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RESEARCH

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Testcross performance of *Striga*-resistant maize inbred lines and testers with varying levels of *Striga* reaction

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Abstract

Background Using a desirable tester is considered one method used to maximise genetic differences among test crosses derived from new inbred lines and improves the overall performance of maize. Thus, this study aimed to evaluate the potency of the tester with varying levels of resistance to *Striga hermonthica* in determining the testcross performance of the hybrids for *Striga* resistance and yield-related traits.

Method The experiment was conducted with these test crosses and two standard checks (susceptible and tolerant) for different *Striga* resistance and agronomic traits during the 2018 cropping season in Abuja and Mokwa, Nigeria. The experiment was laid out in a 23 × 4 alpha-lattice design with two replications in each location. Field evaluation data was collected from *Striga* resistance and yield-related traits to estimate the performance of test crosses. Analysis of variance was conducted to determine the variance of the testcross performance.

Results There were significant differences among test crosses for days to silking, days to pollen shedding, ear at harvest, ear aspect, ear per plant, grain yield, *Striga* damage rating at 8 and 10 weeks after planting (WAP), and *Striga* count at 8 and 10 WAP. Variations among test crosses were always higher than the corresponding variations due to the interaction between test crosses and the environment for all traits.

Conclusion The inbred lines with low yield reduction crossed with different testers under *Striga* infested were recorded. These inbreds should be used to develop high-yielding hybrids and synthetics with elevated levels of *Striga* resistance to improve the maize breeding program.

Keywords Line × tester, Inbred lines, *Striga* hermonthica, Resistance, Testcross

Introduction

Striga damage to crops is considered one of the seven key threats to food security and affects the welfare and livelihood of over 100 million people in sub-Saharan Africa. *Striga hermonthica* has been identified in 32 countries, infesting over 50 million ha of arable land and causing an estimated 7 billion US$ yield loss in Sahle Africa (Ejeta 2007a; Parker 2009, 2012; Rodenburg et al. 2017). It is a pandemic of serious proportions in Africa and has become the major constraint to attaining food security in Sub-Saharan (SSA) (Ejeta 2007b).

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Over 21 million hectares of crops in Africa have been affected by *Striga hermonthica*, a single biological barrier to food production in the region (Sauerborn 1991). This weed species alone can potentially invade over 50 million hectares of cropland in Africa (Ejeta 2007b). From the maize field only, an estimated 20 million ha of land in Africa is affected by *Striga* (Karaya et al. 2012). Lagoke (1998) reported that *Striga hermonthica* can cause 4.1 million megagrams of grain loss in a year, worth about 7000 million US $ in 1986. The level of infestation varied across regions. The Sudan savanna was identified as a major infestation zone, followed by Northern Guinea and Southern Guinea. About 85% of maize and sorghum fields in these zones are infested with *S. hermonthica* (Dugje et al. 2006).

Striga causes visible damage on parts of the plant like blotching, scorching, wilting, loss of vigour and finally, death of the plant. In addition to these, it adversely affects crops, including a reduction in the ear size, plant height, stem diameter and weight of the whole plant. Roots and stem lodging may also be considered as severe damage observed by this weed. Grain yield losses due to *Striga* infestation for most susceptible open-pollinated and hybrid varieties of maize in WCA is estimated to be in the range of 68–79% and even up to 100% reduction depending on variety and environmental condition (Kim et al. 2002; Emechebe et al. 2004).

Producing Maize inbred lines associated with reduced numbers of attached and emerged parasites can contribute to reduced *S. hermonthica* infection alleles to improve Maize germplasm for resistance. Inbred lines derived from a population with diverse genetic backgrounds may possess different alleles that can broaden and diversify the genetic base of *Striga*-resistant adapted germplasm. The durability and resistance levels of *S. hermonthica* in Maize can be enhanced by accumulating complementary resistance alleles using inbred lines with a broad genetic base (Menkir 2006). *Striga*-resistant or tolerant varieties become the most feasible and sustainable approach to reducing the losses caused by this parasitic weed (Oswald & Ransom 2004; Ejeta 2007a, b). Recurrent selection can effectively improve *Striga* resistance in maize (Menkir et al. 2006; Badu-Apraku et al. 2009). In a broad-based population, recurrent selection can reduce *Striga* infestation and, in turn, enhance grain yield under artificial infestation (Ejeta & Gressel 2007). Fewer *Striga* attachments characterise maize crops resistant to *Striga* delayed parasitic development and higher mortality of attached parasites than the susceptible ones. The damage due to *Striga* on a plant can be quantified using *Striga* damage symptom rating as an index for tolerance and *Striga* emergence count and yield performance as an index for resistance (Kim 1994; Badu-Apraku et al. 2010). Kim (1994) screened maize inbred lines under *S. hermonthica* infestation to develop *Striga* -tolerant maize varieties and classified them as highly susceptible, susceptible and moderately tolerant.

Breeding maize cultivars with durable resistance to *S. hermonthica* can be achieved by using diverse resistant parental lines as good sources of different resistance mechanisms (Menkir et al. 2010). Multiple post-attachment barriers to *Striga* parasitism were found in *Zea diploperennis* 05 (ZD05) with a *Zea diploperennis* background. As resistance occurs post-germination, maize deploying this resistance could be important to deplete the amount of *Striga* seeds in the soil. ZD05 was identified as a good source of germplasm for breeding maize cultivars with broad resistance to *Striga* in WA (Menkir et al. 2006). According to these authors, there is progress in the performance of maize inbred lines under *S. hermonthica*infestation using the recurrent selection method. Crosses made among these classes of *Striga* tolerant inbred lines to generate F1 hybrids and evaluated in *S. hermonthica* endemic field under artificial infestation with *Striga* inoculums showed reduced *Striga* infestation in the fields (Olakojo 2004). These results pave the way for a promising future for breeding *Striga* -resistant crop varieties.

The International Institute of Tropical Agriculture (IITA) has been developing yellow endosperm maize hybrids for decades using resistance inbred lines as testers. However, the usefulness of *Striga* -tolerant and susceptible yellow endosperm inbred lines as testers for evaluating *Striga* -resistant inbred lines' combining ability and testcross performance has yet to be studied. Therefore, testing the performance of crosses generated from *Striga* hermonthica resistance inbred lines and testers with varying resistance levels to *S. hermonthica* resistance reaction are crucial.

Materials and method

Experimental materials

Thirty elite yellow endosperm maize inbred lines and three testers with varying levels of *Striga* resistance were used. These lines were derived from a synthetic (developed through crossing of many lines) developed in 1997 by IITA and described by Kling et al. (2000), yellow composite, a bi-parental cross between lines derived from two yellow sources and three testers having different levels of *Striga* resistance with *Striga* tolerant line derived from a backcross containing a temperate inbred line (B73), *Striga* resistant line derived from a backcross containing *Zea diploperennis* in its genome and *Striga* susceptible line derived from a bi-parental cross between a temperate line (B73) and a line from Thailand (KI21) (Table 1). The crossing was carried out in Ibadan,

Table 1 Description of genotyped inbred lines used in the study

S.no	Source population	Number of extracted inbred lines	Pedigree	Grain colour
1	TZISTR1028, TZISTR1029 and TZISTR1030	3	ACR97SYN-Y	Yellow
2	TZSTRI112, TZSTRI113 and TZSTRI114	3	TZE COMP5	Yellow
3	TZISTR1224, TZISTR1215, TZISTR1220, TZISTR1222, TZISTR1223, TZISTR1225, TZISTR1226, TZISTR1227, TZISTR1228, TZISTR1230, TZISTR1231, TZISTR1232, TZISTR1235, TZISTR1214 and TZISTR1233	15	ACR97SYN-Y-S1-79-B*4/ACR97T-ZLComp1-Y, ACR97SYN-Y-S1-24-B*4/ACR97T-ZLComp1-Y and ACR97SYN-Y-S1-79-B*4/ACR97T-ZLComp1-Y	Yellow
4	TZISTR1207 (tolerant tester)	1	9450×CM 116×9450	Yellow
5	TZSTRI109 and TZSTRI110	2	ACR97SYN-Y-S1-79 & 24-B-B-B	Yellow
6	TZISTR1236, TZISTR1237, TZISTR1238, TZISTR1211, TZISTR1216, TZISTR1217 and TZISTR1218	7	ACR97TZLComp1-YS155	Yellow
7	TZISTR1033 (susceptible tester)	1	9450×KI21-3-2-2–2-1-B*8	Yellow
8	TZSTRI106 (resistant tester)	1	Z.diplo.BC4-376-1-1-#-3-1-B-2-B-B	Yellow
Total		33		

Nigeria, in 2017/18. The lines were obtained from diverse origins. The list and pedigrees of the inbred lines used in the line x-tester crosses are explained in (Table 1, Zebire et al. 2020). The testers used in this study were identified by IITA, Nigeria and are used in maize breeding programs to study the combining ability of newly generated maize inbred lines. At the same time, they were used to distinguish the inbred lines into heterotic groups.

Experimental site description

The experiment was conducted in the 2018 main cropping season (Season A) at IITA, mandate areas in Abuja and Mokwa, Nigeria. A total of 92 entries generated from the crossing of 30 elite yellow endosperm maize inbred lines with three testers having varying levels of reaction to *Striga* along with two standard checks (resistance and susceptible) were evaluated under *S. hermonthica* infestation and free condition at Abuja (9°15′ N and 7°20′ E, with an altitude of 431 MASL and an annual rainfall of 1700 mm) and Mokwa (9°21′35.34″ N and 5°1′40.638″ E, with an altitude of 187.80 MASL annual rainfall of 1100 mm) both in the southern Guinea savanna zone of Nigeria where *Striga* is prevalent These two locations experienced monomodal patterns of rainfall. The average temperature in the growing period in Abuja and Mokwa was 15.5–34oc and 20–40oc, respectively.

Striga seed collection, preconditioning and germination

Sufficient seeds of *Striga* were harvested from the floral heads of the *Striga* plants using the paper bag on maize fields or sorghum fields as *Striga* mainly parasitises on sorghum for artificial infestations at the end of the previous cropping season. Only matured and healthy intact capsules were collected during harvesting, and trash was screened using different-sized sieves. Other post-harvest practices like drying, cleaning, and storing *Striga* seeds were done following Berner et al.'s (1997) manual on *Striga* research. Surface sterilised *Striga* seeds were placed in 30 ml sterile water in a sterile Petri dish. Continuous stirring was carried out to sink the seeds and mounted them in the petri dish. The Petri dish with *Striga* seeds was placed in a dark place for 14 days. The water was changed every two days to avoid contamination during this period. Then, spread the seeds on moist filter paper in another Petri dish using a small paintbrush to distribute the seeds evenly over the surface of the filter paper (Berner et al. 1997). Four radii of glass fibre disks radiated from the central well were formed (Fig. 1). A small drop of sterile deionised water was added to the roots in the centre well. 2 ml of synthetic germination stimulant (GR24) was used per Petri dish. The Petri dishes containing conditioned *Striga* seeds were returned to the incubator for 48 h. The number of germinated *Striga* seeds on each glass fibre disk was counted under a stereo microscope after 48 h to determine the germination percentage.

Striga inoculation and experimental field management

Sufficient *Striga* seeds with optimum germination percentage after laboratory analysis were processed for the artificial infestation when planting. *Striga* seeds are very tiny; therefore, to carry out effective infestation, seeds were mixed with sand at a 180-micron sieve. Before *Striga* infestation and planting of Maize seeds, the non-infested rows were treated with ethylene two weeks before planting to stimulate the suicidal germination of

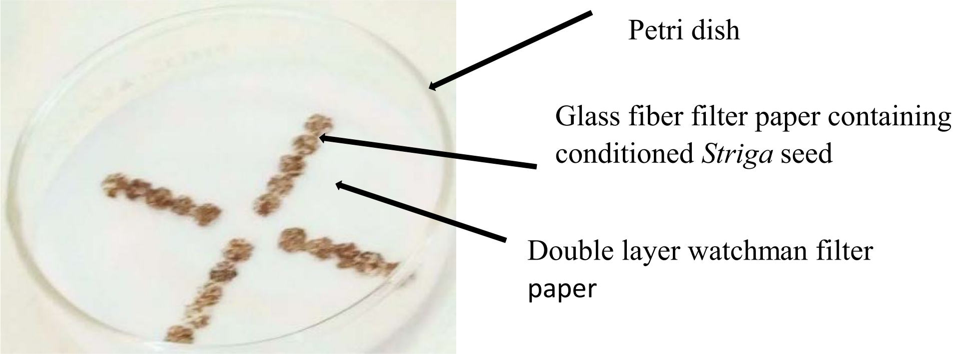


Fig.1 Diagram for the setup of testing *Striga hermonthica* seed germination; conditioned *Striga* seed laid out in double layer watchman filter paper on petri dish to measure germination capacity

existing *Striga* seeds in the soil and eliminate any potential *Striga* seeds present in the soil. Approximately 30 g of *Striga* seeds were mixed with 2 kg of sieved sand with a ratio of 1:99.9 by weight (seed: sand). The sieved sand usually acts as a carrier material to provide adequate volume for rapid and consistent infestation of *Striga* in the field. A scoop of approximately 8.5 g sand mixed with 3000–5000 germinable *Striga* seed was used for infestation. Holes of 10 cm in diameter and 8 cm in depth were dug out using a planter on the ridges. The infestation was carried out by spreading the content of a scoop filled with *Striga* seed mixed with sieved sand in each of the holes of the infested rows. Maize seeds were planted the same day in the non-infested and infested hills above the *Striga* seeds.

For the same genotype, the infested row was planted directly opposite to the non-infested one, separated by 1.5 m alleys to get a precise estimate of yield loss from the *Striga*-infested one. We used one row of maize seeds for each entry. One row of each entry was infested with seeds of *S. hermonthica*, while the other row was *Striga*-free. The *Striga*-infested rows of each entry were arranged so that they were directly opposite the *Striga* -free row of the same entry, separated by a 1.5 m alley. A serpentine fashion was used for plot arrangement so that the *Striga* -infested row was back-to-back in strips across the field, and the other side had *Striga* -free strips. This arrangement can minimise the movement of *Striga* seeds into *Striga* -free plots.

Experimental design and field layout

Thirty *S. hermonthica*-resistant yellow endosperm inbred lines representing diverse genetic backgrounds and three testers with varying *Striga* resistance reactions were crossed in a line x tester design in 2017 at IITA, Ibadan, Nigeria, experimental field to generate 90 test crosses. Testcrosses were harvested and shelled in bulk per cross. The test crosses, along with two checks, were evaluated in Abuja and Mokwa, Nigeria, during the 2018/2019 cropping season. The field experiment was laid out in a 23×4 alpha-lattice design with two replications at each location consisting of 92 experimental units. The size of plots was arranged in 4 m length with one row in each trial. Each plot was prepared based on the standard for maize production and inter and intra-row spacing was maintained according to the spacing requirement of maize. I.e. planting distances were maintained at 0.75 m between rows and 0.25 m between plants on a row plot for each entry. Two seeds were planted per hill in the first week of June and July 2018 at Abuja and Mokwa, respectively and later thinning was carried out to one plant per hill after seedlings were well established to get a plant population of 53,333 plants ha^{-1}. Other agronomic practices were done based on the recommendations in each location. Fertiliser at the rate of 30-30-30 kg NPK ha^{-1} was applied at about 21 days after planting. Weeds other than *Striga* were controlled manually.

Data collection

Data were collected from the plant character and parasite (*Striga*) effect. *Striga* damage at a different stage of growth was assessed. *Striga* damage on a host plant with ratings (STRRAT1 and STRRAT2) (Kim 1988) and *Striga* counts existed in the field (STRCO1 and STRCO2) was recorded at 8 and 10 weeks after planting in *Striga*-infested plots at both locations. *Striga* damage on the host plant per plot was recorded following a scale adapted from Kim (1988) with 1–9 where 1 = no damage, indicating normal plant growth and high resistance, and 9 = complete failure or leaf scorching, stunted growth of the maize plant; i.e., highly susceptible. On maize plant; Days to anthesis: Number of days from planting to when 50% of the plant in a plot shed pollen. Days to Silking: Number of days from planting to when 50% of the plants in a plot produced 2–3 cm long silk. Plant physical characteristics (plant aspect) based on standability, uniformity of plants, and other features were recorded using a scale of 1–9, where 1 = excellent plant type and 9 = poor plant type. In addition, Ear characteristics (ear aspect) based on freedom from disease and insect damage, ear size, uniformity of ears, and grain filling was considered desirable features in evaluating the plant aspect. Plant Height: The height of each plant per plot was measured in centimeters (cm) from the base of the plant to the first tassel branch, and Ear Height as the distance from the base of the plant to the height of the node bearing the topmost ear. Number of Ears per plant: The total number of ears harvested was counted on a per-plot basis, and the number of ears per plant was calculated using the number of ears per plot divided by the total number of plants at harvest. The husk cover was recorded on a scale of 1 to 5, where 1 = husks firmly attached and extended beyond the ear tip and 5 = ear tips exposed. Field Weight: All cobs were weighed from each plot and used for grain yield per ha. Grain Yield: The total grain yield was measured in kg per plot based on adjusted moisture level. The grain yield of crosses under *Striga* infested and free field on harvested ears of each plot was computed by adjusting the grain moisture at 15% and converted to the grain yield per hectare (kg ha^{-1} with the help of a formula suggested by (Carangal et al. (1971) as cited by (Rahman et al. 2013).

$$\text{Grain yield}\left(\text{kg ha}^{-1}\right) = \frac{\text{Fresh ear weight}\left(\text{kg plot}^{-1}\right) \times (100 - \text{MC})}{(100 - 15) \times \text{Area harvested (plot size)}} \times 0.8 \times 10000$$

where Fresh cob weight = Fresh weight of the cob plot-1.

0.8 = Shelling coefficient

85 = Standard value of grain moisture at 15%

MC = Moisture content (%) in grains at harvest.

Data analysis

The data were subjected to analyses of variance with PROC GLM in SAS (SAS Institute 2013). Entries (test crosses + checks) were considered as fixed effects in the analysis of the variance of each trait. Meanwhile, replications and location-year combinations, hereafter referred to as environments, were considered random effects. The significance of the mean squares for the main and interaction effects was tested using the appropriate mean squares obtained from the abovementioned procedure. To illustrate differences in crosses in reaction to *S. hermonthica*, reductions in the number of ears at harvest (REDEHARV), ear per plant (REDEPP), plant height (REDPHT) and grain yield (REDYLD) under *Striga* infestation were calculated for each entry as the difference between means recorded traits under *Striga* infested and non-infested conditions. The principal component analysis was computed using the correlation matrix of *Striga*-sensitive traits, including REDEHARV, REDEPP, REDPHT, REDYLD, and *Striga* damage rating (STRRAT1 and STRRAT2), recorded at 8 and 10 weeks after planting, respectively, and numbers of emerged *Striga* plants (STRCO1 and STRCO2) at 8 and 10 weeks after planting. Correlation analysis was also calculated between traits recorded under *Striga*-infested and free conditions.

Results and discussion

Combined analysis of variance

The analyses of variance showed a highly significant environmental effect on all traits recorded in the field except the ear aspect (Table 2). The interactions of entries by the environment were not significant ($P > 0.05$) for all the traits except for ear at harvest ($P < 0.05$). However, a significant genotype × environment interaction for *Striga* resistance was reported (Karaya et al. 2014; Annor et al. 2019, 2020). There were highly significant differences among the test crosses for each trait recorded under *Striga* infestation, with the variation among entries (test crosses) always being higher than the corresponding variation due to the interaction between entry and environment for all traits (Table 2).

The mean performance of the genotypes varied across environments. Relative to the average grain yield under non-infested conditions, yield reduction under *Striga* infestation was 68% for the susceptible check (8338-1) and 45% for the tolerant check (8425-8). Average testcross grain yield loss due to *Striga* damage was 20, 21 and 27% for T1, T2 and T3, respectively. These results show the superiority of testers T1 and T2 for improved grain yield of the test crosses. The level of tolerance or resistance of maize genotypes determines the difference in grain yield reduction (Akaogu et al. 2013; Zebire et al. 2020).

The best *Striga* resistance commercial check hybrid (8425-8) showed a grain yield reduction of 48% under *Striga* infestation. The yield reduction of the top-yielding *Striga* tolerant testcross TZISTR1222 × TZISTRI106 was 4%, which was quite low compared to other crosses. However, the susceptible check showed the highest yield reduction (75%). Maximum yield reduction was observed on those crosses generated from the susceptible tester (TZISTR1033) (Table 3).

Table 2 Mean squares for grain yield and other traits of testcrosses of yellow maize inbred lines under *Striga* infested condition

Source	DF	PLHT	STRRAT8	STRRAT10	STRCO8	STRCO10	EHARV	EASP	ASI	EPP	YLD
Env	1	68,779.8†	57.1†	72.2†	146,840.2†	840,782.9†	287.0†	0.2	7.6†	2.23†	154,677,505.6†
Block (Env*REP)	88	486.9†	1.2	0.9	1467.1†	3631.7†	5.0	0.3**	0.7**	0.02	1,938,625.3†
REP(Env)	2	1045.4†	0.6	0.9	6234.3†	45,738.6†	55.2†	0.3	2.5***	0.03	1,702,995.5
ENTRY	91	308.3†	2.5†	2.7†	985.4*	1880.7**	12.0†	0.4†	0.5	0.04†	1,996,779.7†
Env*ENTRY	91	81.6	0.9	0.7	486.0	1402.4	6.2*	0.2	0.5	0.02	814,562.0
Error	94	77.5	1.0	0.8	627.5	1091.1	4.3	0.2	0.4	0.02	634,801.8
Mean		166.2	3.8	5.7	51.1	79.9	14.2	3.0	1.9	0.88	3556.4
CV		5.3	26.9	15.7	49.0	41.3	14.5	13.3	33.8	14.85	22.4

ns non-significant, *PLHT* Plant height (cm), *STRRAT8 and STRRAT10 Striga* damage rating using scale 1–9 at 8 and 10 weeks after planting, respectively, *STRCO8 and STRCO10 Striga* emergence count at 8 and 10 weeks after planting, respectively, *EHARV* number of ears at harvest, *EASP* ear aspect (rating at a scale of 1–5), *ASI* Anthesis silking interval, *EPP* ear per plant and *YLD* grain yield (kg/ha)

*,**,***,† significant at 0.05, 0.01, 0.001 and 0.0001 probability levels, respectively

Table 3 Percentage reduction of grain yield and selected secondary traits of the top ten and bottom five hybrids and their checks (arranged according to grain yield)

Crosses	REDYLD	REDPLHT	REDEHARV	REDEPP
TZISTR1114 × TZISTR1033	58	9.8	25.5	26.5
TZISTR1030 × TZISTR1033	53	4.6	36.4	33.3
TZISTR1217 × TZISTR1207	53	14.8	22.4	20.0
TZISTR1227 × TZISTR1033	52	9.0	34.8	36.1
TZISTR1028 × TZISTR1033	50	6.8	30.3	34.6
TZISTR1235 × TZISTRI106	47	10.9	8.0	8.8
TZISTR1214 × TZISTRI106	45	14.6	19.6	17.5
TZISTR1220 × TZISTRI106	44	8.2	6.9	9.8
TZISTR1237 × TZISTR1033	44	12.1	24.2	19.6
TZISTR1211 × TZISTRI106	42	9.0	10.6	13.3
TZISTR1110 × TZISTR1033	41	7.0	31.4	28.3
TZISTR1218 × TZISTR1207	3	7.9	1.3	− 3.3
TZISTR1028 × TZISTRI106	2	5.0	− 22.7	− 16.0
TZISTR1237 × TZISTRI106	2	− 1.1	10.1	8.5
TZISTR1216 × TZISTR1033	− 6	− 0.5	− 8.4	− 4.1
TZISTR1232 × TZISTR1207	− 8	− 2.1	− 6.9	− 9.6
Tolerant check (8425-8)	48	5.6	17.6	10.0
Susceptible check (8338-1)	75	25.0	50.0	55.6

REDYLD, REDPLHT, REDEHARV and REDEPP = yield losses, reduction in height, reduction in the ears at harvest and reduction ear per plant under *Striga* infestation expressed as percentages of grain yields under non-infested condition, respectively

Under *Striga* infestation, the yield range of the top 15 testcrosses generated from the crossing of *Striga* resistance yellow inbred lines and testers with varying levels of *Striga* resistance reaction varied from 4393 kg ha^{-1} to 5520 kg ha^{-1} per hectare while the yield of the standard checks was 1079 kg ha^{-1} and 2545 kg ha^{-1} for the susceptible and resistant check, respectively (Table 4). About all of the top 15 test crosses out-yielded the *Striga*-resistant check (8425-8). On the other hand, under *Striga*-free conditions, the yield of test crosses was 4146 kg ha^{-1} to 6473 kg ha^{-1}, whereas the resistant and susceptible standard checks yielded 4868 kg ha^{-1} and 4282 kg ha^{-1},

Table 4 Grain yield and other traits of testcrosses of the best 15 and the worst 5 based on grain yield and checks assessed under *Striga* infested and *Striga* free growing conditions across environments (2018)

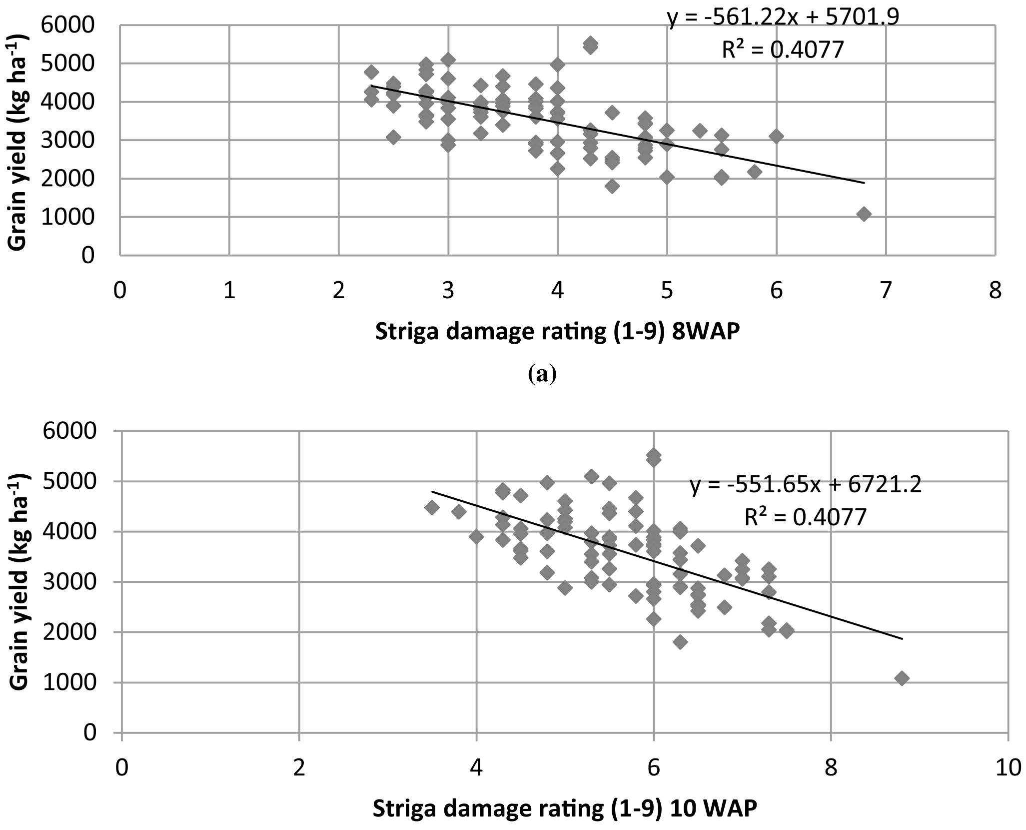
Crosses	YLD		PLHT		EHT	PASP	EHARV		EASP		EPP		STRAT	STRRAT	STRCO	STRCO
	OPT	STR	OPT	STR	OPT	OPT	OPT	STR	OPT	STR	OPT	STR	8WAP	10WAP	8WAP	10WAP
TZISTR1222 × TZISTRI106	5738	5520	195.5	180	87.5	5.5	17.3	15.5	2.9	2.5	1.03	0.94	4.3	6	22	41.8
TZISTR1112 × TZISTRI106	6173	5420	190	182.5	84.5	4.8	16.5	16	2.5	2.8	1.04	0.97	4.3	6	68.8	77.8
TZISTR1232 × TZISTRI106	5431	5089	182.5	177.5	85	5.5	16	15	2.6	2.6	1.03	1	3	5.3	18.8	34
TZISTR1225 × TZISTRI106	6473	4970	211.3	193.3	103	3.5	16	16.5	3.1	2.8	0.99	0.99	2.8	4.8	39.8	65.3
TZISTR1110 × TZISTRI106	6418	4960	194.8	182.3	106	3.3	16.8	15.3	3	3.1	1.03	0.92	4	5.5	25	42.3
TZISTR1220 × TZISTR1207	5011	4824	186.3	176.3	87.5	5	15.3	14.5	2	2.3	0.94	0.94	2.8	4.3	25	38.8
TZISTR1218 × TZISTR1207	6036	4767	195.8	178.8	88.8	5.5	15	14.8	2.5	2.6	0.91	0.97	2.3	4.3	32.5	67.5
TZISTR1224 × TZISTRI106	5888	4710	189.3	180	90	4.3	15.3	15.8	3.1	3	0.96	0.99	2.8	4.5	42	74.5
TZISTR1216 × TZISTRI106	5212	4667	181.5	170	85	3.8	15.8	16.5	3	2.9	1.02	1	3.5	5.8	49.5	126.5
TZISTR1237 × TZISTRI106	4695	4602	174.3	176.3	81.3	3.5	17.8	16	2.8	2.6	1.06	0.97	3	5	34.8	51.5
TZISTR1232 × TZISTR1207	4146	4474	164	167.5	82.5	5.3	14.5	15.5	2.9	2.5	0.94	1.03	2.5	3.5	17	39
TZISTR1217 × TZISTRI106	4989	4454	168.8	158.8	78.8	3.5	17	15.8	2.6	2.9	1.01	0.94	3.8	5.5	30	75.3
TZISTR1030 × TZISTR1207	6333	4425	199.3	177.5	100	5.5	16.3	11.5	2.5	2.8	0.99	0.8	3.3	5	32.8	44.5
TZISTR1109 × TZISTRI106	6193	4397	189.3	167.3	91.3	4.8	15.8	13.8	2.4	2.8	0.99	0.83	3.5	5.8	59.3	111.5
TZISTR1228 × TZISTR1207	5299	4393	182.5	166.8	83.8	5.3	14.3	16.5	2.1	2.5	0.87	1.02	2.5	3.8	57.3	95.5
TZISTR1030xTZISTR1033	4666	2175	181.3	173	87.8	4.3	16.5	10.5	3	3.5	0.99	0.66	5.8	7.3	41.8	77.8
TZISTR1114 × TZISTR1033	4884	2045	173.8	156.8	80.5	5	16.5	12.3	2.8	3.4	0.98	0.72	5.5	7.3	85.5	133.3
TZISTR1237 × TZISTR1033	3620	2037	180	158.3	86.3	5.5	16.5	12.5	3	3.5	0.97	0.78	5	7.5	54.8	88
TZISTR1227 × TZISTR1033	4218	2011	177.5	161.5	76.3	4.5	15.8	10.3	2.8	3.4	0.97	0.62	5.5	7.5	118.8	122
TZISTR1029 × TZISTRI106	2817	1802	172.8	169.8	76.3	6	12.3	7.8	3.3	3.8	0.77	0.47	4.5	6.3	24.8	56
8425-8 (Tolerant check)	4868	2545	162	153	86	6	17	14	3	3	1	0.9	4.5	6.5	59.3	94
8338-1 (Susc. check)	4282	1079	188	141	85	7	14	7	4	5	0.9	0.4	6.8	8.8	127.3	202.3
Mean	4843.6	3556	179.3	166.2	84.6	4.87	15.8	14.2	2.76	2.99	0.97	0.88	3.79	5.71	51.11	79.91
LSD	1164.9	1119	11.67	12.36	8.68	1.5	2.25	2.9	0.49	0.56	0.13	0.18	1.43	1.26	35.17	46.38
CV	17.13	22.4	4.64	5.3	7.31	21.7	10.15	14.6	12.7	13.31	9.27	14.9	26.86	15.66	49.01	41.34

STR Striga infested conditions, *OPT Striga* free environment, *8WAP* 8 weeks after planting, *10WAP* 10 weeks after planting, *YLD* grain yield (kg/ha), *PLHT* plant height (cm), *EHT* ear height (cm), *PASP* Plant aspect, *EHARV* plant at harvest, *EASP* ear aspect, *EPP* ear per plant, *STRRAT Striga* rating using scale of 1–9 and *STRCO Striga* count

respectively. The level of tolerance or resistance of maize genotypes determines the difference in grain yield reduction (Akaogu et al. 2013). Furthermore, the top 15 test crosses produced harvestable ears in a range of 14 to 17 ears per plot under *Striga* -infested and free conditions. At the same time, the susceptible and resistant checks achieved 7 and 14 ears per plot under *Striga* infestation and 14 and 17 ears per plot in a *Striga* -free environment, respectively. The Lowest *Striga* damage rating and *Striga* count were also recorded from the top 15 test crosses. For instance, 2.5 and 3.5 *Striga* damage ratings and 17 and 39 *Striga* counts were recorded at 8 and 10 weeks after planting in the TZISTR1232 × TZISTR1207 testcross. The lowest *Striga* rating and *Striga* count were recorded from crosses obtained from the tolerant tester. Meanwhile, the susceptible and resistance checks maintained a high amount and number of *Striga* damage and *Striga* count. The score of *Striga* damage from susceptible and resistance checks was 4.5 and 6.8 at 8 WAP and 6.5 and 8.8 at 10 WAP, respectively, and they maintained 59 and 127 at 8 WAP and 94 and 202 at 10 WAP *Striga* plant per plot (Table 4). Furthermore, grain yield decreased due to *Striga* damage at 8 and 10 WAP (Fig. 2).

Phenotypic correlation among traits under *Striga*-infested and non-infested conditions across environments

The relationship between grain yield performance, on the one hand, and *Striga* resistance traits and other agronomic traits of the hybrids, on the other hand, was



(a)

(b)

Fig. 2 Regression plot of grain yield and *Striga* damage rating **a** 8 WAP and **b** 10 WAP

estimated by Pearson's correlation coefficient with data combined across environments (Table 5). A highly significant ($P < 0.0001$) and negative correlation was observed between grain yield and STRRAT1 ($r = -0.68$) and STRRAT2 ($r = -0.69$). These results are in line with the findings of Kim et al. (2002), Yallou et al. (2009), Karaya et al. (2012), Badu-Apraku et al. (2013) and Mbogo et al. (2016), all of whom reported a strong correlation between grain yield and *Striga* damage rating. Similarly, grain yield showed a highly significant and negative correlation with STRCO1 ($r = -0.53$), STRCO2 ($r = -0.47$) and EASP ($r = -0.76$), indicating a reduction in grain yield with an increased number of emerged *Striga* plants at 8 and 10 WAP and reduction in ear quality. The presence of strong correlations between these traits indicates the usefulness of these traits, especially *Striga* damage score and EASP, as indices of selection for developing high-yielding *Striga* -resistant hybrids. However, grain yield had a significant positive correlation with ears per plant ($r = 0.72$, $P < 0.0001$) under *Striga* infestation (Table 5). Grain yield under non-infested conditions showed significant ($P < 0.01$–0.001) and negative correlation with EASP ($r = -0.47$), HUSK ($r = -0.34$) and PASP ($r = -0.22$), indicating that these traits significantly affect grain yield production. On the other hand, EHT ($r = 0.43$) had a significant and positive correlation with grain yield (Table 5).

Table 5 Pearson correlation between traits for testcrosses of yellow endosperm maize and checks under *Striga* infested and non-infested conditions in four environments (n = 92)

Traits	***Striga* infested**										
	ASI	**DYSK**	**DYAN**	**EASP**	**EPP**	**PLHT**	**STRCO1**	**STRCO2**	**STRRAT1**	**STRRAT2**	**YLD**
ASI		0.50†	0.39***	0.20	– 0.12	0.13	– 0.13	– 0.02	0.01	0.11	– 0.06
DYSK			0.99†	0.21*	– 0.10	0.36***	– 0.37***	– 0.23*	– 0.23*	– 0.18	0.15
DYAN				0.20*	– 0.12	0.36***	– 0.35***	– 0.23*	– 0.23*	– 0.19	0.15
EASP					– 0.71†	– 0.22*	0.25**	0.25**	0.60†	0.62†	– 0.76†
EPP						0.23	– 0.47†	– 0.45†	– 0.74†	– 0.71†	0.72†
PL HT							– 0.4†	– 0.36***	– 0.38***	– 0.31	0.50†
STRCO1								0.89†	0.54†	0.55†	– 0.53†
STRCO2									0.46†	0.54†	– 0.47†
STRRAT1										0.88†	– 0.68†
STRRAT2											– 0.69†
YLD											

	***Striga* non-infested**									
	ASI	**DYSK**	**DYAN**	**EASP**	**EHT**	**EPP**	**HUSK**	**PASP**	**PLHT**	**YLD**
ASI		0.42†	0.28**	0.22*	0.04	– 0.03	0.23*	0.19	0.00	– 0.12
DYSK			0.99†	0.25**	0.28**	– 0.31**	– 0.04	0.26**	0.30**	0.10
DYAN				0.23*	0.29**	– 0.31**	– 0.08	0.24*	0.32**	0.13
EASP					– 0.08	– 0.23*	0.27**	0.25*	– 0.12	– 0.47†
EHT						– 0.04	– 0.23*	– 0.11	0.80†	0.43†
EPP							– 0.15	– 0.29**	0.04	0.18
HUSK								0.36***	– 0.28**	– 0.34***
PASP									– 0.07	– 0.22*
PL HT										0.54†
YLD										

DYSK Days to 50% silking, *DYAN* Days to 50% anthesis, *PLHT* Plant height (cm), *STRRAT1 and STRRAT2 Striga* damage rating at 8 and 10 WAP, respectively, *STRCO1 and STRCO2 Striga* emergence count at 8 and 10 WAP, respectively, *EASP* ear aspect, *EHT* ear height, *PASP* plant aspect, *HUSK* husk cover, *ASI* Anthesis silking interval, *EPP* ears per plant and *YLD* grain yield (kg/ha)

*,**,***,† Significant at $p < 0.05$, 0.01, 0.001 and 0.0001 levels, respectively

Principal components (PC) for agronomic traits for each tester

The first two principal component axes, PC1 and PC2, accounted for the total variation of 61% for T1, 55% for T2 and 66% for T3 under *Striga* infestation (Table 6). Different combinations of traits were the major contributors to both PC1 and PC2 axes scores for the test crosses of the three testers. Grain yield was an important trait contributing to PC1 under *Striga* infestation. Under *Striga* non-infested condition, PC1 and PC2 jointly explained 55, 58 and 54% of the total variation among T1, T2 and T3 test crosses, respectively (Table 7). Again, different traits contributed to the observed variations in the PC1 and PC2 axes scored for the test crosses of the three testers. Grain yield was not an important trait contributing to the variation in the PC1 axis under non-infested conditions.

Conclusion

In terms of grain yield improvement, the *Striga* resistance hybrids have the potential to provide more than a 75% yield advantage over the susceptible hybrid checks. The combined analysis for yield, agronomic and *Striga*-related traits showed highly significant differences for the sources of variation due to environments, lines, and testers under *Striga*-infested and non-infested conditions.

Table 6 Eigenvectors of the first two principal components (PC1 and PC2) axis as observed in yellow maize testcrosses for each tester across environments under *Striga* infested condition

Traits	Testers					
	T1		T2		T3	
	PC1	PC2	PC1	PC2	PC1	PC2
Grain yield (kg/ha)	-0.31	-0.30	-0.41	-0.23	-0.41	-0.11
Silking (days)	-0.31	0.42	0.44	-0.15	-0.01	0.51
Anthesis (days)	-0.31	0.39	0.44	-0.19	0.01	0.49
Anthesis silking interval (days)	-0.19	0.42	0.05	0.19	0.03	0.35
Striga rating at 8 wk (1–9)	0.36	0.24	0.09	0.21	0.41	0.01
Striga rating at 10 wk (1–9)	0.39	0.18	0.18	0.42	0.44	0.00
Striga count at 8 wk (no.)	0.43	-0.02	-0.12	0.53	0.35	-0.29
Striga count at 10 wk (no.)	0.38	-0.06	-0.05	0.52	0.34	-0.25
Ear aspect (1–5)	0.15	0.50	0.43	-0.03	0.26	0.21
Plant height (cm)	-0.2	-0.03	-0.15	-0.28	0.02	0.39
Ear per plant (no.)	-0.13	-0.25	-0.41	-0.04	-0.4	-0.15
Proportion of variance accounted by	36.9	24.33	34.04	21.4	35.0	31.0
Total variance	61.3		55.4		66.0	

Table 7 Eigenvectors of the first two principal components (PCA1 and PCA2) axis as observed in yellow maize testcrosses for each tester across environments under *Striga* non-infested condition

Traits	Testers					
	T1		T2		T3	
	PC1	PC2	PC1	PC2	PC1	PC2
Grain yield (kg/ha)	– 0.05	0.39	– 0.41	0.18	0.09	– 0.53
Silking (days)	0.53	0	0.4	0.37	0.5	0.27
Anthesis (days)	0.5	0.08	0.41	0.35	0.5	0.23
Anthesis silking interval (days)	0.32	– 0.29	0.06	0.17	0.2	0.37
Husk cover (1–5)	0.08	– 0.36	0.27	– 0.15	– 0.23	0.28
Plant aspect (1–5)	0.37	– 0.16	0.32	– 0.06	– 0.11	0.1
Ear aspect (1–5)	0.32	– 0.27	0.32	0.03	0.05	0.47
Ear height (cm)	0.27	0.47	– 0.22	0.55	0.42	– 0.19
Plant height (cm)	0.19	0.48	– 0.28	0.52	0.43	– 0.28
Ear per plant (no.)	– 0.09	– 0.3	– 0.3	– 0.27	0.14	– 0.21
Proportion of variance accounted by	30.42	24.25	37.37	21.1	29.55	24.4
Total variance (%)	54.7		58.5		53.9	

The presence of highly significant differences among lines and testers demonstrated differences in performance among lines and testers across environments. Testcrosses of T2 showed higher mean grain yield across environments under *Striga*-infested and non-infested conditions. The highest-yielding and most stable hybrid under *Striga*-infested and non-infested conditions should be further tested to confirm the consistency of performance for release in SSA.

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Author contributions

Abebe Menkir: Conceptualization; Degife Zebire and Abebe Menkir: defined research topic and the main hypothesis, planned the research, executed the experimentation and analysed data; Degife Zebire: literature search, data collection and drafted and finalized the manuscript. Abebe Menkir, Melku Gedil, Wende Mengesha and Meseka Silvestro: take part in data acquisition,

manuscript edition and manuscript review. Victor Adetimirin: performed manuscript edition and manuscript review. All authors have read and approved the content of the manuscript.

Data availability

All data generated or analysed during this study were included in the parent document, therefore no additional data was available.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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