AGRONOMIC PERFORMANCE AND HERITABILITY OF GRAIN YIELD AND OTHER YIELD-RELATED TRAITS OF *STRIGA*-TOLERANT MAIZE HYBRIDS UNDER *STRIGA*-INFESTED AND *STRIGA*-FREE ENVIRONMENTS

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ABSTRACT

Striga hermonthica, an obligate root-parasitic weed is a major constraint to maize production in West Africa causing significant yield losses, sometimes up to 100%. Host-plant resistance is considered the most economical and feasible method of *Striga* control. In 2014 and 2015, seventeen single-cross *Striga*-tolerant maize hybrids and a local check were evaluated at Nyankpala and Manga for grain yield (GYLD) and agronomic performance under *Striga*-infested and *Striga*-free environments. Combined analysis of variance across *Striga*-infested and *Striga*-free environments revealed significant effects of genotype and environment on GYLD and most agronomic traits. The genotype-by-environment interaction effect was not significant for most traits, including GYLD, under individual test environments or across environments. This suggested that the GYLD and agronomic performance of the hybrids would be stable across both *Striga*-infested and *Striga*-free environments. *Striga*-free environments had higher heritability for GYLD and other traits (0.42-0.89%) than *Striga*-infested environments (0.01-0.73%). Grain yield under *Striga*-infested environments was positively genetically correlated with GYLD under *Striga*-free environments (r_g = 0.63). This confirmed that GYLD performance under *Striga* infestation can be predicted from GYLD performance under *Striga*-free environments. The hybrids' mean GYLD in *Striga*-free environments was 4.2 t/ha, with a 31% yield reduction in *Striga*-infested conditions. Ears per plant decreased by 16% as a result of the *Striga* infestation, but anthesis-silking interval increased by 34%. The most outstanding hybrids based on a selection index for *Striga* tolerance were M1462-15, M1462-6, and M1462-4. They can be grown in *Striga*-free and *Striga*-endemic conditions and also be used to create new *Striga*-tolerant varieties.

Keywords: *Striga* infestation, heritability, genotype-by-environment interaction, hybrid maize

Introduction

Maize (*Zea mays* L.) is a strategic crop for tackling food security and malnutrition in sub-Saharan Africa (SSA) (Prasanna *et al*., 2021). Being a prominent cereal in the region, maize dominates diets and provides at least 30 % of dietary calories for millions of people who consume between 52 and 450 g/person/day

(Prasanna *et al*., 2021). The population of SSA is projected to double by 2050 (Prasanna *et al*., 2021). Accordingly, demand for cereals, particularly maize for food, is anticipated to outstrip domestic supply (van-Ittersum *et al*., 2016).

All the agro-ecological zones in Ghana are suitable for maize farming, but the savannahs (Guinea and Sudan Zones) offer huge potential because of high solar radiation, low humidity and night temperature, and limited pressure from diseases and pests (Badu-Apraku & Fakorede, 2017). However, the savannahs are prone to recurrent droughts and low soil fertility, now worsened by climate change. Also, cropping systems in the savannahs are characterized by intense land use, mono-cropping, and poor soil management practices with little use of inputs which tend to favour the invasion of parasitic weeds, particularly *Striga* (Gedil & Menkir, 2019; Gowda *et al*., 2021).

Striga is an obligate root parasite that is prevalent in the savannahs where it impedes cereal crop production (Gedil & Menkir, 2019). Among the species of *Striga* that affect maize, *Striga hermonthica* is the most economically destructive (Menkir *et al*., 2012, Teka, 2014). *Striga hermonthica* can attack maize at any stage of development causing severe damage through stunting, leaf chlorosis, and wilting of silks. As a result, infested maize plants produce small ears that are either barren or poorly filled, reducing grain yield (Badu-Apraku & Fakorede, 2017). According to Kim *et al*. (2002) and Ejeta. (2007), grain yield losses in maize due to *Striga* attack vary between 20 and 80 % depending on the growth stage and degree of infestation. However, heavy infestation at the early stages of growth may lead to 100 % yield loss (Akaegu *et al*., 2019; Kamara *et al*., 2020), affecting the sustenance of smallholder farmers.

Among the methods proposed to combat *Striga*, genetic control, which involves the use of tolerant and resistant varieties is considered the most affordable and environmentally safer option for resource-constrained farmers in SSA (Gasura *et al*., 2021; Dossa *et al*., 2023). Under *Striga* infestation, grain yield could be influenced by other agronomic traits and diseases. Menkir *et al*. (2007) identified *Striga* emergence count and *Striga* damage rating as important traits that could be selected alongside grain yield in *Striga* resistance breeding. Estimates of genetic variances, heritability, and genetic correlations for grain yield and traits related to resistance to *Striga* would be vital to determine whether or not to continue with selection during *Striga* resistance breeding.

In this study, we conducted a comprehensive evaluation of 17 single-cross *Striga*-resistant maize hybrids bred specifically for resistance to *Striga hermonthica.* The objectives were to (i) assess the response of the maize hybrids to artificial *Striga* infestation, (ii) Estimate the heritability of grain yield and other agronomic traits, as well as the trait associations contributing to increased resistance in the hybrids and (iii) identify the best hybrid(s) with resistance to *Striga*.

Experimental

Germplasm and experimental design

Seventeen single-cross hybrids and a local check (Opeaburo) were evaluated under artificial *Striga* infestation and *Striga*-free environments at Nyankpala and Manga in 2014 and 2015. Nyankpala and Manga are located in the Guinea Savannah and Sudan Savannah agroecological zones in Ghana, respectively. Each year, two separate experiments were conducted, one under *Striga* infestation conditions and the other under *Striga*-free conditions. A Randomized Complete Block Design with three replications was used, with the hybrids planted in two-row plot. The rows were 5 m long and spaced 0.75 m apart, with plants spaced 0.50 m within rows. For *Striga*-infested trials, each entry was infested with *Striga hermonthica* seeds, using approximately 5000 germinable *Striga* seeds per hill for infestation.

In *Striga*-free plots, NPK 15-15-15 fertilizer was applied at a rate of 60 kg N ha^{-1}, 60 kg K_2O ha^{-1}, and 60 kg P_2O_5 ha^{-1} as basal fertilizer two weeks after planting. Additional N at 30 kg N ha^{-1} was top-dressed four weeks after planting. To encourage *Striga* germination and attachment to host plant roots, fertilizer application was delayed until 21 days after planting (DAP), when 30 kg N ha^{-1}, 30 kg P ha^{-1}, and 30 kg K ha^{-1} were applied. Pre- and post-emergence herbicides were used to manage weeds in *Striga*-free plots as needed, while weeds other than *Striga* were manually controlled in *Striga*-infested plots. Weeding was performed carefully to avoid damaging *Striga* plants. Other agronomic practices followed the recommended guidelines for each experiment (Badu-Apraku *et al*., 2020).

Data collection

Data on yield and its component traits were recorded, including days to 50% anthesis, days to 50% silking, anthesis-silking interval, plant height, ear height, root lodging, stalk lodging, number of plants harvested per plot, number of ears harvested per plot, ears per plant, and grain yield. Additionally, observations were conducted on the *Striga* adaptive characteristics, the number of emerged *Striga* plants (STRC) at 8 and 10 weeks after planting (WAP), and the *Striga* damage syndrome rating (STRR) at the same time intervals. These assessments were performed to evaluate the extent of *Striga* damage on the maize hybrids in the *Striga*-infested trials. For each of the two experiments, the data collection protocols were standardized across all experimental plots, locations, and years following procedures described by Adu *et al.* (2019).

Data analysis

Analyses of variance (ANOVA) were conducted on the collected data under both *Striga*-infested and *Striga*-free conditions using the PROC GLM in SAS (SAS Institute, 2001). The ANOVA procedures followed the methodology outlined by Adu *et al.* (2019). Each combination of location and year was treated as an individual test environment, resulting in a total of eight test environments, comprising four *Striga*-infested environments and four *Striga*-free environments. When the ANOVA yielded significance ($p \leq 0.05$), the means were differentiated using Tukey's multiple range test at a 95% confidence level.

The following selection index was utilized to identify hybrids exhibiting superior performance under *Striga* infestation conditions: [(2 x GYLD) + EPP – (STRR1 + STRR2) – 0.5 (STRC1+ STRC2)], where GYLD represents the mean grain yield of *Striga*-infested and *Striga*-free plots, EPP stands for the number of ears per plant in the *Striga*-infested plots, STRR1 and STRR2 denote the *Striga* damage syndrome rating at 8 and 10 WAP, respectively, and STRC1 and STRC2 indicate the number of emerged *Striga* plants at 8 and 10 WAP, respectively. In both *Striga*-infested and *Striga*-free environments, each trait was standardized with a mean of zero and a standard deviation of 1 to minimize the effects of different scales. Hence, a positive value indicates tolerance, while a negative value indicates susceptibility of a hybrid to *Striga*.

The broad-sense heritability (H^2) estimates for agronomic traits under *Striga*-infested and *Striga*-free environments, and across the test environments were conducted using the META-R (multi-environment trial analysis in R) software (Alvarado *et al*., 2020). Following the methodologies outlined by Alvarado *et al.* (2020), the genetic correlation coefficient (r_G) and phenotypic correlation coefficient (r_p) between grain yield and other agronomic traits were assessed across various environments.

Results and Discussion

Analysis of variance for grain yield and other agronomic traits of the hybrids under Striga-infested and Striga-free environments, and across test environments

The combined ANOVA across *Striga*-infested and *Striga*-free environments revealed significant mean squares for environments across all measured traits. However, mean squares for genotypes were significant only for grain yield, days to 50% anthesis, days to 50% silking, plant height, and ear height (Table 1). Similar results were obtained under *Striga*-infested and *Striga*-free environments (Tables 2 and 3), where environmental mean squares were significant for all measured traits, except for plant height, which was not significant under *Striga*-infested environments, as well as for genotypic mean square, which was significant only for grain yield and *Striga* damage syndrome rating at 8 WAP under *Striga*-infested conditions. The significant mean square for the environment observed for nearly all measured traits signifies the distinctiveness of the eight test environments, offering unique information on the hybrids to facilitate better discrimination among them. The observed significant genotypic mean squares for grain yield and the other traits under and across conditions of *Striga* infestation and non-infestation indicated substantial genetic diversity among the hybrids for those traits. This finding suggested that significant progress could be achieved through the selection of important agronomic traits under both *Striga*-infested and *Striga*-free conditions, notably including *Striga* resistance and increased grain yield under *Striga*-infested environments. Furthermore, the substantial genetic diversity observed among the hybrids for *Striga* damage syndrome rating at 8 WAP indicates that while all the hybrids displayed resistance to *Striga*, the levels or mechanisms of resistance may vary among them. This presents an opportunity to identify and select superior genotypes for further advancement in *Striga* resistance breeding and the development of new *Striga* resistance-enhanced varieties. These results are similar to those reported by Akaogu *et al*. (2020), and Badu-Apraku *et al*. (2011).

The lack of a significant genotype-by-environment (G × E) mean square indicated that the performance of the genotypes (hybrids) did not vary across the eight test environments, implying the broad adaptation of the hybrids to *Striga*-infested and *Striga*-free environments, which suggested that the yield performance of the hybrids will be consistent across those environments. This result was further confirmed by the strong and positive genetic correlations for grain yield between combined means for *Striga*-infested and *Striga*-free environments (by year) and across years (Table 4), indicating that grain yield performance of the hybrids under *Striga* infestation can be predicted from grain yield performance under *Striga*-free environments. Similar results were reported by Akinwale et al. (2013) and Okunlola *et al.* (2023), who found a non-significant G × E interaction for grain yield and most traits observed under *Striga* but inconsistent with the findings of Akaogu *et al.,* (2020), and Badu-Apraku *et al*., (2011).

Heritability estimates of traits evaluated in Striga-infested and Striga-free environments

Heritability, which quantifies the degree to which a phenotype is genetically determined, is a pivotal factor in breeding programs. Regularly estimating heritability within populations over time is crucial, as it can vary due to genetic variance, environmental influences, and observation accuracy, especially in multi-environment trials like those conducted in this study. Broad-sense heritability estimates were ascertained for various traits assessed under both *Striga*-infested and *Striga*-free environments. The heritability estimates for traits in *Striga*-free environments ranged from 0.42 for stalk lodging to 0.89 for ear height (Table 3), whereas under *Striga*-infested environments, they ranged from 0.01 for *Striga* damage syndrome ratings at 10 WAP to 0.73 for days to 50% anthesis (Table 2). Generally, the results obtained indicated that heritability estimates were higher under non-stress environments but lower in stress environments. Studies by Zaidi *et al*. (2007) and Okunlola *et al*. (2023) also revealed reduced broad-sense heritability estimates under stress conditions compared to non-stress environments. This variation in the magnitude of heritability estimates between non-stress and stress environments highlights the intricate interplay between genetics and environmental factors in dictating trait expression. Traits such as grain yield, *Striga* damage syndrome rating at 8 WAP, days to 50% anthesis, days to 50% silking, and plant height exhibited moderate to high heritability estimates under *Striga*-infested conditions, suggesting substantial genetic differences, minimal environmental influence, and high reliability in trait expression across the tested stress environments, and thus, there will be a response to selection. Conversely, traits like *Striga* damage syndrome ratings at 10 WAP, root lodging, stalk lodging, and number of emerged *Striga* plants at 8 WAP and 10 WAP, which displayed very low to moderately low heritability estimates, were significantly influenced by environmental factors in their expression (Covarrubias-Pazaran 2019).

TABLE 1

Mean squares of grain yield and other agronomic traits of hybrids tested across Striga-infested and Striga-free environments at Nyankpala and Manga in 2014 and 2015

Source of variation	DF	Grain yield	Days to 50% anthesis	Days to 50% silking	Anthe-sis-silking interval	Plant height	Ear height	Ears per plant	Ear aspect	Root lodg-ing	Stalk lodging
Environment (E)	7	269.4^{***}	702.8^{***}	857.2^{***}	21.2^{***}	10708.4^{***}	7951.3^{***}	0.4^{***}	13.6^{***}	406.8^{***}	10.5^{***}
Genotype (G)	17	8.3^{***}	24.9^{***}	29.0^{***}	0.9^{ns}	1115.0^{***}	519.0^{***}	0.1^{ns}	0.7^{ns}	20.2^{ns}	0.3^{ns}
G x E	119	3.3^{ns}	5.6^{ns}	7.3^{ns}	1.0^{ns}	470.4^{ns}	193.6^{ns}	0.1^{ns}	0.4^{ns}	10.3^{ns}	0.3^{ns}
Error	135	2.5	8.1	10.2	0.8	521.2	163.1	0.1	0.7	12.4	0.3
Total	279										
Heritability (H^2)		0.87	0.96	0.95	0.02	0.92	0.95	0.55	-	0.84	-

TABLE 2

Mean squares of grain yield and other agronomic traits of hybrids tested under Striga-infested environments at Nyankpala and Manga in 2014 and 2015

Source of variation	DF	Grain yield	Days to 50% anthesis	Days to 50% silking	Anthesis-silking interval	Plant height	Ear height	Ears per plant	Ear aspect
Environment (E)	3	22.1***	1088.1***	3519.7***	12.0***	723.2 ns	1107.9***	0.3***	16.3***
Genotype (G)	17	4.0**	15.7ns	323.0ns	1.2ns	495.8 ns	136.4ns	0.0 ns	0.4ns
G x E	51	2.5ns	7.1ns	497.3 ns	1.2ns	404.6 ns	180.9***	0.0 ns	0.5 ns
Error	67	1.9	10.8	921.7	1.0	348.3	84.0	0.0	0.6
Total	139								
Heritability (H^2)		0.71	0.73	0.69	-	0.63	0.43	-	-

TABLE 2 CONT'D

Mean squares of grain yield and other agronomic traits of hybrids tested under Striga-infested environments at Nyankpala and Manga in 2014 and 2015

Source of variation	DF	Root Lodging	Stalk Lodging	STRC1	STRC2	STRR 1	STRR 2
Environment (E)	3	225.1***	11.5***	4513.8***	2317.5***	15.7**	1.4*
Genotype (G)	17	12.2 ns	0.4ns	118.1ns	150.0 ns	1.6**	0.7ns
G x E	51	8.9 ns	0.5 ns	39.7 ns	68.0 ns	0.3ns	0.6 ns
Error	67	14.3	0.6	66.6	87.4	0.6	0.4
Total	139						
Heritability (H^2)		0.23	0.22	0.21	0.42	0.53	0.01

STRC1 and STRC2, number of emerged Striga plants at 8 and 10 WAP, respectively; STRR 1 and STRR 2, Striga damage syndrome rating at 8 and 10 WAP, respectively.

TABLE 3

Mean squares of grain yield and other agronomic traits of hybrids tested under Striga-free environments at Nyankpala and Manga in 2014 and 2015

Source of variation	DF	Grain yield	Days to 50% anthesis	Days to 50% silking	Anthesis-silking interval	Plant height	Ear height	Ears per plant	Ear aspect	Root lodging	Stalk lodging
Environment (E)	3	407.8***	383.4***	551.4***	24.7***	8894.4***	8894.4**^	0.1ns	9.9***	723.2***	11.1***
Genotype (G)	17	9.4***	13.4**	16.5***	0.7ns	1264.8**	1264.8***	0.1ns	0.7ns	19.0**	0.2*
G x E	51	3.5 ns	4.6ns	5.0ns	0.7 ns	459.2ns	459.2ns	0.2 ns	0.4ns	11.4ns	0.1*
Error	66	3.1	5.4	6.8	0.6	620.5	620.5	0.2	0.8	10.6	0.3
Total	138										
Heritability (H^2)		0.86	0.87	0.87	-	0.87	0.89	0.55	-	0.67	0.42

TABLE 4

Genetic correlations for grain yield between combined means for Striga-infested, and Striga-free environments (by year) and across years

Environment	2014-NSTR	2015-NSTR	Across-NSTR
2014-STR	0.98***		
2015-STR		0.43**	
Across-STR			0.63**

2014-STR and 2015-STR, Striga-infested environments averaged across locations in 2014 and 2015, respectively; Across-STR, Striga-infested environments averaged across locations and years; 2014-NSTR and 2015-NSTR, Striga-free environments averaged across locations in 2014 and 2015, respectively; Across-NSTR, Striga-free environments averaged across locations and years.

Mean Grain yield and agronomic performance of the hybrids in Striga-infested and Striga-free environments

Figures 1A and 1B present the mean values for grain yield and other agronomic traits of the hybrids' performance under and across the *Striga*-infested and *Striga*-free environments. The average grain yield across all test environments was 3.6 t/ha, with 4.2 t/ha in *Striga*-free environments and 2.9 t/ha in *Striga*-infested environments. On average, the yield reduction due to *Striga* infestation was 31%, falling within the range of yield reduction reported under *Striga*-infested environments by Badu-Apraku & Yallou (2009), and Makinde *et al*. (2023), but lower than what was reported by Badu-Apraku *et al.* (2011) and Adu *et al.* (2019). The 31% yield reduction obtained in this study validates that the severity of *Striga* infestation imposed on the test hybrids was sufficient to effectively differentiate between resistant and susceptible hybrids, facilitating the identification of *Striga*-resistant hybrids with substantially higher yielding potential. *Striga* infestation reduced ears per plant by 16% but increased the anthesis-silking interval by 34% (Figure 1A). Furthermore, plant height and ear height decreased by 16.9% and 25.5%, respectively, under *Striga* infestation compared to *Striga*-free conditions (Figure 1B). Nine out of the seventeen test hybrids showed positive resistance to *Striga* infestation based on the multiple-trait selection index described in the methodology section (Table 5). Notably among them were the hybrids M1462-15, M1462-4, M1462-6, and M1462-8, which demonstrated above-average grain yield and desirable traits under *Striga*-infested environments, making them suitable choices for cultivation in *Striga*-endemic areas in Ghana and also in *Striga*-free environments.

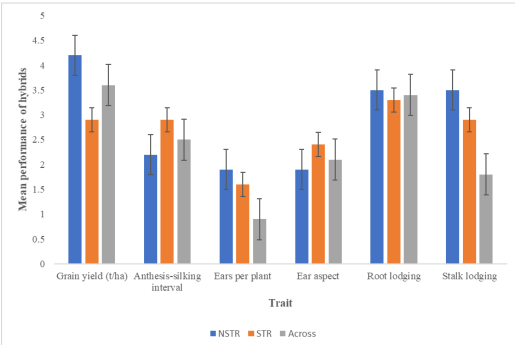

Fig. 1A: Mean grain yield, anthesis-silking interval, ears per plant, ear aspect, root and stalk lodging of the hybrids in *Striga*-free (NSTR) and *Striga*-infested (STR) environments, and across all test environments (Across).

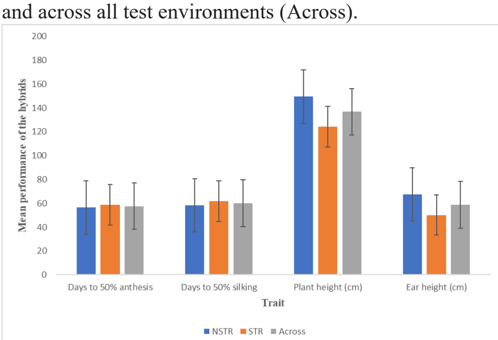

Fig. 1B: Mean days to 50% anthesis, days to 50% silking, plant and ear heights of the hybrids in *Striga*-free (NSTR) and *Striga*-infested (STR) environments, and across all test environments (Across).

TABLE 5

Mean performance of grain yield and other agronomic traits of hybrids evaluated under Striga-infested (STR) and Striga-free (NSTR) environments at Nyankpala and Manga in 2014 and 2015

Variety	GYLD (t/ha)		EH		PH		EPP		STRR1	STRR2	STRC1	STRC2	SI index
	NSTR	STR	NSTR	STR	NSTR	STR	NSTR	STR					
M1462-1	3.5^{abc}	1.7^{a}	66.6^{abc}	42.4^{a}	154.1^{ab}	113.3^{a}	1.0^{a}	0.8^{a}	1.5^{ab}	2.0^{a}	13.5^{a}	19.0^{a}	-0.1
M1462-10	5.1^{bc}	3.5^{abc}	76.1^{bc}	57.5^{a}	162.8^{ab}	138.6^{a}	0.8^{a}	0.9^{a}	2.5^{ab}	2.0^{a}	13.9^{a}	18.0^{a}	1.3
M1462-11	3.5^{abc}	2.6^{abc}	61.5^{abc}	53.2^{a}	137.2^{ab}	125.0^{a}	1.0^{a}	0.8^{a}	2.8^{b}	2.5^{a}	19.5^{a}	22.8^{a}	-1.7
M1462-12	4.2^{abc}	3.3^{abc}	77.4^{bc}	53.7^{a}	161.6^{ab}	129.5^{a}	0.9^{a}	0.8^{a}	2.5^{ab}	2.3^{a}	14.3^{a}	18.5^{a}	-0.2
M1462-13	4.3^{abc}	2.7^{abc}	74.0^{abc}	51.2^{a}	163.2^{ab}	123.0^{a}	1.0^{a}	0.8^{a}	2.0^{ab}	2.3^{a}	18.0^{a}	20.3^{a}	0.1
M1462-14	4.9^{abc}	3.0^{abc}	82.9^{c}	53.3^{a}	156.2^{ab}	124.6^{a}	0.9^{a}	0.8^{a}	2.8^{b}	2.3^{a}	16.3^{a}	18.8^{a}	-0.3
M1462-15	3.1^{ab}	4.1^{c}	51.4^{ab}	48.9^{a}	143.4^{ab}	120.7^{a}	0.8^{a}	0.8^{a}	2.1^{ab}	2.0^{a}	12.6^{a}	22.3^{a}	0.3
M1462-16	2.8^{a}	2.4^{abc}	68.1^{abc}	44.0^{a}	153.5^{ab}	115.5^{a}	1.1^{a}	0.8^{a}	2.3^{ab}	2.3^{a}	23.3^{a}	26.8^{a}	-2.0
M1462-17	4.7^{abc}	3.0^{abc}	67.9^{abc}	45.4^{a}	150.4^{ab}	113.6^{a}	0.8^{a}	0.8^{a}	2.0^{ab}	1.8^{a}	10.5^{a}	19.0^{a}	1.5
Local Check	4.0^{abc}	1.8^{abc}	68.5^{abc}	47.2^{a}	153.0^{ab}	117.3^{a}	1.1^{a}	0.8^{a}	2.5^{ab}	2.3^{a}	21.0^{a}	26.5	-1.6
M1462-2	4.9^{abc}	2.9^{abc}	73.4^{abc}	54.9^{a}	148.2^{ab}	129.4^{a}	0.9^{a}	0.8^{a}	2.5^{ab}	2.8^{a}	17.8^{a}	28.0^{a}	-1.3
M1462-3	4.1^{abc}	3.1^{abc}	58.0^{abc}	48.3^{a}	126.6^{ab}	116.1^{a}	0.9^{a}	0.8^{a}	1.3^{a}	2.3^{a}	13.0^{a}	15.5^{a}	1.2
M1462-4	4.9^{abc}	3.3^{abc}	70.3^{abc}	50.8^{a}	150.9^{ab}	122.4^{a}	0.9^{a}	0.9^{a}	1.8^{ab}	1.7^{a}	20.4^{a}	13.6^{a}	2.1
M1462-5	4.2^{abc}	2.8^{abc}	73.9^{abc}	52.2^{a}	167.6^{b}	136.5^{a}	1.4^{a}	0.9^{a}	1.8^{ab}	2.3^{a}	14.5^{a}	22.3^{a}	0.6
M1462-6	5.6^{c}	4.1^{bc}	68.9^{abc}	52.8^{a}	146.9^{ab}	129.0^{a}	0.9^{a}	0.9^{a}	2.0^{ab}	2.3^{a}	21.3^{a}	21.3^{a}	2.0
M1462-7	4.6^{abc}	2.6^{abc}	62.8^{abc}	46.7^{a}	155.9^{ab}	123.1^{a}	1.1^{a}	0.7^{a}	2.8^{b}	2.3^{a}	19.3^{a}	26.8^{a}	-1.4
M1462-8	4.2^{abc}	3.6^{abc}	64.4^{abc}	53.9^{a}	140.0^{ab}	137.1^{a}	1.0^{a}	0.8^{a}	1.8^{ab}	2.0^{a}	10.8^{a}	26.0^{a}	1.1
M1462-9	3.3^{ab}	2.9^{abc}	47.0^{a}	47.1^{a}	119.5^{a}	121.1^{a}	0.9^{a}	0.9^{a}	1.8^{ab}	3.0^{a}	14.3^{a}	11.5^{a}	-0.2

GYLD, grain yield; EH, ear height; PH, plant height; EPP, ears per plant; STRR1, Striga damage syndrome rating at 8 WAP; STRR2, Striga damage syndrome rating at 10 WAP; STRC1, number of emerged Striga plants at 8 WAP, STRC2, number of emerged Striga plants at 10 WAP; SI index, selection index.

Correlation of grain yield with other traits in contrasting environments

Grain yield showed strong correlations, both genotypic and phenotypic, with days to 50% silking, days to 50% anthesis, ear aspect, plant height, ear height, number of plants and ears haevested per plot across the eight *Striga*-free and *Striga*-infested test environments used in this study. Genetically, it had a negative correlation with days to 50% silking (r_G = -0.9), days to 50% anthesis (r_G = -0.8), and ear aspect (r_G = -1), while positively correlating with plant height (r_G = 0.6) and ear height (r_G = 0.7), and number of ears (r_G = 0.8) and plants (r_G = 0.8) harvested per plot (Table 6). Similarly, phenotypically, it exhibited negative correlations with days to 50% silking (r_G = -0.7), days to 50% anthesis (r_G = -0.7), and ear aspect (r_G = -0.7), and positive correlations with ear height (r_G = 0.6), plant height (r_G = 0.5), and number of ears (r_G = 0.6) and plants (r_G = 0.6) harvested per plot (Table 7). Strong genetic and phenotypic correlations were also observed between pairs of traits such as days to 50% silking and days to 50% to anthesis, plant height and ear aspect, and ear height and ear aspect (Tables 6 and 7), suggesting shared genetic factors and environmental influences. These findings indicate that traits like early flowering, better ear aspect, higher ear placement, and larger number of ears harvested per plot are indicators of a higher genetic potential for high grain yield across *Striga*-infested and non-infested conditions. Hence, days to 50% silking, days to 50% to anthesis, ear aspect, ear height, and number of ears harvested per plot are suitable for precise indirect selection aimed at achieving high grain yield.

In *Striga*-infested environments, similar trait associations were observed between grain yield and other traits as those across all test environments and in *Striga*-free conditions, albeit with reduced magnitude, except for the number of ears (r_p = 0.7) and plants (r_p = 0.7) harvested per plot and root lodging (r_p = -0.5) (Table 8). This finding contrasts with reports by Adu et al. (2019) and Bänziger et al. (2000), which suggested a stronger correlation between grain yield and other yield components under stress conditions. The findings also indicated that high-yielding hybrids among the tested genotypes in *Striga*-infested environments were characterized by a larger number of plants and ears harvested per plot, along with fewer root-lodged plants, similar to the results obtained by Badu-Apraku *et al*. (2019). *Striga* damage syndrome rating at 8 WAP showed a significant positive correlation with the number of emerged *Striga* plants at both 8 (r_p= 0.6) and 10 WAP (r_p= 0.6) (Table 8). This suggests that as the number of emerged *Striga* plants increases, the level of *Striga* damage to the maize plants also increases. These findings highlight the necessity of utilizing a precise quantity of *Striga* inoculant per plot, ensuring uniformity in its application, and implementing recommended agronomic practices during field experiments to attain the desired level of *Striga* emergence. The aim is to impose just enough *Striga* damage stress on test genotypes, avoiding both excessive and insufficient levels of stress. Days to 50% anthesis and silking showed strong positive associations with *Striga* damage syndrome rating at 8 WAP (r_p = 0.6), the number of emerged *Striga* plants at 8 WAP (r_p = 0.7), and ear aspect (r_p = 0.6). Additionally, days to 50% anthesis strongly correlated with number of emerged *Striga* plants at 10 WAP (r_p = 0.6) (Table 8). This implies that days to 50% anthesis and silking could serve as indicators of these *Striga* adaptive traits, with delayed flowering indicating higher levels of *Striga* damage syndrome rating and number of emerged *Striga* plants, signaling severe *Striga* parasitism in the hybrids. These results differ from the findings of Menkir *et al.* (2012), who reported weak and non-significant correlations between days to 50% anthesis and silking with other traits in *Striga*-infested environments in Nigeria and Kenya. They also observed in Nigeria a strong negative correlation between grain yield and *Striga* damage syndrome rating (r = -0.98) and the number of emerged *Striga* plants (r = -0.78), while grain yield was positively correlated with plant height (r = 0.90).

TABLE 6

Genetic correlation coefficients between the grain yield and other agronomic traits of the hybrids across the test environments in 2014 and 2015

Trait	DA	DS	ASI	PH	EH	RL	PHV	EHV	EASP
DS	1.0^{**}								
ASI	0.3^{ns}	0.3^{ns}							
PH	-0.4^{ns}	-0.4^{ns}	-0.4^{ns}						
EH	-0.1^{ns}	-0.2^{ns}	-1.0^{**}	0.9^{ns}					
RL	0.0^{ns}	-0.1^{ns}	-1.0^{**}	-0.1^{**}	0.5^{*}				
PHV	-0.8^{**}	-0.8^{**}	-0.8^{**}	0.3^{ns}	0.4^{ns}	0.8^{**}			
EHV	-0.8^{**}	-0.9^{**}	-1.0^{**}	0.2^{ns}	0.4^{ns}	0.6^{**}	1.0^{**}		
EASP	0.8^{**}	0.8^{**}	0.4^{ns}	-1.0^{**}	-1.0^{**}	-0.5^{*}	-0.6^{**}	0.0^{ns}	
GYD	$-0.^{8*}$*	-0.9^{**}	-1.0^{**}	0.6^{**}	0.7^{**}	0.4^{ns}	0.8^{*}	0.8^{**}	-1.00^{**}

DA, days to 50% anthesis; DS, days to 50% silking; ASI, anthesis-silking interval; PH, plant height; EH, ear height; RL, root lodging; PHV, number of plants harvested per plot; EHV, number of ears harvested per plot; EPP, ears per plant; EASP, ear aspect; GYLD, grain yield.

TABLE 7

Phenotypic correlation coefficients between the grain yield and other agronomic traits of the hybrids across the test environments in 2014 and 2015

Trait	DA	DS	ASI	PH	EH	RL	SL	PHV	EHV	EPP	EASP
DS	1.0^{ns}										
ASI	0.2^{ns}	0.4^{ns}									
PH	-0.2^{ns}	-0.3^{ns}	-0.1^{ns}								
EH	-0.1^{ns}	-0.2^{ns}	-0.3^{ns}	0.8^{ns}							
RL	0.0^{ns}	-0.1^{ns}	-0.2^{ns}	-0.1^{ns}	0.2^{ns}						
SL	-0.4^{ns}	-0.3^{ns}	0.2^{ns}	0.0^{ns}	-0.1^{ns}	0.2^{ns}					
PHV	-0.7^{**}	-0.6^{**}	-0.1^{ns}	0.1^{ns}	0.2^{ns}	0.4^{ns}	0.5^{*}				
EHV	-0.6^{**}	-0.6^{**}	-0.3^{ns}	0.1^{ns}	0.2^{ns}	0.3^{ns}	0.3^{ns}	0.9^{***}			
EPP	0.3^{ns}	0.2^{ns}	-0.1^{ns}	0.2^{ns}	0.0^{ns}	-0.3^{ns}	-0.6^{**}	-0.5^{*}	-0.2^{ns}		
EASP	0.4^{ns}	0.4^{ns}	0.1^{ns}	-0.7^{**}	-0.7^{**}	-0.2^{ns}	-0.2^{ns}	-0.2^{ns}	-0.1^{ns}	0.2^{ns}	
GYD	-0.7^{**}	-0.7^{**}	-0.3^{ns}	0.5^{*}	0.6^{**}	0.2^{ns}	0.3^{ns}	0.6^{**}	0.6^{**}	-0.3^{ns}	-0.7^{**}

DA, days to 50% anthesis; DS, days to 50% silking; ASI, anthesis-silking interval; PH, plant height; EH, ear height; RL, root lodging; PHV, number of plants harvested per plot; EHV, number of ears harvested per plot; EPP, ears per plant; EASP, ear aspect; GYLD, grain yield.

TABLE 8

Phenotypic correlation coefficients between the grain yield and other agronomic traits of the hybrids under Striga-infested environments in 2014 and 2015

Trait	ASI	DA	DS	EASP	EH	EHV	EPP	PH	PHV	RL	SL	STRC1	STRC2	STRR1	STRR2	GYD
ASI	-															
DA	0.1^{ns}	-														
DS	0.3^{**}	1.0^{***}	-													
EASP	-0.1^{ns}	0.6^{***}	0.6^{***}	-												
EH	-0.1^{ns}	-0.4^{**}	-0.4^{***}	-0.4^{***}	-											
EHV	0.1^{ns}	0.2	0.2^{ns}	0.1^{ns}	0.1^{ns}	-										
EPP	0.0^{ns}	0.5^{***}	0.4^{***}	0.4^{***}	-0.2^{ns}	0.5^{***}										
PH	-0.1^{ns}	-0.3^{**}	-0.3^{*}	-0.4^{**}	0.8^{***}	0.1^{ns}	-0.1^{ns}	-								
PHV	0.2^{ns}	0.0^{ns}	0.0^{ns}	-0.2^{ns}	0.2^{ns}	0.8^{***}	0.0^{ns}	0.1^{ns}	-							

RL	0.2^{ns}	0.5^{***}	0.5^{***}	0.2^{ns}	-0.1^{ns}	0.5^{ns}	0.3^{**}	-0.1^{ns}	0.4^{***}	-						
SL	0.2^{ns}	0.0^{ns}	0.1^{ns}	-0.1^{ns}	-0.1^{ns}	0.3^{**}	0.0^{ns}	-0.1^{ns}	0.3^{***}	0.5^{***}	-					
STRC1	0.0^{ns}	0.7^{***}	0.7^{***}	0.6^{***}	-0.2^{ns}	0.2^{ns}	0.4^{**}	-0.2^{ns}	0.0^{ns}	0.4^{***}	-0.2^{ns}	-				
STRC2	0.0^{ns}	0.6^{***}	0.5^{***}	0.5^{***}	-0.3^{*}	0.2^{ns}	0.3^{**}	-0.2^{ns}	0.0^{ns}	0.3^{**}	-0.1^{ns}	0.7^{***}				
STRR1	0.2^{*}	0.6^{***}	0.6^{***}	0.5^{***}	-0.2^{ns}	0.1^{ns}	0.3^{**}	-0.2^{ns}	0.0^{ns}	0.5^{***}	0.0^{ns}	0.6^{***}	0.6^{***}	-		
STRR2	-0.2^{*}	-0.2^{ns}	-0.3^{ns}	-0.2^{ns}	0.2^{ns}	-0.2^{ns}	-0.2^{ns}	0.3^{**}	-0.1^{ns}	-0.4^{***}	-0.4^{***}	-0.2^{ns}	-0.1^{ns}	-0.2^{ns}	-	
GYD	-0.2^{*}	-0.1^{ns}	-0.1^{ns}	-0.2^{ns}	0.3^{**}	0.7^{***}	0.2^{ns}	0.3^{**}	0.7^{***}	-0.5^{***}	0.3^{**}	-0.0^{**}	-0.1^{**}	-0.1^{**}	-0.1^{**}	-

DA, days to 50% anthesis; DS, days to 50% silking; ASI, anthesis-silking interval; PH, plant height; EH, ear height; RL, root lodging; PHV, number of plants harvested per plot; EHV, number of ears harvested per plot; EPP, ears per plant; EASP, ear aspect; GYLD, grain yield; STRR1, Striga damage syndrome rating at 8 WAP; STRR2, Striga damage syndrome rating at 10 WAP; STRC1, number of emerged Striga plants at 8 WAP, STRC2, number of emerged Striga plants at 10 WAP.

Conclusion

Significant genetic diversity was identified among the test hybrids across *Striga*-infested and non-infested conditions, including grain yield and *Striga* damage syndrome rating at 8 WAP in *Striga*-infested environments. This significant genetic diversity showed that potential progress through key agronomic trait selection could be achieved within the hybrids, especially for *Striga* resistance and improved grain yield under *Striga*-infested conditions. The varied genetic diversity in *Striga* damage syndrome rating at 8 WAP implies diverse resistance levels or mechanisms among the hybrids, which will facilitate the identification of superior genotypes for *Striga* resistance breeding and the development of new *Striga*-resistant varieties, ultimately enhancing *Striga* resistance durability in both new and existing varieties. High heritability values were evident in key traits like grain yield, plant height, days to anthesis, ear height, and *Striga* syndrome rating at 8 WAP, along with favourable trait associations among them. These findings are valuable for indirect trait selection and the development of new *Striga*-resistant varieties through breeding efforts. Moreover, delayed flowering, measured as days to 50% anthesis and silking, correlated strongly with higher *Striga* emergence and damage syndrome rating, indicating its potential as a *Striga* susceptibility indicator. This finding underscores the importance of incorporating flowering time into the selection index for breeding *Striga*-resistant maize. The study's evaluation of the test hybrids using a multiple-trait selection index revealed that nine out of the 17 hybrids exhibited resistance to *Striga*. Notably, hybrids M1462-15, M1462-4, M1462-6, and M1462-8, identified as resistant, also showed superior grain yield and desirable traits in *Striga*-infested environments, making them viable options for cultivation in both *Striga*-endemic and *Striga*-free areas in Ghana. They can also be used to develop new *Striga*-resistant varieties.

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