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Response of selected sorghum (*sorghum bicolor* (l.) moench) genotypes to *striga hermonthica* (del.) benth in western Kenya

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Sorghum is an important staple food crop in Kenya, but its yield is low due to many constraints which include diseases, drought, soil fertility, and pests, notably parasitic weed *Striga hermonthica.* Twenty elite sorghum genotypes and one resistant check were evaluated in three replications in a complete randomized design in Agar Gel (AG) experiment and randomized complete block design on selected *Striga* hotspot farms at Kadel and Nyahera in western Kenya. Significant differences (p<0.001) were realized both in the fields (plant height, dry shoot biomass yield, grain yield, field *Striga* count, and *Striga* damage ratings) and in the AG experiment with respect to maximum germination distance and numbers of induced germinated *Striga* seeds. Among the sorghum genotypes evaluated under field conditions, T53B, N57, N68, C26, IESV 92036-SH, T30B, and Uyoma 47 White genotypes had stable yields under *Striga* infestation in the two sites, whereas Nyadundo 1, Nyadundo 2, and Uyoma 8 were susceptible. In the AG experiment, E117B, T30B, Uyoma 8, Uyoma 42 STR, and T53B induced high numbers of germinated *Striga* seeds with maximum germination distances (MGD). In contrast, Uyoma 47 Brown, IESV 92038/2-SH, and IESV 92036-SH sorghum genotypes secreted low amounts of SLS suggesting resistance. This study has identified and selected four *Striga* tolerant (T53B, N68, N57, and T 30B) and resistant (C 26, Uyoma 47 Brown, IESV 92038/2-SH, and IESV 92036-SH) sorghum genotypes which can be utilized in further research programs or adopted to improve sorghum productivity in the highly *Striga* infested regions of western Kenya.

Key words: Striga, sorghum genotypes, resistant, susceptible, tolerant, Agar Gel experiment

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is the fifth most important staple food crop that can meet the increased food needs of more than 500 million people in marginal regions that still experience periodic food deficits (Aragaw et al., 2021). Its drought tolerance and ability to withstand more of other biotic and abiotic stresses compared to maize has made it an important food security crop in most regions of sub-Saharan Africa (Hadebe et al*.,* 2017).

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In Kenya, it is grown mainly under unreliable rain-fed agriculture in *Striga* stricken agricultural regions of Eastern and western Kenya (Muui et al., 2019).The area under subsistence cultivation of sorghum in Kenya has increased from 240,403 ha in 2018 to 301,705 ha in 2019 (FAOSTAT 2019), this owes to the resilience of the crop and frequent maize failures experienced especially in the drought-prone agricultural regions of Kenya (Okeyo et al., 2020). Despite this, the national yield average of sorghum has remained low at 0.8 tons per hectare (Okeyo et al., 2020) attributed to a number of abiotic and biotic constraints, especially drought and increased susceptibility of the cultivars to *Striga* weed. This follows despite sustained research intervention measures such as breeding for better yields and distribution of high-yielding and stress-tolerant sorghum varieties (Atera and Onyango, 2011).*Striga hermonthica* is the largest biological constraint to sorghum production in Sub-Saharan Africa (Yohannes et al., 2017). The weed is invasive and has rapidly invaded new geographical regions that were initially free from *Striga* (Teka, 2014). Studies have shown that *Striga* can reduce host grain yield to almost zero in high field infestation levels and as a result, many farmers have abandoned their fields that are no longer productive (Shaibu et al., 2021). In Sub Saharan Africa, yield losses due to *Striga* in sorghum and millet ranges between 20 to 95 and are estimated at approximately US $ 7 billion annually (Joel and Muchugi, 2018) In Ethiopia and Sudan, grain yield losses of between 65 to 100% have been reported from heavily infested fields (Bejiga, 2019). In Kenya, about 80,000 hectares cropped to Maize, Sorghum, and Millet are severely infested causing an estimated respective average grain yield losses of 1.15, 1.10, and 0.99 tons per hectare (Makete et al., 2017). The observed *Striga*-related high yield losses have occurred mainly due to the wide adoption of cultural methods of *Striga* control such as crop rotation of infested land with non-susceptible crops, prolonged fallowing, sanitation, and hand weeding of mature *Striga* plants particularly in subsistence farming. The practical limitations of these techniques are the more than 3 years required for rotation together with the tedious, and time-consuming nature of hand weeding of mature *Striga* plants that have rendered these *Striga* control methods impractical and less effective in controlling *Striga* (Lee and Thierfelder, 2017). Besides, the recommended chemical control methods such as the application of ethylene for suicidal *Striga* seed germination and use of nitrogen fertilizers go beyond the reach of small-scale farmers and are not feasible due to high costs (Abbas et al., 2018). Biological methods of control on the other hand are less available to farmers due to the required implementation technical skills (Bo et al., 2020). Therefore, developing Striga-resistant sorghum genotypes could provide a sustainable long-term solution to the *Striga* problem especially to the resource-poor farmers since its adoption requires no additional input (Badu-Apraku and Fakorede, 2017). *Striga* damages its

host in several ways which include withdrawal of hosts (photosynthate, water, mineral nutrients, and amino acids), allelopathy, hormonal imbalance, and reduction of the host's photosynthetic parameters. These effects lead to phenotypically reduced heights, leaf necrosis, and relatively small panicle sizes in the infested host (Beyene and Egigu, 2020). The extent of host agronomic damage is determined mainly by its resistance, tolerance, or susceptibility to *Striga*. The genotypes which support the growth of few *Striga* plants and suffer minimal agronomic damage are considered to be resistant while those that are tolerant can produce equally good yield even when under severe field *Striga* infestation (Mbuvi et al., 2017). The susceptible genotypes, on the other hand, incur high yield depression due to reduced panicle sizes and often fail to reach the reproductive stage either when under severe or low *Striga* infestation (Dafaallah and Babiker, 2019). These observations encourages breeders to develop more resistant/tolerant sorghum cultivars to minimize *Striga*-related high yield losses since field observations and surveys still indicate that some genotypes grown locally by farmers are tolerant to *Striga* and can produce good yield even when highly infested with *Striga* (Joel et al., 2018).

Strigolactones (SLs) exuded by sorghum roots and other *Striga* host plants is critical for both host's root symbiotic colonization by arbuscular mycorrhizal (AM) fungi and induction of germination of conditioned soil *Striga* seeds (Waters et al., 2017; Mohemed et al., 2016). The genotypes, which secretes low amounts of SLs stimulates the germination of few conditioned soil *Striga* seeds and consequently support the growth of few *Striga* plants in field trials (Gobena et al., 2017). Conversely, all high producers of SLs lead to severe field *Striga* infestation often associated with susceptibility of the genotypes (Mohemed et al., 2018). Only a few studies have developed sorghum genotypes that are *Striga* resistant based on SLs secretion, thus the need to investigate a billion folds variations in the amount of SLs production among the cultivated and newly released lines/cultivars (Waters et al., 2017). Therefore, characterization of cultivars for SLs production together with field evaluation is a sure way of identifying resistant/tolerant genotypes, the genotypes that could be integrated to improve *Striga* management among small-scale sorghum farmers. The objectives of the study were, therefore, to assess performance of elite sorghum genotypes in yield and yield components under field *Striga hermonthica* infestation and to evaluate the genotypes' variations in SLs production determined by maximum germination distances and numbers of induced germinated *Striga* seeds in agar gel assays under laboratory conditions.

MATERIALS AND METHODS

Twenty-one (21) elite sorghum materials (Table 1) from Maseno

Table 1. Sorghum materials evaluated in the Agar Gel experiment and under natural *Striga hermonthica* infestation at Kadel and Nyahera sites in the seasons of September 2018 and March 2019.

Genotype	Description/ Trait	Source
IESV 92022/1-SH	White seeded and early maturing	ICRISAT
N 13(Resistant Check variety)	Brown seeded and very early maturing	ICRISAT
IESV 92042-SH	White seeded and early maturing	ICRISAT
IESV 92036-SH	White seeded and early maturing	ICRISAT
IESV 92038/2-SH	White seeded and early maturing	ICRISAT
T53B	Red seeded and late maturing	Rongo University
T30B	Red seeded and late maturing	Rongo University
Nyadundo 1	Red seeded and very early maturing	Rongo University
Nyadundo 2	Red seeded and very early maturing	Rongo University
C26	Brown seeded and early maturing	Rongo University
N57	Red seeded and late maturing	Rongo University
MUK60	Red seeded and early maturing	Rongo University
N68	Red seeded and late maturing	Rongo University
E117B	Brown seeded and early maturing	Rongo University
Uyoma 47 Brown	Brown seeded and very early maturing	Maseno University
Maseno 49	Brown seeded and very early maturing	Maseno University
Uyoma 42STR	White seeded and early maturing	Maseno University
Uyoma 8	White seeded and early maturing	Maseno University
Maseno 6	White seeded and early maturing	Maseno University
Uyoma 47 White	White seeded and early maturing	Maseno University
Uyoma 6	White seeded and early maturing	Maseno University

University, Rongo University, and International Centre for Research in Semi-Arid Tropics (ICRISAT) breeding programs were used in the study. Some of the materials have been released as varieties while others are elite materials yet to be released.

Experimental site description

Field trials for *Striga* resistance were respectively conducted in *Striga* hot spots at Nyahera and Kadel in Kisumu and Homabay counties. Nyahera lies at a longitude of 34°53.452′E, latitude of 0°35.977′N, and an altitude of 1490 m with an average annual rainfall of 1650 mm per annum. The soils are classified as ferralic with a pH of 5.9 (Mbogo et al., 2016). Kadel is found at a longitude of 34°24°E, latitude N-0°11'27" S, and an altitude of 1400 m above sea level with an average annual rainfall of 1200 mm (Ogenga et al., 2018). The soils are vertisol with a pH of 7.3 and made of fine loose textured clay soils. The two sites have a bimodal rainfall pattern where the first peak falls between March and June (Long rains season) and the second peak between September and December (short rains season).

Experimental design and field layout

Field trials for *Striga* resistance in the sorghum genotypes were laid out in a randomized complete block design (RCBD) replicated three times with two treatments, *Striga* plots, and *Striga* free plots. Evaluation of genotypes at Nyahera site was carried out under natural *Striga* infestation in the short rains of September 2018 and both under *Striga* free and *Striga* infestation in the long rains of March 2019. Nyahera is a site that had been used for *Striga*

research by various organizations such as Nairobi University and International Maize and Wheat Improvement Center (Mbogo et al., 2016), the site, therefore, had already established *Striga* plots and *Striga* free plots. At Kadel, successful evaluation of sorghum genotypes was carried out only in the long rains of March 2019 under natural *Striga* infestation, given that the whole site was *Striga* infested. Land preparation was done using a disc plough and harrowed twice before planting. Planting in each plot was made in four-rows measuring 3 m in length with a row spacing of 0.75 m and plant spacing of 0.2 m. Hand hoe weeding was carried out before *Striga* emergence and thereafter weeds other than *Striga* were regularly handpicked. In *Striga* free plots, hand hoe weeding was practiced throughout the trial as opposed to hand weeding.

Data collection

In *Striga* infested plots, emerged *Striga* counts and host damage ratings were recorded per genotype in the net plots (two central rows) at intervals of 8, 10, and 12 weeks after crop emergence. *Striga* damage ratings were scored using a scale of 1-5 as described by Haussmann et al. (2000b) where 1=no damage, indicating normal plant growth and high level of tolerance, and 5 representing complete collapse or death of highly susceptible sorghum genotypes. At maturity, the data was collected on dry shoot biomass yield (Kg) and grain yield (t/ha) in both *Striga* plots and *Striga* free plots.

Genotypic variation in SLs secretion among the sorghum genotypes

The Agar Gel experiment was carried out in Maseno University

botanical laboratory using *Striga* seeds obtained from ICRISAT and sorghum genotypes listed in Table 1. Maseno University is found along the equator at a latitude of 0^0, latitude 34° 30'E, and an altitude of 1515 m above sea level.

Surface sterilization of sorghum seeds

Sorghum seeds were surface sterilized for 5 min in 10 ml of 1% sodium hypochlorite solution, rinsed three times with distilled water, and incubated in petri dishes on moist filter papers at 28°C for 24 h. Vigorously and uniformly germinating seeds were selected and used in the agar gel assay.

Surface sterilization, viability test, and conditioning of the *Striga* seeds

0.5 mg of dry *Striga* seeds were surface sterilized in a 10 mL of 1% sodium hypochlorite solution for 5 min in a 50-mL flask containing 3 drops of Tween 20. Floating seeds and debris were discarded and the remaining seeds rinsed thoroughly with 200 ml of sterile distilled water. The *Striga* seeds were spread on a glass fiber filter paper (Whatman GFA) in sterile petri dishes wetted with 5 ml of sterile distilled water. The petri dishes were wrapped with aluminum foil and incubated for 8 days at 30°C. To test for seed viability the procedure described by Gbèhounou et al. (1996) was used. Briefly, 1.5 ml of a 1% tetrazolium salt solution was added to the *Striga* seeds after 8 days of incubation and the viable pink stained *Striga* seeds were counted under a microscope. The viable seeds were then conditioned for 14 days at 30°C following the procedure described by Mohamed et al. (2010).

The Agar Gel Technique (AGT) Assay

The experiment was setup in a completely randomized design (CRD) replicated three times. Approximately 1500 conditioned *Striga* seeds (4 drops of settled seeds) were pipetted into sterile 9 cm diameter Petri dishes. A 0.7% water agar solution (1.05 g bacto agar in 150 ml H_2O) that had been autoclaved for 15 min and cooled for at least one hour was poured before it solidified into petri dishes containing an even distribution of conditioned *Striga* seeds. The radicles of the pre-germinated sorghum seeds were submerged in the center of the solidifying agar near one edge of the plates with the root tips pointing across the plate. The dishes were covered and placed in an incubator at 28°C for five days. The germinated *Striga* seeds were observed through the bottom of the petri dishes using a dissecting microscope and positions of germinated *Striga* seeds marked and the distances in cm between the sorghum roots and the furthest observed germinated *Striga* seeds measured and recorded for each sorghum genotype. The procedure described by Mohamed et al. (2010) was used.

Data analysis

The variance analysis (ANOVA) and mean grain yield, dry shoot biomass yield, *Striga* count, *Striga* damage ratings, and numbers of induced and maximum germination distances in the AG experiment were analyzed using Statistical Analysis System (SAS) software package (release 6.1), tested for significance at 5% level and means separated using 5% least significant difference (L.S.D). Actual field *Striga* counts were transformed using the formula log (X + 1), where X is the original field *Striga* counts. Relative yield loss, which is the differences between genotypes' realized grain yields in *Striga* free plots and *Striga* plots, was calculated using the formula developed by Rodenburg et al. (2006) shown below:

$$RYL= [(Yc – Ys) / Yc] \times 100$$

Where Yc is the average yield of *Striga*-free plots of a specific sorghum genotype and Ys is the observed yield of the same sorghum genotype grown under *Striga* infestation.

RESULTS AND DISCUSSION

Variations in agronomic performance among sorghum genotypes under field *Striga hermonthica* infestation

The elite sorghum genotypes differed significantly (p<0.001) in grain yield and dry shoot biomass yield under field conditions (Table 2). In the first season of Sep 2018 of field evaluation of genotypes under *Striga* infestation at Nyahera, Uyoma 47 White (2.14 t/ha) and T53B (2.03 t/ha) sorghum genotypes recorded the highest mean grain yields, while Uyoma 8 (0.59 t/ha), Nyadundo 1 (0.64 t/ha), and Nyadundo 2 (0.81 t/ha) genotypes recorded the lowest grain means. In the second season of March 2019 at Nyahera, T53B genotype recorded the highest mean grain yield of 2.47 t/ha while Uyoma 8 recorded the lowest yield mean of 0.54 t/ha under *Striga* infestation. In *Striga* free plots at Nyahera in March 2019 season, the highest and lowest yields of 3.57 and 1.7 t/ha were respectively recorded in T53B and Nyadundo 2 sorghum genotypes. In terms of dry biomass yields, IESV 92036-SH, Uyoma 47 White, and Uyoma 47 Brown sorghum genotypes consistently recorded high biomass means both in the *Striga* infested plots and in *Striga* free plots while Nyadundo 1 and Nyadundo 2 recorded low yield means. In March 2019 at field evaluation of genotypes for *Striga* resistance at Kadel, N57, T53 B, N68, and Uyoma 47 Brown sorghum genotypes exhibited high yields of between 2.25 and 2.50 t/ha while Nyadundo 1 (0.57), Nyadundo 2 (0.58 t/ha), E117B (0.66 t/ha) and Uyoma 8 (0.71 t/ha) yielded low (Table 2). Equally, N57 (0.44 kg) and Uyoma 47 Brown (0.34 Kg) in addition to C26 (0.36 Kg) and IESV 92036-SH (0.34 Kg) sorghum genotypes had high dry-shoot biomass yields, while Nyadundo 1 and Nyadundo 2 genotypes recorded low respective yields of 0.12 Kg and 0.08 Kg. In totality, T53B, N 57, N 68, and T 30B genotypes had stable and high grain yield means ranging between 1.9-2.5 t/ha (Table 2) under high *Striga hermonthica* infestation both at Kadel and Nyahera. C 26, IESV 92036-SH and Uyoma 47 white were also some of the genotypes with good yields above 1.85 t/ha under relatively low Striga infestation, while Uyoma 8, Nyadundo 1, and Nyadundo 2 had poor yields less than 1 t/ha in the two sites.

The differences in the agronomic performances of sorghum genotypes under *Striga* infestation indicated the existence of a large genetic variation among the genotypes. This was expected since the evaluated genotypes were of diverse origin. The observed

Table 2. Mean grain yield and dry shoot biomass yields of sorghum genotypes evaluated at Kadel and Nyahera fields during the seasons of March 2019 and September 2018.

| Genotype | Nyahera's field (Long rains of March 2019) | | | | Nyahera's field (Short rains of Sep 2018) | | Kadel's field (Long rains of March 2019) | |
| | Grain Yields t/ha | | Dry shoot biomass yield(Kg) | | | | | |
	Yield (S)	Yield (SF)	Dry biomass (S)	Dry biomass (SF)	Grain yield t/ha(S)	Dry Biomass (Kg) (S)	Grain yield t/ha(S)	Dry Biomass (Kg) (S)
T53B	2.47[a]	3.57[a]	0.18[fdeh]	0.24[j]	2.03[a]	0.21[fgh]	2.49[a]	0.21[gih]
N57	2.34[ba]	2.83[becd]	0.21[fbdehcg]	0.35[cbd]	2.02[a]	0.51[a]	2.50[a]	0.44[a]
C26	2.30[ba]	2.87[bcd]	0.28[bdac]	0.38[b]	1.85[ba]	0.27[fde]	2.13[ba]	0.36[ba]
N68	2.23[bac]	3.07[bc]	0.20[fbdehcg]	0.33[ced]	1.86[ba]	0.20[figh]	2.40[a]	0.30[cebd]
IESV 92042-SH	2.10[bac]	2.90[bcd]	0.27[bdec]	0.38[b]	2.02[a]	0.31[cd]	1.27[dc]	0.28[cefd]
IESV92038/2-H	2.10[bac]	2.70[fbecd]	0.26[fbdec]	0.44[a]	1.78[bac]	0.29[cde]	1.95[ba]	0.26[gefd]
Maseno 6	2.03[bc]	2.57[fgehd]	0.27[fbdec]	0.37[cb]	1.43[edc]	0.23[fge]	1.23[dc]	0.23[gfh]
T30B	2.0[bdc]	3.17[ba]	0.19[fdehcg]	0.29[fgeh]	1.96[a]	0.22[fge]	2.05[ba]	0.25[gef]
Uyoma 47 Brown	1.87[edc]	2.37[fgehi]	0.33[ba]	0.38[b]	1.84[ba]	0.35[cb]	2.25[a]	0.34[bac]
IESV 92036-SH	1.87[edc]	2.57[fgehd]	0.42[a]	0.44[a]	2.03[a]	0.35[cb]	2.17[ba]	0.34[bac]
Maseno 49	1.83[edc]	2.17[ghji]	0.23[fbdehcg]	0.31[fged]	1.5[bdc]	0.19[figh]	1.96[ba]	0.26[gefd]
Uyoma 47 White	1.83[edc]	2.50[fgehd]	0.33[ba]	0.45[a]	2.14[a]	0.43[b]	2.0[ba]	0.33[cbd]
N13	1.60[edf]	2.03[ji]	0.17[fdehg]	0.29[fgih]	0.88[hg]	0.22[gge]	1.09[dfce]	0.20[gijh]
Uyoma 42STR	1.27[egf]	2.23[fghi]	0.25[fbdecg]	0.35[cbd]	0.96[hgf]	0.19[figh]	1.08[dfce]	0.15[kijl]
IESV92022/1-SH	1.47[egf]	2.63[fgecd]	0.20[fbdehcg]	0.28[jfgih]	1.40[ed]	0.31[cd]	1.63[bc]	0.21[gifh]
Muk60	1.40[gf]	2.27[fghi]	0.11[hg]	0.31[fed]	1.29[edf]	0.16[igh]	1.24[ce]	0.17[kijh]
E117B	1.07[hg]	2.63[fgecd]	0.13[fehg]	0.25[jih]	0.88[hg]	0.20[figh]	0.66[fe]	0.13[kmjl]
Uyoma 6	0.87[hi]	2.1[hji]	0.18[fdehg]	0.27[jgih]	1.10[egf]	0.18[igh]	1.19[dce]	0.16[kijl]
Nyadundo 1	0.67[hi]	2.27[fghi]	0.09[h]	0.17[k]	0.64[h]	0.14[ih]	0.57[f]	0.12[kml]
Nyadundo 2	0.57[i]	1.7[j]	0.09[h]	0.24[ji]	0.81[hg]	0.17[igh]	0.58[f]	0.08[m]
Uyoma 8	0.54[i]	2.2[ghi]	0.13[fhg]	0.38[b]	0.59[h]	0.13[i]	0.71[dfe]	0.12[kml]
Grand mean	1.65	2.54	0.21	0.32	1.48	0.25	1.58	0.23
CV	14.78	11.69	40.74	8.67	15.54	18.88	22.5	18.42
SEM	0.78	0.06	0.014	0.09	0.069	0.013	0.75	0.02
LSD (0.05)	0.40	0.49	0.14	0.05	0.38	0.08	0.60	0.07
P	***	***	***	***	***	***	***	***

Means followed by the same letter(s) along the columns are not significantly different at p<0.05. (S)-Striga plot, (SF)- Striga free plot, CV: Coefficient of variation: SEM: Standard error of the mean: ***- Highly significant at (P<0.001, **-significant at   P <0.01, *-Significant at p<0.05). LSD: Least significance difference.

variations in the grain and dry shoot biomass yields under *Striga* infestation imply differences in the genotypes' genetic potential and probable differences in their *Striga* tolerance/resistance mechanism. Although T53B, N57, N68, and T30B sorghum genotypes experienced high *Striga* infestation levels, the genotypes still recorded high yields and had low *Striga* damage scores, and, therefore, were considered as tolerant materials. C26, IESV 92038/2-SH, IESV 92036-SH, and Uyoma 47 Brown had good grain yields but with comparatively low *Striga* counts and were classified as resistant. However, Nyadundo 1, Nyadundo 2, and Uyoma 8 sorghum genotypes were regarded as susceptible after they recorded very low grain yields under high *Striga* infestation.

These findings agree with those of Van et al. (2000) in sorghum and Menkir et al. (2012) on maize hybrids who together observed that both the tolerant and resistant genotypes displayed fewer disease symptoms, had low *Striga* damage ratings and produced relatively higher yields than their susceptible counterparts produce. Akaogu et al. (2013) also reported similar results after evaluating the performance of maize inbreds and hybrid under *Striga*-infested and *Striga*-free environments. The low grain and dry shoot biomass yields especially in the susceptible sorghum genotypes could have resulted due to reduced photosynthetic process together with the withdrawal of photosynthates in the host crop as a result of *Striga* infestation. According to Frost et al. (1997) who investigated the effect of *Striga hermonthica* on the rate

Table 3. Percentage relative losses of grain yield, dry shoot biomass yield, and plant height due to *Striga* infestation of sorghum genotypes evaluated at Nyahera during the long rains of March to June 2019.

Genotype	Relative Yield Loss (%)		
	Grain yield	Dry Shoot Biomass	Plant height
Maseno 49	16	26	14
N57	17	40	22
C26	20	26	15
N 13	21	41	36
Uyoma 47 Brown	21	13	20
Maseno 6	21	27	36
N68	27	39	31
Uyoma 47 White	27	27	12
IESV 92036-SH	27	5	17
IESV 92042-SH	28	29	13
T53B	31	33	34
Muk60	38	65	24
T30B	40	34	38
Uyoma 42STR	43	29	21
IESV92022/1-SH	44	29	13
IESV92038/2-H	48	40	14
Uyoma 6	59	33	13
Nyadundo 2	66	63	29
Nyadundo 1	70	47	35
E117B	74	48	32
Uyoma 8	75	66	34
Mean	37.45	36.19	23.95

Means followed by the same letter(s) along the columns are not significantly different at p<0.05, LSD: Least significant difference. ***- Highly significant at (P<0.001, **-significant at P<0.01, *-Significant at p<0.05), CV: Coefficient of variation: SEM: Standard error of the mean.

of host's photosynthesis, about 80 to 85% of growth loss occur in *Striga* infested susceptible host due to a reduction in the host's photosynthetic capacity to less than half of that in healthy hosts.

The relative grain yield losses ranged from 16 to 75% (Table 3). Uyoma 8 and E117B sorghum genotypes had the highest relative grain yield losses of 75 and 74% respectively while low scores were recorded in Maseno 49 (16%), N57 (17%), C26 (20%), Uyoma 47 Brown (21%), and N13 (21%) genotypes. Reductions in plant dry shoot biomass yields also occurred in the genotypes due to *Striga* infestation. The highest reductions were recorded in Muk 60 (65%), Nyadundo 2 (63%), and Uyoma 8 (66%) genotypes while the lowest reductions of 5 and 13% were respectively obtained in IESV 92036-SH and Uyoma 47 Brown sorghum genotypes (Table 3). For plant height, the highest and lowest reduction of 38 and 12% were respectively recorded in T30B and Uyoma 47 White sorghum genotypes. The high relative grain yield

losses in the susceptible genotypes observed in this study conform to the findings of Mrema et al. (2017) who investigated production constraints of sorghum and *Striga* control practices and reported high yield losses in the susceptible sorghum genotypes infested with *Striga*. The findings of this study are also comparable to previous studies in maize by Badu-Apraku and Akinwale (2011) and sorghum by Abate et al. (2014) who reported significant reductions in plant height, ear height, and smaller panicle sizes in the genotypes evaluated in *Striga* plots than in *Striga* free plots.

Variations in the sorghum genotypes' and fields levels of *Striga* infestation

Significant genotypic variations (p<0.001) in the numbers of emerged *Striga* plants and *Striga* damage ratings were observed among the sorghum genotypes at 12 weeks

Table 4. *Striga* count and *Striga* damage ratings of sorghum genotypes evaluated at Nyahera and Kadel sites in the short rains of September 2018 and long rains of March 2019.

Genotype	Nyahera site (Short rains of Sept 2018)		Nyahera site (long rains of March 2019)		Kadel site (long rains of March 2019)	
	Striga count (12 w.a.c.e)	SDR (12 w.a.c.e)	*Striga* count (12 w.a.c.e)	SDR (12 w.a.c.e)	*Striga* count (12 w.a.c.e)	SDR (12 w.a.c.e)
E117B	2.54[a]	4.0[a]	2.55[a]	3.7[ba]	2.74 [a]	3.3[b]
Uyoma 8	2.53[a]	4.0[a]	2.51[ba]	4.0[a]	2.71[ba]	4.0[a]
Nyadundo 1	2.51[a]	3.0[b]	2.48[ba]	3.0[c]	2.62[bc]	4.0[a]
N57	2.46[ba]	2.33[cbd]	2.47[ba]	2.3[d]	2.60[bc]	2.3[dc]
Nyadundo 2	2.45[ba]	3.0[b]	2.46[ba]	3.3[bc]	2.60[c]	4.0[a]
T53B	2.44[ba]	2.33[cbd]	2.45[ba]	2.0[ed]	2.59[c]	2.0[d]
T30B	2.42[ba]	3.0[b]	2.45[ba]	2.0[ed]	2.58[dc]	2.0[d]
N68	2.40[ba]	2.33[cbd]	2.42[b]	2.0[ed]	2.57[dc]	2.0 [d]
Uyoma 6	2.38[bac]	2.0[ced]	2.41[b]	3.3[bc]	2.48[de]	2.0[d]
Uyoma 42STR	2.37[bdac]	2.67[cb]	2.27[c]	3.0[c]	2.48[de]	2.7[c]
Maseno 6	2.30[bdec]	2.67[cb]	2.26[c]	3.0[c]	2.43[fe]	2.3[dc]
MUK60	2.20[fdec]	3.0[b]	2.24[c]	2.0[ed]	2.39[feg]	2.3[dc]
Uyoma 47 White	2.17[fde]	1.67[fed]	2.20[dc]	2.0[ed]	2.33[fhg]	2.0[d]
IESV92022/1-SH	2.16[feg]	2.0[ced]	2.18[dc]	1.7[e]	2.32[fhg]	2.0[d]
N 13	2.04[fhg]	2.0[ced]	2.1[de]	2.0[ed]	2.29[ihg]	1.3[e]
Maseno 49	1.96[hg]	1.33[fe]	2.08[def]	2.0[ed]	2.26[ihj]	2.0[d]
IESV 92042-SH	1.96[h]	2.0[ced]	2.04[ef]	1.7[e]	2.25[ihj]	2.0[d]
IESV92038/2-SH	1.95[h]	1.67[fed]	2.03[ef]	1.7[e]	2.24[ihj]	2.0[d]
IESV 92036-SH	1.91[h]	1.33[fe]	2.02[ef]	2.0[ed]	2.24[ihj]	2.0[d]
C26	1.91[h]	2.0[ced]	2.02[ef]	2.0[ed]	2.15[ij]	1.3[e]
Uyoma 47 Brown	1.60[i]	1.0[f]	1.98[f]	2.0[ed]	2.24[j]	2.0[d]
Grand mean	2.22	2.35	2.27	2.41	2.43	2.37
CV	5.40	18.58	3.28	13.82	2.70	14.09
SEM	0.034	0.11	0.03	0.025	0.024	0.11
LSD (0.05)	0.20	0.72	0.12	0.55	0.108	0.55
P	***	***	***	***	***	***

Means followed by the same letter(s) along the columns are not significantly different at p<0.0.5.w.a.c.e: Weeks after crop emergence. LSD: Least significance difference. ***- Highly significant at (P<0.001, **-significant at   P <0.01, *-Significant at p<0.05).

after crop emergence (Table 4). At Nyahera site during the short rains of September 2018, C26, IESV 92036-SH, and Uyoma 47 Brown genotypes had the lowest mean emerged *Striga* counts and *Striga* damage ratings while E117B, Uyoma 8, and Nyadundo 1 genotypes had the highest mean emerged *Striga* counts and *Striga* damage ratings. In March 2019 in the same field, E117B, Uyoma 8, Nyadundo 1, N57, Nyadundo 2, T53B, T30B, N68, and Uyoma 6 supported the growth of many *Striga* plants that ranged between 2.41-2.55 per plot compared to *Striga* counts of 1.98 in Uyoma 47 Brown and 2.02 for both C26 and IESV 92036-SH. In terms of *Striga* damage ratings (SDR), the most affected sorghum genotypes under *Striga* infestation were Uyoma 8 and E 117 B with mean SDR scores of 4.0 and 3.7 respectively, while the least affected genotypes were IESV 92042-SH, IESV 92022/1-SH, and IESV 92038/2-SH, all with a low SDR score of

1.7. The *Striga* counts and *Striga* damage ratings followed a similar trend at field evaluation of genotypes for *Striga* resistance at Kadel in March 2019.

The variations in the genotypes' field levels of *Striga* infestation could have been due to their differences in the amount of secreted strigolactone. The productions of root exudates and *Striga* seed germination have been found to correlate positively (Mohemed et al*.,* 2016). The consistently reduced or high numbers of *Striga* plants supported by the evaluated sorghum genotypes under natural field *Striga* infestations in the two sites suggested similarity in response to *Striga* infestation in the two sites.

Kadel site had a higher and significantly different (p<0.001) mean *Striga* count of 2.43 compared to 2.27 realized at Nyahera site (Table 4). The observed difference in *Striga* infestation levels between the two sites could have resulted probably due to a higher pre-

Table 5. Analysis of variance for effects of genotypes, environment, and seasons.

Effect		Value	F	Erro diff	Sig diff
Intercept	Pillai's Trace	1.000	148510.719[b]	125.000	0.000
	Wilks' Lambda	.000	148510.719[b]	125.000	0.000
	Hotelling's Trace	2376.172	148510.719[b]	125.000	0.000
	Roy's Largest Root	2376.172	148510.719[b]	125.000	0.000
Genotype	Pillai's Trace	1.416	15.285	252.000	0.000
	Wilks' Lambda	0.048	22.298[b]	250.000	0.000
	Hotelling's Trace	10.179	31.555	248.000	0.000
	Roy's Largest Root	9.117	57.435[c]	126.000	0.000
Environment	Pillai's Trace	0.747	37.584	252.000	0.000
	Wilks' Lambda	0.310	49.714[b]	250.000	0.000
	Hotelling's Trace	2.038	63.181	248.000	0.000
	Roy's Largest Root	1.943	122.385[c]	126.000	0.000
Season	Pillai's Trace	0.747	37.584	252.000	0.000
	Wilks' Lambda	0.310	49.714[b]	250.000	0.000
	Hotelling's Trace	2.038	63.181	248.000	0.000
	Roy's Largest Root	1.943	122.385[c]	126.000	0.000
genotype*Environment	Pillai's Trace	0.984	3.049	252.000	0.000
	Wilks' Lambda	0.231	3.379[b]	250.000	0.000
	Hotelling's Trace	2.402	3.723	248.000	0.000
	Roy's Largest Root	1.918	6.040[c]	126.000	0.000
genotype * Season	Pillai's Trace	0.984	3.049	252.000	0.000
	Wilks' Lambda	0.231	3.379[b]	250.000	0.000
	Hotelling's Trace	2.402	3.723	248.000	0.000
	Roy's Largest Root	1.918	6.040[c]	126.000	0.000
Season * Environment	Pillai's Trace	0.761	4.681	252.000	0.000
	Wilks' Lambda	0.214	16.132	250.000	0.000
	Hotelling's Trace	3.122	5.988	248.000	0.000
	Roy's Largest Root	1.732	6.040[c]	126.000	0.000

existing soil *Striga* seed bank at Kadel. This is because field *Striga* infestation levels have been found to strongly and positively correlate with soil *Striga* seed bank (Samejima et al. 2016). Moreover, previous studies have also indicated that host crops may increase the amount of secreted strigolactone in response to moisture stress (Bahadur et al., 2019; Vurro et al., 2019) resulting in high *Striga* infestation levels evident at Kadel field (Ogenga et al., 2018).

The significant total genotype × environment (G × E) variance (Table 5) that contains interaction effects between the genotypes and specific climatic and edaphic factors such as soil organic content, soil microorganisms, rainfall, and temperature that probably differed between Kadel and Nyahera could have also contributed to the observed differences in the sites' field numbers of emerged *Striga* plants. This finding conforms with the findings of Haussmann et al. (2001) who investigated

genotype × environment interaction patterns for *Striga* resistance in sorghum in Kenya and Mali and reported sites' differences in levels of *Striga* infestations to have been caused by genotypes' different response to climatic conditions. Interaction effects between (Genotype*Season), and (Season*Environment) were also found to be significant (Table 5) and therefore, combined site and seasonal analysis of *Striga* count, *Striga* damage ratings, and agronomic performance of the genotypes were not performed.

Induced and maximum distances of germinated *Striga* seeds in agar gel experiment

The genotypes showed significant differences (p<001) both in the numbers of induced germinated and distances of the furthest germinated *Striga* seeds (Table 6).

Table 6. Means of induced numbers of germinated *Striga* seeds and maximum germination distance (MGD).

Genotype	No. of induced germinated *Striga* seeds	Maximum germinated distance(cm)
E117B	35.67[a]	4.27[a]
T30B	33.33[ba]	4.0[ba]
Uyoma 8	31.0[bc]	3.7[bc]
Uyoma 42STR	30.0[bcd]	3.93[ba]
T 53 B	28.67[cd]	3.83[bac]
N57	28.33[cd]	3.23[ed]
N68	28.0[ecd]	3.0[edf]
Nyadundo 1	28.0[ecd]	3.87[ba]
Nyadundo 2	26.67[ed]	3.87[ba]
Maseno 49	24.0[ef]	3.40[dc]
Uyoma 47 White	21.67[gf]	2.87[ehgf]
IESV 92022/1-SH	19.67[gh]	3.07[edf]
N 13	18.33[gh]	2.93[egf]
Maseno 6	16.67[ih]	2.77[ihgf]
MUK60	16.0[ihj]	2.63[ihgf]
Uyoma 6	15.67[ihj]	2.47[ih]
C26	12.67[ikj]	2.37[i]
IESV 92042-SH	12.0[kj]	2.43[ih]
IESV 92036-SH	10.67[k]	2.40[i]
IESV 92038/2-SH	10.67[k]	2.53[ihg]
Uyoma 47 Brown	10.0[k]	1.47[j]
Lsd (0.05)	4.12	0.44
P	***	***

Means followed by the same letter(s) along the columns are not significantly different at p<0.05.LSD: Least significance difference. ***- Highly significant at (P<0.001, **-significant at P<0.01, *-Significant at p<0.05).

Cultivars E117B, T30B, Uyoma 8, and Uyoma 42STR induced more than 30 mean counts of in vitro germinated *Striga* seeds. The same genotypes also had the highest mean maximum germination distances of between 3.7-4.3 cm. Uyoma 47 Brown (10), IESV 92038/2-SH (10.7), and IESV 92036-SH (10.7) recorded the lowest mean numbers of induced germinated *Striga* seeds and distances of the furthest germinated *Striga* seeds of 1.5,2.5 and 2.4 cm respectively. The induced few and low mean maximum distances of germinated *Striga* seeds in Uyoma 47 Brown, IESV 92038/2-SH, and IESV 92036-SH indicate secretion of low amounts of *Striga* germination stimulant associated with potential resistance to *Striga* in these genotypes. These findings compare well with that of Mohamed et al. (2010) who carried out an *in vitro* technique for studying specific *Striga* resistance mechanisms in sorghum and reported maximum germination distances of 0.058, 0.3, 1.8, and 2.1 cm respectively in the resistant sorghum genotypes SRN 39, Framida, Dobbs and Serena and 2.9cm and 2.8cm for the susceptible varieties Shanqui-Red and IS 4225.

The differences exhibited in the maximum germination distances and numbers of induced germinated *Striga* seeds is associated with genotypic differences for secretion of strigolactones in the evaluated sorghum genotypes. Higher maximum germination distances together with higher numbers of induced germinated *Striga* seeds suggest higher amounts of secreted strigolactones in sorghum genotypes, an indication of potential susceptibility of the genotypes to *Striga* weed. These findings compare well with those of Yohannes et al. (2016) who evaluated sorghum genotypes for secretion of low *Striga* germination stimulant and Reda et al. (1994) who screened maize genotypes for low *Striga asiatica* stimulant production. Yohannes et al. (2016) reported reduced secretion of germination stimulant and subsequent *Striga* resistance in the evaluated landraces compared to the commercial checks while Reda et al. (1994) reported a high correlation between maximum germination distance and numbers of induced germinated *Striga* seeds. Both Yohannes et al. (2016) and Reda et al. (1994) concluded that high *Striga* germination percentages suggested high germination stimulant production and susceptibility of genotypes and vice versa. The observed low numbers of induced germinated *Striga* seeds in Uyoma 47 Brown, IESV 92038/2-SH, and IESV 92036-SH could have been due to root
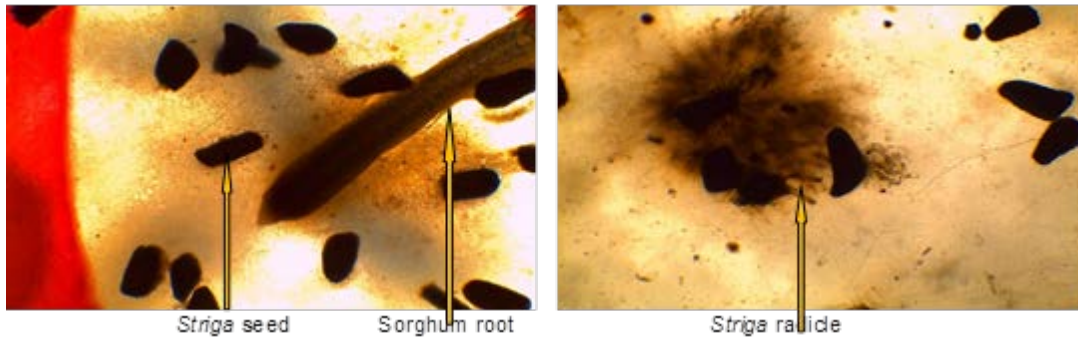
Plate 1a. Germinated *Striga* seeds around; **Plate 1b.** Developing radicle in *Striga* seeds in T 53 B agar gel Nyadundo 1 root periphery
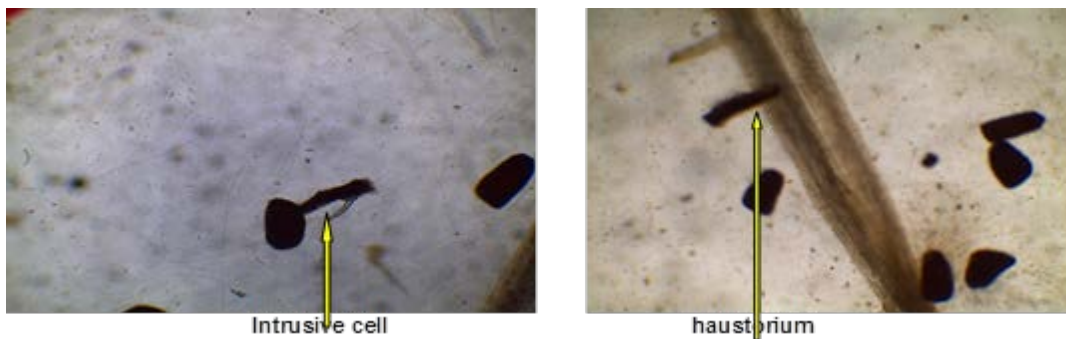

Plate 1c. Intrusive cell developing in *Striga* seed in; **Plate 1d.** Haustorium establishment in Nyadundo 1 sorghum E117B agar gel root

germination-inhibitory compounds that may have interfered with the germination response of the conditioned *Striga* seeds (Mohamed et al., 2010). However, such a hypothesis needs further investigation.

The study also revealed high numbers of induced germinated *Striga* seeds around the root periphery (Plate 1a) which indicated increased concentrations of secreted *Striga* germination stimulant closer to the root zone. This finding conforms with that of Karaya et al. (2012) who studied variations in *Striga* germination stimulants produced in maize and noted that the closer the *Striga* seeds to the source of stimulant the higher the numbers of seeds stimulated to germinate and vice versa. Similarly, Hess et al. (1991) reported host's germination stimulant to be exuded and concentrated mainly in a distance closer to the radius of the root from the root apex. Studies by Yoneyama et al. (2010) also suggested that only *Striga* seeds within the root rhizosphere are capable of germinating upon the perception of root strigolactones.

Different developmental stages of the germinated *Striga* seeds were also observed in some of the sorghum genotypes. T53B revealed a developing radicle (Plate 1b) while the presence of an intrusive cell at the tip of the radicle was observed in E117B (Plate 1c) and even the

establishment of a haustorium connection with Nyadundo 1 sorghum root (Plate 1d). The observations are comparable with those of Mohamed et al. (2010) and Omanya et al. (2004) who observed similar growth responses. The observed growth response could have been due to the secretion of a secondary metabolite in the genotypes' host roots which was required for the development of haustorium. The establishment of haustorium connection with Nyadundo 1 sorghum root suggested that this variety failed to initiate a post-attachment hypersensitivity defense reaction mechanism to *Striga* hence it's susceptible to the weed.

The association between (maximum germination distances and numbers of induced germinated *Striga* seeds) and level of field *Striga*-host infestation levels among the genotypes are presented in Table 7.
The data showed field *Striga* counts in the Kadel and Nyahera sites except for Nyahera's long rains of March 2019 to be highly significant ($P < 0.001$) and positively correlate with both maximum germination distance and numbers of induced germinated *Striga* seeds. This, therefore, emphasizes the role of strigolactones in influencing field-host *Striga* infestation levels. These findings compare well with those of Xie et al. (2008) and Hess et al. (1992) who established a close association

Table 7. Correlations between field *Striga* count, maximum germination distance, and numbers of induced germinated *Striga* seeds in agar gel experiment .

	Kadel (Long rains, March 2019)			Nyahera Short rains (Sept 2018)			Nyahera long rains (March 2019)		
	(FSC)	MGD	(IGSC)	(FSC)	MGD	(IGSC)	(FSC)	MGD	(IGSC)
FSC	1	0.739**	0.832**	1	0.711**	0.766**	1	0.172	0.055
MGD	0.739**	1	0.853**	0.711**	1	0.853**	0.172	1	0.853**
IGSC	0.832**	0.853**	1	0.766**	0.853**	1	0.055	0.853**	1

FSC: Field Striga Count. MGD: Maximum Germination Distance.IGSC: Induced Germinated Striga Count.

between strigolactone levels analyzed under laboratory conditions and field levels of *Striga* infection.

Conclusion

This study obtained significant variations among the genotypes in response to *Striga* infestations both under field and laboratory conditions. *Striga* weed significantly reduced sorghum performance in terms of grain yield, shoot dry mass, and plant height with susceptible genotypes suffering severe losses and recording higher *Striga* damage ratings. This study has identified four *Striga* tolerant (T53B, N57, N68, and T30 B) and *Striga* resistant (C26, IESV 92038/2-SH, IESV 92036-SH, and Uyoma 47 Brown,) sorghum genotypes based on both field and laboratory *Striga* screening techniques. The identified genotypes can be used directly by farmers to improve their yields in *Striga*-prone areas or for further breeding. The study recommends further research to identify possible *Striga* resistance mechanisms that the different varieties exhibited.

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CONFLICT OF INTEREST

The authors have not declared any conflict of interest.

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