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Yield Adaptability and Stability of Grain Sorghum Crosses across Environments under *S. hermonthica* Infestation in Sudan

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Abstract

An experiment was conducted to study yield stability of grain sorghum genotypes obtained by crossing the *Striga hermonthica* resistant genotypes IS9830, 555, SAR33, Framida, N13, ICSV006, ICSV007, PQ-34 Brhan and SRN39 and its derivatives P401, P402 and P405 as donors with the improved, elite Sudanese sorghum cultivars, Wad Ahmed (WA), Tabat (TA), Butana (BU) and Arfagadamek-8 (AG-8) as recurrent parents. The experiment was undertaken in two consecutive seasons (2016/17 and 2017/18) at three sites constituting six environments representing the irrigated and rain-fed sectors in the Sudan. The experiment, set in a randomized complete block design with four replicates, was laid in *S. hermonthica* sick plots. Data analyses, using GenStat software and combined analysis of variance showed highly significant differences ($P \leq 0.01$) among environments, genotypes and their interactions for grain yield. Twenty seven crosses, showing grain yield (20.4-72.4%) exceed the grand mean (898.1 kg ha^{-1}) and 218.5-1475% higher than the maternal parents across the environments. Based on Additive Main Effect and Multiplicative Interaction (AMMI) analysis the crosses Framida x AG-8, PQ-34 x BU, ICSV006 x BU, ICSV007 x BU, SAR33 x BU, SAR33 x TA, P402 x TA, PQ-34 x WA, P405 x WA, P401 x WA, Framida x WA, SAR33 x WA and Brhan x WA were identified as the most stable, endowed with *Striga* resistant and/or tolerance and high grain yield (1139-1548 kg ha^{-1}). It is recommended that these crosses be examined further for grain and nutrimental qualities, resistance mechanisms and potentials for deployment as components of *S. hermonthica* integrated management strategies and/or sources for resistance and/or tolerance.

Keywords: Grain yield, stability, sorghum crosses, environments, *S. hermonthica*.

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench], the fifth most important cereal crop worldwide (FAOSTAT, 2012), serves as a good source of food and nutrition to millions of eople in the semi-arid regions of the world (Reddy *et al.*, 2010). The crop is increasingly gaining importance as livestock feed and biofuel (Zhang *et al.*, 2010). Sorghum is grown in at least 86 countries, on an area of 47 million hectares, with annual grain production of 69 million tons reflecting an average productivity of 1.3-1.5 t ha^{-1} (Elzein *et al*., 2008 and FAOTAT. 2014).

In Sudan sorghum is grown in an area ranging between 4.3 and 7.1 million ha with an average of 5.2 million ha, which accounts for 73% of the total cropped area (Elzein and Elamin, 2006). The national average grain yield is about 600 kg ha^{-1} which is very low compared to the world average of 1.3-1.5 t ha^{-1} (Elzein *et al*., 2008 and FAOSTAT. 2014). The low productivity could be attributed, mainly, to farming systems which are pre-dominated by low-yielding traditional varieties, low-inputs in soils of poor fertility, drought, poor management practices and prevalence of the root parasitic weed *Striga hermonthica* (Del.) Benth. (Ibrahim *et al*., 1995).

The root parasitic weeds (*Striga spp*.), are major biotic constraints and a serious threat to subsistence cereal crops including pearl millet (*Pennisetum glaucum* (L.).R. Br), finger millet (*Eleusine coracana* L. Gaertn), sorghum, maize (*Zea mays* L.) and upland rice (*Oryza sativa* L.) in Africa (Teka, 2014). The area infested by *Striga* in the African savannah is nearly 100 million hectares with annual losses of $US 7 billion (Ejeta, 2005).

To-date, several *Striga* control measures including heavy rates of fertilizers and herbicides have been recommended, but their adoption is minmal as they were missmatch to the predominant low input systems in vogue. Research has shown clearly that *Striga* manageement can only be achieved through integrated strategies with host plant resistance and/or tolerance as key components (Ejeta, 2005). Few *Striga* resistant varieties were identified and most of them are low yeilders and may lack adaptation to *Striga* infested areas (Ejeta, 2007). Resistance based on low stimulant production is the most common (Ejeta, 2007). Moreover, resistance and/or tolerance *per se* do not offer a perfect solution as high yield and economic returns are the targets. Therefore it is axiomatic to identify *Striga* resistant and/or tolerant high yielding, phenotypically stable genotypes, which perform more or less uniformly under different environmental conditions. In *Striga* endmic areas the influence of environment on yield stability is compounded by the complex tripartite interactions between the host, the environment and the parasite, *Striga* seed bank size and virulence of the parasite populations (Ejeta, 2005). The present investigation was therefore undertaken to study grain yield adaptability and stability of several crosses made between *Striga* resistant with four elite Sudanese sorghum cultivars as influenced by environment and reactions to *S. hermonthica*.

Materials and Methods

Forty two sorghum genotypes, obtained by crossing the *Striga* resistant entries, IS9830, 555, SAR33, Framida, N13, ICSV006, ICSV007, PQ-34, Brhan and SRN39 and its derivatives P401, P402 and P405 obtained from Professor Ejeta G. Purdue University USA, with elite Sudanese sorghum cultivars Wad Ahmed, Tabat, Butana and Arfagadamek-8 to study grain yield stability as influenced by environments and S. *hermonthica* infestation.

The trial was conducted in *Striga* sick plots, in which the infestation was augmented annually, during two consecutive seasons (2016/17 and 2017/18) at three sites constituting four irrigated and two rain-fed environments. The irrigated environments were at Gezira Research Station Farm of the Agricultural Research Corporation (ARC) Wad Medani Sudan, (Latitude 13 ^{0}30́ - 15 ^{0} 15́ N and longitude 30 ^{0}33́ E) and the Elsuki Research Station Farm of the ARC (Latitudes 13^{o} 40 N and longitudes 34° 5 E). The rain-fed environments were at Gedarif Research Station Farm of the ARC (latitude

13^{o} 44’ N, longitude 35^{o} 77’ E). Soils, at all, sites are alkaline vertisols low in organic matter, nitrogen and phosphorus (SSAS, 1983). The seeds were sown in the third week of July in each season. In the rain-fed experiments each genotype was sown in four rows of five-meter length each, with spacing of 80 cm between rows and 30 cm between hills. Under irrigation sowing was on ridges 80 cm apart and 30 cm between hills. Sorghum seedlings were thinned to three per hill three weeks after sowing. Nitrogen, in the form of urea, at rate 47.62 kg ha^{-1} was applied, one week after thinning. Weeds, other than *S. hermonthica*, were removed by hand when needed. Plots were irrigated every 14 days in Wad Medani and Elsuki sites. The data recorded for sorghum were days to 50% flowering, plant height, panicle exertion, panicle length, 100-grain biomass and grain yield. Data collected for *S. hermonthica* included counts made at 45-60 and 75 days after sowing (DAS), number of capsules per plant and biomass at harvest. In all experiment, assessments were made in the two central rows of each sub-plot with half a meter discarded from each side. All data were based on 4 m of row length except for days to 50% flowering, which was estimated in the entire sub-plot. Harvesting and threshing were performed by hand.

Crosses were identified as resistant, tolerant or susceptible on an arbitrary scale based on *Striga* emergence and grain yield relative to the respective check cultivar (maternal parent). Crosses were identified as resistant (*Striga* emergence less than that on the corresponding check), tolerant (*Striga* infection more than on the respective check and grain yield significantly higher than the check and the grand mean) or susceptible, where plant growth and yield were comparable to or less than those of the corresponding check. Crosses sustaining higher *S. hermonthica* emergence, but displaying yield significantly higher than the check were designated tolerant (T). Resistance was designated as very low (VL), low (LR), moderate (MR) and high (HR) according to reductions in relative *Striga* emergence in comparison with the respective check. Crosses displaying relative reductions in *Striga* emergence of 1-24%, 25-49%, 50-74% and 75-100% were designated as displaying VL, LR, MR and HR, respectively.

Statistical analysis

Combined analysis of variance was carried out for testing the effects of environments, genotypes and their interactions and stability, using GeneStat 17.1.13780 software program.

Stability analysis

Combined analysis of data generated from different environments were used for estimation of stability parameters adopting the Additive main Effect and Multiplicative Interaction (AMMI) method of stability analysis. AMMI models were computed using the GeneStat 17.1.13780 software program according to the AMMI model developed by Gauch and Zobel (1988) as modified by Nachit *et.al.* (1992).

$$y_{ij} = \mu + g_i + e_j + \sum_{n-1}^{n} \lambda_n \alpha_{in} \gamma_{jn} R_{ij} \qquad n=1$$

Where: y_{ij} is the grain yield of the i^{th} genotype in the j th environment, μ is the grand mean, g_i is the deviation of the genotype mean from the grand mean, e_j is the deviation of the environment mean from grand mean λ_n is the eigenvalue of the n^{th} IPCA, α_{in} and γ_{jn} are the genotype and environmental interaction principle components eigenvectors ($IPCA_g$ and $IPCA_e$, respectively) for axis n; n is the number of IPCA retained in the model; and R_{ij} is the residual. Environmental and genotype IPCA score are expressed as unit vector time the square root of λ_n The multiplicative part of the model is obtained by IPCA (α_{in} and γ_{jn})..

Results

Genotype x Environment interaction (G x E)

The combined analysis of variance showed highly significant differences among environments for grain yield. Further differences in grain yield among genotypes were highly significant. The interaction effect of genotype x environment were highly significant on grain yield (Table 1).

Table (1): The result of combined analysis of variance for grain yield evaluated at three site in two seasons (2016/17 – 2017/18).

S.V	df	SS	SM	F Ratio	Probability
Environment (E)	5	9234211	1846842	654.74	<.001
Genotype (G)	45	204723801	4549418	647.94	<.001
E x G	225	13658543	60705	8.65	<.001
Residual	810	5687324	7021	-	-
Total	1103	233354652	-	-	-

Means of grain yield of crosses under each environment and average across all environments are presented in table 2. Twenty seven crosses displayed yield above the grand mean. The highest yields (1405-1548 kg ha^{-1}) were produced by P405 x WA, SAR33 x WA, Brhan x WA and PQ-34 x BU. The lowest yields were scored by Framida x TA and P405 x AG-8 (205 and 247 kg ha^{-1}, respectively). The highest yielding environment were Wad Medani E4 (981 kg ha^{-1}) followed by Elsuki E2 and E5 (977 and 974 kg ha^{-1}, respectively). The lowest yielding environment was Gedarif E3 (728 kg ha^{-1}). Differences in grain yield among crosses were highly significant ($P \leq 0.1\%$).

Grain Yield Stability:

The interaction effects of genotype x environment were highly significant for grain yield (Table 3). AMMI analysis revealed highly significant four multiplicative terms, IPCA1, IPCA2, IPCA3, and IPCA4, which captured 63.2%, 19.0%, 11.6% and 6.2%, respectively of the variation due to G x E interaction sum of squares (Table 3). The first two interactions principal component axes (IPCA1 and IPCA2) explained 82.2% of the G x E sum of squares (Table 3).

Table (2): Influence of genotype on sorghum grain yield (kg ha^{-1}) under *S. hermonthica* infestation: combined data analysis over six environments (seasons 2016/17 and 2017/18)

Crosses	Environment						G M
	E1	E2	E3	E4	E5	E6	
IS9830 x AG-8	1029	1217	1086	1218	1214	1206	1162
555 x AG-8	1048	1127	995	1113	1230	974	1081
P405 x AG-8	197	310	185	260	230	302	247
Framida x AG-8	1280	1311	1099	1413	1401	1151	1276
N13 x AG-8	437	641	73	595	520	651	486
ICVS007 x AG-8	454	531	424	593	380	565	491
SRN39 x AG-8	1092	1090	969	1290	1280	953	1112
P401 x AG-8	444	699	167	565	499	656	505
SAR33 x AG-8	1355	1118	940	1023	1320	945	1117
P402 x AG-8	1388	1349	1216	1578	1536	1206	1379
Brhan x AG-8	1213	1160	1055	1455	1248	1008	1190
IS9830 x BU	1311	1254	1021	1038	1123	1017	1127
PQ-34 x BU	1445	1434	1070	1620	1609	1250	1405

Framida x BU	1279	1228	953	1070	1381	1029	1157
N13 x BU	1364	1359	1240	1563	1206	1221	1325
ICVS006 x BU	1038	1588	1242	1238	1481	1287	1312
ICVS007 x BU	1244	1089	977	1393	1110	1021	1139
P401 x BU	246	451	177	400	587	445	384
SAR33 x BU	1385	1357	1175	1567	1301	1146	1322
P402 x BU	302	585	96	429	529	529	412
Brhan x BU	1341	1237	969	1500	1181	982	1202
IS9830 x TA	790	1297	1031	1102	1371	1047	1106
P405 x TA	1319	1194	982	1442	1278	1029	1207
Framida x TA	128	288	154	202	200	260	205
N13 x TA	251	52	193	421	421	492	305
ICVS006 x TA	1185	1163	1044	1384	1075	1034	1148
ICVS007 x TA	277	610	260	459	505	557	445
SAR33 x TA	1453	1354	966	1598	1419	995	1298
P402 x TA	1121	1387	1023	1232	1407	1057	1204
Brhan x TA	261	505	149	358	468	448	365
IS9830 x WA	192	495	339	272	515	438	375
555 x WA	410	523	91	585	473	427	418
PQ-34 x WA	1418	1313	987	1603	1317	1044	1280
P405 x WA	1344	1738	1432	1502	1671	1602	1548
Framida x WA	1288	1218	1005	1434	1190	1044	1197
N13 x WA	1422	1198	1063	1156	1240	1013	1182
ICVS006 x WA	401	865	247	664	756	841	629
ICVS007 x WA	594	698	278	461	5671	583	530
P401 x WA	1463	1382	1037	1599	1495	1159	1356
SAR33 x WA	1515	1544	1289	1683	1487	1320	1473
P402 x WA	199	525	216	323	544	440	374
Brhan x WA	1523	1410	1406	1642	1438	1208	1438
AG-8	221	498	484	325	510	539	430
Wad Ahmed	304	660	422	435	672	752	541
Tabat	54	96	78	80	100.8	120	88
Butana	181	323	198	264	311	307	264
E Mean	874	977	728	981	974	854	
Sig. Level	**	**	**	**	**	**	
Grand Mean	898.1						
SE±	41.68						
(C.V. %)	9.3						

E = environment, GM = genotype means. AG-8 = Arfa Gadamak-8, BU = Butana, TA = Tabat, WA = Wad Ahmed.
* and ** = significant at the 0.05 and 0.01 probability levels, respectively.

Table (3): Analysis of variance for the AMMI model of the 46 genotypes for grain yield under *S. hermonthica* infestation across six environments (seasons 2016/17 and 2017/18)

S. V.	df	SS	MS	F	F. prob	Explained (%)
Treatments	275	2.28E+08	827697	117.88	0	-
Genotypes	45	204723801	4549418	647.94	0	-
Environments	5	9234211	1846842	654.74	0	-
Block	18	50773	2821	0.4	0.98764	-
Interactions	225	13658543	60705	8.65	0	-
IPCA1	49	8631148	176146	25.09	0	63.2
IPCA2	47	2564737	54569	7.77	0	19.0
IPCA3	45	1582311	35162	5.01	0	11.6
IPCA4	43	849181	19748	2.81	0	6.2
Residuals	41	31165	760	0.11	1	-
Error	810	5687324	7021	-	-	-
Total	1103	2.33E+08	211564	-	-	-

The highest average yield (981.2 Kg ha^{-1}) was displayed by E-4 followed in descending order by E-2 (976.8 Kg ha^{-1}), E-5 (973.8 Kg ha^{-1}), E-1 (873.9 Kg ha^{-1}), E-6

(854.4 Kg ha^{-1}), and E-3 (728.3 Kg ha^{-1}) (Table 4). E-1 exhibited the largest absolute IPCA1 score (-21.7807) whereas E-3 displayed the smallest score (2.50229). E-3 exhibited the largest absolute IPCA2 score, while E-1 had the smallest score (Table 4).

Table (4): The means of crosses over each environment and IPCA1, IPCA2, IPCA3 and IPCA4 scores for the six growing environments of sorghum genotypes

NE	Environment	E Mean	IPCAe[1]	IPCAe[2]	IPCAe[3]	IPCAe[4]
E1	Wad Medani	873.9	-21.7807	2.00449	-16.991	4.59955
E2	Elsuki	976.8	9.56145	-6.41248	-3.16372	-10.848
E3	Gedarif	728.3	2.50229	24.61135	6.4517	-1.71078
E4	Wad Medani	981.2	-19.9372	-9.72902	16.65958	1.2217
E5	Elsuki	973.8	9.36438	-5.66934	-3.30991	-8.77215
E6	Gedarif	854.4	20.28979	-4.805	0.35335	15.50968

E-1 and E-4 = Wad Medani environment, E-2 and E-5 = Elsuki environment, E-3 and E-6 = Southern Gedarif environment and E Mean = environment grand mean yield.

Most of the crosses showed low IPCA2 across the environments (Table 5). The crosses P402 x WA (G41) and Framida x AG-8 (G4) showed the lowest IPCA2 scores (0.24 and 0.33, respectively) The cross Framida x AG-8 (G4) displayed high grain yield (1276 kg ha^{-1}), while P402 x WA exhibited low grain yield (374 kg ha^{-1}). The crosses SAR33 x BU (G19), Framida x WA (G35), ICSV007 x BU (G17), P405 x WA (G34), SAR33 x WA (G40) and P402 x TA (G29), where IPCA2 scores were 0.46176, -0.65292, 0.69678, 0.76054, -0.7858 and -0.91945, respectively exhibited high grain yield (1139-1548 kg ha^{-1}), while the crosses N13 x AG-8 (G5) and ICSV006 x WA (G37) showed the highest IPCA2 scores (-10.2808 and -10.3043, respectively) and displayed low grain yield (486 and 629 kg ha^{-1}, respectively) (Table 5). The first four AMMI selections per different environments and score of the 42 crosses and four parents are presented in table 6. All crosses in table 6 were more stable, top yielders and *S. hermonthica* resistant and/or tolerant (Tables 6 and 7).

Table (5): Means, scores of IPCA1, IPCA2, IPCA3 and IPCA4 of 46 Genotypes for grain yield kg ha^{-1}

Genotype	NG	GM GY	IPCAg[1]	IPCAg[2]	IPCAg[3]	IPCAg[4]
IS9830 x AG-8	G1	1162	3.05603	2.77892	3.47691	2.44814
555 x AG-8	G2	1081	-0.30391	4.02507	0.0039	-1.33786
P405 x AG-8	G3	247	2.70287	3.72117	0.15253	3.09301
Framida x AG-8	G4	1276	-2.83099	0.33506	0.96479	-0.45505
N13 x AG-8	G5	486	3.48738	-10.2808	-1.83314	4.43937
ICVS007x AG-8	G6	491	1.26934	2.74002	2.33446	5.08684
SRN39 x AG-8	G7	1112	-4.17417	1.86114	3.61877	0.5433
P401 x AG-8	G8	505	4.77053	-7.91732	-2.43061	1.80316
SAR33 x AG-8	G9	1117	-4.24252	4.51732	-11.1556	1.12076
P402 x AG-8	G10	1379	-5.21596	1.29865	3.27953	0.84116
Brhan x AG-8	G11	1190	-6.39646	1.41612	4.92615	0.72498
IS9830 x BU	G12	1127	-0.9003	4.21861	-10.0834	-2.9768
PQ-34 x BU	G13	1405	-5.1704	-5.11721	0.51156	-0.09754
Framida x BU	G14	1157	-1.16221	1.98915	-8.78253	-1.44373
N13 x BU	G15	1325	-4.27971	1.89756	3.66319	0.57911
ICVS006 x BU	G16	1312	8.25771	1.8852	2.02164	-9.4384
ICVS007 x BU	G17	1139	-6.74936	0.69678	2.24562	4.22588

P401 x BU	G18	384	4.05085	-1.30495	0.93115	2.21428
SAR33 x BU	G19	1322	-5.89413	0.46176	2.59312	-1.20069
P402 x BU	G20	412	5.32961	-6.24452	-1.78654	0.97692
Brhan x BU	G21	1202	-8.47163	-2.38594	1.00636	-1.53628
IS9830 x TA	G22	1106	6.96674	1.59096	5.34124	-8.95972
P405 x TA	G23	1207	-7.1295	-1.09789	0.56431	1.10339
Framida x TA	G24	205	3.51168	3.96754	0.44029	2.1612
N13 x TA	G25	305	5.07397	-2.18291	0.95034	1.44427
ICVS006 x TA	G26	1148	-4.56761	1.61254	3.60703	0.84009
ICVS007 x TA	G27	445	6.30074	-2.21407	1.08432	0.0562
SAR33 x TA	G28	1298	-9.95326	-5.04403	-0.48222	-4.19544
P402 x TA	G29	1204	1.68258	-0.91945	-1.23287	-9.03769
Brhan x TA	G30	365	4.97174	-2.33253	-1.35206	0.49435
IS9830 x WA	G31	375	7.25779	4.53616	0.26163	-1.19737
555 x W A	G32	418	-0.82008	-6.24854	0.13204	2.35291
PQ-34 x W A	G33	1280	-9.08264	-4.48792	1.06021	-1.88777
P405 x WA	G34	1548	7.08114	0.76054	1.05477	-3.16891
Framida x W A	G35	1197	-6.1464	-0.65292	1.31966	0.63155
N13 x W A	G36	1182	-4.7539	5.10007	-9.04593	0.24402
ICVS006 x WA	G37	629	8.83501	-10.3043	0.62028	0.65097
ICVS007 x WA	G38	530	2.93211	-2.18421	-7.99389	0.7852
P401 x W A	G39	1356	-7.06165	-4.61083	-0.4812	-0.93918
SAR33 x WA	G40	1473	-4.54083	-0.7858	1.62999	-1.62695
P402 x W A	G41	374	6.631	-0.23648	-0.12001	-1.5838
Brhan x WA	G42	1438	-6.92845	5.74528	2.64483	-0.90513
AG – 8	G43	430	7.7477	7.85651	2.44235	2.14594
Wad Ahmed	G44	541	9.94371	1.08492	0.92453	3.76225
Tabat	G45	88	1.84478	6.55497	0.23327	4.46205
Butana	G46	264	3.07107	3.90055	0.73924	2.75699

Table (6): first four AMMI selection per environment

Environment	Mean GY	Score	1	2	3	4
E6	854.4	20.29	G34	G40	G16	G13
E2	976.8	9.56	G34	G16	G40	G13
E5	973.8	9.36	G34	G16	G40	G13
E3	728.3	2.50	G34	G42	G40	G16
E4	981.2	-19.94	G40	G42	G13	G33
E1	873.9	-21.78	G42	G40	G39	G28

E: Environment, G: Genotype. E1 and E4 = Wad Medani site, E2 and E5 = Elsuki site and E3 and E6 = Gedarif site, GY = grain yield kg ha^{-1}.

Table (7): Reactions of sorghum to S. *hermonthica* as influenced by genotype and environment

Crosses	**Resistance/ Tolerance level**											
	E1		E4		E2		E5		E3		E6	
IS9830 x AG-8	LR	T	MR	TR	LR	T	MR	TR	S	T	S	T
555 x AG-8	MR	TR	MR	TR	LR	T	MR	TR	S	T	S	T
P405 x AG-8	LR	S	LR	S	LR	T	LR	S	S	S	S	S
Framida x AG-8	MR	TR	MR	TR	LR	T	MR	TR	S	T	S	T
N13 x AG-8	LR	S	S	S	LR	S	S	S	S	S	S	S
ICVS007 x AG-8	MR	MR	LR	S	VL	S	LR	S	S	S	S	S
SRN39 x AG-8	MR	TR	LR	T	LR	T	MR	TR	S	T	S	T
P401 x AG-8	S	S	S	S	S	S	S	S	S	S	S	S
SAR33 x AG-8	LR	T	MR	TR	LR	T	MR	TR	S	T	S	T
P402 x AG-8	MR	TR	MR	TR	LR	T	MR	TR	S	T	S	T
Brhan x AG-8	LR	T	LR	T	VL	T	LR	T	S	T	S	T
IS9830 x BU	VL	T	LR	T	LR	T	LR	T	LR	T	S	T
PQ-34 x BU	LR	T	MR	TR	MR	TR	MR	TR	MR	TR	VL	T
Framida x BU	S	T	LR	T	MR	TR	MR	TR	MR	TR	MR	TR
N13 x BU	VL	T	LR	T	LR	T	LR	T	LR	T	LR	T
ICVS006 x BU	S	T	LR	T	LR	T	LR	T	LR	T	LR	T
ICVS007 x BU	LR	T	MR	TR	MR	TR	LR	T	MR	TR	LR	T
P401 x BU	VL	S	LR	S	VL	S	VL	S	VL	S	VL	S
SAR33 x BU	VL	T	MR	TR	LR	T	MR	TR	LR	T	MR	TR
P402 x BU	MR	MR	MR	TR	MR	MR	MR	MR	MR	MR	MR	MR
Brhan x BU	LR	T	MR	TR	MR	TR	LR	T	MR	TR	LR	T
IS9830 x TA	LR	T	LR	T	LR	T	MR	TR	LR	T	MR	TR
P405 x TA	LR	T	LR	T	LR	T	MR	TR	LR	T	MR	TR
Framida x TA	MR	MR	LR	S	LR	S	MR	MR	LR	S	MR	MR
N13 x TA	LR	S	LR	S	LR	S	LR	S	LR	S	LR	S
ICVS006 x TA	LR	T	MR	TR	MR	TR	MR	TR	MR	TR	MR	TR
ICVS007 x TA	MR	MR	LR	S	LR	S	LR	S	LR	S	LR	S
SAR33 x TA	HR	RT	HR	RT	MR	TR	HR	RT	MR	TR	HR	RT
P402 x TA	MR	TR	MR	TR	MR	TR	HR	RT	MR	TR	HR	RT
Brhan x TA	LR	S	LR	S	LR	S	LR	S	LR	S	LR	S
IS9830 x WA	S	S	LR	S	VL	S	LR	S	VL	S	LR	S
555 x WA	S	S	LR	S	VL	S	S	S	VL	S	S	S
PQ-34 x WA	MR	TR	VL	T	MR	TR	MR	TR	MR	TR	MR	TR
P405 x WA	S	T	LR	T	LR	T	LR	T	LR	T	LR	T
Framida x WA	LR	T	LR	T	LR	T	MR	TR	LR	T	MR	TR
N13 x WA	S	T	LR	T	LR	T	LR	T	LR	T	VL	T
ICVS006 x WA	S	S	LR	S	VL	S	VL	S	S	S	VL	T
ICVS007 x WA	S	S	LR	S	S	S	VL	S	S	S	VL	S
P401 x WA	VL	T	HR	RT	MR	TR	MR	TR	MR	TR	MR	TR
SAR33 x WA	LR	T	MR	TR	MR	TR	LR	T	MR	TR	LR	T
P402 x WA	S	S	LR	S	VL	S	VL	S	VL	S	VL	S
Brhan x WA	LR	T	LR	S	LR	T	LR	T	LR	T	LR	T

E-1 and E-4 = Wad Medani environment, E-2 and E-5 = Elsuki environment, E-3 and E-6 = Southern Gedarif environment. T = Tolerance, LR = low resistance, S= Suscetibele, MR = moderate, TR = Tolerance/ resistance , RT= Resistance/ Tolerance and VL = very low resistance

Discussion

The results revealed that grain yield data across the environments displayed highly significant differences ($P \leq 0.01$) among environments, genotypes and genotype x environment interaction (Table 1). The significance of GEI indicates that genotypes responded differently to environments and some are environment specific. Further, the results showed that 27 crosses, consistently observed resistant and/or tolerant, outyielded significantly, their maternal parents and the grand means across the six environments (Tables 2 and 7). For AG-8

70% of the crosses were high yielders and exhibited resistant/tolerant in the irrigated environments (E-1, E-4, E-2 and E-5). None of the crosses however, showed resistant in the rain-fed environments, but they all showed tolerant (Tables 2 and 7). Despite the lack of significant differences in grain yield among the crosses IS9830 x AG-8, Framida x AG-8, P402 x AG-8, Brhan x AG-8, SAR33 x AG-8, SRN39 x AG-8 and 555 x AG-8 they obtained the highest average yields (2.5-to-3.2-fold of the maternal parent) (Tables 2 and 7). For Butana, 80% of the crosses were high yielders. Of the high yielders 5 displayed resistant/tolerant across the six environments and three displayed tolerant across the 6 environments (Tables 2 and 7). Over all crosses N13 x BU, ICSV006 x BU, SAR33 x BU, Burhan x BU, IS9830 x BU, PQ-34 x BU, ICSV007 x BU, and Framida x BU were the highest yielders (4.3- to- 5.2-fold of the maternal parent) (Tables 2 and 7). For Tabat, the most sensitive to *S. hermonthica* among the check cultivars, 56% of the crosses were high yielders and displayed resistant and/or tolerant across the six environments (Tables 2 and 7). Over all the crosses SAR33 x TA, P402 x TA, IS9830 x TA, P405 x TA and ICSV006 x TA displayed the highest grain yield (12.4- to- 14.6-fold of the maternal parent). For Wad Ahmed six crosses were high yielders (2.2- to- 2.9-fold of the maternal parent). Four of these crosses were resistant/ tolerant across the environments, while two showed only tolerant (Tables 2 and 7). Of these crosses P401 x WA (tolerant), Burhan x WA (tolerant), SAR 33 x WA (tolerant/resistant) showed the highest yields (2.5 -to- 2.7- fold of the maternal parent).

In retrospective an ideal genotype should combine high yield, stable and durable resistance/ tolerance across environments. Experience with parasitic weeds showed that resistance could display unpredictable spatiotemporal variability and crop failure as breakdown of resistance is not uncommon (Rodenburg and Bastiaans 2011). Tolerance offers a safeguard against sudden breakdown of resistance. However, it is very difficult to breed for tolerance which is claimed to be polygenic (Rodenburg and Bastiaans 2011). Further, it is also difficult to distinguish between resistance and tolerance based on field infection data (Rodenburg and Bastiaans 2011). The present study focused on introgression of resistance genes from genotypes endowed with different resistance mechanisms encompassing both pre-and post- attachment resistance into high yielding adapted elite cultivars possessing a native background with a premise that co-evolution as reported by Obilana and Ramahia, (1984) could bequeath tolerance and at the same time some of the progenies which combine high yield and good grain quality of the maternal parents may be more acceptable to farmers and consumers than their exotic congeners.

Resistance and tolerance *per se* do not mean a lot to farmers and have to be coupled with high yield which is fairly stable within and between environments. AMMI analysis provides a good model for prediction of stability and adaptability to environments. In the present study, the AMMI analysis (Table 4) revealed four, highly significant multiplicative, terms (IPCA1, IPCA2, IPCA3, and IPCA4) thus as pointed by Crossa *et al*. (1990) and Sintayehu and Kassahun (2017) demonstrated the suitability of the model adopted in the study. Further, the AMMI analysis showed that the first two interactions principal component axes (IPCA1 and IPCA2) explained 82.2% of the G x E sum of squares with 63.2% and 19.0%, respectively (Table 4). It is noteworthy that the values scored by the first two interactions principal component axes (IPCA1 and IPCA2) were lower than those reported for several crops using the same model (Oliveira and Godoy 2006; Silveira *et al*. 2013).

The highest average yield was obtained in E-4 followed by E-2 and E-5 (irrigated environments), whereas E-3 (rain-fed environment) had the lowest grain yield (Table 4). The high yield obtained in the irrigated environments in comparison to their rain-fed congeners could be attributed yield was consistent with a previous report by Ogborn (1972) which showed that *Striga* spp. thrive best and are more damaging under fitful rains.

Environments and genotypes with least IPCA scores (either negative or positive) are endowed with considerable stability. Furthermore, the IPCA2 scores of genotypes in AMMI analysis indicate stability of genotypes across environments. Genotypes displaying high IPCA2 scores (either negative or positive) are unstable, while those with low scores are stable. An ideal genotype should have high and stable mean grain yield across environments (Hagos and Abay 2013). Based on AMMI analysis IPCA absolute values close to zero indicate minimal G x E interactions, whereas large positive or negative IPCA, indicate high G x E interactions. E3 exhibited the largest absolute IPCA2 score, while E1 had the smallest score. Hence, E2 and E5 were the most interactive, while E-3 and E-6 were the least interactive among the six environments (Table 4).

Most of the crosses showed low IPCA2 scores, thus indicating high stability (Table 5). The crosses P402 x WA (G41) and Framida x AG-8 (G4) showed the lowest IPCA2 scores (0.24 and 0.33, respectively), Framida x AG-8 (G4) displayed high grain yield (1276 kg ha^{-1}) scoring 194% increase in grain yield over the respective check, while P402 x WA showed low grain yield (374 kg ha^{-1}) scoring 69% decrease in yield in comparison with the respective check. The differential yield attained by the two

to differential husbandry practices including judicious water management. The low yield displayed in E-3 may be attributed to exacerbation of *S. hermonthica* infection negative impact on grain yield by low and/or poor distribution of rains in southern Gedarif. Exacerbation of the negative impact of *Striga hermonthica* on host growth and

crosses was in line with their reactions to *S. hermonthica*. Framida x AG-8 is consistently resistant and/or tolerant to the parasite, while P402 x WA was susceptible or displayed very low resistant (Table 7). SAR33 x BU (G19), Framida x WA (G35), ICSV007 x BU (G17), P405 x WA (G34), SAR33 x W A (G40) and P402 x TA (G29), displayed low IPCA2 scores and high grain yield (1139-1548 kg ha^{-1}), while the crosses N13 x AG-8 (G5) and ICSV006 x WA (G37) showed the highest IPCA2 scores (-10.2808 and -10.3043, respectively) and low grain yield (486 and 629 kg ha^{-1}, respectively) and were susceptible and/or displayed low resistant to *S. hermonthica* (Tables 5 and 7).

Based on AMMI analysis parameters and reaction to *S. hermonthica* the present study showed that the crosses Framida x AG-8, PQ-34 x BU, ICSV006 x BU, ICSV007 x BU, SAR33 x BU, SAR33 x TA, P402 x TA, PQ-34 x WA, P405 x WA, P401 x WA, Framida x WA, SAR33 x WA and Brhan x WA were more stable and, significantly outyielded their respective maternal parents and the grand means over the six environments (Tables 5 and 7). It thus evident that these crosses were highly stable with respect to grain yield, well adapted to a wide range of environments and endowed with high to satisfactory resistance and/or tolerance to *S. hermonthica*. The potential of these crosses as components of integrated strategies for *S. hermonthica* management has to be validated in national trials set to affirm their abilities to withstand extreme vagaries, variability in *S. hermonthica* seed bank size and virulence of the parasite strains, populations and variants. Crosses showing high resistance, but endowed with low stability with respect to grain yield could be considered as source of resistance.

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ملائمة و ثبات انتاجية بعض هجن محصول الذرة فى بيئات مختلفة موبوءة بطفيل البودا فى السودان

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المستخلص:

أجريت الدراسة في ثلاث مواقع موبوءة بطفيل البودا لموسمين 17/2016 و 18/2017، باجمالى ست بيئات شملت القطاع المروى و المطرى. بهدف تقدير التفاعل بين الهجن و البيئات للانتاجية و التعرف على الهجن ذات ثبات الانتاجبة و مقاومة و تحمل طفيل البودا. تم اختيار اربعة اصناف سودانية مجازة (ود احمد، طابت، بطانة و ارفع قدمك) كأباء رجعية وهى ذات انتاجية عالية و مفضلة لدى المزارعين فقط تنقصها مقاومة الطفيل، و سلالات من الذرة مقاومة لطفيل البودا و هى SRN39, P401, P402 and P405, IS9830, 555, SAR33, Framida, N13, ICSV006, ICSV007, PQ-34, Brhan، كأباء واهبة لصفة المقاومة. ومن ثم التزاوج بينها للحصول على نباتات الجيل الأول ثم تبع ذالك سلسلة من التهجين الرجعى و التلقيح الذاتى حتى الوصول الى نباتات الجيل الثالث التهجين الرجعى الثانى. استخدم تصميم القطاعات الكاملة العشوائية باربع مكررات. لتقييم نسل الهجن المنتجة وتم تقدير التفاعل الوراثي البيئي و تحليل ثبات الأداء. اظهرت نتائج التحليل الاحصائي التجميعى أن هناك فروقات معنوية عالية بين الهجن، البيئات و التفاعل بين الهجن و البيئات للانتاجية مما يشير

إلى أن التركيب الوراثي ظل ثابتًا ومستقراً في أدائه خلال البيئات الستة. كما اوضحت ايضا ان سبعة و عشرون هجيناً انتجت (20.4-72.4 %) اكثر من المتوسط العام (898.1 kg ha^{-1}) و اعلى من ابائها بنسبة 218.5-1475%. فيما يختص بتحليل ثبات الأداء باستخدام الأثر التجميعي الرئيسي والتفاعل التراكمي (AMMI) مع محور المكون الأول (IPCA1) و الثانى (IPCA2) للتعرف على الهجن ذات ثبات الأداء في الانتاجبة. الهجن Framida x AG-8, PQ-34 x BU, ICSV006 x BU, ICSV007 x BU, SAR33 x BU, SAR33 x TA, P402 x TA, PQ-34 x WA, P405 x WA, P401 x WA, Framida x WA, SAR33 x WA and Brhan x WA ثابتة الأداء وعالية الإنتاجية (1139-1548 kg ha^{-1}) و مقاومة او متحمل طفيل البودا فى البيئات الست. اوضحت النتايج الحوجة لدراسات تتعلق باليات المقاومة و التحمل و جودة الغلة مع ادخال نسل الهجن ذات الإنتاجية العالية جيدة الغلة و ثابتة الاداء فى منظومة متكاملة لادارة الطفيل مع اعتبار الهجن عالية المقاومة كمصدر لصفات المقومة.