings, we found that environment accounted for 1.01%-37% of the variation, $G \times E$ genotype for 33.22% - 98.41%, and $G \times E$ interaction for 0.57%-59.15%. Our results for grain yield and Brix value are broadly similar to the findings reported by Putto et al., 2008. In addition, the larger contribution of $G \times E$ interaction to variations in fodder yield and days to 50% flowering is consistent with Rakshit et al. (2012).

G × E genotypic stability

Performance and stability of $G \times E$ genotypes are characterized as principal components (PCs) and presented graphically in Figures 1 to 4 (Yan and Tinker, 2006). If the total variability explained by the first two PCs is more than 60% and the variability explained by $G \times E$ is more than 10%, then it is possible to elaborate the information from the $G \times E$ data (Yang et al. 2009; Yan et al. 2010) with the average environment coordination (AEC) method. We generated tester-centered $G + G \times E$ biplots with no scaling for grain yield, fodder yield, days to 50% flowering and Brix value. The first two PCs for grain yield represented 85.06% of the variation; for fodder yield they accounted for 84.18% of the variation; for days to 50% flowering they accounted for 96.2%, and for Brix value they explained 99.95% of the variation. It is clear from above results that our $G \times E$ data for all traits except Brix value can be used for further elaboration, given that the contribution of $G \times E$ to Brix value is only 0.75% (less than 10%).

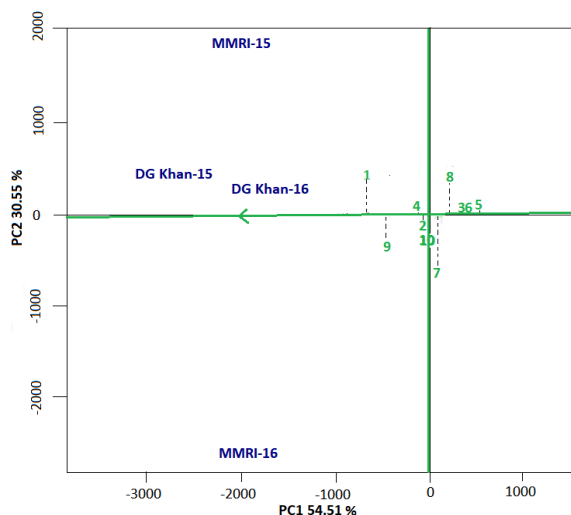


Figure 1. GGE biplots of the combined analysis for grain yield

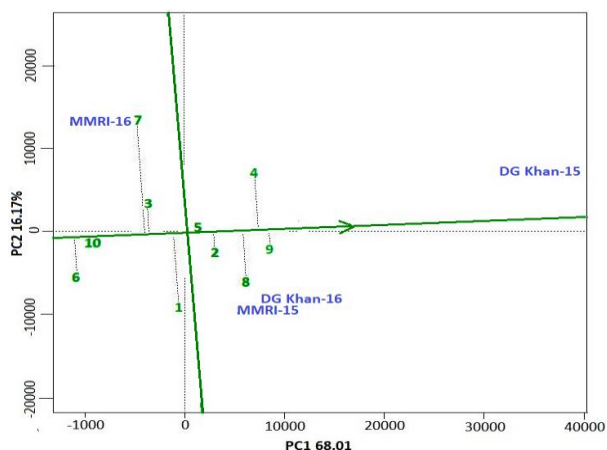


Figure 2 GGE biplots of the combined analysis for fodder yield

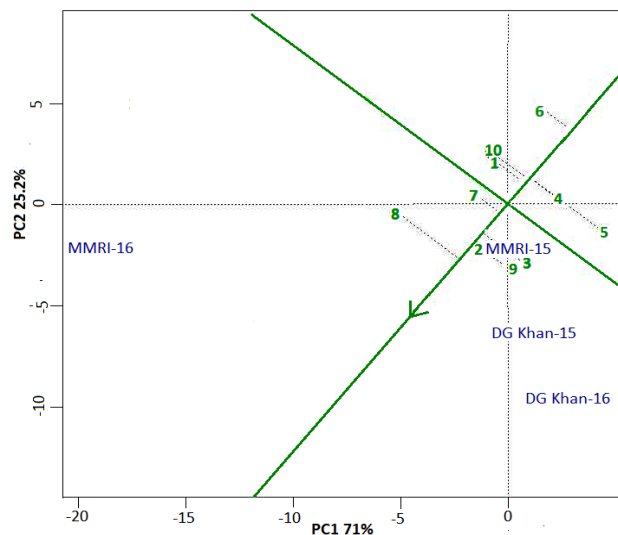


Figure 3. GGE biplots of the combined analysis for days to 50% flowering

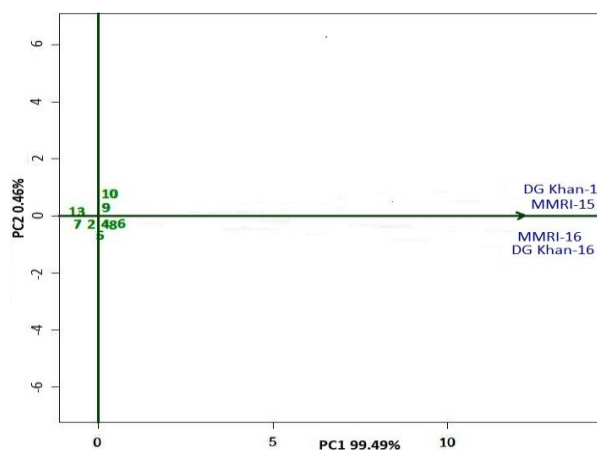


Figure 4 GGE biplots of the combined analysis for Brix value

The vertical line with a single arrowhead passing through the origin is called the AEC abscissa. The $G \times E$ genotypes closest to the arrowheads on the abscissa are the ones that come closest to the ideal performance. The average environments have near-average PC1 and PC2 scores; in other words, the environmental situation can be considered normal (Yan, 2001). The perpendicular line which passes through the origin is referred to as the AEC ordinate. The shorter the projection of a cultivar on this line, the more stable the cultivar is likely to be (Kaya et al., 2006).

The grain yield was observed in a range of 2858.34 Kg ha⁻¹ to 5266.33 Kg ha⁻¹. These results are similar with the findings of Rakhsit et al. (2012) in India (2180 Kg ha⁻¹ to 4234 Kg ha⁻¹) and Mumtaz et al. (2018) in Pakistan (2562 Kg ha⁻¹ to 5190 Kg ha⁻¹). Hybrid 1 (Lasani) showed the highest grain yield, followed by hybrid 9 (YSH-95). However, YSH-95 was more stable than Lasani, as shown by its shorter AEC ordinate compared to Lasani. The most stable hybrids were 5 (YSH-121) and 6 (YSH-1227); however, their yields were lower than other hybrids. Hybrids 4 (YSH-120) and 2 (YS-16) also showed good stability but their yields were near the middle of the range

for all hybrids (Fig. 1 and Table 4). For fodder yield, they range of 28663 Kg ha⁻¹ to 45667 Kg ha⁻¹ was observed. Similar findings were observed by Dhar et al., 2005(29600 Kg ha⁻¹ to 39700 Kg ha⁻¹) in India while observed the very less fodder yield in India (9405 Kg ha⁻¹ to 18649 Kg ha⁻¹) while Ayub et al., 2004 observed very high range fodder yield (40920 Kg ha⁻¹ - 68090 Kg ha⁻¹) in Pakistan. The highest yielded was hybrid 9 (YSH-95) followed by hybrid 4 (YSH-120). Moreover, YSH-95 was more stable in terms of fodder yield. The most stable hybrids were 10 (YSS-98) and 5 (YSH-121), but YSS-98

had the lowest yield, and YSH-121 was a medium yielder (Fig. 2). The days to 50% flowering was observed in range of (76-81). Mumtaz et al., 2018 in Pakistan (72-82) and Rakhsit et al., 2012 in India (59-77) observed similar findings. Hybrid 8 (YSH-75) had the longest period to 50% flowering followed by hybrid 9 (YSH-95). Hybrid 6 (YSH-1227) had the shortest period to 50% flowering, and for hybrid 7 (YSH-61) this period was of average duration. YSH-95, YSH-1227 and YSH-61 were more stable than other hybrids (Fig. 3).

Table 4. Mean time to 50% flowering, Brix value, fodder yield and grain yield of sorghum hybrids per year and per location

Genotype /Year	Grain yield (Kg ha ⁻¹)			Days to 50% flowering			Brix value (%)			Fodder yield (Kg ha ⁻¹)		
	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean.
Lasani ©	5793.76	4738.90	5266.33	75.67	78.25	76.96	8.50	8.06	8.28	37257.02	36979.24	37118.13
YS-16 ©	4445.15	3584.73	4014.94	77.83	81.33	79.58	11.64	12.23	11.94	40972.30	39965.36	40468.83
YSH-118	3620.84	2943.06	3281.95	79.33	80.75	80.04	9.54	8.72	9.13	37882.02	37708.41	37795.22
YSH-120	4614.59	3670.15	4142.37	78.00	78.25	78.13	16.54	17.48	17.01	48750.10	42048.70	45399.40
YSH-121	3322.92	2393.76	2858.34	79.08	78.33	78.71	13.65	13.84	13.75	40416.75	33680.62	37048.69
YSH-1227	3211.12	2955.56	3083.34	76.33	75.67	76.00	17.67	19.17	18.42	26319.50	31007.01	28663.25
YSH-61	3300.70	3265.28	3282.99	78.92	80.50	79.71	9.09	8.26	8.68	33541.73	35069.51	34305.62
YSH-75	3797.92	3077.78	3437.85	78.75	82.58	80.67	16.82	19.04	17.93	43437.59	39861.19	41649.39
YSH-95	4444.45	4513.82	4479.14	80.00	81.58	80.79	16.03	16.51	16.27	47083.43	44270.92	45677.18
YSS-98 ©	3979.17	3546.54	3762.86	76.25	78.00	77.13	17.88	17.53	17.71	31909.79	30173.67	31041.73
Genotype /Location	MMRI	DG Khan	Mean	MMRI	DG Khan	Mean	MMRI	DG Khan	Mean	MMRI	DG Khan	Mean
Lasani	4678.48	5854.18	5266.33	79.08	74.83	76.96	8.13	8.43	8.28	37465.35	36770.91	37118.13
YS-16	3502.09	4527.79	4014.94	80.67	78.50	79.58	11.40	12.47	11.94	36527.85	44409.81	40468.83
YSH-118	3390.28	3173.62	3281.95	79.25	80.83	80.04	9.28	8.98	9.13	41007.03	34583.40	37795.22
YSH-120	3368.06	4916.68	4142.37	79.08	77.17	78.13	15.99	18.03	17.01	39375.08	51423.71	45399.40
YSH-121	2383.34	3333.34	2858.34	78.42	79.00	78.71	13.23	14.27	13.75	33263.96	40833.42	37048.69
YSH-1227	2958.34	3208.34	3083.34	78.50	73.50	76.00	17.15	19.68	18.42	35000.07	22326.43	28663.25
YSH-61	2565.98	4000.01	3282.99	82.92	76.50	79.71	8.73	8.62	8.68	32638.95	35972.29	34305.62
YSH-75	2722.92	4152.79	3437.85	84.75	76.58	80.67	16.46	19.40	17.93	34132.01	49166.77	41649.39
YSH-95	3680.48	5277.79	4479.14	81.33	80.25	80.79	15.28	17.27	16.27	38680.63	52673.72	45677.18
YSS-98	3838.20	3687.51	3762.86	79.75	74.50	77.13	16.96	18.45	17.71	37882.02	24201.44	31041.73

MMRI, Maize and Millets Research Institute, Yusafwala, Sahiwal; DG Khan, Sorghum Research Sub-Station Dera Gazi Khan

The sugar content of juice extracted from stalks of the sorghum defined as Brix value (%). The results for Brix value were confirmed in Figure 4. There was a large variation in brix value (8.28 to 18.42) due to diverse germplasm especially with respect to parental lines, some are from ICRISAT India, and some are from Pakistan. A large variation in brix value was also observed by Mumtaz et al., 2018 in Pakistan (3.41-18.12). The greatest proportion of variation in Brix value is explained by genotype, i.e. almost all variation is explained by the first PC (99.94%). As a result, the G × E biplot is ambiguous and cannot be used for further analysis (Fig. 4). The results show that YSH-95 was the highest yielded, and was also more stable in terms of fodder yield and grain yield. For days to 50% flowering, hybrid YSH-95 had the second longest flowering period but was stable, as shown by its location nearest to AEC ordinate. Genotype stability was also determined by Dehghani et al. (2006) in barely, Kaya et al. (2006) in wheat, Sabaghnia et al. (2008) in lentil, Dehghani et al. (2008) rapeseed, Khalil et al. (2011) in maize, Rakhsit et al. (2012) in sorghum, Munawar et al. (2013) in maize and Kendal et al. (2016) in triticale. Rakhsit et al. (2012) reported that the first two PCs accounted for 70% of the cumulative variation in four

traits. Rakhsit et al. (2012) found that G × E interaction explained 10% of the total variation for all traits.

Environmental evaluation (ideal and discriminating environments)

To better understand the capacity for adaptation of different G × E genotypes and further study the environments compared here, we ranked the four environments on the basis of grain yield, fodder yield, days to 50% flowering and Brix value. The relationships among environments can be determined as the angles between their vectors, and their correlations can be predicted from the cosine of the angles between the vectors (Yan and Tinker, 2006). For grain yield, DG Khan-15 and DG Khan-16 were highly correlated, whereas MMRI-15 and MMRI-16 were divergent. We identified two mega-environments; the first comprised DG Khan-15, DG Khan-16 and MMRI-15 while the second included only MMRI-16 (Fig. 5). Similar patterns were observed for fodder yield and days to 50% flowering; however, fodder yield values correlated more closely between MMRI-15 and DG Khan-16 than between either of these environments and DG Khan-15 (Figs. 6, 7).

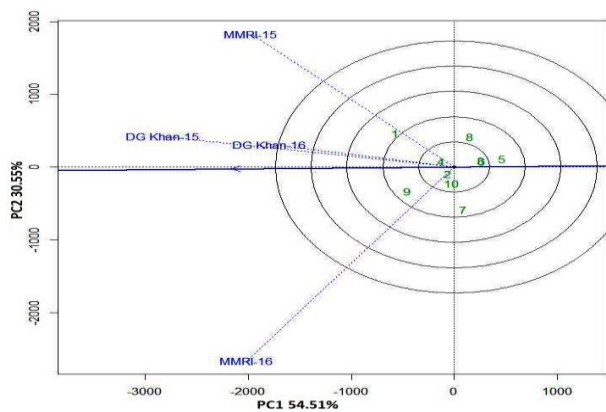


Figure 5 Relation among environments for grain yield

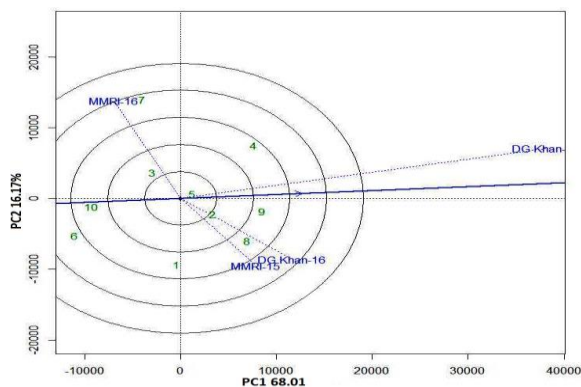


Figure 6. Relation among environments for fodder yield

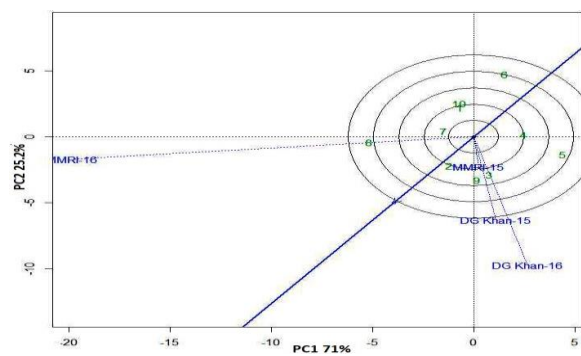


Figure 7 Relation among environments for days to 50% flowering

The discriminating ability of environments can be predicted from their projections across concentric circles. For grain yield, MMRI-15 and MMRI-16 were more discriminating than DG-Khan-15 or DG-Khan-16. This result indicates that DG Khan-15 came closest to the ideal environment, followed by DG-Khan 16. DG Khan-15 thus proved to be an ideal environment for generally adapted sorghum hybrids (Fig. 5). On the other hand, MMRI-15 and MMRI-16 were the most discriminating environments for specifically adapted sorghum hybrids. This result is consistent with the data shown in Table 4. Grain yield was highest at the two DG Khan environments for all hybrids except YSS-98. Thus hybrid Lasani should be

recommended for cultivation in all four environments compared here, while YSH-95 should be recommend for cultivation at MMRI.

For Brix value, the results were ambiguous and did not lend themselves to elaboration (Fig. 8).

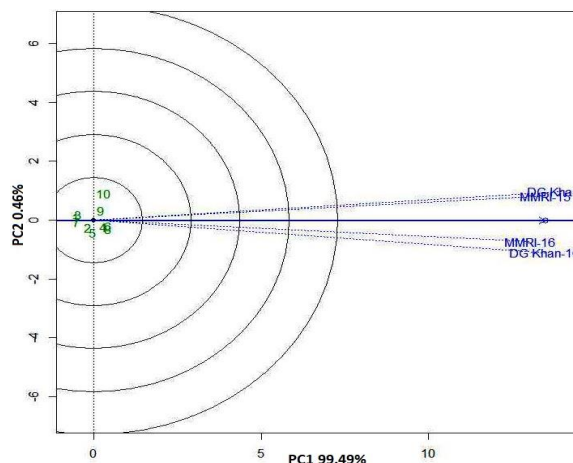


Figure 8 Relation among environments for Brix value

Our results suggest that to evaluate different hybrids, trials should be conducted at MMRI for two consecutive years in order to control for fluctuations in environmental conditions. In contrast, the results of sorghum hybrid trials at DG Khan for one year can be considered reliable. Environmental evaluations with the method used here were also reported by Khali et al. (2011), Mitrovic et al. (2012), Rakhsit et al. (2012) and Munawar et al. (2013).

Ideal genotype

Given the most important trait is grain yield, we ranked grain yield for all $G \times E$ genotypes with reference to the ideal $G \times E$ genotype in Figure 9. The ideal genotype can be identified by its position nearest the center of the concentric circles, and genotypes closest to the ideal genotype can be considered the most desirable. This analysis extends the information that can be deduced from the mean values summarized in Table 4. Figure 9 shows that hybrid 9 (YSH-95) was closest to the ideal $G \times E$ genotype, followed by hybrid 1 (Lasani). Hybrids YSH-95 ($4604.05 \text{ Kg ha}^{-1}$) and Lasani ($4314.59 \text{ Kg ha}^{-1}$) had the highest grain yields (Table 4). Among earlier reports that identified ideal genotypes with this method are those by Deghani et al. (2006), Kaya et al. (2006), Sabaghnia et al. (2008), Deghani et al. (2008), Khalil et al. (2011), Mitrovic et al. (2012), Rakhsit et al. (2012) and Munawar et al. (2013).

Mega-environment identification with which-won-where analysis

The which-won-where graphs show polygons to illustrate the performance of $G \times E$ genotypes in different environments in order to summarize multi-environment data. Equality lines are drawn perpendicular to the origin of the biplot through the sides of the polygon (Yan, 2001). $G \times E$ genotypes are identified as suitable or less desirable according to their positions at the polygon vertices. The G

× E genotype positioned at the vertex falling within the sectors is considered the best (Yan, 2002; Yan and tinker 2006). Which-won-where biplots for grain yield, fodder yield, days to 50% flowering and Brix value are presented in Figures 10 to 13. These results show that only the grain yield biplot provides a clear picture, whereas the biplots for fodder yield, Brix value and days to 50% flowering are much less informative. Accordingly, we discuss here only the grain yield biplot.

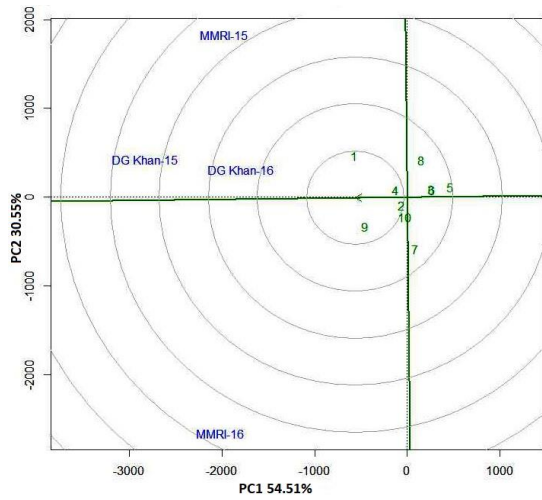


Figure 9 Ranking of ideal genotypes

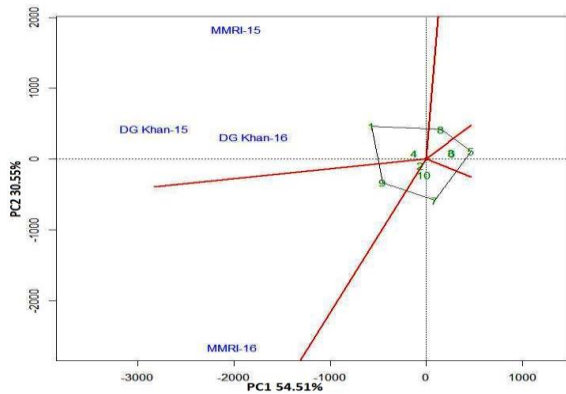


Figure 10 Which-won-where analysis of the genotypes for grain yield

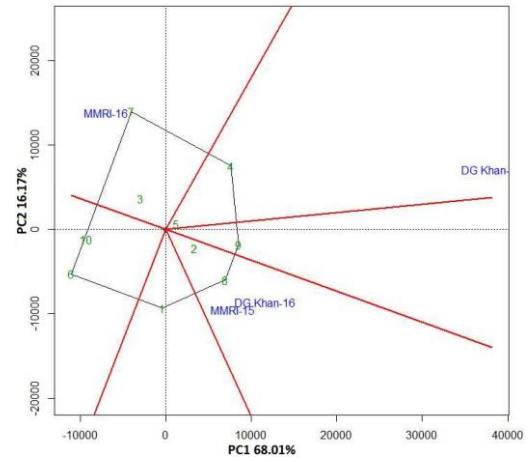


Figure 11 Which-won-where analysis of the genotypes for fodder yield

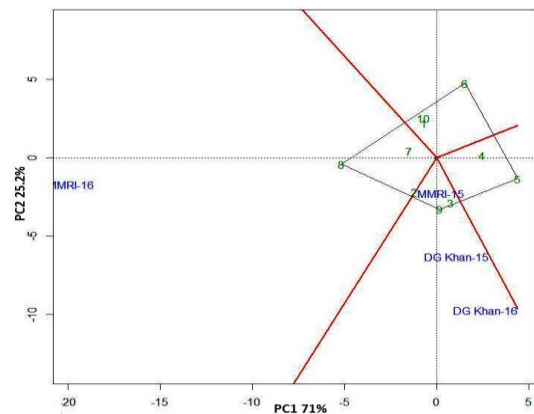


Figure 12 Which-won-where analysis of the genotypes for days to 50% flowering

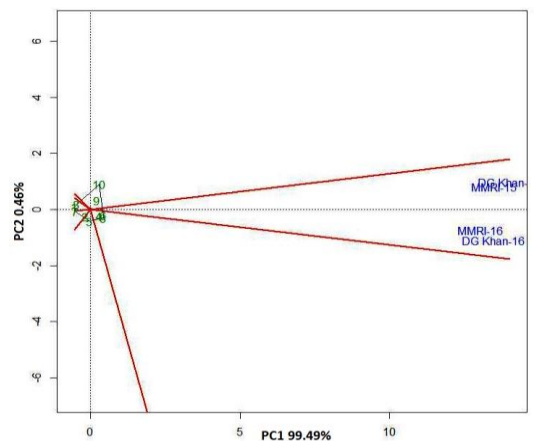


Figure 13 Which-won-where analysis of the genotypes for Brix value

The polygon in Figure 10 has five G × E genotypes at the vertices. Hybrid 9 (YSH-95) performed best at MMRI-16, and hybrid 1 (Lasani) performed best at DG Khan-15, DG Khan-16 and MMRI-15. The equality lines divide the biplot into five sectors, and indicate that the testing locations can be divided into two mega-environments. One contains MMRI-15, DG Khan-15 and DG Khan-16, with Lasani as best performing hybrid, while the other contains MMRI-16 with YSH-95 as the best performing hybrid. These results confirm the results of our environmental evaluation above. A similar approach to mega-environment identification and specific adaptation was also used by (Gauch and Zobel (1997), Yan et al. (2000), Yan and Tinker (2006), Putto et al. (2008), Rao et al. (2011), Rakshit et al. (2012), Khalil et al. (2011), Munawar et al. (2013) and Mitrovic et al. (2013).

CONCLUSION

Ten hybrids including three checks were evaluated in 2015 and 2016 at four environments: MMRI-15, MMRI-16, DG Khan-15, DG Khan-16. Four traits were considered: grain yield, fodder yield, days to 50% flowering and Brix value. Our results showed that G, E and G × E were significant ($P < 0.05$) for all traits, and that the data for all traits except Brix value can be used for further study. The contribution of G × E to Brix value was only 0.75% (less than 10%). According to grain yield and fodder yield, hybrid YSH-95 was the most suitable due to its high yield and greater stability. This hybrid has the second longest time to 50% flowering yet was also stable. Hybrid YSH-1227 had the shortest time to 50% flowering but was a poor yielder. The DG Khan location was non-discriminating and was thus best for generally adapted hybrids, whereas for specific selected hybrids, MMRI was a more discriminating location. Our results also suggest that trials designed to evaluate different hybrids should be conducted at MMRI for two consecutive years to control for environmental fluctuations, whereas trials run for a single year at the DG Khan location can be assumed to produced reliable data. From our which-won-where biplots we conclude that Lasani is the best general hybrid for all four environments, whereas hybrid YSH-95 is the best hybrid for the specific environment at the Maize and Millets Research Institute, Yusafwala, Sahiwal.

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