Research Article

Germlasm Bred for Resistance to *Striga hermonthica* Exhibited High Resistance Levels to *Striga asiatica* Compared to Commercial Checks

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Parasitic weeds belonging to the *Orobanchaceae* family are a menace in Sub-Saharan African (SSA). Specifically, the two *Striga* species: *Striga hermonthica* (Del.) Benth. and *Striga asiatica* L. Kuntze from the *Orobanchaceae* family [1–3]. However, Mabasa [4] reported *Striga asiatica* as the most prevalent of the *Striga* species in southern Africa with particular reference to Zimbabwe whereas *S. hermonthica* is more prevalent in the west and east of Africa, causing serious damage to cereal yield reductions [5–7]. These two *Striga* species affect maize, sorghum, and rice among other cereals through root attachment and are hence classified as obligate root parasites [8–10].

1. Introduction

In Africa, many smallholder farmers are seriously facing weed problems in their maize production systems, especially parasitic weeds. Among the most problematic parasitic weeds in Sub-Saharan Africa (SSA) are the two *Striga* species: *Striga hermonthica* (Del.) Benth. and *Striga asiatica* L. Kuntze from the *Orobanchaceae* family [1–3]. However, Mabasa [4] reported *Striga asiatica* as the most prevalent of the *Striga* species in southern Africa with particular reference to Zimbabwe whereas *S. hermonthica* is more prevalent in the west and east of Africa, causing serious damage to cereal yield reductions [5–7]. These two *Striga* species affect maize, sorghum, and rice among other cereals through root attachment and are hence classified as obligate root parasites [8–10].

*Striga* spp. only germinates in the presence of germination stimulants from the host crop [11, 12]. Germination stimulants known as strigolactones released by host crops such as maize are responsible for *Striga* spp. germination,
hence parasitizing the plant through haustoria formation [11, 13, 14]. Striga spp. is one of the biotic factors limiting maize production in Africa and some parts of Asia [14, 15]. Studies have shown that S. asiatica has occupied more than 50 million hectares allocated to cereal production in Africa, hence causing a problem of food insecurity among smallholder farmers [16, 17].

In SSA, Striga spp. has infested more than 50 million ha of land including 40% of cereal production areas [16, 18]. Locally, fields infested with S. asiatica were identified in all provinces but most aggressive in areas such as Chiredzi, Masvingo, Gokwe, and Matopos in Zimbabwe [19]. Several authors have associated Striga species’ predominance with semiarid tropical type of climatic conditions, which includes infertile sandy soils and erratic rainfall patterns [20–22]. The high affinity of this parasitic weed to soils with low nutrition and poor rainfalls explains why subsistence farmers on marginal soils are the most affected [23, 24].

Yield losses as a result of Striga spp. are influenced by crop cultivar, weather conditions, and the severity of infestation [25, 26]. According to Karaya et al. [27] and Midega et al. [28], maize grain yield losses from Striga spp. infestation range from 20 to 80% and these losses can sometimes reach 100% in susceptible maize cultivars under severe field infestation. Yield losses converted to monetary value have been estimated to exceed US$7 billion annually [29]. Different Striga control methods have been long devised but the most effective ones are relatively expensive or not feasible for resource-limited smallholder farmers in SSA to implement. Control methods are classified as cultural, biological, and chemical types [30, 31]. Chemical control methods being the most effective involve the use of chemical germination stimulants such as strigol, Striga analogues, and ethylene gas for suicidal germination has been implemented with success in the United States [32]. Berner et al. [33] and Kanampiu et al. [34] showed that acetolactate synthase (ALS) resistant maize dressed with imazapyr herbicide was effective in controlling Striga hermonthica. However, other control methods (cultural) exist which include intercropping, trap crops, catch crops, and hand pulling though they are not as effective as the chemical controls described earlier but if integrated together, they form a better Striga management program [9, 35–37]. Successful Striga suppression by green manure cover crops (GMCCs) such as Desmodium species has been reported by several authors including [28]. These GMCCs used either in crop rotation schemes or as intercrops suppress the effects of Striga spp. through their natural fixation of atmospheric nitrogen into the soil, hence improving soil fertility to the benefit of the host crop as well as hindering the development of the parasite thereby reducing the seed bank density [38, 39].

Currently, it is being emphasized that the exploitation of genotypes’ natural genetic defense against Striga spp. is the best way to combat the scourge for resource-poor farmers [30, 40, 41]. Karaya et al. [27] stated that the most feasible and effective control strategy is the development of host plant resistance and tolerance. This is considered the most practical option for reducing yield losses caused by Striga spp. for farmers who lack the capital to use high-input management practices. As a definition, resistant maize genotypes allow low Striga counts per plant, whilst tolerant ones support high Striga counts per plant without any significant yield losses incurred. Several authors have screened different maize, sorghum, and rice genotypes for their resistance or tolerance to S. asiatica and S. hermonthica [28, 42–45]. In crops such as rice and sorghum, S. hermonthica resistant genotypes have been well identified [46, 47]. With reference to Gurney et al. [48], maize genotypes which are completely resistant to Striga hermonthica have not yet been identified, but wild relatives such as Tesxtis and Tripsacum have been recognized as a valuable source of genetic resistance [49]. There are limitations to the development of maize genotypes resistant to Striga spp. and among them, there is a lack of knowledge on the mechanisms expressing tolerance in the crops. There is a lack of knowledge on the sources of resistance as well as the complicated genetics associated with weed-crop resistance. However, successes have been forthcoming by Striga research organizations such as the International Institute of Tropical Agriculture (IITA) and partners including the International Maize and Wheat Improvement Centre (CIMMYT) [50, 51]. In particular, IITA has developed some varieties, which are resistant to S. hermonthica; these include the Zea diploperennis (ZD05), IWD STR, and TZL pools [40, 50]. The University of Zimbabwe has used the germplasm from IITA that was bred for Striga hermonthica to breed new maize hybrids with potential resistance to Striga asiatica. The International Maize and Wheat Improvement Centre has also been developing biotic and abiotic stress tolerant genotypes, which are currently under rigorous screening in the region [52].

Most of the locally grown maize genotypes are still susceptible to S. asiatica infestation though some have shown some better tolerance levels and this has seriously affected the maize yields, especially in the smallholder farming sector in Striga prevalence areas such as Gokwe and Rushinga. Research that has been conducted to evaluate the reactions of the available different maize genotypes to S. asiatica infestation in the country is still little. The performance of the new maize hybrids developed by the University of Zimbabwe using resistance sources from IITA germplasm bred for Striga hermonthica resistance, locally bred hybrid checks genotypes, and CIMMYT genotypes is not known for resistance/tolerance against S. asiatica. As a result, this study was carried out to identify maize varieties with high levels of S. asiatica tolerance/resistance by screening local commercial maize hybrids, University of Zimbabwe maize hybrids developed from IITA germplasm, and CIMMYT genotypes. The screening was carried out under artificial infestation using the pot experiment and laboratory agar gel technique.

2. Materials and Methods
2.1. Germplasm Description. The fourteen maize genotypes used in this study were obtained from CIMMYT, the University of Zimbabwe, Seed Co. Pvt. Ltd., and the
Scientific and Industrial Research Development Authority (SIRDA) (Table 1).

2.2. Pot Experiment Procedure. *S. asiatica* seeds used in this experiment were collected from farmer fields in Rushinga. The pot experiment was arranged in $14 \times 2$ factorial treatments in a $7 \times 4$ α-lattice design replicated four times during the 2014/2015 cropping season from 1 November 2014 to 31 January 2015. Factor one was maize variety with fourteen levels, and the second factor was *S. asiatica* infestation with two levels (*S. asiatica* infested and noninfested maize). A total of 112 pots measuring 15 cm diameter and 20 cm height were filled with 3,000 cm$^3$ of sandy soil. Prior to the establishment of this experiment in November 2014, soil samples of the sandy soil used for this experiment were taken from a field at 0–20 cm depth and were fully analysed. The following parameters were characterized: total nitrogen (N), available phosphorus (P), organic matter, and exchangeable bases using the micro-Kjeldahl, Olsen, Walkley-Black, and ammonium acetate methods, respectively [53, 54]. The characteristics of the soil are presented in Table S1. A total of 8 g pot$^{-1}$ of compound D (7% N: 14% P$_2$O$_5$: 7% K$_2$O) were applied in all the pots to achieve an application rate of 11.2 kg N·ha$^{-1}$, 9.8 kg P·ha$^{-1}$, and 9.3 kg K·ha$^{-1}$ for early root development [55, 56]. In 56 pots, the top 8 cm were thoroughly mixed with 0.05 g of *S. asiatica* seeds (approximately 12,580 seeds). Mixing of *S. asiatica* seeds with soil was done by shaking the soil with seeds in a polythene bag. The pots were watered to field capacity after the application of *Striga* seeds. Watering was done after four days later and left for two weeks of preconditioning period before planting maize genotypes. Three maize seeds were sown into each top 3 cm deep for all the maize genotypes in both the infested and noninfested pots. All the processes from pot filling to sowing were taking place from noninfested to infested pots to avoid contamination. Seedlings were thinned to one plant pot$^{-1}$ two weeks after crop emergence (WACE). Watering was done whenever necessary. Other weeds were removed from the pots by hand pulling to allow interaction only between maize and *S. asiatica*. Ammonium nitrate (34.5% N) was applied once as 1 g pot$^{-1}$ at four WACE to achieve a rate of less than 30 kg N·ha$^{-1}$; these low N-levels were used to mimic typical smallholder farmer conditions [50, 57, 58].

2.3. Data Collection. Maize plant height was measured weekly from 2$^{nd}$ WACE until 9$^{th}$ WACE. *S. asiatica* counts and biomass of the emerged plants were recorded. Data were also collected on the root to shoot ratio, leaf, stem, cob, root, and total biomass of maize.

2.4. Data Analyses. Analysis of variance (ANOVA) was carried out using GenStat statistical package version 14 [59]. Repeated measures ANOVA was carried out for weekly plant heights and *Striga* counts. Significant differences among means were separated using Fischer’s protected least significant difference (LSD) test. The symbols *, **, and *** represent significance at 0.5, 0.01, and 0.001 probability levels.

| Entry code | Genotype name | Source |
|------------|---------------|--------|
| 1          | TH114911      | CIMMYT |
| 2          | TH14910       | CIMMYT |
| 3          | TH128799      | CIMMYT |
| 4          | SC513         | Seed Co. Pvt. Ltd. |
| 5          | SC537         | Seed Co. Pvt. Ltd. |
| 6          | SC637         | Seed Co. Pvt. Ltd. |
| 7          | Ax31          | University of Zimbabwe |
| 8          | Bx31          | University of Zimbabwe |
| 9          | Ax28          | University of Zimbabwe |
| 10         | Ax27          | University of Zimbabwe |
| 11         | Ax7           | University of Zimbabwe |
| 12         | Ax32          | University of Zimbabwe |
| 13         | R201          | SIRDA  |
| 14         | TH14949       | CIMMYT |

| Source of variation | Degrees of freedom | Height | Stem biomass | Leaf biomass | Cob biomass | Root biomass | Total biomass | Root to shoot |
|---------------------|--------------------|--------|--------------|--------------|-------------|--------------|---------------|---------------|
| Replication         | 3                  | 1727.2 | 175.5        | 414.5        | 1426.9      | 87.9         | 6376          | 0.06306       |
| Replication block   | 24                 | 1650.2 | 237.8        | 450.3        | 657         | 152.4        | 2025          | 0.09027       |
| Genotype            | 13                 | 1545.7**| 850.7***     | 435.8        | 605.1       | 159.7        | 4789***       | 0.30525***    |
| *Striga*            | 1                  | 68754.6***| 155.9       | 2897.5**     | 4143.9**    | 1978.8****   | 39961***      | 0.02291       |
| Genotype × *Striga* | 13                 | 4450.6***| 256.4*       | 475.7        | 985.3       | 498.7***     | 4036**        | 0.10153       |
| Residual            | 57                 | 682.1  | 126.8        | 318.4        | 595.4       | 103.6        | 1340          | 0.08627       |
| Total               | 111                | 2075.4 | 252.4        | 404.9        | 715.3       | 183.5        | 2692          | 0.11337       |

Cob biomass residual degrees of freedom were 52. The symbols *, **, and *** represent significance at 0.5, 0.01, and 0.001 probability levels.
Table 3: Comparison of *Striga asiatica* main effects (infested and noninfested).

| Striga        | Height | Stem biomass | Leaf biomass | Cob biomass | Root biomass | Total biomass | Root to shoot ratio |
|---------------|--------|--------------|--------------|-------------|--------------|---------------|----------------------|
| Infested      | 108    | 27.83        | 24.01        | 27.54       | 24.06        | 65.93         | 0.59                 |
| Noninfested   | 171.4  | 26.52        | 12.12        | 15.24       | 17.42        | 106.52        | 0.49                 |
| *p* value     | <0.001 | 0.272        | 0.004        | 0.011       | <0.001       | <0.001        | 0.61                 |
| 5% least significant difference | 36.20 | NS           | 24.73        | 33.82       | 14.11        | 50.73         | NS                   |

NS: not significant at 5% probability level.

Table 4: Means of maize traits recorded during a greenhouse experiment at the University of Zimbabwe.

| Genotype | Height | Stem biomass | Leaf biomass | Cob biomass | Root biomass | Total biomass | Root to shoot biomass |
|----------|--------|--------------|--------------|-------------|--------------|---------------|-----------------------|
| Ax28     | 142.60 | 39.81        | 19.04        | 20.72       | 20.71        | 105.47        | 0.23                  |
| Bx31     | 135.80 | 22.45        | 18.62        | 19.34       | 20.03        | 58.14         | 0.67                  |
| Ax31     | 149.10 | 33.26        | 41.42        | 28.71       | 17.64        | 125.35        | 0.24                  |
| R201     | 144.60 | 11.31        | 13.05        | 3.27        | 12.67        | 50.70         | 0.52                  |
| SC 513   | 144.70 | 8.11         | 4.20         | 3.62        | 24.00        | 45.72         | 0.85                  |
| SC 537   | 144.00 | 38.07        | 17.11        | 29.18       | 24.74        | 112.86        | 0.49                  |
| SC 637   | 114.30 | 15.62        | 13.51        | 5.66        | 25.74        | 75.73         | 1.01                  |
| Ax27     | 141.30 | 20.60        | 22.97        | 29.69       | 17.27        | 87.88         | 0.66                  |
| TH114911 | 101.80 | 32.19        | 12.89        | 30.14       | 18.81        | 83.90         | 0.44                  |
| TH128799 | 141.50 | 37.13        | 18.03        | 27.12       | 23.55        | 107.89        | 0.41                  |
| TH14910  | 175.70 | 36.88        | 24.32        | 31.83       | 16.86        | 87.79         | 0.36                  |
| TH14949  | 150.30 | 20.88        | 13.80        | 20.24       | 29.77        | 86.48         | 0.80                  |
| Ax7      | 143.10 | 46.49        | 19.58        | 18.37       | 21.80        | 119.72        | 0.30                  |
| Ax32     | 126.60 | 17.70        | 14.39        | 24.56       | 16.82        | 59.49         | 0.55                  |
| Mean     | 139.67 | 27.18        | 18.07        | 20.89       | 20.74        | 86.22         | 0.54                  |

NS: not significant at 5% probability level.

**Figure 1:** Stem biomass weight of individual maize genotypes across *Striga asiatica* infested and noninfested levels in pot experiment. Error bars indicate the standard errors of the difference between means.
significant differences at 5% probability level. Graphs were plotted using R statistical package version 1.0.136 [60].

2.5. Agar Gel Procedure. The fourteen maize genotypes used for the pot experiment (Table 1) were also tested for stimulant production and haustorium initiation of S. asiatica in the Weed Science Laboratory, Department of Plant Production Sciences and Technologies, University of Zimbabwe, using the agar gel technique as described by IITA [55]. The experiment was arranged in a complete randomized design and replicated four times. Sterilization of S. asiatica seeds was achieved by immersing them in 1% sodium hypochlorite solution for 30 minutes before setting up the assay. A total of 0.2 g of Striga seeds were placed in 50 ml flasks and thereafter rinsed three times in 10 ml of double-distilled water. The seeds were then placed in 9 cm diameter Petri dishes, sealed with a parafilm, and placed in the dark at 25°C for 14 days. Maize seeds were soaked in 1% sodium hypochlorite solution for 30 minutes and afterwards rinsed three times with double distilled water. The maize seeds were then transferred to 9 cm diameter Petri dishes with moist Whatman number 2 filter papers and incubated in the dark at 28°C for 48 hours. Only the healthy-looking germinated seeds were selected for the agar gel assay. The conditioned S. asiatica seeds (50 μl) were pipetted into 9 cm diameter Petri dishes. A total of 30 ml (1.05 mg of agar) of autoclaved water agar in 150 ml of double-distilled water was poured into the S. asiatica seeds in each Petri dish before it solidified. A germinating maize seed was then submerged in the solidifying agar near the edge of the plate, with the root tip pointing across the plate. The Petri dishes were subsequently incubated for 72 hours before the first data recordings.

2.6. Data Collection. Data were collected on S. asiatica seed germination percentage and furthest germination distance of S. asiatica seed from the maize radicle.

2.7. Data Analyses. Analysis of variance was done and significantly different means were separated using Fischer’s protected least significant difference at 5% significant level using GenStat software, 14th edition [59]. Graphs were plotted using R statistical package, version 1.0.136 [60].

3. Results

Significant variations ($p < 0.05$) were recorded on S. asiatica and genotype main effects across different traits (Table 2). Genotype and S. asiatica interactions were only significant ($p < 0.05$) for plant height, stem biomass, root biomass, and total biomass (Table 2). Moreover, S. asiatica infested plants recorded lower plant height and total biomass means than

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**Figure 2:** Comparison of individual genotypes’ leaf biomass across the two Striga levels in pot experiment. Error bars indicate the standard errors of the difference between means.
noninfested varieties (Table 3). The University of Zimbabwe bred varieties, Ax31, Ax28, Ax7, and one local check (SC357), recorded the greatest total biomass at 125.4 g, 105.5 g, 119.7 g, and 112.7 g, respectively (Table 4). The local checks, SC635, SC513, and SC537, showed significant differences \((p < 0.05)\) in terms of stem biomass across the two *Striga* levels (Figure 1). Significant differences \((p < 0.05)\) in leaf biomass were also recorded for individual genotypes such as SC513 between *S. asiatica* infested and noninfested levels (Figure 2). Moreover, the genotypes, SC513, SC535, SC637, and TH14910, had significantly different \((p < 0.05)\) cob biomass across the two *S. asiatica* levels (Figure 3).

Repeated measures ANOVA revealed significant variations \((p < 0.05)\) for genotype and *Striga* main effects and the interaction of time \(\times\) genotype \(\times\) *Striga* (Table 5). Genotypes such as Ax31, Ax28, Ax7, TH14949, Bx31, and R201 had heights which were not significantly different \((p > 0.05)\) across the two *Striga* levels (Figure 4). The rest of the checks showed significant differences \((p < 0.05)\) between *Striga* infested and noninfested genotypes in terms of plant height (Figure 4). *Striga* counts over time also showed significant variations \((p < 0.05)\) among the fourteen maize genotypes (Table 6).

There were also significant differences \((p < 0.05)\) among the varieties in terms of *S. asiatica* germination percentage and furthest germination distance (Table 7).

The University of Zimbabwe bred genotypes such as Ax31, Ax28 Ax7, and Bx31, as well as TH14949 (CIMMYT), recorded the lowest *S. asiatica* germination percentage, which were significantly different \((p < 0.05)\) from the checks with the only exception of R201 (Tables 7 and 8). Furthermore, the University of Zimbabwe bred genotypes including Ax31 and the check R201 had the least *S. asiatica* germination distance compared to the rest of the local checks (Tables 7 and 8).
4. Discussion

Generally, the University of Zimbabwe hybrids bred from IITA *S. hermonthica* resistant varieties proved to be resistant and tolerant to *S. asiatica* compared to local checks. This is not surprising as IITA and partner organizations such as CIMMYT have been rigorously working towards the breeding of *Striga* resistant varieties derived from wild maize relatives, which are naturally resistant to *S. hermonthica* [49]. One such example of the successful *S. hermonthica* resistant genotype by the IITA is the ZD05 [10, 49]. According to Barker et al. [61], Frost et al. [62], and Gurney et al. [63], biomass accumulation and allocation particularly stem biomass and plant height have been used as indicators to assess the tolerance of genotypes to *S. asiatica*. In line with that, the University of Zimbabwe bred genotypes (Figure 1) showed insignificant sensitivity to *S. asiatica* in terms of biomass accumulation and allocation as compared to checks with the only exception of R201 (Figures 1–3). This shows that the University of Zimbabwe bred genotypes using the IITA *S. hermonthica* resistant genotypes can tolerate *S. asiatica* infestation. These findings are in agreement with those reported by Kim and Adetimirin [64] and Gethi and Smith [65] that *S. hermonthica* resistant and tolerant genotypes also exhibit comparable resistance and tolerance to *S. asiatica*. The University of Zimbabwe bred genotypes, Ax31, Ax28, and Ax7 (Figure 4), did not show any significant differences in terms of height of *S. asiatica* infested and noninfested levels, indicating that they are able to tolerate the negative effects of the parasite. Several researchers including Press and Stewart [66], Taylor et al. [67], and Chitagu et al. [68] reported that, among other parameters, plant height is a good measure of varieties’ tolerance to *S. asiatica*. This is mainly because the witchweed had phytotoxic effects and it is also a strong sink for mineral nutrients and carbohydrates which in most cases outcompetes the host crop leaving it stunted [63, 69–71]. Moreover, it was evident from the results that the University of Zimbabwe developed genotypes that did not suffer significantly reduced stem biomass to *Striga asiatica*, the explanation being that these varieties were again able to withstand *Striga* effects. *Striga* is known to affect biomass accumulation and allocation in susceptible plants; one example is reduced biomass allocation to the stems [72, 73]. Stem biomass has been explained by Gurney et al. [74] as a parameter which indicates tolerance levels to *S. asiatica* in sorghum varieties.

![Figure 4: Maize plant heights recorded from 2nd WACE up to 9th WACE. Error bars indicate the standard errors shared between four replications.](image-url)
So given that most of the University of Zimbabwe bred varieties were not sensitive to *S. asiatica* in terms of plant height and stem biomass, these varieties are highly tolerant to the parasite.

The University of Zimbabwe bred genotypes, Ax31, Bx31, Ax27, and Ax28, had the least furthest *S. asiatica* germination distances, which are less than 10 mm, the index that denotes resistance as described by Hess et al. [75]. Interestingly, some of these genotypes such Ax31, which had furthest *S. asiatica* germinating distances of less than 10 mm also had comparably low *Striga* seed germination percentage, confirming low germination stimulant production, hence resistance to *S. asiatica*. However, those found to be resistant only exhibited preattachment mechanism of resistance based on low germination stimulant production; no postattachment resistance was noted since all the genotypes were not significantly different in terms of *S. asiatica* counts, which was high in the pot experiment. These findings are in line with studies conducted by Oswald and Ransom [76], which revealed no postattachment resistance to *S. hermonthica* in maize genotypes.

Despite the fact that these materials were developed using *S. hermonthica* resistance/tolerance, they also proved to be able to withstand *S. asiatica* infestation as well. These findings are in line with Gethi and Smith [65], who conveyed that the TZL pools were good sources of *S. asiatica* resistance/tolerance. It was found that though the two *Striga* species are different, similarities exist in the way they respond to germination stimulation, how they attach their haustoria to the host crop, and the host defense mechanisms exhibited against these parasitic weeds [77]. Hence, this study provides a detailed insight into the similarity of host resistance to these two *Striga* species. This information on the relative similarity of host resistance/tolerance to

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**Table 6: Analysis of variance for *Striga* counts recorded from 42nd day after planting (DAP) to 72nd DAP.**

| Source of variation | Degrees of freedom | Weekly counts |
|---------------------|--------------------|---------------|
| Replication         | 3                  | 737.47        |
| Genotype            | 13                 | 995.47        |
| Residual            | 36                 | 735.94        |
| Time                | 5                  | 2553.97**    |
| Time × genotype     | 49                 | 219.64***     |
| Residual            | 127                | 18.87         |
| Total               | 233                |               |

The symbols *, **, and *** represent significance at 0.5, 0.01, and 0.001 probability levels.

**Table 7: Analysis of variance for *Striga* germination percentage and furthest germination distance (mm).**

| Source of variation | Degrees of freedom | Germination distance | Germination percentage |
|---------------------|--------------------|----------------------|------------------------|
| Replication         | 3                  | 34.83                | 329.7                  |
| Genotype            | 13                 | 351.68***            | 945.1***               |
| Residual            | 39                 | 32.9                 | 232                    |
| Total               | 55                 |                      |                        |

The symbols *, **, and *** represent significance at 0.5, 0.01, and 0.001 probability levels.

**Table 8: Germination percentages and furthest germination distance means of IITA and local checks recorded under laboratory conditions.**

| Genotype | Germination percentage | Genotype | Germination distance (mm) |
|----------|------------------------|----------|---------------------------|
| Ax31     | 12.8                   | Ax31     | 1.5                       |
| Ax28     | 18.0                   | TH114911 | 5.0                       |
| TH14949  | 21.5                   | Bx31     | 6.3                       |
| Bx31     | 22.9                   | R201     | 8.0                       |
| R201     | 23.9                   | TH14949  | 8.5                       |
| Ax32     | 25.2                   | Ax27     | 9.8                       |
| Ax27     | 32.1                   | Ax28     | 10.0                      |
| Ax7      | 35.5                   | Ax32     | 12.5                      |
| TH114911 | 40.6                   | Ax7      | 14.8                      |
| SC637    | 46.0                   | TH14910  | 17.5                      |
| TH14910  | 51.4                   | TH128799 | 22.0                      |
| SC513    | 54.6                   | SC637    | 24.8                      |
| SC537    | 56.0                   | SC513    | 30.3                      |
| TH128799 | 57.2                   | SC537    | 31.0                      |
| Mean     | 35.6                   |           | 14.4                      |
| p value  | <0.001                 |           | <0.001                    |
| Least significant difference at 5% | 11.3   | 4.2          |
S. asiatica and S. hermonthica is good news to breeders and farmers, as these genotypes will be a two in one approach for the control of the two Striga species. That is, the University of Zimbabwe bred genotypes will be a fit in all as they can be grown in both S. asiatica and S. hermonthica endemic areas without any significant yield losses incurred. These genotypes are a testimony to the amount of work which has been conducted by the IITA and partner organizations such as CIMMYT. This is because the genotypes, which were bred by CIMMYT also showed significant resistance/tolerance to S. asiatica even though they were advanced from inbred parents developed for S. hermonthica resistance by the IITA. Basically, most checks succumbed to Striga with the only exception of R201. This local check, R201, displayed desirable levels of resistance/tolerance, which is comparable to the University of Zimbabwe hybrids bred from IITA resistance sources. Previous research reveals that this genotype (R201) is resistant/tolerant to S. asiatica [68]; however, its response to S. hermonthica is still to be determined. This is because genetic variations naturally exist even among these local checks. It is important to note that CIMMYT and IITA parent materials are used by many seed houses during their breeding programs and hence the exhibition of resistance/tolerance of these genotypes to Striga is a welcome development in the fight against Striga. This Striga resistant/tolerant characteristic of the developed genotypes can be a major boost to local breeding programs if incorporated to produce locally adapted Striga resistant genotypes. Striga resistant/tolerant genotypes will provide a lifeline to resource-limited smallholder farmers in their effort to curb the Striga scourge endemic in their arable lands. The integration of resistant/tolerant genotypes and other low-cost Striga control methods, either cultural or mechanical methods, will be of great agronomic advantage to the African farmer.

5. Conclusion

The University of Zimbabwe maize hybrids bred from IITA germplasm with resistance to S. hermonthica resistant/tolerant genotypes displayed desirable resistance/tolerance to S. asiatica relative to local commercial checks. Examples of such genotypes are Ax31, Ax28, Ax7, and Ax32. This clearly highlights the similarity of host genetic resistance/tolerance to the two Striga species. Hence, these genotypes of the University of Zimbabwe can be used in the breeding programs of seed houses to breed Striga resistant/tolerant genotypes for a better and feasible Striga control option if integrated together with other Striga control strategies for smallholder farmers in Striga rife areas.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Table S1 shows the nutritional composition of the soil used in the pot experiments. Fertilizer rates were applied in all the pots used in this study to achieve an application rate of 11.2 kg-N·ha⁻¹, 9.8 kg-P·ha⁻¹, and 9.3 kg-K·ha⁻¹. (Supplementary Materials)

References

[1] G. O. Abayo, T. English, R. E. Epleee, F. K. Kanampiu, J. K. Ransom, and J. Gressel, “Control of parasitic weeds (Striga spp.) on corn (Zea mays) resistant to acetolactate synthase inhibitors,” Weed Science, vol. 46, no. 4, pp. 459–466, 1998.
[2] J. G. Gethi, M. E. Smith, S. E. Mitchell, and S. Kresovich, “Genetic diversity of Striga hermonthica and Striga asiatica populations in Kenya,” Weed Research, vol. 45, no. 1, pp. 64–73, 2005.
[3] H. B. Tek, “Advance research on Striga control: a review,” African Journal of Plant Science, vol. 8, pp. 492–506, 2014.
[4] S. Mabasa, “Screening sorghum cultivars for resistance to witchweed (Striga asiatica) in Zimbabwe,” in Proceedings of the SADC/ICRISAT Regional Sorghum and Pearl Millet Workshop, pp. 25–29, Gaborone, Botswana, July 1994.
[5] E. K. Avedi, D. M. W. Ochieno, S. Ajanga et al., “Fusarium oxysporum f. sp. strigae strain Foxy 2 did not achieve biological control of Striga hermonthica parasitizing maize in Western Kenya,” Biological Control, vol. 77, pp. 7–14, 2014.
[6] H. S. Nzioki, F. Oyosi, C. E. Morris et al., “Striga biocontrol on a toothpick: a readily deployable and inexpensive method for smallholder farmers,” Frontiers in Plant Science, vol. 71121 pages, 2016.
[7] J. Rodenburg, M. Demont, S. J. Zwart, and L. Bastiaans, “Parasitic weed incidence and related economic losses in rice in Africa,” Agriculture, Ecosystems & Environment, vol. 235, pp. 306–317, 2016.
[8] D. Mbuvi, C. Masiga, E. Kuria et al., “Novel sources of witchweed (striga) resistance from wild sorghum accessions,” Frontiers in Plant Science, vol. 8, pp. 1–15, 2017.
[9] E. Mrema, H. Shimelis, M. Laing, and T. Buecheyki, “Screening of sorghum genotypes for resistance to Striga hermonthica and S. asiatica and compatibility with Fusarium oxysporum f.sp. strigae,” Acta Agriculturae Scandinavica, Section B-Soil & Plant Science, vol. 67, no. 5, pp. 395–404, 2017.
[10] J. Rodenburg, M. Cissoko, N. Kayongo et al., “Genetic variation and host–parasite specificity of striga resistance and tolerance in rice: the need for predictive breeding,” New Phytologist, vol. 214, 2017.
[11] J. M. García-Garrido, V. Lendzemo, V. Castellanos-Morales, S. Steinkellner, and H. Vierheilig, “Strigolactones, signals for parasitic plants and arbuscular mycorrhizal fungi,” Mycorrhiza, vol. 19, no. 7, pp. 449–459, 2009.
[12] S. Steinkellner, V. Lendzemo, L. Langer et al., “Flavonoids and strigolactones in root exudates as signals in symbiotic and pathogenic plant-fungus interactions,” Molecules, vol. 12, no. 7, pp. 1290–1306, 2007.
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10

[13] A. A. Awad, D. Sato, D. Kusumoto, H. Kamioka, Y. Takeuchi, and K. Yoneyama, “Characterization of strigolactones, germination stimulants for the root parasitic plants Striga and Orobanche, produced by maize, millet and sorghum,” Plant Growth Regulation, vol. 48, pp. 221–227, 2006.

[14] D. Gobena, M. Shimels, P. J. Rich et al., “Mutation in sorghum low germination stimulant 1 alters strigolactones and causes Striga resistance,” Proceedings of the National Academy of Sciences, vol. 114, no. 17, pp. 4471–4476, 2017.

[15] W. A. Mengesha, A. Menkiri, N. Unahchukwu et al., “Genetic diversity of tropical maize inbred lines combining resistance to Striga hermonthica with drought tolerance using SNP markers,” Plant Breeding, vol. 136, no. 3, pp. 338–343, 2017.

[16] G. Ejeta, “Breeding for resistance in sorghum: exploitation of an intricate host–parasite biology,” Crop Science, vol. 47, pp. S216–S227, 2007.

[17] F. K. Kanampiu, V. Kabambe, C. Massawe et al., “Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistance maize controls Striga spp. and increases yields in several African countries,” Crop Protection, vol. 22, no. 5, pp. 697–706, 2003.

[18] D. Musambasi, O. Chivinge, and I. Mariga, “Intercropping maize with grain legumes for Striga control in Zimbabwe,” African Crop Science Journal, vol. 10, pp. 163–171, 2002.

[19] O. Chivinge, “A weed survey of arable lands of the small-scale farming sector of Zimbabwe,” Zambezia, vol. 15, pp. 167–179, 1988.

[20] K. Nail, D. J. Kriticos, J. K. Scott, T. Yonow, and N. Ota, “Striga asiatica,” Harvest Choice Pest Geography, vol. 2, pp. 1–6, 2014.

[21] E. Z. Nyakudya and L. Strooijnjier, “Conservation tillage of rainy season maize in semi-arid Zimbabwe: a review,” Soil and Tillage Research, vol. 145, pp. 184–197, 2015.

[22] I. O. Amusan, P. J. Rich, A. Menkiri, T. Housley, and G. Ejeta, “Resistance to Striga hermonthica in a maize inbred line derived from Zea diploperennis,” New Phytologist, vol. 178, no. 1, pp. 157–166, 2008.

[23] S. K. Kim, V. O. Adetimirin, C. Thé, and R. Dossou, “Yield losses in maize due to striga hermonthica in west and central Africa,” International Journal of Pest Management, vol. 48, no. 3, pp. 211–217, 2002.

[24] H. Karaya, K. Njoroge, S. Mugoia, E. Ariga, F. Kanampiu, and J. Ndiritub, “Determination of levels of Striga germination stimulants for maize gene bank accessions and elite inbred lines,” International Journal of Plant Production, vol. 6, pp. 209–224, 2012.

[25] C. A. O. Midega, C. J. Wasonga, A. M. Hooper, J. A. Pickett, and Z. R. Khan, “Drought-tolerant Desmidium species effectively suppress parasitic striga weed and improve cereal grain yields in western Kenya,” Crop Protection, vol. 98, pp. 94–101, 2017.

[26] D. Rubiales, J. Verkleij, M. Vurro, A. J. Murdoch, and D. M. Joel, “Parasitic plant management in sustainable agriculture,” Weed Research, vol. 49, pp. 1–5, 2009.

[27] I. K. Amegbor, B. Badu-Apraku, and B. Annor, “Combining ability and heterotic patterns of extra-early maturing white maize inbreds with genes from Zea diploperennis under multiple environments,” Euphytica, vol. 213, no. 1, 24 pages, 2017.

[28] D. S. Meena, C. G. Om Prakash Patidar, R. S. Hari Mohan Meena, and V. Prakash, “Management of finger millet based cropping systems for sustainable production,” International Journal of Current Microbiology and Applied Sciences, vol. 6, no. 3, pp. 676–686, 2017.

[29] A. Oswald, “Striga control-technologies and their dissemination,” Crop Protection, vol. 24, no. 4, pp. 333–342, 2005.

[30] D. K. Berner, F. O. Ikie, and J. M. Green, “ALS-inhibiting herbicide seed treatments control Striga hermonthica in ALS-modified corn (Zea mays),” Weed Technology, vol. 11, no. 4, pp. 704–707, 1997.

[31] D. K. Kanampiu, I. K. Ransom, and J. Gressel, “Imazapyr seed dressings for Striga control on acetolactate synthase target-site resistant maize,” Crop Protection, vol. 20, no. 10, pp. 885–895, 2001.

[32] D. Berner, R. Carsky, K. Dashiell, J. Kling, and V. Manyong, “A land management based approach to integrated Striga hermonthica control in sub-Saharan Africa,” Outlook on Agriculture, vol. 25, no. 3, pp. 157–164, 1996.

[33] M. B. Hassan, L. J. S. Baiyegunhi, G. F. Ortmann, and T. Abdoulaye, “Adoption ofstriga(striga hermonthica) management technologies in northern Nigeria,” Agrokon, vol. 55, no. 1-2, pp. 168–188, 2016.

[34] S. Schulz, M. A. Hussaini, J. G. Kling, D. K. Berner, and F. O. Ikie, “Evaluation of integrated Striga hermonthica control technologies under farmer management,” Experimental Agriculture, vol. 39, no. 1, pp. 99–108, 2003.

[35] R. J. Carsky, L. Singh, and R. Ndikawa, “Suppression of Striga hermonthica on sorghum using a cowpea intercrop,” Experimental Agriculture, vol. 30, no. 3, pp. 349–358, 1994.

[36] Z. R. Khan, J. A. Pickett, L. J. Wadhans, A. Hassanali, and C. A. O. Midega, “Combined control of Striga hermonthica and stemborers by maize-Demedium spp. intercrops,” Crop Protection, vol. 25, no. 9, pp. 989–995, 2006.

[37] C. Kouakou, L. Akanvou, I. A. Z. Bi, H. A. N’Da, and R. Akanvou, “The use of genetically tolerant maize (Zea mays L.) in the control of Striga hermonthica in northern côte d’Ivoire,” American Journal of Experimental Agriculture, vol. 4, no. 5, pp. 563–574, 2014.

[38] T. Yohannes, K. Ngugi, E. Ariga, M. Ahonsi, N. Yao, and T. Abraha, “A diagnostic appraisal of sorghum farming in sorghum endemic areas of Eritrea,” Journal of Agricultural Science, vol. 9, no. 5, 133 pages, 2017.

[39] A. L. Gurney, J. Slate, M. C. Press, and J. D. Scholes, “A novel form of resistance in rice to the angiosperm parasite Striga hermonthica,” New Phytologist, vol. 169, no. 1, pp. 199–208, 2006.

[40] E. J. Kenyi, A. G. E. T. Babikri, S. M. Omer, and P. Wani, “Evaluation of sorghum genotypes for tolerance to striga hermonthica (del.) (lamiales: Orobanchaceae) and yield in the rain fed areas of damazin, Sudan,” International Journal of Life-Sciences Scientific Research, vol. 3, pp. 1003–1006, 2017.

[41] P. J. Swarbrick, K. Huang, G. Liu, J. Slate, M. C. Press, and J. D. Scholes, “Global patterns of gene expression in rice
cultivars undergoing a susceptible or resistant interaction with the parasitic plant *Striga hermonthica*, *New Phytologist*, vol. 179, no. 2, pp. 915–929, 2008.

[45] T. Yohannes, K. Ngugi, E. Ariga et al., "Genotypic variation for low striga germination stimulation in sorghum ‘sorghum bicolor (L.) moench’ landraces from Eritrea," *American Journal of Plant Sciences*, vol. 7, no. 17, pp. 2470–2482, 2016.

[46] R. Ali, A. H. Mohamed, A. Elhussein, and C. T. Hash, "Saturation of striga resistance qtls in sorghum (Sorghum bicolor (L.) moench)," *World Journal of Biology and Biotechnology*, vol. 1, no. 1, pp. 43–48, 2016.

[47] J. Rodenburg, M. Cissoko, J. Kayeke et al., "Do NERICA rice cultivars express resistance to Striga hermonthica (Del.) Benth. and Striga asiatica (L.) Kunzte under field conditions?" *Field Crops Research*, vol. 170, pp. 83–94, 2015.

[48] A. L. Gurney, D. Grimanelli, F. Kanampiu, D. Hoisington, J. Rodenburg, M. Cissoko, J. Kayeke et al., "Do NERICA rice cultivars express resistance to Striga hermonthica (Del.) Benth. and Striga asiatica (L.) Kunzte under field conditions?" *Field Crops Research*, vol. 170, pp. 83–94, 2015.

[49] A. L. Gurney, D. Grimanelli, F. Kanampiu, D. Hoisington, J. Rodenburg, M. Cissoko, J. Kayeke et al., "Do NERICA rice cultivars express resistance to Striga hermonthica (Del.) Benth. and Striga asiatica (L.) Kunzte under field conditions?" *Field Crops Research*, vol. 170, pp. 83–94, 2015.

[50] B. Badu-Apraku, M. A. B. Fakorede, and M. Oyekunle, "Agronomic traits associated with genetic gains in maize yield during three breeding eras in West Africa," *Maydica*, vol. 59, pp. 49–57, 2014.

[51] N. Harford, J. Le Breton, and B. Oldreive, "Farming for the future: a guide to conservation agriculture in Zimbabwe," *Zimbabwe Conservation Agriculture Task Force*, Blacksburgh, VA, USA, 2009.

[52] GenStat, *14.1 Laves Agricultural Trust, Rothamsted Experimental Station*, Registered to Cranfield University, Harpenden, UK, 2011.

[53] RStudio, *RStudio: Integrated Development Environment for R Version 1.0.136–62009-2016 [Computer software]*, RStudio, Inc., Boston, MA, USA, 2009.

[54] E. R. Barker, M. C. Press, J. D. Scholes, and W. P. Quick, "Interactions between the parasitic angiosperm Orobanche aegyptiaca and its tomato host: growth and biomass allocation," *New Phytologist*, vol. 133, no. 4, pp. 637–642, 1996.

[55] D. L. Frost, A. L. Gurney, M. C. Press, and J. D. Scholes, "Striga hermonthica reduces photosynthesis in sorghum: the importance of stomatal limitations and a potential role for ABA?" *Plant, Cell and Environment*, vol. 20, no. 4, pp. 483–492, 1997.

[56] A. L. Gurney, M. C. Press, and J. D. Scholes, "Infection time and density influence the response of sorghum to the parasitic angiosperm Striga hermonthica," *New Phytologist*, vol. 143, no. 3, pp. 573–580, 1999.

[57] S. Kim and V. Adetimirin, "Overview of tolerance and resistance of maize to Striga hermonthica and S. asiatica," in *Proceedings of the Eastern and Southern Africa Regional Maize Conference*, Harare, Zimbabwe, January 1995.

[58] J. G. Gethi and M. E. Smith, "Genetic responses of single crosses of maize to Striga hermonthica (Del.) Benth. and Striga asiatica (L.) Kunzte," *Crop Science*, vol. 44, no. 6, pp. 2068–2077, 2004.

[59] M. C. Press and G. R. Stewart, "Growth and photosynthesis in Sorghum bicolor infected with Striga hermonthica," *Annals of Botany*, vol. 60, no. 6, pp. 657–662, 1987.

[60] A. Taylor, J. Martin, and W. E. Seel, "Physiology of the parasitic association between maize and witchweed (Striga hermonthica): is ABA involved?" *Journal of Experimental Botany*, vol. 47, no. 8, pp. 1057–1065, 1996.

[61] M. Chitagu, J. T. Rugare, and S. Mabasa, "Screening maize (Zea mays) genotypes for tolerance to witchweed (striga asiatica L. Kunzte) infection," *Journal of Agricultural Science*, vol. 6160 pages, 2014.

[62] E. Aigbobohan, D. Berner, and L. Muselman, "Influence of dual infection of maize by Striga aspera and Striga hermonthica on parasitic development and host performance," *Nigerian Journal of Botany*, vol. 23, pp. 27–40, 2010.

[63] B. Badu-Apraku, M. A. B. Fakorede, and A. Fontem Lum, "Evaluation of experimental varieties from recurrent selection for Striga resistance in two extra-early maize populations in the savannas of West and Central Africa," *Experimental Agriculture*, vol. 43, no. 2, pp. 183–200, 2007.

[64] R. Stevens, "Prospects for using marker-assisted breeding to improve maize production in Africa," *Journal of the Science of Food and Agriculture*, vol. 88, no. 5, pp. 745–755, 2008.

[65] A. Bawa, I. Addai, M. Abdulai, and J. Kugbe, "Evaluation of some genotypes of maize (Zea mays L.) for tolerance to Striga hermonthica (Del.) Benth in northern Ghana," *Research in Plant Biology*, vol. 5, pp. 1–12, 2015.

[66] M. Ronald, M. Charles, M. Stanford, and M. Eddie, "Existence of different physiological "strains" of Striga asiatica (L.) Kuntze on sorghum species [Sorghum bicolor (L.) Moench and Sorghum arundinaceum (Desv.) Stapf] in Zimbabwe," *Research on Crops*, vol. 17, no. 3, pp. 468–478, 2016.

[67] A. L. Gurney, M. C. Press, and J. D. Scholes, "Can wild relatives of sorghum provide new sources of resistance or tolerance against Striga species?" *Weed Research*, vol. 42, no. 4, pp. 317–324, 2002.

[68] D. E. Hess, G. Ejeta, and L. G. Butler, "Selecting sorghum genotypes expressing a quantitative biosynthetic trait that confers resistance to Striga," *Phytochemistry*, vol. 31, no. 2, pp. 493–497, 1992.

[69] A. Oswald and J. K. Ransom, "Response of maize varieties to Striga infestation," *Crop Protection*, vol. 23, no. 2, pp. 89–94, 2004.

[70] S. K. Kim, "Genetics of maize tolerance of Striga hermonthica," *Crop Science*, vol. 34, no. 4, pp. 900–907, 1994.