Selection of Tolerant Sorghum Varieties Grown in a Striga Infested Field for Future Breeding Purposes

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Abstract

Sorghum is a crucial food security crop with outstanding potential to meet growing global demand for food at a time of uncertainty posed by climate change. Striga (*Striga hermonthica*) is an important parasitic weed in sorghum causing huge loses under heavy infestation. Fourteen sorghum lines were assessed for their response to Striga infection under field condition to select lines that seem tolerant to Striga infection for future breeding purposes. An introgression line, Asareca T1, tolerant to Striga and Tabat, susceptible to Striga were included as controls. The experiment was carried out in a Striga sick field at the Food Crop Improvement Centre, Kenya Agricultural and Livestock Research Organization (KARLO) experimental fields in Alupe, Busia County. It comprised of two nitrogen fertilizer levels: N0 (N_o nitrogen) and N_1 (90 kg N Ha^{-1}) laid out in a randomized complete block design with two replications. Application of fertilizer significantly reduced days to Striga emergency, Striga count, and days to maturity, while it increased plant height, grain yield, panicle length, and dry weight in Asareca T1, 2026, 2038, 2048, 2054, and 2060. Striga count was negatively correlated with plant height ($r = -0.81, p < 0.05$), grain yield ($r = -0.74, p < 0.05$), dry weight ($r = -0.78, p < 0.05$), days to Striga emergence ($r = -0.64, p < 0.05$), and panicle length ($r = -0.74, p < 0.05$) in Tabat, 2011, 2015, 2021, 2028 and 2030. Striga count was positively correlated to number of tillers ($r = 0.66, p < 0.05$) and days to maturity ($r = 0.76, p < 0.05$) in Tabat, 2028, 2015, 2006, 2011, 2012, and 2006. The application of optimum fertilizer 60 kg ha^{-1} suppressed Striga emergence. It was also found that Tabat, 2006, 2011, 2012, 2015, 2021, 2028, and 2030 lines were susceptible to Striga attack based on the total number of Striga seedlings attached, which was more than six. Sorghum lines Asareca T1, 2026, 2029, 2038, 2040, 2048, 2054, and 2060 seem to be tolerant to Striga infectivity. Therefore, these lines have been selected for inclusion in future breeding programmes in selecting sorghum lines that are tolerant to Striga and that are preferred by farmers. Considerable efforts have been invested in breeding for Striga tolerance in sorghum and significant progress has been made in the development of improved selection methods.

Key words: *Striga hermonthica, Sorghum bicolor*, strigolactones, Striga-sick field, susceptibility, hosts, tolerance.

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a C4 plant from the grass family that is known for its versatility and increased water-use efficiency in relation to other grasses (Pescott, 2013). It has a significant genetic variability with more than 30,000 selections across the world (Aruna & Visarada, 2017). Sorghum is divided into grain and sweet sorghum. The cultivated sorghum varieties belong to the subspecies bicolor with races such as guinea, caudatum, kafir, bicolor, durra, and ten intermediate races (Kimber, 2003). The wild sorghum races have been used for breeding purposes to create hybrids with improved yield (Ezeaku & Gupta, 2004). The hybrid races under the sub-species *S. bicolor* include sweet sorghum known for its high Brix content accumulation in their stems (Winberry, 2013).

Sorghum is the fifth most important crop, grown across the globe for human consumption after maize (*Zea mays*), rice (*Oryza sativa*), wheat (*Triticum eastivum*), and barley (*Hordeum vulgare*), respectively (FAO, 2019; Temesgen, 2021). It is an important resource for human food, building materials, fodder and bioenergy (Kudra et al., 2014). The future of sorghum economy is linked to its contribution to food security, income growth, poverty alleviation in developing nations and efficient water use in drought-prone regions in the developed world.

Climate change poses a threat to climate sensitive economic sectors such as agriculture and is likely to adversely affect food security in most parts of the world (Sultan et al., 2014). Sorghum has an unlimited range of phenotypic diversity and varied tolerance to biotic stresses, which can enable it to play an important role in alleviating climate change (Kimber et al., 2013). Drought and heat tolerance traits in sorghum have been demonstrated to increase yield under climate change (Singh et al., 2014).

However, with more than 70 million tons annual production and a yield of 1400 kg ha^{-1}, smallholder farmers in the Sub-Saharan Africa have reported losses of between 20% and 80% (Atera et al., 2011; Kimber et al., 2013; Kountche et al., 2013). Yield loses can be attributed to insect pests, abiotic stress, birds, viruses, fungal pathogens and parasites. The Striga weed species (*Striga hermonthica*) poses a serious threat to Sorghum production in sub-Saharan Africa. It inflicts severe injury to its host making a bottleneck an important bottleneck to yield loses by smallholder farmers.

Sorghum cultivars respond differently to Striga infectivity based on phenotypic and genotypic composition. Hypersensitive response has been observed in Sorghum with the appearance of a necrotic lesion around the site of attempted infection, followed closely by death of the affected host cells within hours of the attack (De Cuyper & Goormachtig, 2017). The root hemiparasite has a marked influence on growth and photosynthesis in certain Sorghum varieties. Similarly, Fujioka et al. (2019) reported that the variation in genotype response might be partly explained by later attachment of the parasite and lower infection levels. Despite numerous studies on the response of Sorghum in different natural habitats (Atera et al., 2013; Hiraoka & Sugimoto; 2008; Beyene & Egigu, 2020; Daffallah, 2020), few have focused on selecting tolerant varieties in a naturally infested Striga field. Therefore, there are urgent demands and great interest in generating Striga tolerant sorghum cultivars through selection on the basis of their morphological responses to Striga infectivity in a Striga sick field to ensure global food security and for sustainable development of agriculture.

In this study, fourteen Sorghum genotypes (2026, 2029, 2038, 2040, 2048, 2054, 2060, 2006, 2011, 2012, 2015, 2021, 2028, and 2030) obtained from the Institute of Botany, Chinese Academy of Sciences were assessed in a Striga sick field to determine their response to Striga infectivity. Asareca T1, developed by ASARECA and partners reported to be resistant to Striga, and Tabat; Striga-susceptible sorghum variety was included as controls in the study (Mohammed et al., 2014). Sorghum lines that seem tolerant to Striga infectivity will be selected for further breeding through modern molecular breeding technologies.

Materials and Methods

The experimental site

The experiment was carried out in a Striga sick field at the Food Crop Improvement Centre, Kenya Agricultural and Livestock Research Organization (KALRO) experimental fields in Alupe, Busia County, Kenya. Alupe is situated at Latitude: 0°30'0"N and Longitude: 34°7'50.02"E. The experimental site lies in an altitude of 1,130 m above sea level with an average rainfall of 880 mm/year and temperatures ranging between 23^0 C and 29^0 C. The soils in the experimental site are ferralo-orthic acrisols with a pH of 5.4 (KALRO, 2019).

The experiment consisted of two levels of nitrogen fertilizers: N0 (No nitrogen) and N1 (90 kg N Ha-1) laid out in a randomized complete block design with two replications. The experiment was conducted using recommended agronomic practices for sorghum in the region (Olweny *et al*., 2014). The field was ploughed using a tractor and harrowed by hand to get a fine tilth. Each of the sorghum lines was planted in a single row, 5 m long and replicated twice in the fertilized and non-fertilized plots. The inter-row spacing was 50 cm and intra-row spacing was 15 cm. Weeds other than Striga were regularly handpicked.

Plant materials

All the Sorghum lines were generously provided by the Institute of Botany, Chinese Academy of Sciences, Beijing, China (Table 1). Asareca T1 was used as a resistance control alongside a susceptible control (Tabat) as their responses to Striga infectivity is well documented.

Table 1: Sorghum lines used in this study

Sorghum lines	2026, 2029, 2038, 2040, 2048, 2054, 2060, 2006, 2011, 2012, 2015, 2021, 2028 and 2030
Controls	Tabat (Susceptible to Striga infection)
	Asareca T1 (Tolerant to Striga infection)

Planting and management of Sorghum lines in Striga sick field

Sorghum lines were planted during three scheduled planting seasons in 2018, 2019 and 2020 in the same field. The field was prepared by clearing the existing vegetation, tilled using a tractor-drawn disc plough and followed by cross-wise harrowing. The seeds were sown at a depth of 30mm. Sowing was done by drilling at row-to-row distance of 25 cm.

The plant-to-plant spacing was 25 cm and the row width was 90 cm. The seeding rate was 35 kg/ha. At planting, a 50 kg bag per acre of compound fertilizer NPK (17: 17:17) was applied and top dressed with a 50 kg bag per acre of calcium ammonium nitrate (CAN) three weeks after germination. Thinning was carried out three weeks leaving 3 plants per stool. Hand weeding was done to eliminate every other weed other than Striga.

Bull dock star and carbofuran/malathion (Shri Ram Agro) @ 125 ml/ha was applied to control stem borer. A broad-spectrum insecticide, Marshal, with an active ingredient Carbosulfan 25% EC (Amiran) was sprayed two weeks after germination to control the sorghum shoot fly. Birds were controlled through bagging and scaring using human labour.

Data Collection

The response of sorghum cultivars to Striga infectivity was scored by measuring the following variables during growth and development cycle of the cultivars: The number of Striga per plant, grain yield, days to Striga emergence, plant height, number of sorghum plants per plot, and days to maturity. The number of Striga plants emerging from sorghum roots was counted every week from the 4th week after planting (4-5 leave stage). Sorghum plant height was measured at 4, 5, 6, 7, 8, 9, and 10 weeks after sowing. The results for the grain yield, days to Striga emergence, plant dry weight and days to maturity were scored once at the end of the planting period for the three seasons. Yields were expressed as the total weight of grains per plot.

Data analysis

All the plant variables and Striga counts were subjected to analysis using the R statistical package. Differences between variables were compared using ($p < 0.05$). Linear relationships among the agronomic parameters and Striga counts were determined by computing the Pearson's correlation coefficient.

Results

Days to Striga emergency

Results of the number of days Striga took to germinate and or emerge from sorghum roots in a Striga infested field are presented in Table 2. Data show that it took more days for Striga shoots to emerge from sorghum lines in plots in which fertiliser was applied when compared to plots in which fertiliser was not applied with significant differences among them.

In addition, Striga took less days to emerge from the sorghum varieties in plots in which fertiliser was not applied with significant differences among them. In the cultivars that were colonized late by the parasitic weed, it may seem that they are susceptible. Therefore, on the basis of this variable, future breeding could focus on cultivars could focus on the cultivars (2026, 2011, 2048, 2029, and 2040) in which Striga took more days to attach to roots and emerge in both plots. These varieties can be selected because they appear to be the tolerant lines, which can be explained by a delay in the onset of attachment.

Number of Striga attached and emerged (Striga count)

We counted the total number of Striga seedlings that had attached and emerged on sorghum accession at the very end of the experiment (3 months) when no additional Striga could emerge. Sorghum lines grown in plots in which fertiliser was not applied had more Striga shoots attached and emerged compared to sorghum lines growing in plots in which fertilizer had been applied with significant differences among them. Sorghum lines responded differently to indicate their tolerance levels based on the number of emerged and attached Striga shoots, as shown in Table 3.

Table 2: Days to Striga emergence, Striga count and grain yield.

	Days to Striga emergence		**Striga count**		**Grain Yield**	
Treatment	**+F**	**-F**	**+F**	**-F**	**+F**	**-F**
Asareca T1	21.00±0.016^{a}	19.67±0.007^{a}	7.33±0.014^{abcd}	10.67±0.003^{abc}	585.33±26.85^{a}	445.66±29.75^{ab}
Tabat	15.00±0.023^{bcd}	5.67±0.018^{e}	23.33±0.009^{a}	25.00±0.059^{ab}	168.33±13.56^{ef}	124.23±6.24^{g}
2006	13.33±0.022^{bcd}	8.67±0.015^{de}	6.33±0.032^{bcd}	9.00±0.022^{efghi}	137.33±2.02^{ef}	130.66±5.20^{g}
2011	15.33±0.09^{bcd}	9.00±0.006^{de}	4.67±0.049^{cd}	9.33±0.030^{efghi}	192.66±2.84^{e}	137.66±7.85^{fg}
2012	12.00±0.007^{cd}	9.33±0.011^{de}	6.00±0.026^{bcd}	12.00±0.020^{cdefghi}	125.00±10.99^{f}	123.33±6.69^{def}
2015	10.00±0.012^{d}	6.33±0.003^{e}	6.00±0.057^{bcd}	7.67±0.025^{ghi}	179.33±8.25^{ef}	135.33±2.40^{efg}
2021	13.33±0.065^{bcd}	7.00±0.001^{de}	6.00±0.061^{bcd}	11.00±0.008^{cdefghi}	178.33±5.81^{ef}	181.33±4.26^{def}
2026	21.00±0.071^{a}	15.00±0.005^{b}	10.00±0.049^{abcd}	26.00±0.032^{a}	356.33±22.80^{d}	309.66±7.53^{b}
2028	12.00±0.022^{cd}	8.00±0.042^{de}	4.67±0.018^{cd}	6.33±0.024^{i}	152.333±24.22^{d}	111.45±6.08^{def}
2029	18.33±0.003^{ab}	11.33±0.065^{bcd}	10.67±0.054^{abcd}	18.00±0.033^{abcde}	352.66±51.81^{d}	257.53±9.02^{ab}
2030	13.00±0.034^{bcd}	6.33±0.013^{e}	3.67±0.011^{d}	7.00±0.008^{hi}	178.66±8.35^{ef}	129.33±8.56^{de}
2038	14.67±0.025^{bcd}	10.00±0.011^{cde}	11.33±0.020^{abcd}	16.67±0.045^{bcdefg}	302.00±10.01^{d}	214.23±24.45^{b}
2040	18.00±0.041^{ab}	11.00±0.023^{bcd}	10.67±0.035^{abcd}	17.33±0.027^{abcdef}	422.66±606^{c}	391.67±7.17^{b}
2048	16.33±0.019^{abc}	14.00±0.009^{bc}	12.67±0.041^{ab}	20.00±0.006^{abcd}	523.00±11.26^{b}	435.67±7.42^{a}
2054	17.67±0.009^{ab}	9.00±0.006^{de}	12.3315.67±0.056^{abcd}	15.67±0.012^{bcdefgh}	497.00±15.01^{b}	412.34±6.96^{bc}
2060	14.00±0.021^{bcd}	10.00±0.004^{cde}	3.67±0.021^{d}	8.33±0.010^{fghi}	585.33±29.94^{b}	211.93±8.08^{g}

[a] Means that do not share a letter are significantly different at $p = 0.05$ determined under Fischer's LSD test. With fertilizer (+F) and without fertilizer (-F).

Table 3: Days to Striga emergence, Striga count and grain yield based on degree of tolerance.

Days to Striga emergence				**Striga count**				**Grain yield**			
Treatment	+F	Treatment	-F	Treatment	+F	Treatment	-F	Treatment	+F	Treatment	-F
1.2026	21	Asareca T1	19	Tabat	23	2026	26	AcerecaT1	585	Asareca T1	445
2.Acereca T1	21	2026	15	2048	12	Tabat	25	2060	585	2048	435
3.2029	18	2048	14	2054	12	2048	20	2048	523	2054	412
4.2040	18	2029	11	2038	11	2029	18	2054	497	2040	391
5.2054	17	2040	11	2040	10	2040	17	2040	422	2028	309
6.2048	16	2060	10	2029	10	2038	16	2026	356	2029	257
7.Tabat	15	2038	10	2026	10	2054	15	2029	352	2038	214
8.2011	15	2054	9	Asareca T1	7	2012	12	2038	302	2060	211
9.2038	14	2011	9	2015	6	2021	11	2011	192	2021	181
10.2060	14	2012	9	2012	6	Asareca T1	10	2015	179	2011	137
11.2030	13	2028	8	2006	6	2006	9	2021	178	2015	135
13.2021	13	2006	8	2021	6	2011	9	2030	178	2006	130
14.2006	13	2021	7	2028	4	2060	8	Tabat	168	2030	129
15.2012	12	2015	6	2030	3	2030	7	2006	137	Tabat	124
16.2015	10	Tabat	5	2060	3	2028	6	2012	125	2028	111

Fertilised (+F) and Without Fertiliser (-F).

Reduced Striga attachment and emergence was evident in plots augmented with fertiliser for all the cultivars. However, in both the fertilised and unfertilised plots, the number of Striga that were attached to the sorghum lines at the end of the experiment was higher in plots without fertilizer suggesting that the lines produced more strigolactone. It means that they are the best lines for selection for future molecular breeding purposes as less Striga attached and emerged in the plots with and those without fertilizer.

Grain yield

Striga tolerance is associated with genetic gain in grain yield and other associated yield traits including plant height and panicle length. A comparison was made in this study to determine sorghum lines with the highest grain yield under Striga infectivity in plots augmented with fertiliser and in plots without fertiliser with significant differences among them.

An analysis of variance of individual plots revealed significant differences among the study lines and controls in the plots augmented with fertilizer and the plots without fertilizer. The Striga infestation affected the overall grain yield in all the studied genotypes but there was no significant difference for Tabat and 2006 in plots without fertilizer and those augmented with fertilizer. The data showed that Asareca T1, 2060, 2040 and 2048 seemed tolerant to Striga infectivity on the basis of their average yields in plots applied with fertilizer and those without fertilizer. On the contrary, Tabat and 2030 showed higher susceptibility traits as evidenced by their low grain yields in both plots applied with fertilizer and those without fertilizer.

Days to maturity

The mature sorghum cultivars were measured at 50% flowering in the three planting seasons. The genotypes matured at different times with. As indicated in Table 4, the early maturing cultivars took less days to mature in plots applied with fertiliser, it took less days for the varieties to attain physiological maturity as the fertiliser adds growth vigour to the plant.

Sorghum lines exhibited different maturity periods under Striga infestation in the plots without fertilizer. In fertiliser augmented plots and those without fertiliser, the sorghum lines attained physiological maturity on different dates. As shown in Table 5, it can be noted that the good candidates for selection took less days to attain maturity as they can be labelled as the tolerant varieties. Therefore, Asareca T1, 2026, 2029, 2060, and 2048 are good candidate accessions that can be integrated into varieties preferred by farmers through breeding.

Panicle length

As a sorghum plant grows, is absorbs nutrients from the soil used in grain filling. The length of panicle in sorghum was measured the effect of Striga on the host entails the removal of water, assimilates, and other nutrients. The panicle (at maturity) was measured to determine the maximum height. The sorghum genotypes differed significantly ($p < .005$) in the panicle length as a yield component, under fertilised and unfertilised conditions. However, under the fertilized and unfertilized conditions, lines 2006, 2011, 2012, 2021, 2030, and Tabat had no significant differences observed among them.

Table 4: Days to maturity, panicle length, and dry weight.

Treatments	**Days to maturity**		**Panicle length**		**Dry weight**	
	+ F	**-F**	**+ F**	**- F**	**+ F**	**-F**
2006	105.33 ± 2.02^{ab}	110.24 ± 3.055^{ab}	14.29 ± 2.18^{cd}	9.66 ± 0.881^{e}	235.37 ± 8.71^{g}	174.33 ± 3.480^{f}
2011	113.33 ± 5.23^{a}	119.33 ± 5.364^{a}	15.67 ± 1.201^{cd}	12.67 ± 2.403^{e}	264.92 ± 9.84^{fg}	264.33 ± 16.89^{e}
2012	100.33 ± 7.12^{bc}	116.33 ± 6.765^{a}	14.67 ± 1.452^{cd}	15.111 ± 1.527^{cde}	332.85 ± 27.75^{def}	298.67 ± 17.89^{de}
2015	108.66 ± 2.84^{ab}	109.67 ± 5.2387^{ab}	14.67 ± 0.667^{cd}	16.25 ± 1.154^{cde}	282.67 ± 5.897^{efg}	258.33 ± 9.2074^{e}
2021	107.24 ± 3.05^{ab}	109.67 ± 3.929^{ab}	13.31 ± 1.333^{d}	11.67 ± 0.881^{e}	329.33 ± 12.032^{def}	296.67 ± 12.679^{de}
2026	65.22 ± 2.081^{e}	92.36 ± 1.1547^{cd}	23.62 ± 2.027^{a}	23.33 ± 2.027^{ab}	498.66 ± 54.044^{b}	375.33 ± 26.027^{c}
2028	86.33 ± 6.437^{d}	117.33 ± 9.2436^{a}	13.33 ± 1.452^{d}	12.33 ± 1.855^{e}	345.72 ± 6.928^{def}	285.04 ± 15.044^{de}
2029	62.72 ± 1.154^{e}	76.11 ± 3.214^{ef}	25.12 ± 2.027^{a}	19.67 ± 1.201^{bcd}	553.33 ± 16.230^{ab}	437.05 ± 26.210^{b}
2030	102.33 ± 7.51^{abc}	119.33 ± 1.666^{a}	$18.58\pm1.08b^{c}$	13.44 ± 0.577^{de}	358.67 ± 26.459^{de}	288.33 ± 16.045^{de}
2038	64.35 ± 2.08^{e}	74.55 ± 2.645^{f}	25.33 ± 1.201^{a}	21.09 ± 0.333^{bc}	560.33 ± 73.567^{ab}	551.91 ± 21.962^{a}
2040	65.57 ± 1.15^{e}	78.08 ± 4.041^{def}	22.71 ± 1.154^{ab}	23.40 ± 5.567^{b}	391.17 ± 41.590^{cd}	331.67 ± 11.170^{cd}
2048	85.67 ± 2.96^{d}	87.67 ± 7.310^{cdef}	22.33 ± 1.763^{ab}	20.37 ± 5.174^{bc}	602.39 ± 11.532^{a}	547.67 ± 27.168^{a}
2054	73.33 ± 2.031^{e}	90.61 ± 5.547^{cde}	24.13 ± 1.452^{a}	24.85 ± 2.403^{ab}	482.33 ± 32.502^{bc}	457.33 ± 11.020^{b}
2060	93.25 ± 6.027^{cd}	95.21 ± 4.255^{bc}	18.42 ± 0.881^{bc}	15.67 ± 2.403^{cde}	229.43 ± 9.905^{g}	185.26 ± 15.50^{f}
Asareca T1	65.33 ± 1.452^{e}	83.33 ± 7.688^{cdef}	24.03 ± 2.081^{a}	24.22 ± 0.667^{ab}	545.98 ± 12.836^{ab}	433.33 ± 7.881^{b}
Tabat	108.22 ± 3.124^{ab}	113.33 ± 2.9627^{a}	15.33 ± 1.201^{cd}	30.54 ± 1.732^{a}	632.33 ± 53.136^{a}	546.33 ± 21.67^{a}

Means that do not share a letter are significantly different at $p = 0.05$ determined under Fischer's LSD test. With fertilizer (+F) and without fertilizer (-F).

Table 5: Table 3: Days to maturity, panicle length and dry weight based on degree of tolerance. Fertilized (+F) and Without Fertilizer (-F).

Days to maturity				Panicle length				Dry weight			
Treatment	+F	Treatment	-F	Treatment	+F	Treatment	-F	Treatment	+F	Treatment	-F
1. 2011	113	2011	119	2029	25	Tabat	30	Tabat	632	2038	551
2.2015	108	2030	119	2038	25	Asareca T1	24	2048	602	2048	547
3.Tabat	108	2028	117	2054	24	2054	24	2038	560	Tabat	546
4.2021	107	2012	116	Asareca T1	24	2040	23	2029	553	2054	457
5.2006	105	Tabat	113	2026	23	2026	23	Asareca T1	545	2029	437
6.2030	102	2006	110	2040	22	2038	21	2026	498	Asareca T1	433
7.2012	100	2015	109	2048	22	2048	20	2054	482	2026	375
8.2060	93	2021	109	2030	18	2029	19	2040	391	2040	331
9.2028	86	2060	95	2060	18	2015	16	2030	358	2012	298
10.2048	85	2026	92	Tabat	15	2012	15	2028	345	2021	296
11.2054	73	2054	90	2011	15	2060	15	2012	332	2030	288
13.2040	65	2048	87	2006	14	2030	13	2021	329	2028	285
14.2026	65	Asareca T1	83	2012	14	2011	12	2015	282	2011	264
15.Asareca T1	65	2040	78	2015	14	2028	12	2011	264	2015	258
16. 2038	64	2029	76	2021	13	2021	11	2006	235	2060	185
16.2029	62	2038	74	2028	13	2006	9	2060	229	2006	174

A comparison between the fertilised and non-fertilised plots shows that in all the genotypes fertiliser application increased the panicle length across all the three seasons, which future breeding techniques can employ. A comparison between plots with fertiliser and those without based on the degree of tolerance showed that the sorghum lines that had longer panicle lengths in both plots (2040, 2060, 2026, 2029, 2012, and 2021) could be selected for future breeding to tolerance to Striga infectivity.

Sorghum dry biomass

Sorghum varieties show different levels of vigour and reaction to Striga parasitism resulting in a crop producing higher or lower dry biomass. The analysis revealed no significant differences ($p < 0.055$) between treatments for the total biomass observed in plots augmented with inorganic fertiliser. The total biomass obtained with the susceptible control (Tabat) was significantly lower than all other sorghum lines and was not significantly different from 2048, 2038, and 2029. Although 2048 recorded the highest mean value of 602kg/ha, it was not significantly different from Asareca T1 in both the plots augmented with fertilizer and those without fertilizer (Table 4). It shows that it can be selected for advancement in breeding using modern molecular techniques.

Significant associations of Striga tolerance can be linked the overall yield that the sorghum lines produced. Based on their degree of tolerance, it was also revealed that the most tolerant lines had a higher biomass in both the fertilized plots and those which fertilizer was not applied. However, consistent with the observed increase in dry weight of all the sorghum lines in fertilized plots compared with those in plots without fertilizer, it can be seen that the application of fertilizer increased the sorghum line's final dry weight (Table 5). In general, mean biomass of sorghum genotypes differed significantly with application of fertilizer treatment. Therefore, on assessment of the biomass above ground, sorghum lines 2030, 2060, 2021, 2026, 2038, 2040, and 2048 are good candidates for selection for the next breeding phase based on dry weight and the number of days it took for the Striga to emerge and attach parameters. In addition, in general, genotypes with short panicle lengths also had few Striga attachments and therefore a correspondingly low biomass (2006, 2030, 2060, and 2040).

The height of sorghum from ground level to the tip of the panicle (at maturity) was measured to determine the maximum height attained under Striga infestation. Comparison of relative plant heights between sorghum lines with similar infection levels indicated differentiation in Striga effects. The tallest plant was Tabat (172cm) followed by 2028 (164 cm) and shortest was 2021 (47 cm), but with no significant difference among them in plots where fertilizer was applied. In plots without fertilizer, 2038 was the tallest (132 cm) (Table 6). The time of parasite attachment affects host performance and might explain much of the variation in the height of the plants at the end of the experiment. It can be seen that Striga attack reduced the sorghum height in all the studied sorghum lines with significant differences among them. It was found that the sorghum plants in plots without fertiliser with emerged and attached Striga shoots were shorter in terms of height.

As shown in Table 7, based on the variable plant height, we can affirm that the tall varieties can be selected to proceed to the next phase of breeding for tolerance to Striga infectivity. It was also revealed that there was no significant difference in plant height for 2026, 2029, 208, 2040, 2048, 2054 and Asareca T1 in plots without fertiliser. It means that these lines can be put together during selection in the next stage of breeding for tolerance to Striga attack.

Table 6: Plant height and number of plants.

Treatments	**Plant height**		**No. of plants**	
	+F	**-F**	**+F**	**-F**
2006	92.67±2.905^{e}	83.58±5.56^{b}	9.07±1.527^{fg}	6.33±1.763^{cd}
2011	74.33±2.728^{fg}	71.67±9.820^{bc}	9.39±1.383^{fg}	4.67±1.336^{d}
2012	80.39±7.423^{ef}	68.13±1.527^{bcd}	12.14±1.154^{def}	6.72±1.527^{cd}
2015	67.09±4.163^{fg}	59.24±4.910^{cd}	7.57±1.667^{fg}	6.07±1.154^{cd}
2021	47.67±5.364^{i}	42.33±7.218^{e}	11.35±1.732^{efg}	6.79±1.527^{cd}
2026	143.34±7.712^{cd}	131.67±1.452^{a}	26.18±1.732^{a}	10.48±0.577^{bc}
2028	49.17±1.732^{hi}	43.15±8.089^{e}	6.37±0.667^{g}	4.67±1.661^{d}
2029	164.31±3.711^{ab}	126.67±5.65^{a}	18.19±1.732^{c}	10.47±2.027^{b}
2030	62.73±3.179^{gh}	55.33±6.064^{de}	7.06±2.081^{fg}	3.67±0.881^{d}
2038	156.04±6.350^{bc}	132.67±5.925^{a}	16.67±1.201^{cd}	11.38±1.855^{ab}
2040	141.31±7.881^{d}	129.22±2.516^{a}	17.37±1.201^{c}	10.17±1.336^{b}
2048	147.33±3.844^{cd}	129.33±3.929^{a}	20.42±1.154^{bc}	12.67±0.881^{ab}
2054	143.88±4.932^{cd}	132.14±5.238^{a}	15.67±1.855^{cde}	12.37±1.763^{ab}
2060	73.15±2.081^{fg}	69.33±2.185^{bcd}	8.36±0.669^{fg}	3.645±0.33^{d}
Asareca T1	147.67±2.185^{cd}	127.21±2.516^{a}	20.67±2.905^{bc}	11.23±0.353^{ab}
Tabat	172.67±4.630^{a}	130.07±6.027^{b}	23.327±3.282a^{b}	15.77±2.645^{a}

Means that do not share a letter are significantly different at p = 0.05 determined under Fischer's LSD test. With fertilizer (+F) and without fertilizer (-F).

Table 7: Plant height and final sorghum stand count based on degree of tolerance.

Plant height				Final stand count			
Treatment	+F	Treatment	-F	Treatment	+F	Treatment	-F
1.Tabat	172	2038	132	2026	26	Tabat	15
2.2029	164	2054	132	Tabat	23	2048	12
3.2038	156	2026	131	Asareca T1	20	2054	12
4.Asareca T1	147	Tabat	130	2048	20	Asareca T1	11
5.2048	147	2040	129	2029	18	2038	11
6.2054	143	2048	129	2040	17	2029	10
7.2026	143	Asareca T1	127	2038	16	2026	10
8.2040	141	2029	126	2054	15	2040	10
9.2006	92	2006	83	2012	12	2006	6
10.2012	80	2011	71	2021	11	2012	6
11.2011	74	2060	69	2006	9	2015	6
12.2060	73	2012	68	2011	9	2021	6
13.2015	67	2015	59	2060	8	2011	4
14.2030	62	2030	55	2030	7	2028	4
15.2028	49	2028	43	2015	7	2030	3
16.2021	47	2021	42	2028	6	2060	3

Fertilized (+F) and Without Fertilizer (-F)

Number of sorghum plants (Final stand count).

Striga attacks sorghum before germination and infectivity affects plant growth and development such that death results in the very susceptible line affecting the final stand count. The number of plants were counted physically every week for 10 weeks and scored. The initial and final stand count was used to determine the severity of the Striga attack in plots under fertilisation and no fertilization. All the studied Sorghum cultivars had different final stand count with significant differences among them. . As shown in Table 7, it can be seen that the lines 2048, 2038, Asareca T1 and 2029 were among the highest ranking based on the final stand count, which makes them suitable candidates for selection to the next breeding phase. The conventional plant breeding for Striga resistance will involve field evaluation of the selected germplasm under artificial or natural infestation.

Correlations

A correlation analysis was carried out to determine the sorghum cultivars that seem tolerant to Striga infectivity on the basis of the growth variables measured in the previous sections. The relationship between the application of fertiliser and recorded parameters revealed that all the parameters studied showed highly significant relationships with each other. The coefficients of correlation between performance of lines and their agronomic performance were strong for most of the traits, ranging from -0.61 ($p \leq 0.05$) to 0.81 ($p \leq 0.05$) as shown in Table 8 below. Traits with the same physiology were highly correlated. There was a strong and positive ($p < 0.001$) relationship between the days to Striga emergence and Striga count. Striga damage was positively correlated to the number of sorghum plants ($r = 0.1$, $p = 0.49$) and height ($r = 0.31$, $p < 0.04$) of emerged sorghum plants with significant differences among them, showing that Striga damage was more significant when Striga number and/or plant height increases. The panicle length has a positive correlation to sorghum yield ($r = 0.57$, $p < 0.05$) (Table 8). A negative significant correlation between Striga number and plant height ($r = -0.774$, $p < 0.05$) was also revealed. A negative significant correlation ($p < 0.05$) was recorded between Striga emergence count and plant height. The number of days to maturity was observed to be negatively correlated to the number of germinated Striga. In addition, there was no significant correlation between grain yield and Striga emergence count.

The effect of non-fertilisation on linear relationships showed a negative correlation between striga count and plant height ($r = -0.69$), number of plants/final stand count ($r = -0.72$, $p < 0.05$), dry weight ($r = -0.75$, $p < 0.05$), grain yield ($r = -0.80$, $p < 0.05$) and panicle length ($r = -0.66$, $p < 0.05$) except days to maturity ($r = 0.72$, $p < 0.05$) and number of tillers ($r = 0.70$, $p < 0.05$) (Table 8). Overall, breeding ideal sorghum genotypes with improved seed yields and Striga tolerance needs selection of host genotypes with relatively heavy panicles, fewer days for Striga emergence and attachment, high seed yield, few Striga counts and less days to attaining maturity.

Table 8: Phenotypic correlation among certain agronomic and striga tolerance traits in sorghum cultivars [Fertilized plots]

	Days to maturity	Days to striga emergence	Plant height	Number of plants	Striga Count	Dry weight	Grain yield	Panicle length
Days to maturity	1	-0.69***	-0.81***	-0.71***	0.76***	-0.80***	-0.76***	-0.66***
Days to Striga emergence	-	1	0.62***	0.60***	-0.64***	0.65***	0.68***	0.45***
Plant height	-	-	1	0.73***	-0.74***	0.77***	0.73***	0.68***
Number of plants	-	-	-	1	-0.73***	0.73***	0.79***	0.72***
Striga Count	-	-	-	-	1	-0.78***	-0.74***	-0.74***
Dry weight	-	-	-	-	-	1	0.77***	0.75***
Grain yield	-	-	-	-	-	-	1	0.69***
Panicle length	-	-	-	-	-	-	-	1

*** Significant at 5% and 1% probability levels

Table 9: Phenotypic correlation among agronomic and Striga tolerance traits in sorghum cultivars [Un-fertilized plots]

	Days to maturity	Days to striga emergence	Plant height	Number of plants	Striga count	Dry weight	Grain yield	Panicle length
Days to maturity	1	-0.60***	-0.74***	-0.70***	0.72***	-0.77***	-0.69***	-0.69***
Days to striga emergence	-	1	0.62***	0.50***	-0.65***	0.57***	0.68***	0.45***
Plant height	-	-	1	0.69***	-0.81***	0.76***	0.73***	0.66***
Number of plants	-	-	-	1	-0.72***	0.77***	0.81***	0.59***
Striga count	-	-	-	-	1	-0.75***	-0.80***	-0.66***
Dry weight	-	-	-	-	-	1	0.78***	0.68***
Grain yield	-	-	-	-	-	-	1	0.57***
Panicle length	-	-	-	-	-	-	-	1

s – Significant ***

Discussion

The study examined the response of fourteen sorghum lines to Striga parasitism in a Striga sick field where optimum fertilizer (60:60:0) was applied and in plots without fertiliser application. The tolerant sorghum lines were compared against the wild relatives. There is a tripartite interaction between Striga, sorghum, and the application of fertilizer. The nutrition balance of a plant affects its resistance to diseases (Tadesse 2018. Enhancing soil fertility through fertilization limits Striga infestation (Gebremariam & Assefa, 2015). Application of nitrogen and phosphorus-rich fertilizers reduced Striga attack as shown in Table 2. Fertilizers are majorly comprised of macro-nutrients including nitrogen. Deficiency in phosphorus and nitrogen promotes strigolactone exudation (Akdeniz et al., 2016). Nitrogen fertiliser delays Striga emergence because it reduces the stimulant exudation from the host plant. Application of fertiliser to the Striga infested sorghum field has a significant effect on the plant's height, days to Striga emergence, and dry weight of sorghum (Table 3 and 5).

Striga traits

Most of the Striga emerged 25 days after planting. The parasitic weed did emerge in all the plots managing to attach to the roots of all the sorghum genotypes used in this study. The delay in emergence can be explained by the presence of a resistance gene that prevented the attachment of haustorium to the host plant (Pescott, 2013). Sorghum line Asareca T1 known to be tolerant to Striga infectivity was found to have the least mean number of Striga seedlings attached and emerged in both plots with or without fertiliser. In plots without fertiliser application, sorghum line 2026 was colonized by 26 Striga seedlings. In plots in which fertilizer was augmented, sorghum line Tabat was colonised with 25 Striga seedlings with significant differences observed between 2026 and Tabat. There were no significant differences observed in the number of Striga that attached and emerged in sorghum lines Asareca T1, Tabat, 2029, 2026, 2028, 2038, 2040, 2048, 2054, 2060, and 2006 in plots augmented with fertiliser and those without fertilizer.

The tolerant lines supported few attachments of the hemi-parasite. It can be partly being explained by the low stimulant production capacity of the genotypes. It is currently known that strigolactone production, a group of Striga germination stimulant produced by the host plant result in Striga seeds germination (Beyena & Egigu, 2018; Mrema *et al*. 2017). It is also widely acknowledged that production of strigolactones among the host genotypes is responsible for variations in the number of Striga attachment among the genotypes (Jamil *et al*., 2011; Runyon *et al*., 2009). The number of Striga seedlings attached and emerged on sorghum cultivars is an indicator of their tolerance or susceptibility to Striga infectivity. In addition thecapacity of genotypes to produce stimulants has not been examined yet. Therefore, there is a need for further research to be carried to establish if differences in the attachment on the genotype are because of varieties' onset and capacity to produce germination stimulants. These findings indicate that application of fertilizer impacted on the Striga count. Analysis of the three-year data showed significant differences among sorghum genotypes and fertiliser rates in all the studied variablesparameters.

Similarly, Striga took longer days to emerge in varieties that seemed tolerant. The study outcomes agree with that of Showewimo et al (2012), which found that fertiliser application delays Striga germination. The nitrogen delayed the production of Striga germination stimulants. Reduced soil fertility through non-fertilization resulted in increased Striga infestation in plots without fertilizer plots in all the studied genotypes. Based on the Striga count, the susceptible lines lacked the genes for host resistance to Striga attack. Fertilizer application reduced Striga count (Table 2). Akdeniz et al. (2016), reported that higher Striga emergence occurs in soils with low fertility. From the study, plots without fertiliser recorded higher incidences of Striga colonisation.

Sorghum agronomic traits

Most of the Striga had emerged 25 days after planting. The parasitic weed did not emerge in all the plots managing to attach to the roots of all the sorghum genotypes used in this study. The delay in the Striga emergence can be explained the presence of a resistance gene that prevented the attachment of the haustorium to the host plant (Pescott, 2013). From the study, the tolerant lines supported few attachments of the parasite. This can be partly being explained by the low stimulant production capacity of the genotypes. It is currently known that strigolactone production, a group of Striga germination stimulant produced by the host plant result in Striga seeds germination. It is also widely acknowledged that the production of strigolactones among the host genotypes is responsible for variations in number of Striga attachment among the genotypes (Jamil *et al*., 2011; Runyon *et al*., 2009). The capacity of genotypes to produce stimulants has not been examined yet. Therefore, there is need to further research to be carried to establish if the differences in attachment on the genotype is as a result of their onset and capacity to produce germination stimulants. These findings indicate that the application of fertilizer impacted on the striga count. Analysis of variance of the three-year data showed significant differences among sorghum genotypes and nitrogen rates in all the studied parameters.

Parasitism of sorghum by S. hermonthica and reduction of its growth and grain yield due to this parasitic weed had been reported by Showemimo (2010) as well as by Runo and Kuria (2018). Infestations by *S. hermonthica* causes severe sorghum yield reduction in which farmers lose sometimes up to 100 percent percent grain production (Zerihun, 2015). The percentage yield loss of course depends on factors such as the density of the parasite, sorghum variety, soil nutrient status and rainfall patterns (Atera et al., 2012). From the table on grain yield, it can be seen that fertilization had a significant effect on the total yield in all the sorghum genotypes. The tolerant varieties recorded the highest yields. It shows that the lines can perform better when they are planted with fertilizer but the yield is not that much when fertilizer was not applied. In this regard, the grain sorghum variety Asareca T1, used as a control recorded the highest mean yield in both plots together with the sorghum lines 2029, 2026, 2040, 2038, 2048, 2060, and 2054, which may be advanced for further breeding. They are consistently higher regardless of whether fertilizer was applied or not. In general, it can be observed that based on the degree of tolerance, the sorghum line 2040, Asareca T1, 2054, and 2060 can be selected as the best variety according to the number of days Striga emerged, number of attached Striga and grain output (Table 3). The tolerant lines showed significantly lower and delayed emergence of *S. hermonthica* and higher grain yield than the susceptible cultivars. Since there is a significant ($p < 0.05$) relationship between fertilised and unfertilised plots, the total grain yield in all the varieties was the highest in fertilised plots and lowest in non-fertilised plots. It may be concluded that that the tolerant lines are not only Striga resistant but also unlock the productivity potentials of their recurrent parents in Striga endemic areas.

There are significant ($p > 0.05$) differences in plant height between the two fertiliser regimes. The variation in plant height cannot be attributed to the different fertilisation levels. Under infestation, sorghum growth, as indicated by height was differentially affected by variety. Plant height of uninfected sorghum was significantly different from that of infected plants/susceptible varieties. According to Rebeka *et al*. (2013), the MAXI gene is present in all the sorghum cultivars susceptible to Striga. The MAXI gene is a reliable molecular marker in sorghum to accurately differentiate resistant and susceptible sorghum cultivars to *S. hermonthica.* The expression of plant height in the field is regulated by the genetic composition of the variety, growth environment, and management practices such as fertilization and hand weeding. The interactions of all these three contributed to tolerant sorghum lines producing taller plants, while the susceptible lines produced shorter plants.

It was found that there were significant differences ($p < 0.05$) in the panicle length between the fertilised and non-fertilised plots. When fertiliser was not applied the genotypes recorded reduced panicle length meaning that the total grain yield was less. This result confirms the finding of Gebremedhin *et al*. (2000) noted that under the competition for water and nutrients with *S. hermonthica*, the sorghum plants may strategically divert their dry matter to roots and leaves so that the morphological changes due to the parasite were best observed on the panicle. The results agree with that of Press et al. (2013) who reported a drop in dry matter in two sorghum cultivars, CSH and Ochuti, infected with *S. hermonthica*. Reduction in the total dry weight under infestation was more pronounced in the susceptible lines grown in plots without fertilizer. Sorghum line 2030 had the lowest dry matter regardless of the Striga count, while the variety 2026 had the highest total dry matter in both fertilized and un-fertilized plots. *S. hermonthica* has deleterious effects on the grain yield among the susceptible sorghum genotypes because it depletes the plant nitrogen, carbon and inorganic salts (Hassan *et al*., 2009).

The results showed that, when sorghum is grown under high Striga infestation, it generates less biomass (Table 5). The responses of sorghum biomass to the two fertilisation rates were significantly different ($p < 0.05$). The *Striga hermonthica* infection clearly had a stronger effect on every cultivar, although the parasite affected growth and dry matter allocation in both cultivars (Table 5). The reduction in biomass production was accompanied by a relatively increased allocation of dry matter to the roots. These observations are well-known symptoms of infected host plants (Patrick *et al*., 2004). These findings were consistent with what our study reported. It implies that when fertiliser is applied to sorghum lines infected with Striga, they would have increased dry matter content. Fertilisation plays a major role in increasing or reducing the height of a plant. As seen in Table 6, the plant height varied between the fertilizer rates.

Days to maturity negatively correlated with all the traits except Striga count ($r = 0.76$, $p < 0.05$) because as the Striga attacked the plants in large numbers they competed the same nutrient supply. The number of Striga that emerged and attached to the host plant reduced with increased days to maturity because the plants responded to the increased stress from Striga attack. If one structure is favoured than another, a negative correlation is evident. Days to Striga emergence ($r = 0.62$) was positively correlated to all parameters except Striga count ($r = - 0.64$, $p < 0.05$). The plants that took more days to record Striga emergence produced less strigolactone, which prevented the attachment of the haustorium and are considered as the tolerant cultivars. Striga is an obligate out-crossing parasite, which is responsive to germination stimulants including strigolactone (Beyene *et al*., 2016). It enables the weed to locate the roots of the host plant. The positive correlation between the days to Striga emergence and number of Striga indicates the plant had no defensive mechanism against the Striga attack because they are susceptible, which led to increased germination.

Further, the correlation results imply that the more days the sorghum cultivars took to mature the lesser the grain yield, lower dry weight, shorter panicles, and reduced plant height. These cultivars can be classified as susceptible. There was a positive correlation between days to maturity and Striga count. The ones that took more days to mature and had more tillers can be categorized as susceptible cultivars. The plants in plots with fewer Striga count took less days to mature and had fewer tillers. These cultivars can be categorized as tolerant the activity of the germination stimulant is controlled by a single recessive gene (lgs), with lines with low germination-inducing activity having good tolerance towards Striga (Daffallah, 2018). However, the Striga count has negative correlation with other traits grain yield because as a hemi-parasite it means that even though it can photosynthesize, it relies on its host for nutrients and water. The results agree with that of Kim *et al*. (2012) in maize.

Tolerant genotypes exhibit smaller variations in yield than susceptible genotypes under the same level of Striga infestation and conditions (Haussmann *et al*., 2000). The positive correlations in these results show that the selection of high yielding and Striga tolerance should include vigorous plants because good plant vigour discourages early Striga infestation that may lead to total crop loss. Increased plant height, grain yield and longer panicle length are among the phenotypic traits that can be used to select Striga tolerant varieties. It can be concluded that all the studied traits under Striga attack are quantitatively heritable. They can easily be improved through selection for higher grain yield.

Conclusion

This study obtained significant variations among the genotypes in response to Striga infestations both under field conditions. Striga weed significantly reduced sorghum performance in terms of plant height, dry shoot mass, and grain yield with susceptible genotypes suffering severe losses and recording higher Striga damage ratings. In this study it was observed that the sorghum genotypes Asareca T1, 2026, 2029, 2038, 2040, 2048, 2054, and 2060 are tolerant to *S. hermonthica* infestation, while Tabat, 2006, 2011, 2012, 2015, 2021, 2028, and 2030 lines were susceptible Striga attack. Growth reduction and the consequent loss of Sorghum yield as a result of infestation and parasitic activity of Striga as observed in this study require integrated management approaches including selection for resistance for increased Sorghum production. . The tolerant varieties have the potential to be grown in Striga endemic areas where majority of resource poor farmers are situated. The studied variables confirm that the hypothesis that sorghum genotypes have varied sensitivities to Striga attack under fertilised and non-fertilised conditions. All the genotypes recorded improvements when optimum fertilizer (60:60:0) was applied. The work revealed high Striga resistance in the wild sorghum accession (Asareca T1). Striga infestation can be controlled using optimum fertilization and tolerant sorghum lines. Grain yield losses are determined by the levels of tolerance of the host genotype, by severity of infestation and by the levels of soil fertility. The following lines can be selected for advanced breeding purposes: 2026, 2029, 2038, 2040, 2048, 2054, and 2060 because they appear to be tolerant to Striga infectivity because of the reduced days to Striga attack, higher yields, longer panicles, and higher dry biomass. The identified genotypes can be used directly by farmers to improve their yields in Striga prone areas or for further breeding. Further research can be done on how the different strains of *S. hermonthica* affects these sorghum genotypes and their capacity to produce stimulants.

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