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Combining ability of some sorghum lines for dry lands and sub-humid environments of East Africa

Ringo Justin[1,4]*, Beatrice Were[1], Mary Mgonja[2], Deshpande Santosh[3], Rathore Abhishek[3], Mneney Emmarold[4], Onkware Agustino[5] and Gudu Samuel[5]

[1]School of Science, University of Eldoret. P. O. Box 1125, Kenya.
[2]International Crops Research Institute for Semi Arid Tropics (ICRISAT), P. O. Box 39063, Nairobi, Kenya.
[3]International Crops Research Institute for Semi Arid Tropics (ICRISAT), P. O. Box 502 324, Patancheru, India.
[4]Mikocheni Agricultural Research Institute, P. O. Box 6226, Dar Es Salaam, Tanzania.
[5]Rongo University College, P. O. Box 103-40404, Rongo, Kenya.

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Sorghum (*Sorghum bicolor* L. Moench) is a major food crop grown in dry lands and sub-humid areas of East Africa. A study was conducted between 2010 to 2012 in dry lands (Miwaleni, Kiboko) and sub-humid (Ukiriguru) environments to identify parents for hybrid production. It involved 121 lines from ICRISAT and 121 hybrids developed from 36 male sterile lines and 42 restorer lines in a line × tester crossing. Experiments were planted in an alpha lattice design with three replications. Analysis revealed significant (P < 0.05) differences between parents and between crosses for yield and yield components, indicative of potentiality for exploitation. Line IESV23010 expressed best (-6.5) general combing ability (*GCA)* for days to 50% flowering (DAF). Highest general combiner for height was -55.4 expressed in ICSR24007 and for yield was 382.8 expressed in IESV92156DL. The crosses SDSA4×ICSR43 and SDSA4×ICSR59059 exhibited high and significant specific combining ability (*SCA*) for DAF. Lines IESB2 and ICSB44 were suited to sub-humid, whereas BTX623, ICSB15 and ICSB6 to dry lands environments. Testers IESV91104DL, IESV91131DL, ICSR93034 were well suited to dry lands whereas KARI-MTAMA1 and IESV23019 to sub-humid environments. The parents identified could be used to produce hybrids and varieties for the dry lands and sub-humid environments.

Key words: Combining ability, lines, restorers, sorghum, top-cross hybrids.

INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is a major staple crop grown in water stressed areas of the tropics (Abdulai et al., 2012), because of its resiliency. Lately, sorghum has received significant attention because of its multiple uses as food, feed, and raw material in brewing and biofuel industries (Paterson, 2008). According to FAO (2010), Africa contributes over 60% to the total land area dedicated to cultivation of sorghum. A report by Tanzania's Ministry of Agriculture Food Security and Cooperatives (MAFSC, 2012) indicates that, annual demand for white sorghum in Tanzania is 3,360 metric tonnes while the supply in the country during 2011/2012 was only 1,084 metric tonnes, indicating a significant difference between demand and supply. Further, demand

*Corresponding author. E-mail: ringojustinh@yahoo.com

for white sorghum in East Africa has increased dramatically after the East Africa Breweries Limited company started to use it for beer production. However, according to FAO (2010), sorghum productivity in Eastern Africa has been low (<1 t ha^{-1}). Among the main causes for this low production level is the continuous use of low yielding landraces (Aruna and Audilakshmi, 2008) which could mainly be attributed to scarcity of adapted hybrids (Makanda et al., 2012). Deployment of adapted sorghum hybrids could be a practical and fast approach to boost productivity. Report by Makanda et al. (2012), Patil (2007) and Bantilan et al. (2004) indicates that sorghum hybrids can out yield non-hybrid cultivars by up to 60%. Despite all these benefits, most national sorghum breeding programs in the region have been focused on development of open pollinated varieties, with less emphasis on hybrids possibly due to lack of suitable parents for hybrid production and lack of means to buy seed every season. Sustainable sorghum hybrid program requires availability of locally adapted male sterile and restorer lines. The International Crops Research Institute for Semi Arid Tropics (ICRISAT) introduced new inbred lines from India and collections from various parts of East Africa but their combing ability has not been studied. Knowledge of general combining ability (*GCA*) and specific combing ability (*SCA*) is vital to start a hybrid program. The *GCA* assesses the average performance of an inbred line in hybrid combinations, while *SCA* identifies the crosses in which its combinations perform relatively better or worse than would be expected on the basis of *GCA* of the parents (Reddy et al., 2007). Theobjective of this study was to identify the best hybrids and their parents through estimation of *GCA* and *SCA* for yield and yield components of a comprehensive set of introduced inbred lines for sub-humid and dry low-lands of East Africa.

MATERIALS AND METHODS

Description of experimental sites

Experiments were conducted in Tanzania (Ukiriguru and Miwaleni) and Kenya (Kiboko) locations respectively. Ukiriguru is found in sub-humid climate (ILCA, 1987) and is located at 2° 43' 0" S and 33° 1' 0" E on 1198 m above sea level. Temperatures vary from 18.3 to 29.6°C and annual rainfall of about 861 mm. Soil is mainly sandy loam. Miwaleni is located at 3° 25' 30" S and 37° 26' 45" E at 720 m above sea level. The soil types are reddish brown and the area experience tropical semi-arid climate. Temperatures range between 10 to 39°C and the annual rainfall ranging from 500 to 700 mm (John, 2010). Kiboko lies between 37°45'E and 2°15'S at 960 m above sea level and experiences a semi-arid tropical climate with a bimodal rainfall pattern. The annual rainfall is 655 mm (www.kari.org). The temperature varies from 13.7 to 24.7°C. The soil type at this location is sandy clay group.

Development, selection and evaluation of hybrid sorghum

A total of 121 sorghum lines including 36 pairs of male sterile (A, B lines) and 42 restorers (R-lines) were obtained from ICRISAT-Nairobi (Appendix 1) for evaluation and generating experimental hybrids. Production of the hybrids was conducted at Kiboko in 2010. Seed for all parents was hand planted in 2-m rows. Two rows of A-lines were grown parallel to 1 row of B-lines (for maintenance of A-lines and data collection on yield) alongside a block of R-lines. Each R- line occupied a single row. All plants were bagged before flowering to avoid cross pollination. Pollen was collected in paper bags from R-lines in morning (before 11:00) and dusted on to female panicles. Each single head of A-line was pollinated by single R-line and both bagged right after pollination. A total of 353 hybrids developed but only 121 had enough seed for multi-location testing to determine combining ability. These hybrids were sown in single, 4-m rows with 60 cm between rows and 50 cm between plants. A basal fertilizer application of 20 kg ha^{-1} (N/ha), and 20 kg ha^{-1} (P/ha) was applied during sowing. Five plants from each entry were selfed with pollination bags before flowering to determine the fertility status of the hybrid. Pollination bags were removed at the soft dough stage and the seed set on bagged heads was assessed visually using a scale of 0 to 100%; where 0% represented a completely sterile head without seed set, and 100% represented a completely fertile head with complete seed set. Thinning was done two weeks after emergence to 2 plants per hill. Top-dressing with urea, at the equivalent of 45 kg ha^{-1} was done at four weeks after emergence. Other agronomic practices including weeding and disease control was practiced as per requirements. Data were recorded for days to 50% flowering (whole-plot), plant height, tillers per plant, panicle length, panicle width, panicle exsertion, grain colour and grain yield using sorghum descriptors (IPGRI, 1993) on the five plants that were randomly selected and bagged before flowering.

Statistical analysis

The *GCA* and *SCA* effects were determined using SAS General Linear Model (GLM) procedure, (SAS Institute 2008, SAS V9.2). Both *GCA* and *SCA* effects were significantly different at P<0.05 and were calculated according to Kearsey and Pooni (1996)

Where by: $GCA_f = X_f - \mu$ and $GCA_m = X_m - \mu$

Note: X_f, X_m = mean performance of female and male lines in crosses respectively; GCA_f and GCA_m= GCA for female and male parents respectively; µ = grand mean of all crosses.

$$SCA_X = X_x - E(X_x) = X_x - GCA_f + GCA_m + \mu$$

where: SCA_X = SCA effects of the two parents in the cross; X_x= observed mean value of the cross; $E(X_x)$= expected value of the cross basing on the GCA effects of the two parents; GCA_f and GCA_m= GCA for female and male parents respectively and µ = grand mean of the crosses.

RESULTS AND DISCUSSION

Data on mean monthly temperature, rainfall and relative humidity from three locations are presented in Figures 1, 2 and 3 respectively. Ukiriguru experienced high relative humidity (77 to 79%) and temperatures (18.4 to 29.3°C)

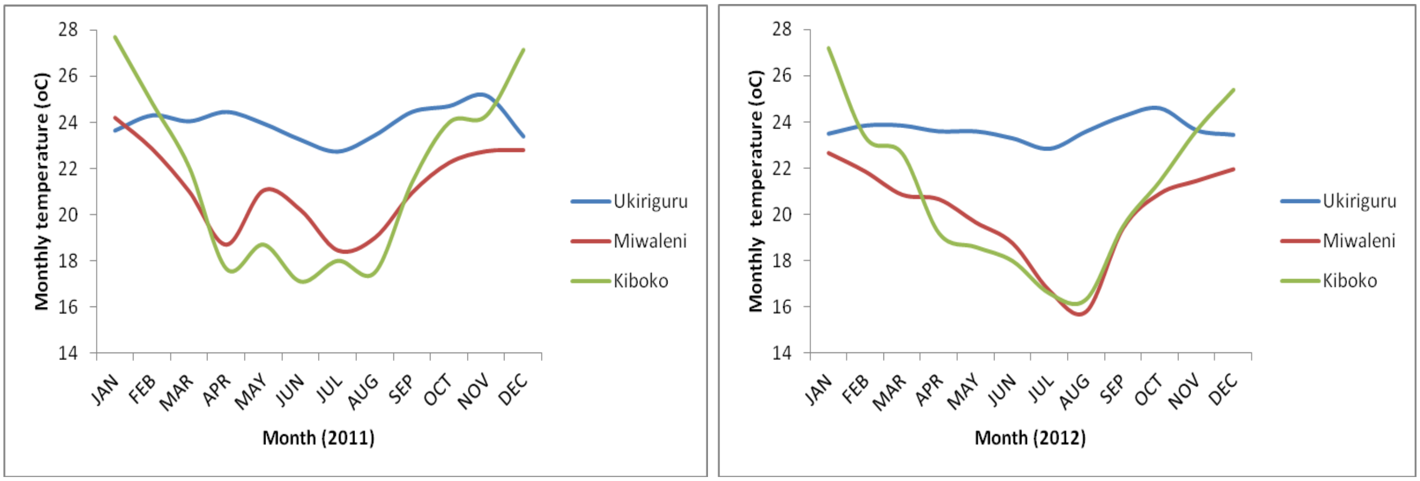

Figure 1. Monthly temperature (^{o}C) at Ukiriguru, Miwaleni and Kiboko during 2011 and 2012 growing seasons.

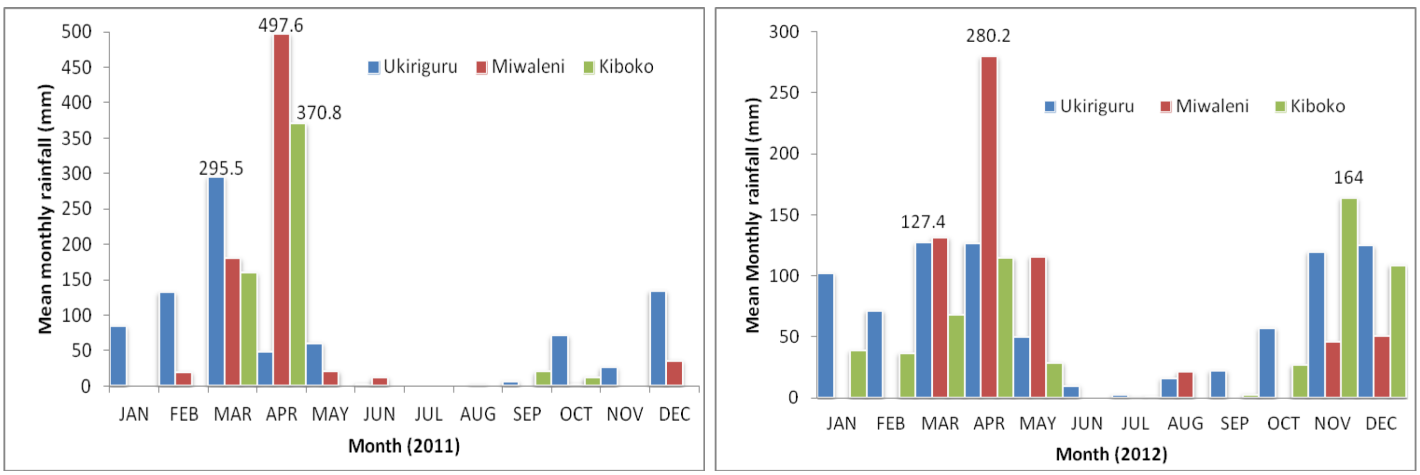

Figure 2. Monthly rainfall (mm) at Ukiriguru, Miwaleni and Kiboko during 2011 and 2012 growing seasons.

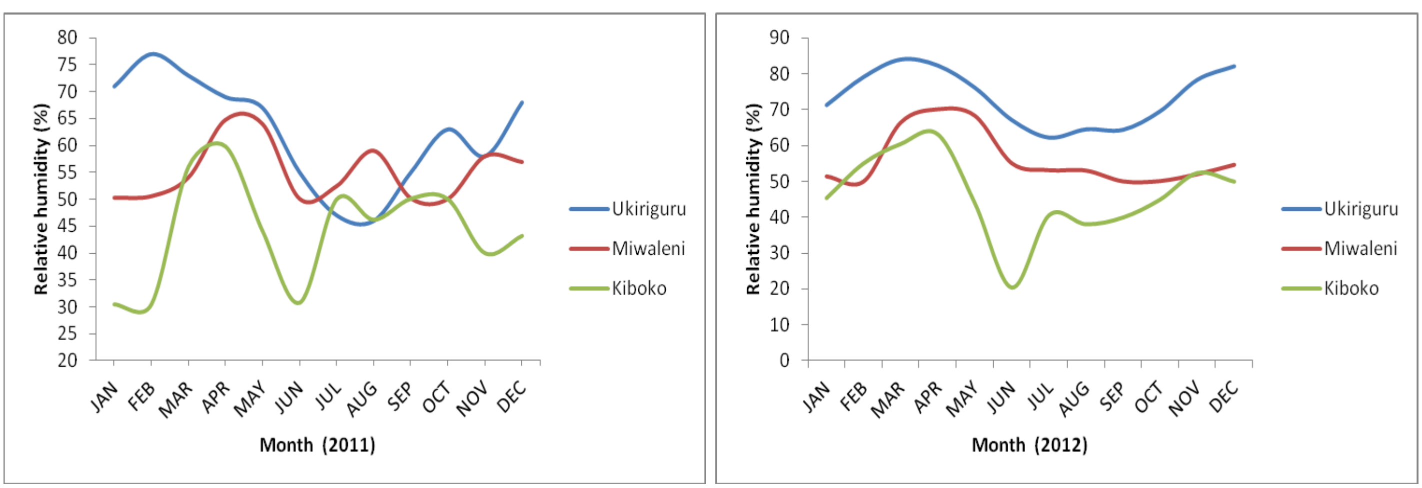

Figure 3. Monthly relative humidity (%) at Ukiriguru, Miwaleni and Kiboko during 2011 and 2012 growing seasons.

Table 1. Analysis of variance for some traits evaluated in sorghum across dry lands and sub-humid environments of Tanzania and Kenya.

Source of variation	Mean squares							
	Df	Days to 50% flowering	Productive tillers	Plant height (cm)	Panicle length (cm)	Panicle width (cm)	Grain yield /panicle (g)	Grain yield/plot (g)
Environment (Env)	2	2382.2**	468.8**	179447.7**	2839.1**	962.6**	111459.7**	89300603.4**
Crosses	91	56.5**	3.2**	5316.3**	49.5**	9.6**	1700.6**	467301.8**
Females	27	157	5.6	6714.1**	106.1**	18.4**	1933.9**	518475.6
Males	45	18.7**	2.0*	7540.4**	35.2**	6.9**	1587.2**	486877.4**
Females × Males	26	8.9	2.5**	528.6	12.4**	4.4**	1628.6**	384797.2
Env × Crosses	184	13.4**	2.9	616.1**	8.2**	3.4	785.2	454484.6**
Env × Females	54	19.1**	4.8**	720.3**	10.6**	5.3	883.4	454590.6**
Env × Males	78	11.1	1.9	550.6**	8.8**	2.9	721.6	420757.0**
Env × Females × Males	52	10.8	2.4**	606.2**	4.8	2.1	778.5	504965.9**
Error	420	5.6	0.9	221.9	4.7	1.5	580.6	187013.2

*, ** Significant at 1 and 5% level respectively

Table 2. Rating scale and summary for seed set of sorghum evaluated at Kiboko and Miwaleni in 2011 season.

Seed set (%) range	Description	Number of hybrids		Total	% Hybrids
		Kiboko	Miwaleni		
100	The whole head is filled with grain seed set.	64	46	110	32.6
80 to <100	Seed set above three quarters of head.	166	147	313	92.9
60 to <80	Above two thirds of the head showing seed set.	2	28	30	8.9
40 to <60	Half of the total head showing seed set.	12	11	23	6.8
20 to <40	About a quarter of the head showing seed set.	4	23	27	8.0
1 to <20	Less than a quarter of the head showing seed set.	17	34	51	15.1
0	Total sterility, no seed set on the head.	72	48	120	35.6

Seed set percent range adopted from sorghum descriptors (IPGRI, 1993)

especially during flowering (February). The mean monthly rainfall was lower (102 mm average) during the same period. Miwaleni location was characterised by relatively higher monthly rainfall (average of 156.2 mm), low temperatures (17.3 to 24.4°C) and low relative humidity (54 to 66.3%) during flowering (March). Kiboko experienced similar conditions to Miwaleni except that rainfall was relatively lower (114 mm) in March. Differences in grain yield and its associated traits between environments could be due to location's differences in weather during growing season and genetic potential of the specific cultivar. Significant variations in sorghum for yield and yield traits across environments have also been reported by Warkard et al. (2008). Kiboko location received relatively higher rainfall than other location resulting to overall high grain yield.

Differences among crosses and among male lines were significant ($P \leq 0.05$) for days to 50% flowering, productive tillers, plant height, panicle length, panicle width and yield (Table 1) indicating broad genetic diversity of sorghum materials used in this study. There was no significant difference between female parents. This could be due to the fact that, the female lines were purposely derived for developing hybrids suitable for dry lowlands and sub humid environments hence comparatively same background. Moreover, the differences recorded for parents and crosses imply that the materials are suitable for combining ability studies. The interaction between females and males were not significantly different for days to 50% flowering, plant height and panicle exsertion. The significant differences for Female × Male interaction for the productive tillers, panicle length, panicle width, panicle shape and grain yield indicate high contribution of SCA effects to those traits and, therefore, predominance of non-additive gene action. Similar results were reported by Vinaykumar et al. (2011). This necessitated testing the parents and hybrids for GCA and SCA effects across several environments and enable identification of outstanding cultivars for general and specific adaptation.

The summary of fertility restoration for experimental hybrids tested at Kiboko and Miwaleni is presented in Table 2. There was high difference in seed setting among the hybrids (Figure 4). Most of the test hybrids, 313

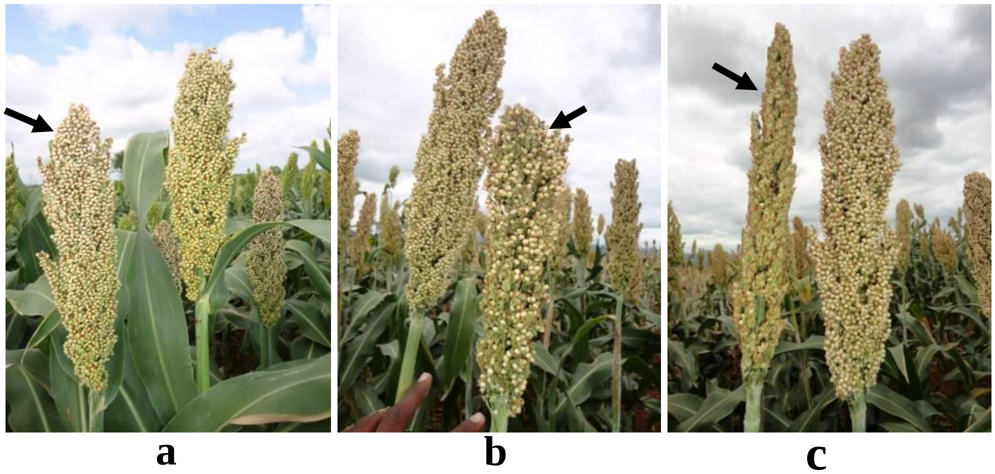

Figure 4. Fertility status of some hybrids tested at Kiboko and Miwaleni (a) fully restored (b) partially restored (c) extremely low restoration on bagged panicles indicated by arrows.

(93%) exhibited ≥ 80% seed set, with Kiboko registering higher values than Miwaleni. Only 110 (32%) of the hybrids had 100% restoration; among those, 64 were at Kiboko, and 46 at Miwaleni. One hundred and twenty hybrids (35.6%) did not produce seed at all in the bagged panicles in both locations. Three female lines A2DN55, ICSA479, ICSA469, consistently produced poor hybrids in terms of seed set irrespective of male parent used. A total of 171 hybrids were within the recommended fertility restoration range, 80 to 100%, for multi-location advanced trials. Due to seed availability, only 121 hybrids were tested in three sites alongside their parental lines for yield and its components and combining ability. There were significant differences observed in fertility restoration among hybrids and could be attributed to the specific interaction between the male and female parent genotypes and the environmental influences. Relatively lower mean temperatures at Ukiriguru and Miwaleni coupled with high relative humidity could have resulted in the low seed set. Effect of temperature and relative humidity has also been reported by Leland and House (1985).

The hybrids that failed to produce seed on the bagged panicles indicates that the corresponding male parents in such hybrid were non-restorers as also reported by Singh et al. (1997), and could serve as a source of A-lines. The hybrids that expressed full seed set in some bagged panicles but not others within and across environments were an indication that the male parents for such hybrids were segregating for fertility restoration, and cannot be used as they are in a breeding program (Murty et al., 1994). The A-lines A2DN55, ICSA479 and ICSA469 produced poor hybrids in terms of seed set irrespective of male parent could be due to the environmental effects and/or the genetic background of the A-line (Sleeper and Poehlman, 2006). Purification through recurrent backcrossing is recommended for these lines before used for hybrid production. Since these male sterile lines were recently introduced into Africa from different climatic conditions, some could be poorly suited for the new agroecologies. The temperature at the three locations ranged between 18 and 29.3°C which is within the optimum range for most sorghum cultivars (Reddy et al., 2007).

Negative GCA for plant height, days to flowering and positive GCA for yield and productive tillers is desired for a good genotype. This study found no parent that exhibited high and desired GCA for all traits evaluated including yield, plant height productive tillers (Table 3). The top 3 male sterile and restorer lines for early flowering were MB6, CK60B, ICSB11, and IESV 23010DL, S35, SP74279. Early maturing sorghum hybrids and parental lines could be favourable for semi-arid areas because they can utilize the limited moisture available and hence escape terminal drought. The male-sterile lines and restorer lines for plant height that expressed high and negative *GCA* were ICSB91002, ICSB89004 and ICSB90001; and ICSR24007, ICSR89001 and ICSR38. Negative *GCA* for plant height in sorghum is preferable as it is directly related to dwarfness, hence making plants less susceptible to lodging (Singh et al., 1997) and easier to handle for harvesting. Modification of plant height could be possible using the above lines as the height in those lines was determined by a relatively large proportion of additive genes, as shown by their significant *GCA* effect. The potential general combiners for productive tillers were ICSB654, ICSB687, and ICSB479 and ICSR153, Siaya#66-2, and IESV23011DL. A total of 14 male sterile parents revealed significantly negative (undesirable) *GCA* on productive tillers per plant of which SDSB4, ICSB366 and ICSB9 expressed highly negative significant effects.

Table 3. Estimates of general combining ability (gca) for selected traits in some sorghum lines evaluated across 3 locations.

Parents	Days to 50% flowering	Tillers /plant	Height (cm)	Panicle exertion (cm)	Panicle length (cm)	Panicle width (cm)	Grain weight /panicle (g)
BTX623	-1.6**	-0.1	1.94*	-0.17	-0.39**	-0.24**	10.31**
CK 60B	-5.4**	0.6**	-15.42**	3.72**	-2.48**	-0.59**	5.01**
ICSB 11	-4.5**	0.2**	-14.72**	1.43**	-1.75**	-1.40**	0.74
ICSB 12	0.7**	0.1	11.06**	-0.21	-0.06	-0.23**	6.27**
ICSB 15	-0.1	0.1	13.98**	-0.16	1.27**	-0.34**	10.85**
ICSB 276	2.1**	0.2**	21.39**	3.93**	0.60**	1.08**	0.42
ICSB 293	1.20**	0.18**	-21.33**	6.17**	1.74**	1.40**	28.62**
ICSB 366	-2.55**	-0.65**	-4.66**	-1.64**	-2.23**	-0.32**	-3.57*
ICSB 371	-3.88**	-0.41**	-9.60**	0.3	-2.01**	-0.89**	-3.06*
ICSB 376	-2.30**	0.11	43.90**	9.62**	-1.69**	0.53**	-11.68**
ICSB 44	-0.13	-0.36**	12.07**	0.16	-3.71**	0.61**	9.93**
ICSB 479	3.87**	1.83**	-0.62	-7.08**	-8.99**	-1.22**	-17.23**
ICSB 6	0.42**	0.34**	15.54**	-0.64**	0.92**	1.04**	15.62**
ICSB 654	-2.97**	2.44**	-14.90**	3.37**	-1.64**	-1.45**	-18.26**
ICSB 687	-3.72**	1.88**	-15.81**	-2.53**	1.54**	2.58**	-3.20*
ICSB77	0.03	-0.04	-21.63**	0.92**	-0.71**	0.19**	-12.68**
ICSB 88001	-0.07	-0.09	15.19**	-2.38**	2.38**	1.60**	9.94**
ICSB 88006	2.70**	0.02	7.81**	0.68**	0.54**	-0.87**	-0.35
ICSB 89003	1.48**	-0.21**	2.81**	1.83**	1.49**	-0.03	-8.47**
ICSB 89004	3.37**	-0.49**	-42.50**	-3.17**	3.22**	1.13**	9.32**
ICSB 9	0.45**	-0.56**	-8.67**	3.16**	1.77**	-1.37**	-17.97**
ICSB 90001	3.44**	-0.25**	-29.61**	-3.70**	3.32**	1.16**	0.85
ICSB 91002	-2.13**	-0.51**	-43.25**	1.77**	-0.39**	-0.09	-6.91**
IESB 2	-0.33*	-0.16*	-22.22**	-5.18**	-2.01**	0.64**	-11.45**
MB 6	-6.08**	0.24**	24.11**	9.67**	-3.80**	-0.65**	-11.32**
SDSB 1	3.06**	-0.38**	20.86**	-0.72**	-0.26*	-1.13**	-6.28**
SDSB 4	5.26**	-0.81**	-3.88**	-2.92**	4.94**	-0.95**	-14.05**
ICSB73	-1.30**	-0.2**	2.81**	2.08**	-0.22*	0.03**	-7.21*
AIHR91075	-3.30**	-0.79**	-23.87**	4.08**	-3.53**	-1.05**	-10.44**
GADAM	-4.80**	-0.16	6.57**	-0.32	-2.49**	-0.25**	13.41**
ICSR 108	0.45*	-0.21*	-17.80**	0.78**	0.38*	0.70**	-13.89**
ICSR 153	-2.97**	2.44**	-14.90**	3.37**	-1.64**	-1.45**	-18.26**
ICSR 160	0.98**	-0.41**	-8.89**	-1.67**	2.61**	0.49**	-0.26
ICSR 162	0.58**	-0.07	17.59**	0.70*	1.22**	0.31**	2.26
ICSR 172	-0.07	-0.22**	-34.11**	-0.71*	-1.38**	-1.19**	-1.97
ICSR 196	1.37**	0.28**	-18.33**	0.45	-0.33	-0.24**	-5.38**
ICSR 23019	-0.13	-0.52**	32.27**	-0.78**	0.92**	0.43**	23.89**
ICSR 24007	-1.97**	-0.09	-55.37**	-3.35**	-3.31**	-0.54**	-27.18**
ICSR 24008	2.03**	-0.32**	-14.88**	-2.23**	2.43**	1.78**	-0.73
ICSR 24009	3.32**	-0.34**	-18.67**	-1.26**	1.90**	-0.55**	-8.45**
ICSR 24010	1.20**	-0.19*	39.65**	0.1	-2.17**	0.96**	-7.90**
ICSR 38	-2.13**	-0.51**	-43.25**	1.77**	-0.39*	-0.09	-6.91**
ICSR 43	4.70**	-0.77**	-15.54**	-1.78**	5.11**	0.18*	-7.24**
ICSR 56	0.03	-0.59**	-2.93*	5.48**	0.14	-1.49**	-16.89**
ICSR 89001	3.37**	0.01	-50.17**	-2.70**	4.19**	1.05**	18.59**
ICSR 89028	3.37**	-0.49**	-42.50**	-3.17**	3.22**	1.13**	9.32**
ICSR 89058	1.87**	-0.54**	-26.13**	-1.48**	3.94**	-0.14	-15.17**
ICSR 89059	4.53**	-0.76**	-7.90**	-4.50**	5.44**	-0.84**	-13.01**
ICSR 92003	2.78**	-0.16	-13.67**	-1.70**	2.11**	0.59**	-3.47
ICSR 93001	1.70**	-0.26**	9.05**	-0.93**	1.79**	0.05	19.87**

Table 3. Contd.

ICSR 93034	-0.38	0.68**	28.21**	-3.14**	2.17**	1.60**	16.56**
ICSV 95022	-2.13**	0.18*	-31.77**	-2.10**	2.76**	0.60**	-7.16**
IESV 23010 DL	-6.47**	-0.22**	7.88**	4.69**	-3.08**	-0.58**	-1.69
IESV 23011DL	-0.41*	1.54**	18.15**	1.71**	0.61**	1.86**	9.46**
IESV 23013 DL	-2.30**	0.11	43.90**	9.62**	-1.69**	0.53**	-11.68**
IESV 23019 DL	2.20**	0.44**	51.00**	1.78**	1.37**	0.60**	4.57*
IESV 91104 DL	1.14**	-0.02	8.11**	-1.34**	-2.66**	0.57**	20.81**
IESV 91136 DL	1.98**	-0.17*	-25.31**	0.21	-0.14	-1.80**	-11.14**
IESV91131DL	-0.80**	-0.29**	-20.83**	2.28**	1.56**	-0.82**	1.16
IESV92156	0.03	0.19*	-18.23**	-0.12	1.37**	-0.47**	-1.94
IESV92158DL	0.70**	1.18**	-21.60**	-0.80**	-0.48**	-0.84**	-7.99**
IESV92172 DL	-1.63**	-0.01	-19.50**	4.85**	1.09**	-0.99**	-2.49
KARIMTAMA 1	-0.66**	-0.1	22.55**	-1.12**	-1.43**	0.52**	19.21**
MACIA	-3.15**	0.01	-17.39**	-0.53	-0.11	-0.33**	-5.86**
MAKUENILOCAL	-4.24**	0.11	39.36**	5.02**	-1.55**	0.68**	-8.81**
S35	-6.47**	0.93**	23.97**	6.38**	-3.66**	-0.93**	6.49**
SIAYA # 66 – 2	3.87**	1.83**	-0.62	-7.08**	-8.99**	-1.22**	-17.23**
SIAYA #46-2	2.37**	-0.06	42.17**	-4.10**	-2.01**	-0.55**	-1.19
SIAYA#42	1.03**	0.31**	-17.57**	-8.27**	-4.08**	-1.17**	-14.49**
SP 74278	-4.63**	0.38**	-25.30**	9.65**	-3.09**	-1.67**	-11.19**
SP 74279	-6.13**	0.04	-37.13**	3.40**	-0.59**	-2.14**	-17.61**
TEGEMEO	-2.47**	0.41**	43.20**	2.62**	-0.73**	0.36**	22.72**
BUSIA #28-1	3.20**	-0.29**	47.53**	-4.88**	-6.04**	-0.90**	-1.59
R8602	-4.80**	0.94**	-42.07**	1.60**	-1.09**	-1.09**	-17.69**

*, ** significant at 5 and 1% level respectively.

Tillering is generally among important traits affecting accumulation of biomass and ultimately grain yield in sorghum. Hammer et al. (1996) reported significant yield advantage of high-tillering sorghum types when water was plentiful, whereas such types incurred a significant disadvantage under water-limited circumstances. Generally, tillering is undesirable in sorghum male sterile lines as this give rise to a range in seed size and maturity in the field but it is desirable in pollen parent (restorers) as this gives a longer duration of pollen shed, as stated by Singh et al. (1997).

Panicle exsertion is an important attribute for clean seed in sorghum. The expression of *GCA* effects ranged from -7.1 (ICSB479) to 9.7 (MB6). Negative *GCA* for panicle exsertion is undesired (Dogget, 1988), because the leaf sheath provides favorable conditions for fungi and insects to develop at the base of the panicle hence extend to the whole panicle. The line MB6 is therefore the best source breeding material for well exerted-panicle sorghum hybrids. Positive and significant *GCA* effect on panicle width was recorded on 11 male sterile lines and 20 restorers. The male sterile lines ICSB687, ICSB88001 and ICSB293 were the best general combiners for panicle width. Basing on the same trait for the restorers, ICSR24008, IESV23011 and ICSR93034 had positive and significant *GCA* effects. Four lines; SDSB4, ICSB90001, ICSB88001 and ICSB89004 were best general combiners for panicle length across environments. The least general combiners for panicle length were ICSB479, MB6 and ICSB44 among the female lines. The best restorers for panicle length were ICSR89059, ICSR43 and ICSR89001. Panicle characteristics including length, width and shape is positively related to the final yield in sorghum as also reported by Can et al. (1997). Long, broad and compact panicles results into higher yields compared to their counterparts.

The best general combiners for grain yield were ICSB293, ICSB6, ICSB15 and BTX623, for female lines, and ICSR23019, Tegemeo, IESV91104DL and KARI MTAMA1 for restorers. In general, the means from all locations indicate that line ICSB687 expressed significant negative (desired) GCA effects for four traits viz days to 50% flowering, mature plant height, panicle length and panicle width. This parent could be utilized as a source of breeding lines for both dry lands and sub-humid areas. The potential combination for developing hybrids from the best parents basing on the GCA effects of the parents can be easily worked out and ranked (Table 4). The rank for the combination is obtained by taking combining ability as significant positive (high), non-significant (average) and significant negative (low). For days to 50%

Table 4. Possible combinations for hybrids basing on gca effects of the best 6 parents.

Possible hybrid combination	Agronomic trait considered		
	Days to 50% flowering	**Plant height (cm)**	**Grain weight per plot (g)**
IESA2 × IESV91104DL	High × Low	High × Low	High × High
IESA2 × KARI MTAMA1	High × High	High × Low	High × High
IESA2 × IESV91131DL	High × High	High × High	High × High
IESA2 × MACIA	High × High	High × High	High × Average
ICSA15 × IESV91104DL	Average × Low	Low × Low	High × High
ICSA15 × KARI MTAMA1	Average × High	Low × Low	High × High
ICSA15 × IESV91131DL	Average × High	Low × High	High × High
ICSA15 × MACIA	Average × High	Low × High	High × Average
ATX623 × IESV91104DL	High × Low	Low × Low	High × High
ATX623 × KARI MTAMA1	High × High	Low × Low	High × High
ATX623 × IESV91131DL	High × High	Low × High	High × High
ATX623 × MACIA	High × High	Low × High	High × Average

Rank for the combination is obtained by taking gca effects as significant positive (high), non-significant (average) and significant negative (low). For days to 50% flowering and plant height, significant positive combining ability effects is taken as low, non-significant as average and significant negative as high combining ability.

flowering and plant height, significant positive combining ability effects is taken as low, non-significant as average and significant negative as high. A majority of the potential cross combinations could not possess all traits in a desired manner.

The SCA estimates for some phenotypic traits are presented in Table 5. The best specific combiner for days to flowering were SDSA4×ICSR89059 (-5.26), SDSA4×ICSR43 (-4.59), SDSA1×ICSR43 (-4.06), ICSA479×Siaya#66-2 (-3.87) and ICSA90001 ×ICSR89001 (-3.44). The negative combing ability effect is desirable as it is associated with earliness in sorghum. Similar results have been reported by Makanda et al. (2012). The best cross combinations that showed significant and positive *SCA* effects for productive tillers per plant were ATX623×*Macia*, ICSA88001×ICSR 93034 and ICSA90001×ICSR162. Productive tillers in sorghum parents are desirable as they provide pollen for longer time as compared to non-tillering ones and do add to grain yield of a particular parent as supported by Reddy et al. (2007) and Singh et al. (1997). Considering the plant height, the best crosses that expressed significant negative (desired) *SCA* effect comprised of ICSA376×IESV23O13DL (-43.90), ICSA6×ICSR93034 (-43.25), ICSA276 × IESV91104DL (-31.26), MA6×S35 (-28.35) and MA6×Makueni local (-23.73). As for the *GCA*, negative *SCA* for plant height is desired as it is directly related to shortness and less lodging in sorghum as supported by Singh et al. (1997).

Crosses ICSA479×Siaya#66-2, ICSA44×Makueni local, ICSA11×S35 and CK60A×IESV 23010 showed highly significant positive specific combination for panicle length. Furthermore, ICSA11×S35, ICSA645×ICSR153, ICSA11×SP74279 and ICSA9×ICSR56 showed highly significant positive *SCA* effect for panicle width. The significant positive panicle length and width are related to grain yield per plant in sorghum hence total yield. Furthermore, the ultimate yield in sorghum depends on grain yield per plant through various other components such as panicle characteristics (Figure 5), and thus determination of grain yield per panicle deserves attention. The results in the present study revealed the existence of considerable positive *SCA* effect for yield per panicle in five crosses which included ATX623×IESV91104DL, ICSA12×ICSR172, ICSA15×IESV91104DL, CK60A×KARI MTAMA1 and ICSA12×KARI MTAMA1. Specific combining ability for panicle exsertion varied from -9.2 (ICSA376×IESV23013) to 6.0 (SDSA1×ICSR43). Negative *SCA* for panicle exsertion is undesired (Dogget, 1988), because the leaf sheath provides favourable conditions for fungi and insects to develop at the base of the panicle and can destroy the entire panicle. Based on days to 50% flowering, plant height and grain yield, it is interesting to note that IESV91104DL produced 3 early maturing crosses including ICSA44×IESV91104DL, ICSA15×IESV91104DL and ATX623×IESV91104DL. Although IESV91104DL expressed positive but low general combining ability effect for days to flowering and plant height, the yield was significantly high across locations. The positive significant effect of the two traits has no bad implications on synchrony to flowering and pollen to recipient sterile lines because, as reported by Singh et al. (1997), female parents should be 125 to 175 cm shorter while male parents are supposed to be 175 to 250 cm taller.

Conclusion

Significant differences recorded for parents and crosses

Table 5. Specific combining ability (sca) effects of sorghum hybrid parents for various traits across dry low land and sub-humid environments.

Cross	Days to 50% flowering	Productive tillers	Height (cm)	Exertion (cm)	Panicle length (cm)	Panicle width (cm)	Weight per plot (g)
ATX623×GADAM	1.6	0.0	-1.9	0.2	0.4	0.2	104.4
ATX623×ICSR23019	1.6	0.0	-1.9	0.2	0.4	0.2	104.3
ATX623×ICSV95022	1.6	0.0	-1.9	0.2	0.4	0.2	104.3
ATX623×IESV91104DL	-0.2*	-0.2	-11.1	-0.4	0.1	-0.1	276.9**
ATX623×IESV91131DL	0.4	-0.3	-3.2	0.0	0.3	0.6	242.7
ATX623×IESV91136DL	1.6	0.0	-1.9	0.1	0.4	0.2	-104.3
ATX623×KARI-MTAMA1	0.3	-0.1	-6.2	0.1	-1.3	-0.8	-170.0
ATX623×MACIA	2.9**	1.1**	-8.0	0.8	1.7	0.3	198.6
ATX623×MAKUENI LOCAL	2.1*	0.3	-7.0	-2.5	0.7	-0.6	-173.0
CK60A×IESV23010DL	3.7**	-0.7	10.4	-6.9**	3.0**	0.4	-237.7
CK60A×KARI-MTAMA1	-1.9**	0.7	-4.3	-0.4	0.6	1.1*	332.3**
CK60A×SP74278	5.4**	-0.5	15.4*	-3.7*	2.5**	0.6	-109.6
CK60A×R8602	5.4**	-0.5	15.4*	-3.7*	2.4**	0.6	-109.6
ICSA11×ICSR172	2.9**	-0.5	13.6*	-1.9	0.4	1.0*	136.1
ICSA11×S35	5.2**	0.0	18.9**	-5.6**	3.4**	1.8**	-192.4
ICSA11×SP74279	4.5**	-0.2	14.7*	-1.4	1.7*	1.4**	-182.1
ICSA12×ICSR162	-0.7	-0.5	3.3	1.2	-0.5	-0.4	-113.8
ICSA12×ICSR172	-2.2*	-0.5	-7.8	0.7	1.4	0.4	435.2*
ICSA12×ICSR93001	-1.8	0.2	-21.2**	-0.8	0.3	0.2	-162.1
ICSA12×IESV23019DL	-0.7	0.0	-11.1	0.2	0.1	0.2	-179.4
ICSA12×IESV91104DL	0.6	0.2	-4.1	0.4	0.2	0.6	212.5
ICSA12×IESV92156	-0.7	-0.1	-11.1	0.2	0.1	0.2	-179.4
ICSA12×IESV92158DL	-0.7	-0.1	-11.1	0.2	0.1	0.2	-179.4
ICSA12×IESV92172DL	-0.7	-0.1	-11.1	0.2	0.1	0.2	-179.4
ICSA12×KARI-MTAMA1	1.3	-0.3	-1.9	-0.8	-0.7	-0.1	249.4**
ICSA12×SIAYA46-2	-0.7	-0.1	-11.1	0.2	0.1	0.2	-179.4
ICSA15×ICSR160	-0.9	0.2	-16.2*	0.9	1.7	-0.2	-130.0
ICSA15×ICSR162	0.6	-0.6	-15.5*	-2.0	1.6	0.2	-451.7*
ICSA15×ICSR172	-0.3	0.7	4.4	0.6	0.0	-0.1	-287.4
ICSA15×IESV91104DL	0.4	0.1	-14.6*	0.6	-1.1	-0.6	267.8**
ICSA15×TEGEMEO	0.1	-0.1	-13.9*	0.2	-1.3	0.3	-379.4*
ICSA276×ICSR162	-0.2	0.2	8.8	1.6	-1.8*	-0.7	293.9
ICSA276×ICSR24008	-1.8	-0.1	-18.4**	2.6	-1.4	-2.4**	187.9
ICSA276×IESV91104DL	-1.7	0.3	-31.2**	-1.3	2.3**	0.5	-559.4**
ICSA293×ICSR24009	-3.3**	0.3	18.6**	1.2	-1.9*	0.5	258.3
ICSA366×KARI-MTAMA1	1.5	0.0	-3.1	0.8	0.6	-0.5	-211.5
ICSA366×MACIA	2.2*	0.1	-2.1	0.7	0.8	0.3	-130.6
ICSA371×MACIA	3.1**	-0.1	17.3**	0.5	0.1	0.3	165.7
ICSA376×IESV23013DL	2.3*	-0.1	-43.9**	-9.6**	1.7	-0.5	170.6
ICSA44×ICSR172	1.9	0.3	-18.8**	2.8	-0.3	-1.7**	-177.4
ICSA44×IESV91104DL	-0.5	-0.2	-17.2**	-2.8	1.6	0.5	191.9
ICSA44×MAKUENI LOCAL	1.7	0.0	-7.2	-2.9*	4.2**	1.1*	-216.0
ICSA479×SIAYA66-2	-3.8**	-1.8**	0.6	4.1**	8.9**	1.2**	485.5*
ICSA6×ICSR162	-0.5	-0.8	-17.8**	-3.7*	-0.3	-0.2	-314.7
ICSA6×ICSR93034	0.9	-1.3**	-43.2**	1.5	-1.7*	-2.3**	-140.2
ICSA6×IESV23011DL	-0.3	-0.1	-2.8	2.9*	-1.8*	-1.2**	144.1
ICSA654×ICSR153	2.9**	-2.4**	14.9*	-3.3*	1.6	1.4**	187.6
ICS687×ICSR162	-2.2*	-1.4**	-15.6*	1.0	-2.2*	-1.0*	168.7
ICS687×IESV23011DL	1.9	-0.1	-20.1**	-3.4*	0.3	-1.1*	-272.1
ICSA77×ICSR108	-0.9	0.4	14.9*	-1.3	0.1	-0.5	151.6

Table 5. Contd.

ICSA77×ICSR160	-1.8	-0.1	8.4	2.6	-3.4**	-0.2	-170.2
ICSA77×ICSR196	-0.1	0.0	21.6**	-0.9	0.7	-0.2	231.2
ICSA88001×ICSR108	0.9	-0.3	-8.5	2.7	-1.7*	-1.2**	106.6
ICSA88001×ICSR160	2.7**	0.0	0.3	-1.9	-1.1	-0.9*	179.0
ICSA88001×ICSR93034	-1.3	1.1*	12.5*	1.4	-1.5	-0.3	130.4
ICSA88001×KARI-MTAMA1	0.5	-0.73	-0.9	1.6	1.2	0.6	-178.8
ICSA88001×MACIA	-0.2	-0.1	-10.1	1.7	-0.4	-1.1*	96.1
ICSA88006×ICSR162	-0.9	-0.3	1.5	1.4	-0.4	-0.1	165.4
ICSA88006×IESV91131DL	-1.5	0.2	-17.0**	0.1	-0.9	0.6	119.8
ICSA88006×KARI-MTAMA1	0.5	0.4	0.6	-1.3	1.7	0.3	-272.3
ICSA89003×ICSR89058	-1.1	0.2	0.2	-0.8	-1.6	0.1	188.6
ICSA89003×ICSR92003	-3.2**	0.8	0.8	0.5	-2.6**	-1.2**	-48.1
ICSA89003×IESV23011DL	0.1	-1.8**	20.5**	1.8	-2.3**	-1.2*	-46.5
ICSA 89004×ICSR89028	-3.3**	0.5	42.5**	3.2*	-3.2**	-1.1*	-264.2
ICSA9×ICSR56	-0.4	0.5	8.6	-3.2*	-1.7*	1.3**	152.1
ICSA9×ICSR89058	-1.4	0.5	20.4**	-0.8	-2.3**	0.2	165.8
ICSA90001×ICSR162	-1.8	0.8*	10.7	3.1*	-4.5**	-2.1**	53.0
ICSA90001×ICSR172	-1.6	0.1	15.7*	0.2	-0.6	0.5	187.2
ICSA90001×ICSR24008	-0.7	0.4	26.1**	2.7	-1.4	0.0	-77.3
ICSA90001×ICSR43	-3.1**	0.5	13.9*	-1.6	-2.8**	0.2	340.2
ICSA90001×ICSR89001	-3.4**	0.2	29.6**	3.7*	-3.3**	-1.1*	129.3
ICSA90001×ICSR89058	-2.7**	0.3	14.8*	0.4	-2.6**	-0.1	-99.1
ICSA90001×ICSR92003	-1.7	-0.3	25.9**	1.3	-2.2*	0.1	241.3
ICSA91002×ICSR38	2.1*	0.5	43.2**	-1.7	0.4	0.1	121.7
IESA2×ICSR24007	0.3	0.2	22.2**	5.2**	2.0*	-0.6	136.1
IESA2×ICSR24008	-2.6*	-0.1	22.8**	-0.3	0.9	-0.4	392.2*
IESA2×ICSR24009	-2.4*	0.1	-5.2	-0.8	-0.3	0.2	229.9
IESA2×ICSR24010	-1.2	0.3	4.8	5.8**	0.6	1.0*	218.3
MA6×MAKUENI LOCAL	4.0**	-0.1	-23.7**	-4.2**	2.9**	-0.2	-173.3
MA6×S35	5.4**	-0.4	-28.3**	-5.4**	2.1*	0.2	-272.8
SDSA1×ICSR24009	-0.6	0.4	-14.5*	0.6	1.3	-0.2	94.6
SDSA1×ICSR24010	-1.5	0.2	-3.5	0.0	1.6	-0.5	-159.0
SDSA1×ICSR43	-4.0**	0.2	-11.9	6.0*	-1.0	0.0	172.6
SDSA1×ICSR93001	-1.8	0.2	-10.6	1.7	-0.1	1.1*	85.9
SDSA1×IESV91104DL	-3.0**	0.2	-3	0.7	-0.5	-0.8	-332.3
SDSA1×IESV91131DL	-3.0**	0.4	-10.3	0.0	0.6	0.8	173.0
SDSA1×BUSIA28-1	-3.1**	0.3	-20.8**	0.7	0.3	1.1*	123.2
SDSA4×ICSR24009	-2.7**	0.3	27.6**	1.6	-3.4**	-0.4	154.4
SDSA4×ICSR43	-4.6**	0.7	10.6	2.9*	-4.1**	0.7	-149.0
SDSA4×ICSR89059	-5.2**	0.8	3.8	2.9*	-4.9**	0.9*	211.3

*, ** significant at 5 and 1% level respectively.

for yield and yield components suggest presence of promising combining ability character for exploitation. Majority of sorghum expressed desirable >90% restoration capacity. Only A2DN55, ICSA479 and ICSA469 produced poor hybrids in terms of seed set irrespective of male parent used probably due to environmental effects and/or the genetic background of the lines. These lines should be avoided in breeding programs as they require purification through recurrent backcrossing which is time and resource consuming. The best general combiner for days to flowering was IESV23010 whereas best specific combiners for the same trait were SDSA4×ICSR43 and SDSA4×ICSR59059. The best general combiner for yield and height were IESV92156DL and ICSR24007 respectively. Basing on overall performance, lines IESB2 and ICSB44 were well suited to sub-humid, whereas BTX623, ICSB15 and ICSB6 were more appropriate to

(i) Makueni local (ii) IESV 95046 (iii) ICSV 189 (iv) Siaya # 46-1

Figure 5. Panicle shapes and exsertion of sorghum evaluated: (i) semi loose drooping primary branches (ii) semi compact elliptic- (iii) compact oval (iv) compact elliptic.

dry lands environments. Restorer lines IESV91104DL, IESV91131DL, ICSR93034 were well suited to dry lands while KARI-MTAMA1 and IESV23019 were better adapted to sub-humid environments. These materials could be employed in hybrid program to produce high yielding, short and early maturing hybrids in East Africa and regions with similar condition. The information gathered is essential in selecting parental lines for producing suitable hybrid for particular agro-ecological zones of East Africa.

Conflict of Interest

The authors have not declared any conflict of interest.

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Appendix 1. List of sorghum lines used in this study

S/no	A-lines	Origin	Status	S/no	A-lines	Origin	Status	S/no	R-lines	Origin	Status
1	A_2 DN_{55}	ICRISAT-India	Inbred line	28	ICSA 89003	ICRISAT-India	Inbred line	17	ICSR 108	ICRISAT -India	Inbred line
2	ATX 623	ICRISAT-India	Inbred line	29	ICSA 9	ICRISAT-India	Inbred line	18	ICSR 153	ICRISAT -India	Inbred line
3	CK 60A	ICRISAT-India	Inbred line	30	ICSA 90001	ICRISAT-India	Inbred line	19	ICSR 160	ICRISAT -India	Inbred line
4	ICSA 11	ICRISAT-India	Inbred line	31	ICSA 91002	ICRISAT-India	Inbred line	20	ICSR 162	ICRISAT -India	Inbred line
5	ICSA 12	ICRISAT-India	Inbred line	32	IESA 2	ICRISAT-India	Inbred line	21	ICSR 172	ICRISAT -India	Inbred line
6	ICSA 15	ICRISAT-India	Inbred line	33	MA 6	ICRISAT-India	Inbred line	22	ICSR 24007	ICRISAT -India	Inbred line
7	ICSA 276	ICRISAT-India	Inbred line	34	SDSA 1	ICRISAT-India	Inbred line	23	ICSR 24008	ICRISAT -India	Inbred line
8	ICSA 293	ICRISAT-India	Inbred line	35	SDSA 29	ICRISAT-India	Inbred line	24	ICSR 24009	ICRISAT -India	Inbred line
9	ICSA 324	ICRISAT-India	Inbred line	36	SDSA 4	ICRISAT-India	Inbred line	25	ICSR 24010	ICRISAT -India	Inbred line
10	ICSA 366	ICRISAT-India	Inbred line		**R-lines**	**Origin**	**Status**	26	ICSR 38	ICRISAT -India	Inbred line
11	ICSA 371	ICRISAT-India	Inbred line	1	Busia #28-1	ICRISAT-Nairobi	Landrace	27	ICSR 43	ICRISAT -India	Inbred line
12	ICSA 376	ICRISAT-India	Inbred line	2	SIAYA # 42	ICRISAT-Nairobi	Landrace	28	ICSR 56	ICRISAT -India	Inbred line
13	ICSA 44	ICRISAT-India	Inbred line	3	AIHR 91075	ICRISAT-Nairobi	Landrace	29	ICSR 89001	ICRISAT -India	Inbred line
14	ICSA 452	ICRISAT-India	Inbred line	4	GADAM	ICRISAT-Nairobi	Variety	30	ICSR 89028	ICRISAT -India	Inbred line
15	ICSA 469	ICRISAT-India	Inbred line	5	IESV 23011 DL	ICRISAT -India	Inbred line	31	ICSR 89058	ICRISAT -India	Inbred line
16	ICSA 479	ICRISAT-India	Inbred line	6	IESV23010DL	ICRISAT-India	Inbred line	32	R 8602	ICRISAT -India	Inbred line
17	ICSA 592	ICRISAT-India	Inbred line	7	TEGEMEO	ICRISAT-Nairobi	Variety	33	ICSR 92003	ICRISAT -India	Inbred line
18	ICSA 6	ICRISAT-India	Inbred line	8	SIAYA # 66-1	ICRISAT-Nairobi	Landrace	34	ICSR 93001	ICRISAT -India	Inbred line
19	ICSA 654	ICRISAT-India	Inbred line	9	SP 74278	ICRISAT-Nairobi	Landrace	35	ICSR 93034	ICRISAT -India	Inbred line
20	ICSA 43	ICRISAT-India	Inbred line	10	SP 74279	ICRISAT-Nairobi	Landrace	36	ICSV 95022	ICRISAT -India	Inbred line
21	ICSA 683	ICRISAT-India	Inbred line	11	MACIA	ICRISAT -India	Variety	37	MAKUENI LOCAL	ICRISAT-Nairobi	Landrace
22	ICSA 686	ICRISAT-India	Inbred line	12	IESV23019DL	ICRISAT -India	Inbred line	38	S 35	ICRISAT-Nairobi	Landrace
23	ICSA 687	ICRISAT-India	Inbred line	13	IESV 91136 DL	ICRISAT -India	Inbred line	39	SIAYA # 46-2	ICRISAT-Nairobi	Landrace
24	ICSA 73	ICRISAT-India	Inbred line	14	IESV 23019 DL	ICRISAT -India	Inbred line	40	IESV 92156	ICRISAT -India	Inbred line
25	ICSA 77	ICRISAT-India	Inbred line	15	IESV 91104 DL	ICRISAT -India	Inbred line	41	KARI MTAMA 1	ICRISAT -India	Inbred line
26	ICSA 88001	ICRISAT-India	Inbred line	16	IESV 91131 DL	ICRISAT -India	Inbred line	42	AIHR 91075	ICRISAT -India	Inbred line
27	ICSA 88006	ICRISAT-India	Inbred line								