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Multi-environment trial and spatial analysis for yield performance of sorghum [*Sorghum bicolor* (L.) Moench] hybrids in dry lowland sorghum growing areas of Ethiopia

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Sorghum is one of the most widely preferred and cultivated crops in Ethiopia. It is grown for food and feed components. In the developed world, exploitation of heterosis in most crops (Maize, Sorghum, Rice, etc.) is high. There is a clear need to develop sorghum hybrids in Ethiopia to improve their livelihood by increasing sorghum production and productivity. One of the strategies for increasing sorghum yield is through the exploitation of heterosis because sorghum hybrids are high yielder than OPV lines. Properly selected sorghum hybrids can help growers to increase yield, use less water, reduce lodging losses, increase feed quality, and manage maturation time. In Ethiopia, the National Sorghum Research Program runs a multiple technology development work in Ethiopia with the collaboration of International and National Institutions and Universities. One of the oversea collaborative Universities is Purdue University and the Sorghum program received sorghum hybrids to evaluate their performance across sorghum growing dry lowland areas. A total of 35 sorghum hybrid genotypes were introduced and evaluated at six sorghum growing lowland areas of Ethiopia including two recently released hybrid check in 2014. Based on the experimental data submitted to national variety releasing committee, candidate 9187 has been approved for farmers and commercial seed producers in 2018; it is named ESH-5. This hybrid variety is released with a merit of seed color, over all agronomic performance, head shape and yield superior to the recently released hybrid check by 11% yield advantage.

Key words: Hybrid, heritability, sorghum, stability.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is an African-domesticated diploid C4 cereal crop. It is an extremely productive, dry-resistant C_4 grass used for grain, forage, sugar and biomass cultivation (Casto et al., 2018). It has

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a chromosome of 2n=20 and a ~800 Mb genome size (Paterson et al., 2009; Mace et al., 2013) . Sorghum is a predominantly self-pollinated short-day crop with the degree of spontaneous cross-pollination reaching in some instances up to 30%, depending on the form and type of panicles. It is an indigenous crop of Ethiopia mostly cultivated with low rainfall areas, low soil fertility and high temperature conditions in extremely varied settings. In Ethiopia, sorghum develops from lowland regions that receive reduced rainfall and have elevated altitude temperatures characterized by low temperatures and greater rainfall levels (Mindaye et al., 2015).

Sorghum is the world's fifth largest cereal crop and third largest dry land crop in Ethiopia cultivated by 6 million smallholder farmers in over 1.9 million hectares of soil with 25% area coverage from cereal crops; sorghum contributed 17% of cereal production (Maize, Teff and Wheat) which is about 51.7 M quintals of production (CSA, 2018).

Most sorghum cultivars released in Ethiopia are open-pollinated, but hybrids could offer yield and seed production advantages. Hybrids have confirmed the yield advantage in comparison to the pure line types (Mindaye et al., 2015), although, the genetic foundation for the extended energy is not widely known. The complementarity among alleles of the parental lines is cautioned to have vast contribution (Han et al., 2016). Improvement of high yielding and stable performing hybrid is the key riding element to interact the personal seed sectors and commercialize sorghum in Ethiopia (Wagaw, 2019). The F1 hybrid in sorghum is derived as a result of healing of male fertility while male sterile (A line) crossed with line confers restorer gene (R strains). The male sterile A line is maintained *via* crossing with an isogenic line by B line (Kidanemaryam et al., 2018). Sorghum hybrid improvement research in Ethiopia has been achieved for longer than 4 decades. Even though, the technology has no longer been exploited due to the predominance of the conventional cultivation of sorghum that is relying on the lengthy maturing excessive biomass producing sorghums along with lack of strong value chain and week extension system (Tadesse et al., 2008).

Hybrids evolved from the breeding program and introduced sorghum hybrids from overseas institutions were evaluated for sterility response, biomass production and grain yield performance within the dry lowland sorghum growing areas in Ethiopia for a long period of time; there is a huge evaluation of oversea hybrid genotypes. The primary hybrids designated through the name ESH-1 and ESH-2 have been released in 2009 having 28% grain yield advantage in comparison of OPV and ESH-3 and ESH-4 (red sorghum hybrid) were released for lowland areas with merit of seed color and grain yield in 2012 and 2016 respectively. In 2018, one early maturing seeded sorghum hybrid (ESH-5) was released for end users, among the imported hybrid genotypes to evaluate their performance; from Purdue University executed under this experiment.

Five sorghum hybrids with the ESH series were released and registered for production under dry lowland sorghum growing areas of Ethiopia; but, due to the problems of seed manufacturing, the observation of hybrids ESH-2 and ESH-3 was tough and additionally had confined preference *via* farmers. The hybrids were proven on farmers' field and demand became valid for ESH-1 hybrid within the lowlands of Tigray, North Shewa and West Hararghae areas. Considering this demand ESH-5 was brought by the National Sorghum Research Program to the areas demanding for it.

Exploiting the locally tailored and farmers favored sorts for hybrid improvement could be very important to be beneficial to tap the genetic sources and address the created demand for farmers. Past studies using Ethiopian sorghum landraces have shown excessive yielding hybrids of 7.2 t ha^{-1} with the most excessive determined heterosis up to 60% (Mindaye et al., 2015). Additionally, the demand found out the capability of hybrids for the intermediate and highland environment. But, development of seed determines viable for hybrid seed production with the tall and overdue maturing restorer lines and adapted to the highland and intermediate environment could be a concern for these environments. Due to the latest intervention to illustrate sorghum hybrids for farmers and seed growers there is a growing demand for sorghum hybrids. Efforts have been made to apply the nearby landraces for hybrid improvement and primarily based on their flowering response; within the F1 hybrids 670 restorer traces and 156 B lines were identified by the National Sorghum Program. The restorer strains getting used for the male determine inbred line improvement and the conversion of the B lines as seed discern being underway. To date, the National Sorghum Research Program evolved six seed female and male parents named by MARC1A to MARC6A being used for hybrid improvement.

In Ethiopia, sorghum breeding has been mostly restricted to germplasm characterization using phenotypic traits and exotic sorghum hybrid parental lines. There is also an increment in developing hybrid parental lines from the local available sorghum lines. Even though, there is a high level of genetic diversity and the potential of local developed inbred liens for hybrid cultivar development has not yet been exhaustively assessed. Although, evaluation and verification of introduced hybrid genotypes across environments in dry lowland areas is pertinent to feed the fast-growing population with high yielder and stable cultivars in the resource limited areas. The behavior of hybrids can be exploited to maximize fertilization and grain production in the sorghum hybrids. In this experiment introduced sorghum hybrid genotypes were evaluated over location to evaluate and exploit their yield performance and stability to verify for farmers and seed growers under moisture stress areas of Ethiopia.

Table 1. Testing location description.

Location	Longitude	Latitude	Altitude in m.a.s.l.	Soil type	Rain fall in mm	Minimum T°	Maximum T°
Kobo	39°38'E	12°09'N	1513	Vertisol	678	14.8	32
Miesso	39°21'E	8°30'N	1470	Vertisol	571	16	31
Shiraro	39°9'E	14°6'N	1179	Vertisol	615	20.4	34
Shewarobit	39°93'E	10°35'N	1500	Vertisol	713	17.7	33
Humera	40^{0}9'E	9°16'N	750	Vertisol and fluvisol	590	26.7	40.8
Erer	42^{0}15'E	9°10'N	1297	Vertisol	778	17°C	37°C

Source: Center profile assessed from each center (Humera assessed on 19/08/2019).

MATERIALS AND METHODS

The field testing was conducted during the main cropping season of six locations (Kobo, Mieso, Shiraro, Erer, Humera and Shewarobit); they represent the moisture stressed lowland areas of Ethiopia located in the altitude range of 750-1513 m.a.s.l, where sorghum is predominantly grown by small holder farmers (Table 1).

Description of the hybrids (genetic materials)

A total of 37 candidate sorghum hybrid genotypes including one popular released variety (Dekeba) and hybrid variety (ESH-3) as a standard check were evaluated in 2014 at six dry lowland areas of Ethiopia (Table 1). The genotypes (Table 2) were introduced from Purdue University to evaluate their grain yield performance and stability under moisture stressed sorghum growing areas of Ethiopia.

Statistical design

The experiment was conducted at Mieso, Shiraro, Shewarobit and Kobo in 2014. Randomized Complete Block Design (RCBD) was used to lay out the hybrids with two replications in a row- column arrangement to minimize the spatial variability (trends) in estimating the genetic value. Each plot contained two rows of 5 m length separated by 0.75 m. At all locations sowing was done in between last week of June to first week of July when enough rain was received. Plantation was done manually by drilling along the farrow, and population was adjusted by thinning considering 0.20 m as spacing between plants. DAP fertilizer was applied at planting time with the rate of 100 kg/ha and urea was side dressed when the plant reached knee height at 50 kg/ha basis. Weeding was conducted at least three times during the growing period in each of the test sites depending on the level of weed infestation in the experimental plot.

The following agronomic traits were collected and analyzed to identify stable and superior hybrids compared with the standard check:

Days to 50% flowering (DTF)

This is the time between days to emergence to 50% of the plants in a plot reaching half-bloom stage.

Plant height (PHT)

This is the length from the base of the plant to the tip of the panicle in cm.

Grain yield per plot (GY)

This is grain yield in kilogram of plants from the three rows and adjusted to 13% moisture level and converted to t ha^{-1}.

Days to 90% physiological maturity (DTM)

This is the number of days from emergence to the stage when 90% of the plants in a plot reached physiological maturity, that is the stage at which the panicle loses its pigmentation and begins to dry.

Plant aspect (PAS)

Over all agronomic desirability score (drought tolerance, earliness, head exertion and compactness, grain size and shape, thresh ability, disease and insect resistance, etc.) was scored using 1-5 score where 1=excellent and 5=poor.

Statistical analysis

The concurrence of genotypes and populations between testing site was used to allow the trial series to be analyzed as a single MET as of each trial consisting similar hybrids, which is the current best practice method for analyzing field trials for plant breeding programs (Smith et al., 2001). The META for sorghum hybrid included 35 candidate hybrids and 1 hybrid with 1 variety as standard check and run in six environments. Spatial effects were fitted to each trial and then a variance structure was created to produce between trials (environmental) correlations using factor analytic (FA) method (Smith et al., 2001). Heritability (or repeatability) estimates on a line mean basis were calculated for the different environmental (trials) groups according to the method proposed by Ullis et al. (2006).

For each trait, the genotype x environment (GxE) interactions was considered. These interactions were created by considering a pair-wise correlation matrix for the correlations of each pair of trials. The analysis results in a genetic variance for each trial along with a set of loadings that represent FA frameworks can be used to recreate the correlation matrix (Smith et al., 2001). Although the agronomic traits were measured as usual measurement and score, we are confident that the values satisfy an assumption of normality. The genetic correlations between the hybrid trials at the six sites were identified, with a mean genetic correlation between the sites. These results indicated that there was little GxE interaction for the hybrid agronomic trait. In contrast, the genetic correlations between sites for grain yield were indicated (Figure 2, Figure 3 and Figure 5).

Table 2. Descriptions and list of genetic materials evaluated.

SN	Genotypes	Pedigree	Source
1	9035	P9511A/PRL020765	Introduction
2	9203	P-0102105A/TX2737	Introduction
3	9133	PBL984610A/TX2737	Introduction
4	9130	PBL984594-3A/TX2737	Introduction
5	9224	P-0102043A/TX436	Introduction
6	9128	PBL984594-1A/TX2737	Introduction
7	9140	2001-2002-34A/TX2737	Introduction
8	9058	P9511A/PRL020817	Introduction
9	9149	PBL984594-3A/TX436	Introduction
10	9063	P9511A/PRL020962	Introduction
11	9187	PBL984594-3A/PU304	Introduction
12	9228	P-0102105A/TX436	Introduction
13	9227	P-0102028A/TX436	Introduction
14	9136	PBL984724/TX2737	Introduction
15	9190	PBL984610A/PU304	Introduction
16	9061	P9511A/PRL020884	Introduction
17	9186	PBL984594-2A/PU304	Introduction
18	9147	PBL984594-1A/TX436	Introduction
19	9159	2001-2002-34A/TX436	Introduction
20	9204	P-0102008A/TX436	Introduction
21	9142	2001-2002-103A/TX2737	Introduction
22	9036	P9511A/PRL020772	Introduction
23	9205	P9511A/TX2737	Introduction
24	9041	P9511A/PRL020777	Introduction
25	9076	P9511A/TX436	Introduction
26	9229	P-0102032A/TX2737	Introduction
27	9059	P9511A/PRL020839	Introduction
28	9056	P9511A/PRL020811	Introduction
29	9132	PBL984608A/TX2737	Introduction
30	15	HD1	Introduction
31	9161	2001-2002-103A/TX436	Introduction
32	9034	P9511A/PRL020761	Introduction
33	32	P9401	Introduction
34	9062	P9511A/PRL020888	Introduction
35	9144	2001-2002-197A/TX2737	Introduction
36	ESH-3	ICSA15/M5568	MARC breeder seed
37	Dekeba	ICSR24004	MARC breeder seed

The spatial mixed model used for the MET data analysis is written a

$$y = X_\tau + Z_u + e$$

$$= \quad X_\tau + Z_0 u_0 + Z_g\, u_g + e$$

The fixed effect τ includes environmental main effects and trial specific effects for extraneous field variation (Gilmour et al., 1997), u_g is variety effects at each environment with associated design matrix $Z_g{}^{(nxmp)}$ and u_0 comprises additional random effect with design matrixZ_0, and variance matrix G_0.

RESULTS AND DISCUSSION

A visual display of residual variation before spatial adjustment is presented in Figure 1. In large field trials, field variation among and within locations is a substantial source of error, since similar sites can show similar characteristics compared to those that are different. Figure 1 indicates locations of high and low yields in the field. Thus, there is need to include spatial correlation in variance-covariance analysis, to handle location trend

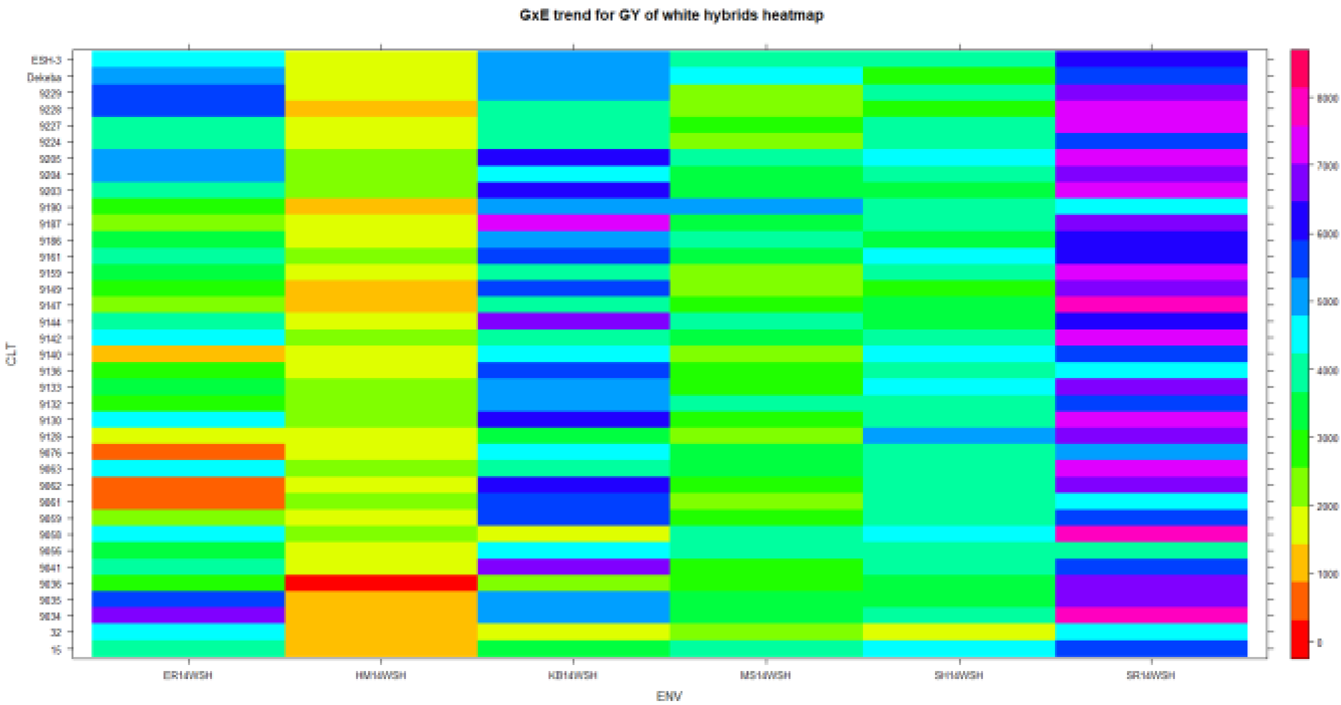

Figure 1. GxE trend of trials for grain yield to show location trend for these hybrids.

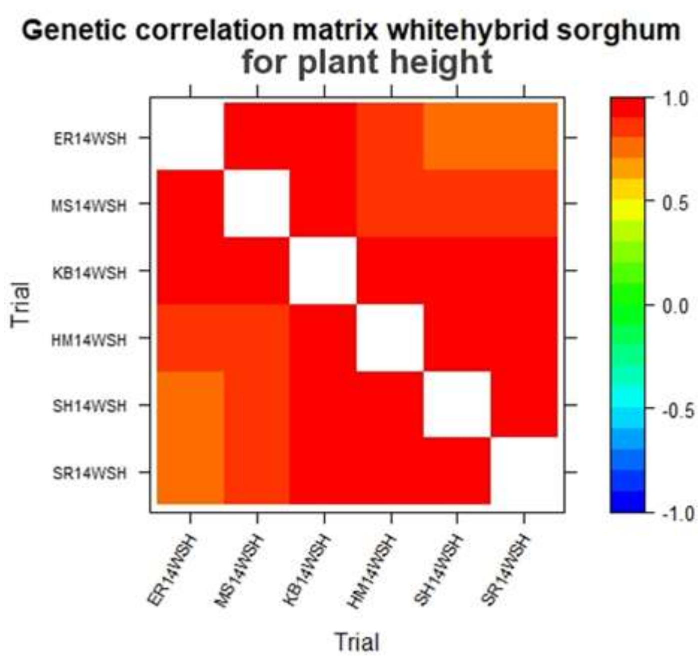

Figure 2. Genetic correlation matrix for plant height across environments.

that extends from one point to the other at the plot and trial level.

The range of trial mean yields among the six trials varied from 1.59 at Humera to 6.39 at Shewarobit (Table 3). The main reason for the lower mean yield at Humera (HM14) is the prevalence of striga infestation in the site

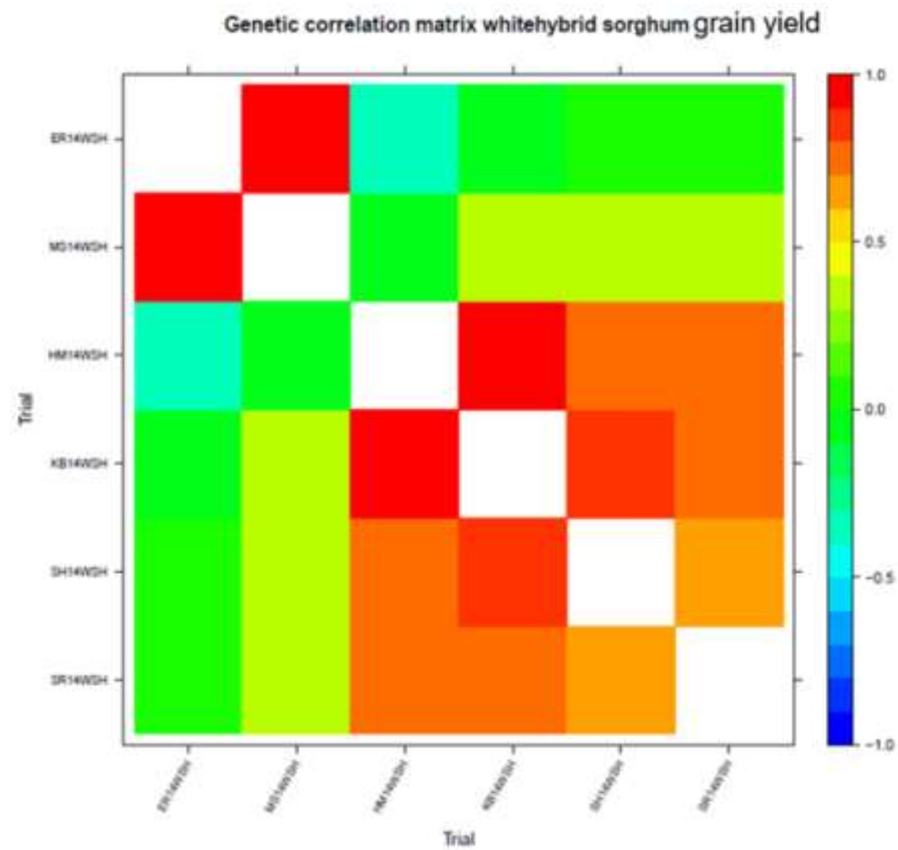

Figure 3. Genetic correlation of trials in respect to their testing sites for grain yield.

Table 3. Over all mean and heritability performance for yield, days to flowering and plant height of hybrids at each of site.

Trial	Grain yield				Days to flowering				Plant height			
	Mean	Genetic σ	Error σ	H_2	Mean	Genetic σ	Error σ	H_2	Mean	Genetic σ	Error σ	H2
ER14WSH	3.61	0.249	1.595	70.61	68.76	5.09	7.97	93.88	129.46	33.21	307.46	90.99
HM14WSH	1.59	0.049	0.156	64.07	47.80	15.80	3.87	92.52	118.93	154.44	118.95	95.83
KB14WSH	4.61	0.058	1.617	65.7	73.27	7.10	2.32	91.72	128.89	247.10	67.83	96.87
MS14WSH	2.94	0.237	0.215	76.75	64.32	3.34	2.00	85.11	115.15	178.76	40.90	93.27
SH14WSH	3.66	0.067	0.539	51.6	63.61	7.96	1.42	94.71	135.41	245.54	108.08	96.24
SR14WSH	6.39	0.245	0.821	59.27	134.14	291.77	91.90	88.18	135.32	298.10	45.42	96.41

during the experiment.

The associated heritability of grain yield varies from 51.6 to 76.75% and averaging 64.67% (Table 3). Heritability for days to flowering and plant height also show a better repeatability ranged from 85.11% to 94.71% with an average of 91.02% of reputability over all testing environments. This indicates that days to flowering is one of the traits that are highly heritable from parent to progenies (Table 3). Similarly, plant height is one of the most preferred traits that researchers need to invest more on to improve grain yield. There is no compromising the biomass component for the framers which is the best input for animal feeding and forage in Ethiopia and other like areas specially where an agrarian life mostly depends on mixed farming system like animal husbandry and cropping. Based on this experiment output, plant height (the main component for biomass production in sorghum) is highly heritable (Table 3) and all the environments are highly correlated (Figure 2) for plant height.

Based on the result, repeatability for plant height ranged from 90.99% to 96.87%, with an overall mean of 94.94% across testing environments. This indicates that taking more samples to measure plant height may not give significant (varied) result different from the result obtained from single observation.

The predicted mean for each of hybrids across testing site ranged from 4.2 to 3.15 t/ha, with an overall mean of 3.8 t/ha of grain yield. Based on the agronomic preference (PAS) and others (PHT, GY and DTF) 9187 named ESH-5 is released over ESH-3 and ESH-4 in 2018. This hybrid variety has a good agronomic preference as compared to ESH-3 and now the outreach system is under way by external funded projects. 9187 has been scored 1.6 followed by the 2nd candidate 9059 rated 1.8 for plant aspect; while the rest of the hybrids scored 2.00 and above (Table 4). Next to molecular aspect (in case of MAS a technology which is used to test the presence of desired gene in early generation), plant aspect (PAS) which encompasses drought tolerance, grain color, farmer preference, thresh-ability, earliness, biomass condition, shattering, tiller capacity, uniformity, lodging, resistance to disease and insect, etc. is the most important technique to identify (evaluate) the genetic materials for a given set of experimental objectives.

The genetic correlations for yield between the six sites varied between -0.371 and 0.933 (average 0.281), indicating the presence of significant amounts of GxE interaction for grain yield and reflecting changes in genotype ranking between sites (Table 4 and Figure 1). The stronger the correlations between trails (locations) indicated that GxE interactions were not as important for this trait and were not causing as much reordering of genotypes between sites (Jordan et al., 2012).

Most of the testing sites are correlated strongly and are not important to test hybrids across the sites since they do not bring change in rank of these hybrids. Trials at HM14 and ER14 were negatively correlated and testing the hybrid will change in rank and might be important to test hybrids in contrast, that is, low correlated (negatively) environments (Figure 3 and 4); whereas ER14 is correlated at zero or null correlation with SR14, SH14 and KB14. MS14 is moderately correlated with SR14, SH14 and KB14. Less angle between biplot lines for trial sites and deep red colored trials showed they are strongly correlated and testing these genotypes in one of them will give reliable information. Locations such as SH, HM and KB, ER and MS, SH and SR are also strongly correlated locations (Figures 3 and 4). As those sites exhibited less angle and strong correlation, selection of the best genotypes based on one of the environments does not change the ranks of the genotypes in another environment.

Among the testing hybrids two of them (9063 and 9058) scored above the standard check variety Dekeba with an average BLUP of 4.2 and 4.19 t/ha of grain yield respectively; while the standard check variety Dekeba

respectively; while the standard check variety Dekeba predicted 4.1 t/ha grain yield and similar sorghum growing locations.

Graphical explanation of the MET biplot data is commonly used to explain genotype by environment (Figure 3). The plots show that the environment with longest line from the center measures the discriminativeness of that environment when compared with others. For example, ER14WSH and MS14WSH were among the most discriminative environments followed by SR14WSH. This means these environments had considerable contributions in discriminating genetic variations. On the other hand, environments with less distances from the center were those stable environments, hence they explained less genetic variations. In addition, when a specific genotype is close to a given environment, it indicates that the genotype is the winner for that specific environment. That means, that genotype is the best performer for that trial. Hybrid 9187 is the closer genotype to the center of all the locations plot and this genotype is the most stable and winner in all the testing environments. The reason for releasing is being stable and winner across all testing environments.

The other important trait to be considered for the variety to be released and preferred by end users especially by farmers who need to have multiple uses is earliness. Nowadays, one of the cross-cutting issues for agriculture especially for crop farming is climate change when there is lack of enough rainfall to grow a crop. In this case, days to flowering is one of the major important traits to judge a given variety that suits the drought prone years and environments. It can help the breeder (researcher) to give relevant information whether that variety can escape the drought time or not. Mostly days to flowering can tell us the period required to give reasonable yield within the given time span starting from the date to planting. So, days to flowering is repeatable by an average of 91.02% across testing sites.

Conclusion

The hybrid sorghum genetic material is introduced from Purdue University and evaluated as part of an international hybrids' evaluation trial in collaboration with the university. The candidate hybrid has parental line PBL984594-3A/PU304. The parental lines are evaluated based on flowering time and plant height, which has serious implication for large seed production.

Based on the presented data and report one early maturing high yielder hybrid variety is released with good agronomic preference and a merit of seed color, yield and other important parameters with the inclusion of farmer preference mark. The variety is verified mainly for its high grain yield (11% advantage over the hybrid check and 19% over the best OPV check). The candidate variety showed better performance in uniformity and

Table 4. BLUPs for grain yield, days to flowering and plant height performance of the hybrids in specific site and over all locations.

Genotypes	ER14			HM14			KB14			MS14			SH14			SR14			Mean			
	GY	DTF	PHT	GY	DTF	PHT	GY	DTF	PHT	GY	DTF	PHT	GY	DTF	PHT	GY	DTF	PHT	GY	DTF	PHT	PAS
9063	3.89	69.28	133.98	1.82	47.30	130.71	4.95	72.91	144.38	3.50	64.16	127.34	3.95	63.67	150.84	7.09	150.27	142.11	4.2	77.93	138.23	2.31
9058	3.79	69.57	141.41	1.86	47.40	150.30	4.98	71.51	168.92	3.40	63.28	146.91	4.00	63.50	174.91	7.11	166.89	132.94	4.19	80.36	152.57	2.31
Dekeba	4.52	74.25	146.52	1.47	57.44	127.30	4.65	78.29	151.30	3.86	68.67	142.79	3.70	70.86	142.59	6.39	138.43	137.27	4.1	81.32	141.29	2.36
9034	4.36	51.89	120.84	1.51	73.85	134.29	4.66	64.21	121.85	3.68	65.21	137.07	3.70	147.41	137.27	6.66	147.41	133.69	4.09	91.66	130.83	2
9205	3.74	65.87	128.40	1.76	42.63	117.76	4.85	70.68	126.88	3.24	62.34	113.11	3.89	59.73	134.09	6.95	132.34	141.24	4.07	72.27	126.91	2.69
ESH-3	4.18	69.31	137.47	1.51	48.19	144.50	4.64	71.09	160.35	3.51	62.74	138.80	3.72	63.33	168.44	6.65	164.16	114.38	4.04	79.8	143.99	2.14
9132	3.32	66.70	127.56	1.93	45.72	114.57	4.97	71.87	122.97	2.94	63.62	110.32	3.98	61.12	129.76	6.91	124.01	155.96	4.01	72.17	126.85	2.69
9144	3.83	66.21	123.22	1.68	42.65	117.38	4.77	69.27	122.10	3.29	63.22	105.76	3.81	60.27	134.78	6.51	138.85	179.03	3.98	73.41	130.38	2.25
9204	4.09	71.30	130.19	1.49	51.55	108.96	4.59	77.21	120.57	3.41	65.61	111.60	3.65	67.34	122.57	6.41	126.58	159.09	3.94	76.6	125.5	2.38
9133	3.38	66.58	126.47	1.77	43.74	111.23	4.79	71.17	118.81	2.88	63.53	107.16	3.85	61.14	125.43	6.72	128.81	154.61	3.9	72.49	123.95	2.75
9161	3.61	69.65	135.18	1.69	48.81	116.41	4.74	75.25	131.42	3.05	64.76	121.88	3.74	65.10	130.76	6.56	127.72	177.43	3.9	75.22	135.51	2.56
9203	3.51	64.79	126.16	1.73	42.27	115.33	4.77	69.45	123.01	2.97	62.28	109.01	3.81	58.82	131.84	6.60	123.24	152.41	3.9	70.14	126.29	2.5
9130	3.34	67.95	122.36	1.81	47.29	113.20	4.82	72.65	117.17	2.84	64.52	102.42	3.86	62.90	129.03	6.71	125.89	138.25	3.89	73.53	120.41	2.63
9076	3.72	46.39	120.95	1.58	74.13	131.51	4.63	63.90	117.21	3.10	63.32	138.03	3.66	145.21	138.25	6.53	145.21	132.05	3.87	89.69	129.67	2.5
9190	4.31	69.13	126.63	1.32	51.06	108.88	4.44	74.03	117.27	3.53	65.47	106.54	3.57	64.02	123.01	6.06	126.07	128.19	3.87	74.96	118.42	2.13
9035	4.27	52.06	117.33	1.30	75.13	128.02	4.40	65.46	114.89	3.43	65.29	133.89	3.53	126.81	133.69	6.13	126.81	129.10	3.84	85.26	126.15	2.19
9142	3.88	65.56	125.61	1.48	42.48	110.58	4.54	70.80	117.87	3.15	61.95	105.86	3.62	59.73	125.34	6.30	125.76	124.31	3.83	71.05	118.26	2.44
9187	3.63	70.14	126.50	1.61	51.55	110.96	4.64	75.37	118.83	2.99	66.51	107.20	3.70	65.75	125.43	6.45	120.91	108.57	3.83	75.04	116.25	1.69
9228	3.45	69.76	128.50	1.68	48.19	117.60	4.69	74.89	126.53	2.85	65.82	113.03	3.64	64.83	133.44	6.66	132.61	110.67	3.83	76.02	121.63	2.56
15	4.39	50.09	125.61	1.24	75.29	145.48	4.36	66.71	135.21	3.55	65.43	141.32	3.46	130.85	142.11	5.89	130.85	124.20	3.81	86.54	135.66	2.5
9062	3.19	46.82	148.48	1.73	69.58	160.87	4.72	61.60	136.16	2.68	62.27	173.59	3.77	178.30	177.43	6.69	178.30	134.52	3.8	99.48	155.18	2.19
9061	3.37	45.44	133.21	1.70	70.96	143.67	4.71	62.54	124.97	2.83	62.30	152.88	3.72	156.35	154.61	6.40	156.35	134.76	3.79	92.32	140.68	2.5
9186	3.48	70.03	128.67	1.61	50.96	110.24	4.62	75.13	120.08	2.84	66.68	109.90	3.66	65.44	124.06	6.54	124.23	128.91	3.79	75.41	120.31	2.13
9056	3.62	42.26	133.82	1.49	68.67	146.51	4.50	61.69	128.29	2.91	60.62	154.07	3.57	154.12	155.96	6.10	154.12	118.87	3.7	90.25	139.59	2.38
9136	3.27	41.80	100.30	1.67	70.74	107.07	4.66	62.89	99.65	2.65	60.01	111.13	3.69	110.53	108.57	6.28	110.53	130.36	3.7	76.08	109.51	3.13
9128	2.80	47.89	116.38	1.82	73.45	123.77	4.74	65.08	109.70	2.27	63.35	132.47	3.78	128.84	132.05	6.68	128.84	122.86	3.68	84.57	122.87	2.63
9041	3.65	50.66	103.90	1.44	75.28	110.79	4.45	64.27	101.53	2.86	64.67	116.42	3.50	116.67	114.38	6.06	116.67	124.32	3.66	81.37	111.89	2.19
9229	3.31	65.67	124.69	1.57	43.89	110.94	4.54	71.25	117.70	2.61	62.59	104.91	3.62	60.61	126.42	6.33	111.04	121.66	3.66	69.18	117.72	2.69
9059	3.15	44.94	135.87	1.68	71.12	149.74	4.64	62.81	131.09	2.54	61.73	156.89	3.74	149.74	159.09	6.02	149.74	131.36	3.63	90.01	144.01	1.81
9224	3.24	70.00	121.56	1.56	49.60	110.37	4.51	74.33	113.88	2.51	64.22	99.98	3.61	65.48	125.52	6.11	135.77	121.26	3.59	76.57	115.43	2.63
9036	3.57	52.54	121.91	1.38	74.29	128.32	4.37	64.34	110.73	2.77	65.23	140.85	3.42	142.93	141.24	5.99	142.93	133.89	3.58	90.38	129.49	2.5
9147	3.32	51.84	117.68	1.51	76.84	125.43	4.47	66.59	110.46	2.59	67.48	134.93	3.43	138.71	134.76	6.17	138.71	124.31	3.58	90.03	124.59	2.56
9140	3.12	41.97	101.40	1.54	70.93	106.01	4.47	63.39	96.82	2.40	59.26	113.09	3.54	107.85	110.67	6.03	107.85	131.61	3.52	75.21	109.94	3.44
9149	3.35	52.41	114.11	1.46	77.58	121.48	4.42	66.52	108.27	2.55	67.89	129.61	3.45	124.90	128.91	5.89	124.90	133.17	3.52	85.7	122.59	2.75
9159	3.16	48.53	107.53	1.48	75.72	117.65	4.41	64.65	108.80	2.38	64.28	120.42	3.50	114.71	118.87	6.12	114.71	125.37	3.51	80.43	116.44	3
9227	3.45	49.43	115.60	1.36	75.68	125.36	4.32	65.32	112.27	2.61	65.81	132.03	3.35	130.48	131.61	5.99	130.48	143.61	3.51	86.2	126.74	2.5
32	3.13	49.32	116.80	1.23	74.60	123.00	4.10	66.16	108.03	2.09	65.69	133.30	3.09	137.94	132.94	5.26	137.94	171.83	3.15	88.61	130.98	3

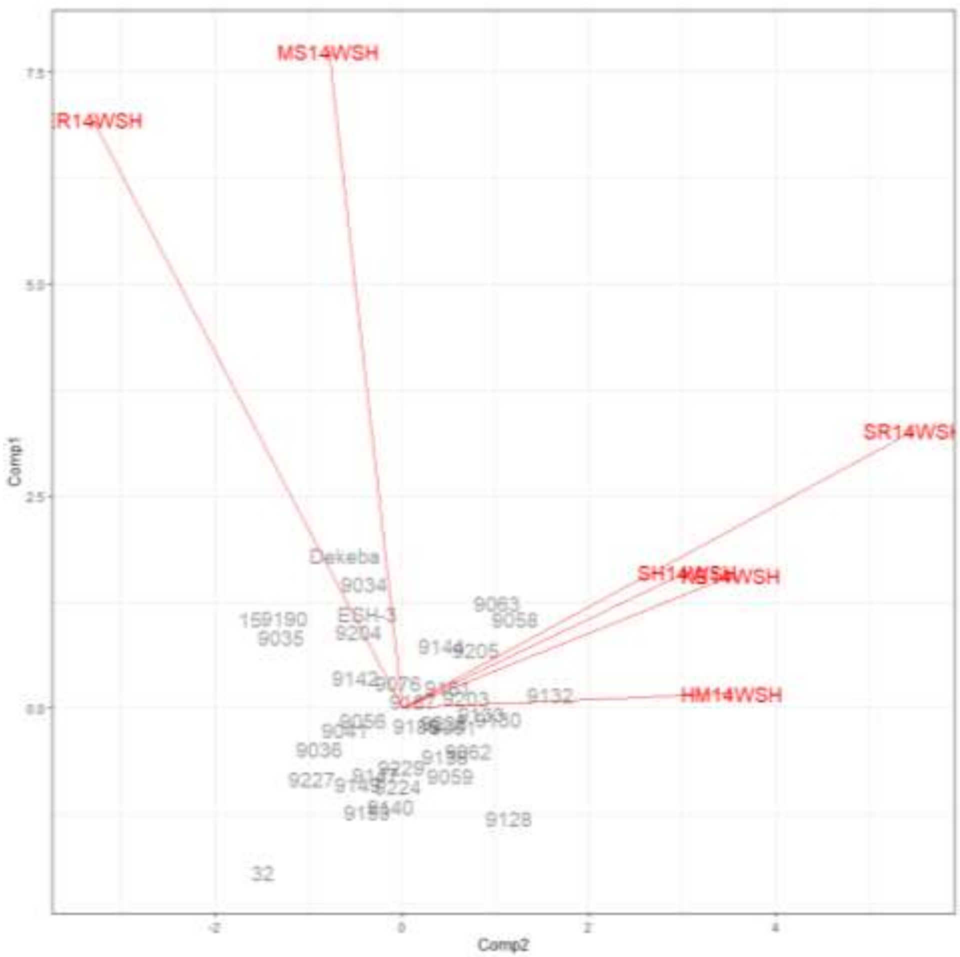

Figure 4. GxE biplot of candidate hybrids.

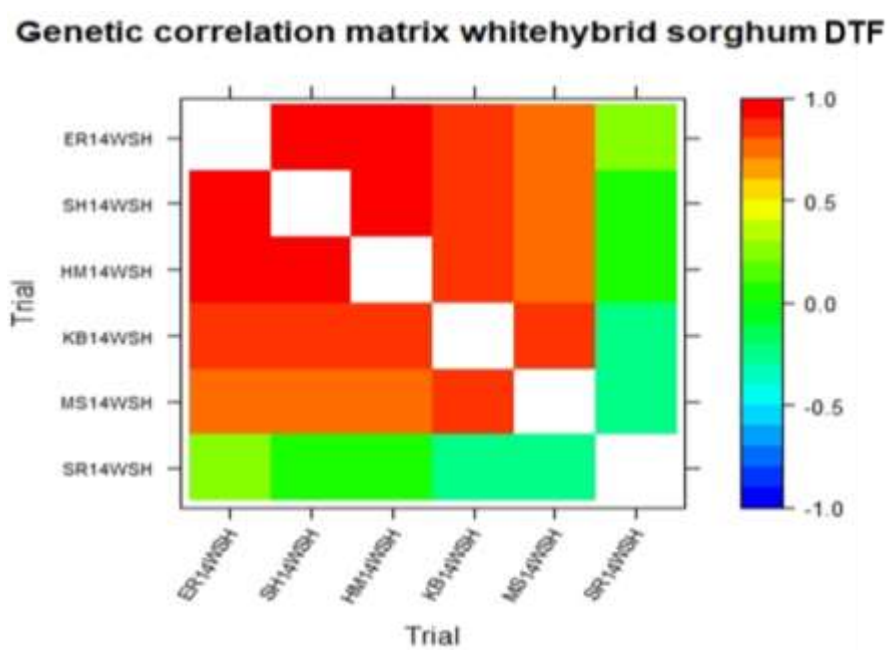

Figure 5. Genetic correlation of hybrids for their days to flowering.

stability in areas where moisture is a limiting factor. The variety is preferred mainly for best overall plant aspect, excellent grain and better yield over the check. Over all agronomic desirability score (includes drought tolerance, earliness, head exsertion and compactness, grain size and shape, threshability, disease and insect resistance, etc.) was measured using 1-5 score where 1 is excellent and 5 is poor. The candidate 9187 recorded the best overall score value of 1.69 on average while the standard checks scored 2.14 and 2.36.

The candidate variety was stable across all the testing locations, mostly in the area where the growing of sorghum is characterized by water moisture deficient and different biotic and abiotic constraints. This variety is verified in favor of these factors. An ideal sorghum hybrid is 175-180 cm tall and flowers in 68-70 days. Whereas, this hybrid has a plant height of 116.25 cm and flowering time of 75 days on average. Such hybrids generally yield 10-32% higher than OPV varieties. The current variety has 19 % yield advantage over OPV check. Across the environments, hybrid yield should be more stable than yield of OPV varieties. This study confirms that the verified hybrid variety is stable across the test environments for grain production.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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