Screening finger millet (*Eleusine coracana* Gaertn) genotypes for resistance to witch weed (*Striga asiatica* L. Kuntze) infection under controlled environments

By

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The undersigned certify that they have read, and recommended to the Department of Crop Science for acceptance, the thesis entitled:

Screening finger millet (*Eleusine coracana* L. Gaertn) genotypes for resistance to witch weed (*Striga asiatica* L. Kuntze) infection under controlled environments

Submitted by **Kudzai Walter Makani** in partial fulfilment of the requirements for the degree of

Master of Science in Crop Science (Agronomy)

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DECLARATION

I**, Kudzai Walter Makani**, do hereby declare that this thesis is a result of my original research work except where clearly and specifically acknowledged. This is being submitted for the fulfilment of the degree of Master in Agronomy. This thesis has not been submitted in any form before for any degree or examination in any other university.

..... ……

Kudzai Walter Makani Date

ABSTRACT

Witch weed (*Striga asiatica* L. Kuntze) is an obligate hemi-parasitic weed that causes severe yield losses in cereals. The use of tolerant or resistant genotypes is perceived to be the most economically feasible and effective method of control. Hence this project aimed to determine the response of finger millet genotypes to *S. asiatica* infection. Three genotypes that were bred at the International Crop Research Institute of Semi-arid tropics (ICRISAT) were evaluated with *Striga* and without *Striga* infestation under glasshouse conditions at the University of Zimbabwe during the 2017/2018 growing season. The greenhouse study was laid out as a 3 x 2 factorial in a Randomised Complete Block Design (RCBD) with finger millet genotype and *Striga* infestation level as factors. In the laboratory assay, the three finger millet genotypes were screened for pre-attachment resistance using the Ager-gel technique arranged in a Complete Randomized Design (CRD) with ten replications. The finger millet genotype SDFM1702 had significantly ($p<0.05$) lower *Striga* germination percentage and shorter *Striga* germination distance from the finger millet root than the other genotypes. In the glasshouse experiment there was a significant ($p<0.05$) genotype x *Striga* interaction on stem biomass, root biomass, total above ground biomass and grain yield where SDFM1702 showed tolerance. However, *Striga* infection did not significantly ($p>0.05$) reduce the final plant height of the genotype SDFM1702. There was a significant ($p<0.05$) difference on *Striga* count where SDFM1702 recorded the least emerged *S. asiatica* weeds. *Striga asiatica* infection significantly ($p<0.05$) reduced grain yield of all genotypes. The finger millet genotypes screened showed different levels of tolerance to *Striga* infection, where genotype SDFM1702 appeared to be tolerant. Therefore, this high yielding genotype and *Striga* have the potential to be widely adopted as they are adaptable and suitable to the dry and *Striga* endemic areas.

Key words: *Eleusine corocana*, *Striga asiatica*, resistance, tolerance, witch weed

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DEDICATION

I dedicate this project to my late mother and late grandmother. They meant so much to me and they always believed in me. May their souls rest in eternal peace.

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CHAPTER ONE

INTRODUCTION

1.1 Background

Finger millet (*Eleusine coracana* L. Gaertn) is a primary food grain crop for millions of people located in the tropical and sub-tropical areas of Africa and India (Roden *et al.,* 2007). By the year 2014, the area under finger millet was estimated to be 24.2 million hectares worldwide (FAO, 2014). Finger millet is ranked the sixth most important cereal crop in the world after wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), rice (*Oryza sativum* L.*),* barley *(Hordeum vulgare* L.*)* and sorghum (*Sorghum bicolour* L.*)* (Mason *et al.,* 2015). The presence of high levels of essential amino acids and important micronutrients such as iron and zinc in its grain makes it superior to some of the commonly grown cereals (Roden *et al.*, 2007).

Finger millet production is affected by a parasitic weed in the *Striga* genus which is commonly known as witch weed and belongs to the family Orobanchaceae (Atera *et al.*, 2013). There are many *Striga* species, but the major species in agriculture are *S. hermonthica* and *S. asiatica* which infect cereals such as rice, maize, millets and sorghum (Parker, 2009). *Striga* is regarded as a major pest that affects productivity in cereals. It is identified as the greatest biological constraint to cereal food production and has been estimated to infect around 64% of the total area that is under cereal production in West Africa (Gressel *et al.*, 2004: Parker, 2012).

Striga is an obligate hemi-parasite that causes tremendous damage to the host plants before it emerges from the soil (Bouwmeester *et al.,* 2003). Several germination stimulants have been identified in the root exudates of maize, sorghum, millets and these are collectively known as strigolactones (Parker, 2009). The *Striga* seeds will only germinate after induction of chemical

signals has been exuded from the roots of the host plant (Mabasa, 2003). The exudates that are produced by the host plant activate the responsible genes for the initiation of the germination process.

In Zimbabwe, finger millet is mainly grown by small scale farmers who are located in marginal areas (agro-ecological region IV and V) which are characterised by low rains and poor rainfall (>450 - 650mm) (Moyo, 2000). These farmers are resource constrained and also lack knowledge of good agricultural practices. Hence, due to poor soils and low fertiliser application, *Striga* is the most limiting biotic factor in the production of finger millet by smallholder farmers in rain-fed agricultural areas of the semi-arid tropics (Ejeta and Butler, 1993). Traditionally, control of *Striga* seed in the soil has been minimized by long fallow periods, but with increased food crop demand due to the increased world population, there is increased utilization of the land hence long fallow periods are no longer practical and feasible (Mason *et al.,* 2015). Practices such as crop rotation, late planting, recommended fertilizer application rates, inter-cropping have widely been used to control witch weed infection but they are not effective (Mason *et al.,* 2015). The demographic pressure and market demands are promoting intensive cultivation on the agricultural lands; which in turn adversely contributes to the build-up of pest populations and a reduction in soil nutrients (Elisaba, 2006). Hence, the search for an economically benign and effective *Striga* management strategy is important in ensuring improved and sustained production of finger millet.

1.2 Problem statement

The problem of *S. asiatica* has been in existence from as early as 1936 in the agricultural fields of farmers where it is causing huge losses (Khan *et al.*, 2006). In Zimbabwe, *Striga* parasitism is negatively impacting cereal production because farmers continue to grow landraces that are very

susceptible to this parasitic angiosperm. In Africa, infection by *Striga* causes an estimated loss of 4.1 million tonnes of the total cereal grain yield produced and as a result, the welfare of over 100 million people is affected (Jamil *et al.,* 2012). These losses have been due to the large densities of *Striga* in the field, the genotype and host species, the land use system, the low and erratic rainfall patterns and also cereal monoculture (Atera *et al.,* 2012). In Africa, crops that are infected by *Striga* can result in grain yield losses ranging from 20-80%, but under severe circumstances, the losses can reach up to 100% (Gurney *et al.,* 2002). This has contributed to major food shortages in developing countries where finger millet is a major crop. Finger millet is mainly grown by poorly resourced small-scale farmers that recycle seed. Hence, the *Striga* population has worsened in the field due to the continuous use of retained seed that is susceptible to the weed and also very poor fertilizer regimes by the farmers since *Striga* favours poorly nourished soils (Gressel, 2007).

1.3 Justification

It is important to find other methods of controlling *Striga* that will reduce further losses due to the root parasite (Berner and Singh, 1995). Several methods have been practiced to control *Striga* infection such as crop rotations (Oswald and Ransom, 2001). Crop rotations may not be viable in the case where land is limiting especially where people mono-crop cereals (Gurney *et al.,* 2003). There has been an increase in the human population that has led to continuous cropping systems being undertaken, avoiding crop rotations at the expense of soil fertility (Sikwese *et al.,* 2003). Amongst the smallholder farmers, hand hoeing is the most common practice for controlling the weed but it is not very effective because *Striga* causes damage well before it emerges above the ground. At the same time, due to the financial constraints, the smallholder farmers have not been able to adapt to management practices such as the use of trap crops or catch crops (Sun *et al.,* 2007).

There is a renewed interest in the commercialisation of finger millet genotype since it is a crop that can withstand the adverse effects of climate change in areas where maize production is no longer viable. As a result, it is important to identify finger millet genotypes that do well in *Striga* endemic areas since maize monoculture has already caused a build-up of *Striga* seed reserves in the soil.

1.4 Aim of research

To screen finger millet genotypes for pre and post attachment resistance to *S. asiatica*.

1.5 Specific objectives

1. To assess whether finger millet genotypes used in the study have pre-attachment resistance to *S. asiatica* using the agar gel assay technique.
2. To examine the effect of *S. asiatica* infection on the vegetative, physiological and yield parameters of finger millet under glasshouse conditions.
3. To evaluate the effect of finger millet genotypes on the emergence, haustoria attachments and biomass of *S. asiatica*.

1.6 Hypotheses

1. At least one of the finger millet genotypes used in the study has pre-attachment resistance to *S. asiatica* infection.
2. Vegetative, physiological and yield parameters of resistant/tolerant sorghum genotypes are not significantly affected by *S. asiatica* infection.
3. Some finger millet genotypes reduce *Striga* emergence, haustoria attachments and biomass.

CHAPTER TWO

LITERATURE REVIEW

2.1 Parasitic plants

Parasitic weeds are heterotrophic flowering plants which are also known as angiosperms that can attach and obtain nutrition and growth factors from their host crop through the haustorium (Nickrent and Musselman, 2004). The haustorium serves as the bridge or physiological linkage between the host plant and the parasite (Nickrent and Musselman, 2004). There are four different classes in which plant parasites can be categorised into and these are; hemi-parasites (which have pigments with chlorophyll only in the mature stages of their life cycle), the holo-parasites (which lack the chlorophyll), the facultative parasites (which have the ability to survive without the host but require a host at some stage) and the obligate parasites (which require the host for maturation) (Nickrent and Musselman, 2004).

Amongst the parasitic plants, the *Orobanchaceae* family is the most destructive to host plants (Elzien and Kroschel, 2004; Westwood *et al*., 2012). Of the *Orobanchaceae* species, approximately thirty hemi-root-parasites are classified under the genus *Striga* (Spallek *et al*., 2013). *Striga* species are obligate hemi-parasites with the ability to attach to the roots of the host cereal crop such as maize (*Zea mays* L.), millets (*Eleusine corocana* Gaertn. and *Pennisetum glaucum* L.), sorghum, and rice (*Oryza sativa* L.) in the process, it synchronizes its life cycle with that of the host hence increasing its competitive ability with the host plant (Gurney *et al*., 2003). In the sub-Saharan Africa (SSA), *S. asiatica, S. hermonthica,* and *S. gesneroides* cause heavy losses in agricultural production (Spallek *et al*., 2013). *Striga hermonthica* is mostly abundant in the Eastern and Western regions of Africa, and it is well characterized by a distinct lavender colouration of the flowers whilst *S. asiatica* has red flowers and is a major constraint in

crop production in Southern Africa (Woomer and Savala, 2007). *Striga* is an annual obligate hemi-parasite that has the capacity to photosynthesize (Spallek *et al*., 2013) and cause severe problems to monocots (Nail *et al*., 2014).

2.2 Origin, distribution and economic importance of the parasitic weeds

Striga asiatica is believed to have originated from Sudan and the Semien mountains of Ethiopia where there are conducive environments for the weed to exert its full potential (Atera *et al.*, 2013). More importantly, *Striga* is characterised by its major dominance in marginalised soils with poor fertility and low organic matter, however, they can be found in a range of soils (Nail *et al.*, 2014). Cereal crops are being produced worldwide and through continuous cultivation by men, the weed has spread to other parts of SSA. As a result, there has been at least twenty-five countries in Africa that have reported *Striga* infestation in their fields meaning half of the continent is now under threat by the parasitic witch weed (De Groote *et al.*, 2008). *Striga* species are noxious and persistent weeds which are reducing the cereal productivity levels around the globe (Timko *et al*., 2012). Distribution of these *Striga* species is governed by the exudation of germination stimulants, soil nutrient status and temperature (Spallek *et al*., 2013).

Striga has a wide host range in which it can successfully inhabit in and cause damage (Mohamed *et al.*, 2003). In some rare cases, *Striga* has managed to form an attachment with some non-traditional host crops such as barley (*Hodeum vulgare*) and wheat (*Triticum aestivum*) and this has had negative effects on the rotations (Gurney *et al*., 2003). Figure 2.1 shows the distribution of *Striga* in the world.

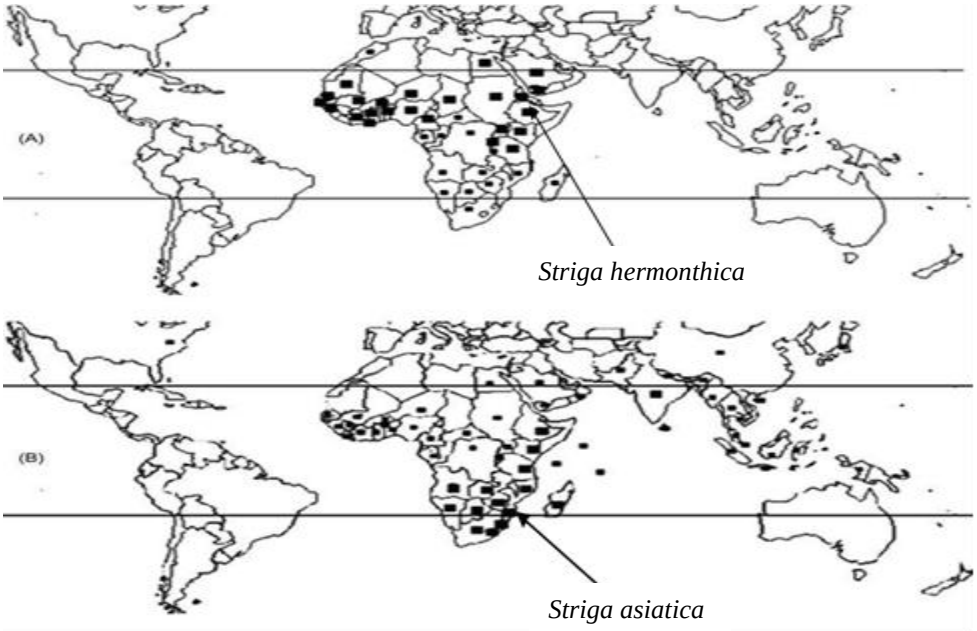

Figure 2.1 Worldwide distribution, *Striga hermonthica* (A) and *Striga asiatica* (B). (Source Parker, 2012).

2.3 Crop production in Africa and *Striga*'s main hosts

In Africa, the major food crops that are grown are maize, sorghum (*Sorghum bicolor* L.), wheat and finger millet (Taylor, 2009; Atera *et al.*, 2012). According to FAO (2006) the total yield of cereals in SSA has increased by just 29% between 1961 and 2005 as compared to Asia and Latin America that have had an increase of 177% and 144%, respectively. However, during the same period of time, the population in the SSA also grew by 216% (United Nations Population Division, 2007). These statistics mean that the ultimate production of cereals has to be increased in SSA to feed the growing population.

In Zimbabwe, *Striga* infection has spread over large proportions in the smallholder sector. A survey that was done by Mabasa, (1994) found out that about 54 % of the farmers reported that *Striga* infestation was on the increase. As a result, the socioeconomic implications of *Striga*

infestation include abandonment of the field and changing the cropping systems which also has serious consequences to the farmer's family and food security for the whole nation.

Cereal crops play a pivotal role of supplying food in Zimbabwe, but the production of such crops has been poor lately. The country's food production system has not been able to keep pace with the increasing demand for food. It was reported by Scholes and Press (2008) that about 50 million hectares of arable farmland in SSA that is under cultivation with both cereals and legumes is affected by one or more *Striga* species. Table 2.1 shows common *Striga* species and their host crops.

Table 2. 1 Main hosts and occasional hosts of different *Striga* species

Species	Main host	Occasional host
S. asiatica	*Sorghum bicolor, Zeamays*, and millets	Wild grasses, *Rottboelia cochinchinensis, Urochloa spp, Setaria spp.*
S. hermonthica	*Zea mays, Oryza sativa, Pennisetum glaucum, Sorghum bicolor*	*Saccharum officinarum, Hordeum vulgare, Triticum aestivium and* wild grasses
S. gesneiroides	*Arachis hypogaea*	*Ricardia scabra, Nicotiana tabacum, Ipomoea batatas*, Siratro grasses, *Mucuna pruriens, Ipomea, Tephrosia purpurea,*

Source: Mandumbu *et al*. (2018)

Striga has diverse hosts on which it can survive on, hence this means that even when rotation has been practiced, it may not be successful in reducing the seed bank because *Striga* will always be available on the alternative host. In the event that all three problematic *Striga* species occur at the same time, rotation to manage weeds will be difficult to practice; as rotation by the smallholder farmers is usually of cereals to legume on a yearly basis (Mandumbu *et al.*, 2018).

2.4 The Ontogeny of *Striga*

The life cycle of *Striga* comprises of two phases which are the subterranean phase and the aerial phase. The aerial phase is the processes whereby there will be above ground activities and the subterranean phase refers to activities occurring below the soil surface (Ejeta and Butler, 1993). There are numerous mechanisms that ensure the synchrony of the parasite's life cycle to that of the host plant. *Striga* has a lot of growth stages but the most significant stages are germination, growth of the radicle, haustorium formation and its attachment to the host plant (Mwakaboko, 2015). Mabasa (2003) reported that the most problematic *Striga* species in Zimbabwe is *S. asiatica*, even though there are other species such as *S. hermonthica* and *Striga forbesii* and *S. gesneriodes*. Through different morphotypes that are possessed by *S. asiatica*, the weed can be identified through its different flower colours which range from red, pink to yellow (Nail *et al.*, 2014). Figure 2.2 shows the *Striga* life cycle.

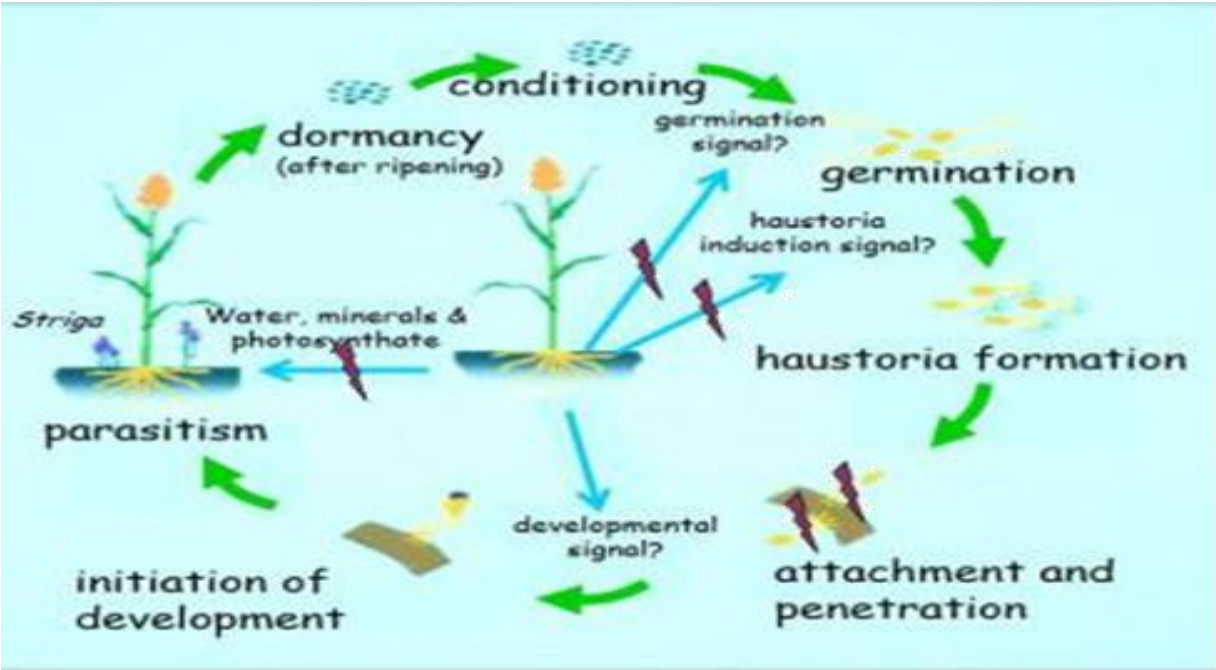

Figure 2.2 *Striga asiatica* life cycle (Source: Ejeta and Butler, 1993)

2.4.1 Germination

Striga asiatica has the capacity to produce thousands of seeds with a longevity of up to 20 years and will only germinate after the release of a chemical cue from the roots of the host plant

(Mabasa, 1994). There have been studies on a number of germination stimulants which were extracted from the root exudates of different hosts and these have been shown to belong to one chemical class known as strigolactones. The different stimulants that have been identified are strigol, which is found in millets, cotton (*Gossypium hirsutum* L.), sorghum and maize; alectrol which is produced by cowpeas (*Vigna anguiculata* L.) and sorgolactone which is found in sorghum (Mwakaboko, 2015). Although the germination stimulants are derived from different varieties of crops and induce germination of a range of *Striga* species, the compounds are comparable and the structures also bear resemblances (Bouwmeester *et al*., 2003).

For the *Striga* seed to germinate, it requires an after ripening period which is the time in which the viable seed will not germinate so that it completes the physiological processes and achieve full maturity (Bouwmeester *et al*., 2003). The duration of the after ripening period differs with the *Striga* species and the geographical location from a few days to two years. When the ripening period is over, *Striga* seed will then germinate after it has been conditioned. During conditioning/preconditioning *Striga* seeds will be exposed to favourable or optimum conditions. In this process seeds will take up water for a period of 14 to 21 days at temperatures between 30^{o}C and 40^{o}C (Mohamed *et al*., 2001). Pre-conditioning is done to leach out chemical inhibitors from the seed which could prevent the seed from germinating (Parker and Riches, 1993).

2.4.2 Haustorium formation and attachment

After germination of the *Striga* seeds has taken place, the radicle of the *Striga* seedling starts to grow chemotropically towards the roots of the host plant (Amudavi *et al.,* 2007). Once there is contact of the radicle and the roots of the host plant, the radicle swells up at the tip to form a haustorium which then penetrates the roots of the host plant (Spallek *et al*., 2013). The haustorium is used to divert carbohydrates and nutrients from the host plant to the *Striga* plant.

The formation of the haustorium is initiated by 2.4 dimethoxy benzoquinone (DMBQ) which is a haustoria inducing compound exuded by host roots (Ishida *et al.,* 2017). If the connection of *Striga* and its host plant is successfully established, the parasite then grows whilst attached to the roots underground for about six to eight weeks before it emerges from the ground (Mwakaboko, 2015).

2.5 Effects of *Striga* infection the host plant

Whilst *Striga* is below the soil surface, it is fully depends on the host plant for carbon (Van Ast and Bastiaans, 2006) and the plants infected lose 80% carbon due to decreased photosynthesis caused by the parasite (Smith *et al*., 1995). As a result, *Striga* negatively affects the allocation of biomass as there is the redirection of water and photo-assimilates as the parasite becomes the sink and the end result will be stunting of plant growth and reduction of yield (Spallek *et al*., 2013). According to Umehara, (2011) that is the reason why plants that are affected by *Striga* usually possess a higher root to shoot biomass because the roots become the sink for the photo-assimilates in order to nourish the parasite. There is an increase in abscisic acid (ABA) concentration of xylem sap in plants infected by *Striga* which is possibly induced by wounds created by the penetration of parasite through host roots (Taylor *et al.,* 1996).

2.6 Economic importance of *Striga*

A total loss of 30-50% of Africa's agriculture has been realised on 40% of its arable land due to infection with *Striga* (Amudavi *et al.,* 2007). In a survey conducted in Nigeria, farmers rated *Striga* as the main constraint to arable crop production along with poor soil fertility resulting in yield losses ranging from 10% to 100% (Dugje *et al.,* 2006). According to MacOpiyo *et al.* (2010), the average yield loss in finger millet due to *Striga* infection is 0.99 tons per hectare. This clearly shows the negative effect caused by *Striga* in finger millet production and this renders small scale farmers helpless.

2.7 *Striga* control strategies

Control of *Striga* can be combated by implementing control measures such as timely planting, application of herbicides (pre and post emergent) and crop rotation with a non-host crop (Agbaje *et al*., 2008). Cultural methods, biological techniques, chemical control and breeding for resistance can also be employed in *Striga* management programmes (Mahmoud *et al*., 2013). Karaya *et al.* (2014) highlighted that *Striga* species can be controlled using cultural methods (such as hand hoeing), biological weed control (through host plant resistance) and the use of pre- and post-emergence herbicides. According to Esilaba (2006) these *Striga* control techniques have not been widely adopted, because they are not economically feasible and limited research has been done to assess their applicability. It is therefore imperative to develop integrated *Striga* management techniques suitable for the different agro-ecosystems (Esilaba, 2006). Woomer and Savala (2007) supported this by asserting that, eradication of *Striga* species can only be achieved through a combination of different control approaches.

2.7.1 Cultural control methods

2.7.1.1 Soil fertility management - Nitrogen and Phosphorus

Striga species inflict more damage on dilapidated soils with low nutrients, hence soil nutrient supplementation will enhance the growth of the host at the expense of the parasite (Kayeke *et al*., 2007). The addition of nitrogen (N) to the soil hinders the development of the parasite and at the same time promotes the establishment of the host (Anjorin, 2013). The application of fertilisers such as urea, ammonium sulphate (NH4SO4), nitrogen, phosphorus (P), potassium (K) and calcium ammonium nitrate (CAN) suppresses the infestations of *Striga* in the field and increase the grain yield of host crops (Mahmoud *et al*., 2013). According to Esilaba (2006) it has been reported that application of N at a rate of up to 140 kg ha^{-1} reduces the population of *Striga* weeds in an infested field. Ifie (2013) also reported a positive correlation between *Striga* resistance and tolerance to low N soils. Increasing the supply of N has a positive effect on the

performance of a susceptible host under severe infestations (Chitagu *et al*., 2014) and a negative effect on the growth phases of *Striga* (Kabambe *et al*., 2008).

2.7.1.2 Crop rotations and inter cropping

The incorporation of non-host crops in the rotation scheme in the fields that are infested with *Striga* as well as having a fallow period have been recommended for the effective control of *Striga* species (Esilaba, 2006). The incorporation of catch and trap crops has been proven to be highly effective in controlling *Striga* infestations (Fernández-Aparicio *et al*., 2011). The combined use of a cereal and legume intercrop system has shown a marginal improvement in reducing *Striga* infestations in areas where it was used (Elzein and Kroschel, 2004). Intercropping has the ability to suppress weeds through surface shedding, transformation of the soil chemical nutrition status especially with legume crops and modification of the soil temperature (Fernández-Aparicio *et al*., 2011).

2.7.1.3 Trap and catch cropping

Trap cropping offers a cheaper alternative *Striga* control technique for the subsistence farmers (Ahom and Magani, 2010). Trap cropping is the cultivation of commercially valuable crops with the aim of reducing the size of the soil seed bank (Fernández-Aparicio *et al*., 2011). Crops such as cowpea, soya bean (*Glycine max* L.), pigeon pea (*Cajanus cajan* L.), sunflower (*Helianthus annuus* L.) and groundnuts (*Arachis hypogaea* L.) have widely been used for trap and catch cropping and these have shown to suppress *Striga* populations (Esilaba, 2006). These crops have the rare ability to produce germination stimulants which are specific for *S. asiatica* germination thereby promoting a reduction in the soil-seed bank size (Esilaba, 2006; Spallek *et al*., 2013).

The best trap crops for *Striga* control are soya bean and cotton (Elzein and Kroschel, 2004); whereas sorghum produces strigolactones that are compatible with *S. hermonthica* (Fernández-

Aparicio *et al*., 2011). Trap cropping reduces the size of the soil seed bank by the technique known as suicidal germination (Mahmoud *et al*., 2013). Suicidal germination is a situation whereby the *Striga* or parasitic seeds are induced to germinate under unfavourable conditions for their growth and survival (Fernández-Aparicio *et al*., 2011). The soya bean crop induces suicidal germination of *Striga* seeds since it is incompatible for seedling attachment (Mahmoud *et al*., 2013).

Esilaba (2006) highlighted that catch cropping is a control method that involves planting host crops that induce germination of the *Striga* seeds and these crop stands are then ploughed down before the weed flowers. Usually susceptible crop species that can release the ideal type of germination stimulants for *Striga* species are used for catch cropping (Woomer and Savala, 2007). This has a negative effect on the seed bank population dynamics of the *Striga* weeds (Esilaba, 2006). The only limitation of using catch cropping is that a farmer cannot derive a profit from the catch cropping practice (Fernández-Aparicio *et al*., 2011).

2.7.1.4 Other non-chemical control techniques

Hand weeding and the use of tolerant varieties also offer possibilities for the production of cereals in endemic regions (Esilaba, 2006). Hand weeding is less effective since the weed species undergo several stages of its life cycle that disturbs the growth of the host before it emerges on the soil surface (Woomer and Savala, 2007). In addition, sowing date has also proved to have an effect on the severity and incidences of *Striga* densities in the mid-season production cycle (Esilaba, 2006). Early planting increases the tolerance capacity of the crop to *Striga* infestations as well as the grain yield (Esilaba, 2006). The use of certified seed is one of the cultural control techniques that can minimize the introduction of the *Striga* seeds into an un-infested field (Esilaba, 2006).

2.7.2 Chemical Control

Esilaba (2006) highlighted that chemical control can be achieved through herbicide applications for instance dicamba and also through the use of germination stimulants such as ethylene and strigol which promote germination of *Striga*. With herbicide use, pre-emergence herbicides are the most effective control method for the root parasites (Elzein and Kroschel, 2004). Dicamba is a symplastically translocated post-emergence herbicide that can control *Striga* when applied immediately after attachment (Elzein and Kroschel, 2004). The combination of Chlorosulfuron, Dicamba, and urea has been reported to confer an effective control method for *Striga* (Esilaba, 2006). Nickrent and Musselman (2004) also asserted that, selective phenoxy herbicide 2.4D is effective in controlling *Striga* in cereal crops. Application of 2.4D suppresses the parasitic effect of *Striga* on crops (Mahmoud *et al*., 2013). Metolachlor inhibits attachment of *Striga* to host root system and investigations on 2.2 kg active ingredient ha^{-1} application rates have exhibited an 80% control rate for *Striga* (Kabambe *et al*., 2008).

Use of germination stimulants such as Nijmegen 1 and GR24 can also be utilised to reduce the size of the soil seed bank (Elzein and Kroschel, 2004). Due to lack of resources, use of germination stimulants and the supplementation of N is not applicable in subsistence farming programmes (Elzein and Kroschel, 2004). Application of the synthetic strigolactones is eco-friendly because they have a low side effect to the environment (Fernández-Aparicio *et al*., 2011). Breeding schemes should also target the incorporation of genes responsible for the production of germination stimulants on non-host crop species to mimic the 'catch cropping' technique (Fernández-Aparicio *et al*., 2011).

2.7.3 Use of resistant genotypes and tolerance (HPR)

It has been reported that genetic defence is the most effective and promising way of controlling *Striga* in the smallholder farming community (Rich and Ejeta, 2008). According to Beyene *et al.*

(2013), host plant resistance (HPR) is a biological approach that provides resistance to an infection by the parasitic weed and is an important trait that should be incorporated in the seed distributed to subsistence farmers. Karaya *et al.* (2014) reported that host plant resistance inhibits the attachment of the hemi-parasite *Striga* to the crop. In return, this offers a more effective, sustainable and economic control technique for the smallholder farmers in the SSA region (Karaya *et al*., 2014). Incorporation of HPR to the crop genome has the capacity to improve productivity by reducing reliance on agrochemicals and also losses that result from infection by the parasite (Karaya *et al*., 2009). The HPR approach is a more practical control technique which can be exploited by the small scale farmers in the Sub-Saharan Africa region (Beyene *et al*., 2013).

Haussmann *et al.* (2000) reported that, HPR is an essential constituent of the integrated Weed Management Programme (IWM). Host plant resistance is divided into two mechanisms which are tolerance and resistance. Tolerance is the capacity of the crop to yield under high infestations of *Striga* whereas resistance is the ability of the crop to inhibit infection of the *Striga* parasite (Karaya *et al*., 2009). However, complete resistance to *Striga* has not been documented (Gurney *et al*., 2003). Tolerance is the only genetic *Striga* resistance store in cereal crops (Spallek *et al*., 2013).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental site

The laboratory and glass house experiments were carried out in the laboratory and glasshouse in the Department of Crop Science, University of Zimbabwe (UZ) during the 2018/2019 season. The geographical co-ordinates for the UZ are 17.78^0S, 31.05^0E and altitude of 1523m. The temperature within the glasshouse ranged from 27 to 32 ^{o}C with relative humidity of 80% and the temperature in the laboratory ranged from 20 to 25 ^{o}C.

3.2 Genetic stock

The finger millet experimental lines that were used in the study were local varieties which were bred and obtained from ICRISAT (International Crop Research Institute of Semi-arid Tropics). The genotypes were SDFM1702, KNE624 and KNE814. Witch weed seed was obtained from Henderson Research station in the 2018 growing season.

3.3 Experiment one: Evaluating the effect of *S. asiatica* infection on finger millet growth and productivity under glasshouse conditions

3.3.1 Experimental design

A pot experiment was carried out in the glass house at the University of Zimbabwe. The experiment was laid down in a 3x2 factorial in a Randomised Complete Block Design (RCBD) with six replications. The factors were genotypes (KNE624, KNE814 and SDFM1702) and *Striga* infestation levels (infested and un-infested). GenStat version 14 was used to randomize the treatments and the blocking factor was the distance of the treatments from the door.

3.3.2 Planting and establishment

The experiment was done in pots measuring 23 cm x 24 cm x 16 cm for the top diameter, height and bottom diameter, respectively. The pots were filled up to three quarters with sandy soil that was collected from Henderson Research Station. Sandy soils were used for the experiment so as to mimic edaphic factors in which the parasite exerts its dominance. The inoculation of *S. asiatica* seeds to the soil was done 14 days prior to planting. *Striga asiatica* seeds (0.02 grams, approximately 4900 seeds) were thoroughly mixed within the top five to eight cm of dry soil in 18 pots. This was achieved through mixing of the soil that was collected from the top 5-8 cm depth in plastic and then placing back the soil in the pots. Basal fertilizer compound D (8% N, 14% P_2O_5, 7% K_2O) was applied at the rate of 2 g per pot in order to match the fertilizer quantities that the small-scale farmers apply. Watering was done to field capacity soon after inoculation with the *Striga* seed. All work in the pots was done separately starting with the un-infected pots so as to avoid contamination.

After 14 days, finger millet seed was broadcasted within the top 2 cm of the soil. All the pots, whether infested or not, were all planted at the same time. Thinning was done two weeks after planting, leaving two plants per pot and further thinning was done a week later to leave one plant per pot.

3.3.3 Agronomic practices

Ammonium nitrate (34.5%N) was applied at a rate of 2grams per pot as top dressing at six weeks after crop emergence (WACE). Weeds other than *S. asiatica* were hand pulled as soon as they emerged so as to allow interaction of finger millet and the parasitic weed. Water was applied at 800 ml per pot after every seven days. Carbaryl 50% WP was sprayed at six weeks to control aphids.

3.3.4 Data collection

3.3.4.1 Plant height

The plant height of finger millet was measured from the soil level to the ligule of the last fully expanded leaf weekly from week 7 until week 15 using a meter ruler.

3.3.4.2 Days to emergence of *S. asiatica*

The number of days to first *Striga* emergence were recorded for each variety.

3.3.4.3 *Striga* count

Total number of *Striga* plants was counted weekly from 11 up to 15 WACE per pot.

3.3.4.4 Chlorophyll content

The chlorophyll content was measured using a chlorophyll meter SPAD-502 Plus (Minolta Corporation, Ltd., Osaka, Japan) from 8 WACE up to week 15. The readings were taken on young leaves that were fully developed between 12 pm and 1 pm.

3.3.4.5 Chlorophyll fluorescence

Chlorophyll fluorescence ($F_v/F_{m)}$ where (F_v = variable fluorescence and F_m = maximum fluorescence value) was measured using a portable, pulse modulated $OS30p^+$ chlorophyll fluorometer (Opt-Sciences, Inc, Hudson, NH, USA) in week 14 and 15. The measurements were taken on the youngest fully developed leaves after initiation of darkness on the leaves using clips that are provided with the instrument. The readings were taken between 12 pm and 3 pm.

3.3.4.6 Plant biomass

After harvesting, the stems were cut off at the base just above the roots and the leaves were pruned off the stem and then placed in khaki envelops. Samples were oven dried for 36 hours in an oven at 80 ^{o}C. The roots were uprooted, cleaned using water before being placed in the khaki papers and then oven dried. After drying, different plant parts were weighed using a sensitive balance (Model Analytical Balance Sartorius Research R200D). Total above ground biomass was obtained by adding the dry weight of the leaves and the stem.

3.3.4.7 Root to shoot ratio

The root biomass of each genotype was divided by the total above ground biomass (leaves and stem) to obtain the root to shoot ratio.

3.3.4.8 Total grain yield

Harvesting was done 145 DACE when grain had reached 14% moisture content.

3.3.4.9 Number of haustoria

After harvesting, *S. asiatica* plants and finger millet roots were pulled from the soil and the roots were washed before physically counting the haustoria on the crop roots. This was done on the same day that the crops were harvested.

3.4 Experiment two: Screening finger millet genotypes for pre-attachment resistance to *S. asiatica*

The three finger millet genotypes (KNE624, KNE814 and SDFM1702) were arranged in a Completely Randomised Design CRD) with ten replicates. The study was carried out using the standard procedure that was developed at IITA (Hess *et al.,* 1992).

3.4.1 Pre-conditioning of *S. asiatica* seeds

The seeds were preconditioned for 14 days in the glass house to break dormancy using the method described by Nyakurwa *et al.* (2018). Sterilisation of *S. asiatica* seeds was achieved by immersing them in 1% sodium hypochlorite (NaCIO) for ten minutes. A total of 0.04 grams of *S. asiatica* seeds were placed in 50 ml conical flasks and then rinsed three times with distilled water before being evenly placed into the 90 mm diameter Petri dishes lined with on one sheet of no.2 Whatman filter paper. Forty-five millimetres of double distilled water were then poured into the Petri dishes to moisten the filter paper after which they were sealed using paraffin film. Thereafter, the Petri dishes were covered with black plastic to prevent light penetration and were then placed in the glasshouse for 14 days.

3.4.2 Pre-germination of finger millet seeds

Finger millet seeds were pre-germinated before being used in the Ager-gel assay. The seeds were immersed in 1% sodium hypochlorite (NaCIO) for ten minutes and then rinsed three times using double distilled water. Seeds were then placed in the 90 mm diameter Petri dishes lined with a Whatman no.2 filter paper. Distilled water (45 ml) was poured inside the Petri dishes to provide ideal conditions for seed germination. Parafilm was used to seal the Petri dishes. The Petri dishes were covered using foil paper to avoid penetration of sunlight. Samples where then placed in dark room which had temperatures ranging from 25 to 30 ^{O}C for 48 hours. Only healthy-looking germinated finger millet seeds were selected for the Ager-gel assay.

3.4.3 Surface and equipment sterilization

Sterilization of forceps, culturing surfaces and the laminar flow hood was done using 70% alcohol.

3.4.4 Ager gel preparation

Agar-gel was prepared using a ratio of 10g bacto agar: 1 litre distilled water (Nyakurwa *et al.*, 2018). The agar was poured into 500ml conical flasks which had distilled water and then shaken to mix the agar and water. After mixing, the flasks were sealed using cotton wool and aluminium foil and the media was autoclaved at a pressure of 15 psi and temperature of 121^{O}C for 20 minutes using an automatic graduated autoclave.

3.4.5 Agar gel assay technique

After preparing the agar gel and cooling off, the media was poured into 90 mm diameter Petri dishes (45 ml of agar in each dish) under the laminar flow hood and then it was allowed to solidify. A micropipette (50µl) was used to pipette 200µl (approximately 1000 seeds) of preconditioned *S. asiatica* seed into the Petri dishes before the media solidified. The Petri dishes were gently shaken in order to incorporate and ensure even distribution of the *S. asiatica* seeds

throughout the media. One pre-germinated finger millet seed was then placed on the solidifying culture media near the edge of the Petri dish with the tip of the root pointing across the Petri dish as described by Reda *et al.* (1994). The Petri dishes were incubated using Mains Scientific incubator at 30 ^{o}C for 72 hours before the first readings were taken. Figure 3.1 shows prepared Petri dishes with demarcations for data collection.

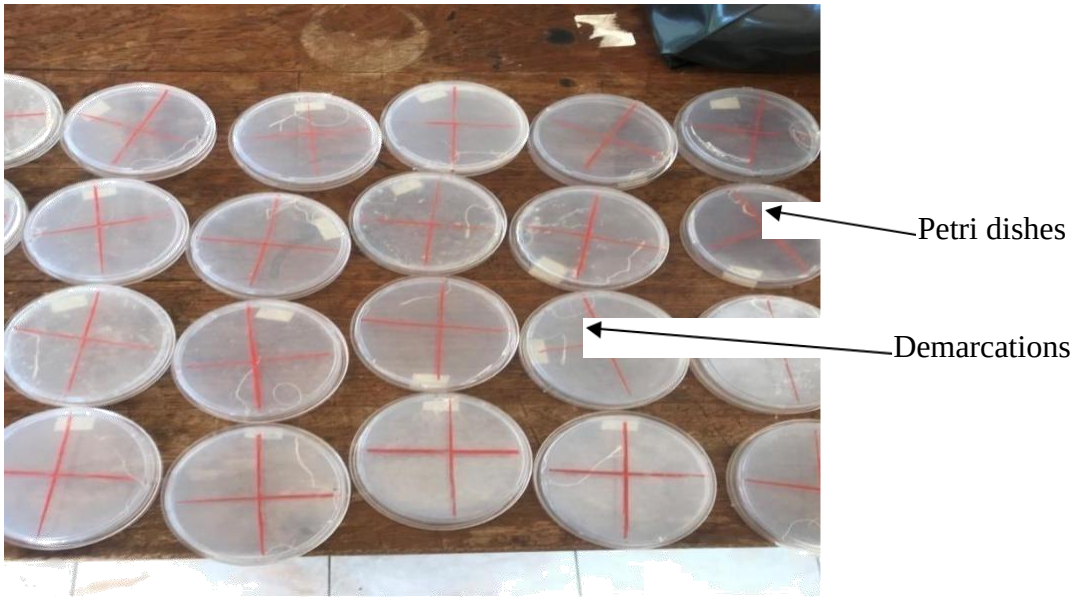

Figure 3.1 Set up of the Ager-gel assay and demarcated Petri dishes for data collection in the weed science laboratory at the University of Zimbabwe. Picture was taken by Kudzai Makani (6/5/19).

3.4.6 Data collection

3.4.6.1 Germination percentage

The Petri dish was divided into four quarters as shown in Figure 3.1. Within the demarcated boxes, the total number of *S. asiatica* seeds and total number of germinated seed focused from the bottom of the Petri dish in each quarter of the Petri dish was recorded. The results collected from four different spots were averaged and expressed as a percentage. The results were recorded cumulatively from day 3, 7 and then day 10.

$$\text{Germination (\%)} = \frac{\text{Number of germinated seeds in the demarcated box} * 100}{\text{Total Number of seeds in the demarcated box}}$$

3.4.6.2 Furthest germination distance

Furthest germination distance of *S. asiatica* seeds from the finger millet root was measured using a microscope fitted with a micrometre ruler. The distance was measured from the germinated seed to the closest part of the root.

3.5 Data analysis

Data were analysed using Genstat 14th version and mean separation was done using Fisher's Protected LSD at 5% significance level. Repeated measures Analysis of variance was carried out for plant height, chlorophyll content and chlorophyll fluorescence data.

CHAPTER FOUR

RESULTS

4.1 Glasshouse experiment

4.1.1 Plant height

There was no significant interaction ($p>0.05$) between *S. asiatica* infestations x genotype x time, time x *S. asiatica* and *S. asiatica* x genotype on the height of finger millet genotypes. *Striga asiatica* infection significantly ($p<0.05$) reduced the height of KNE624 and KNE 624 but not SDMF1702 (Figure 4.1). *Striga asiatica* infection did not significantly ($p<0.05$) reduce the finger millet height (Figure 4.2).

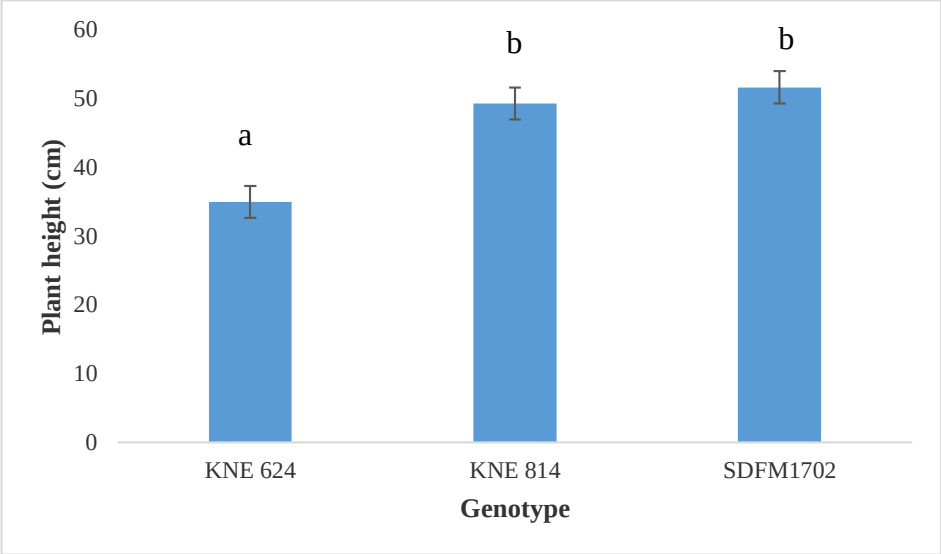

Figure 4.1 Response of finger millet genotypes to *S. asiatica* parasitism on plant height (cm) evaluated in pots under glasshouse conditions at the University of Zimbabwe in the 2018-2019 crop growing season. Error bars represent least significant differences (lsd) at $p<0.05$

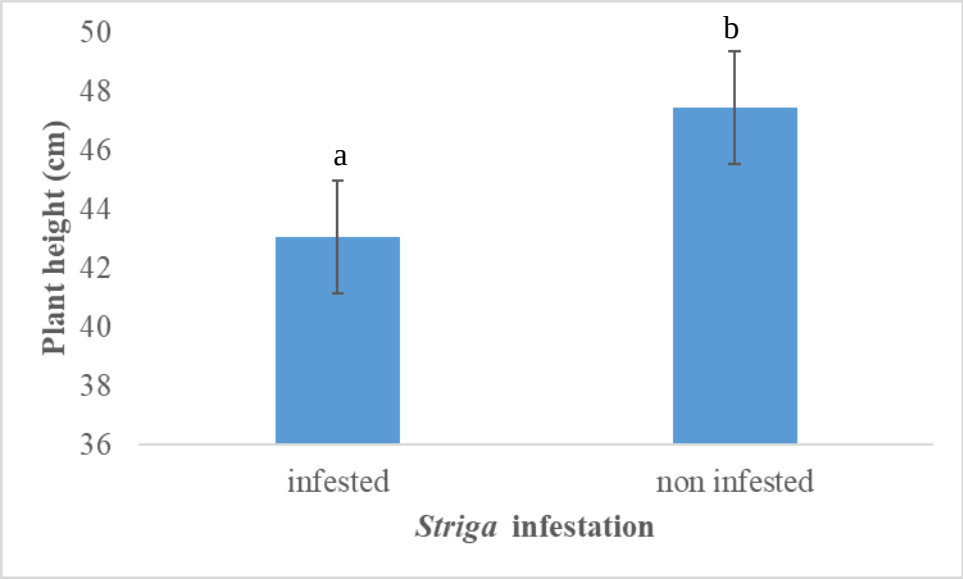

Figure 4. 2 Effect of *S. asiatica* infestation on finger millet height (cm) evaluated in pots under glasshouse conditions at the University of Zimbabwe in the 2018-2019 crop growing season. Error bars represent lsd at $p<0.05$

4.1.2 *Striga* counts

The time x variety interaction was not significant ($p>0.05$) on *S. asiatica* counts. There was no significant ($p>0.05$) variation among genotypes KNE614, KNE814 and SDMF1702 genotypes on the number of *Striga* plants in infested pots (Figure 4.3). *Striga* counts increased significantly ($p<0.005$) from week 11 to 15 (Figure 4.4) and were significantly higher in week 15 than in week 11.

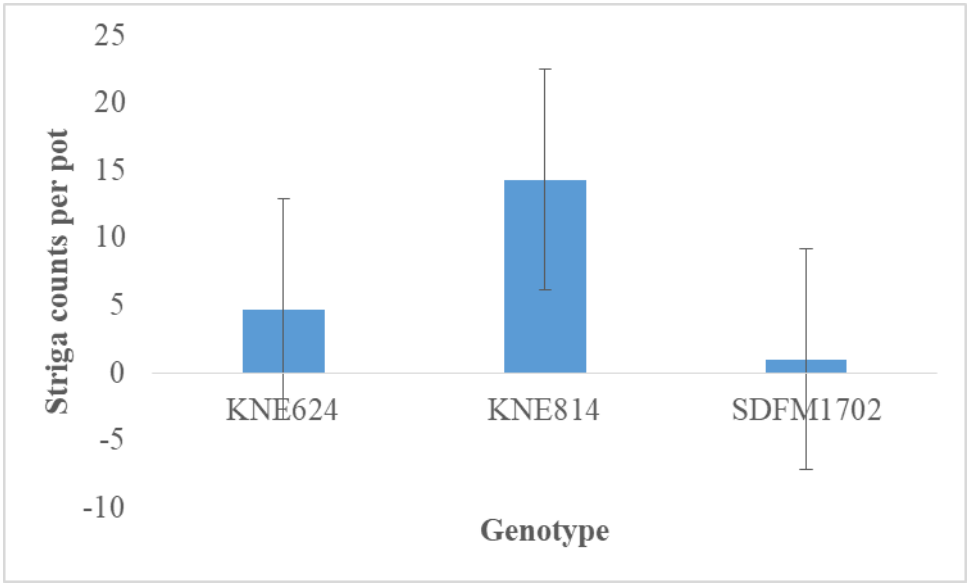

Figure 4.3 *Striga* counts (per pot) on different finger millet genotypes. Error bars represent lsd at p<0.05

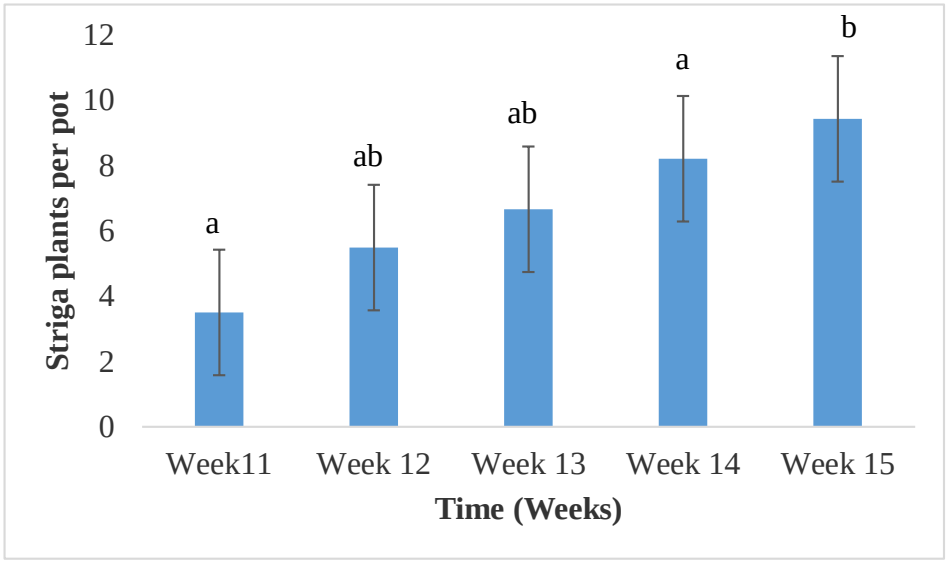

Figure 4.4 *Striga* counts (per pot) from week 11 to week 15. Error bars represent lsd at p<0.05.

4.1.3 Chlorophyll content

There was no significant ($p>0.05$) difference on time x *Striga* infestation x genotype, time x genotype and *Striga* x genotype interaction on chlorophyll content. *Striga* infection significantly ($p>0.05$) reduce chlorophyll content of all finger millet genotypes (Figure 4.5). However, there were no significant differences ($p>0.05$) in chlorophyll content among genotypes (Figure 4.6).

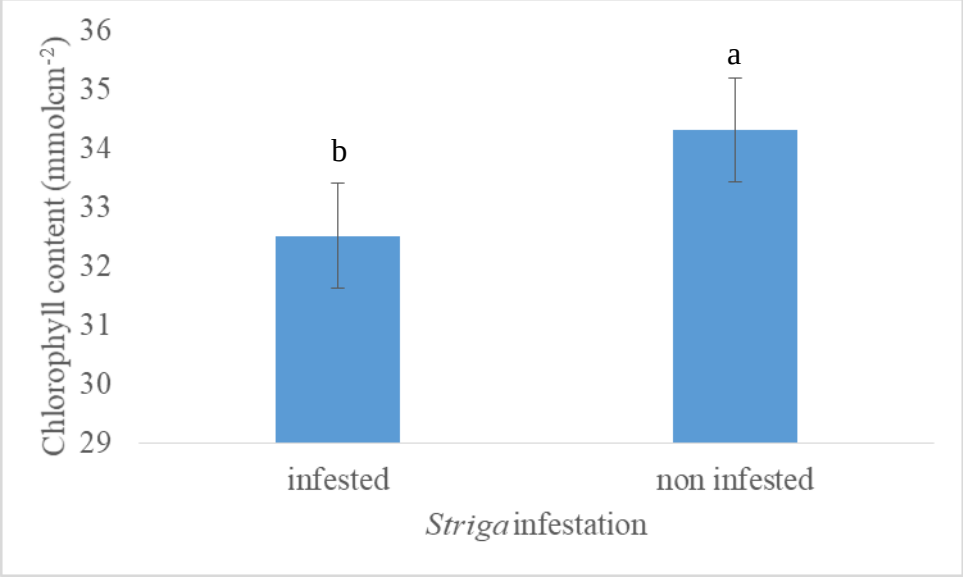

Figure 4.5 Effect of *Striga* infection on chlorophyll content ($mmolcm^{-2}$) of finger millet genotypes. Error bars represent lsd at $p<0.05$.

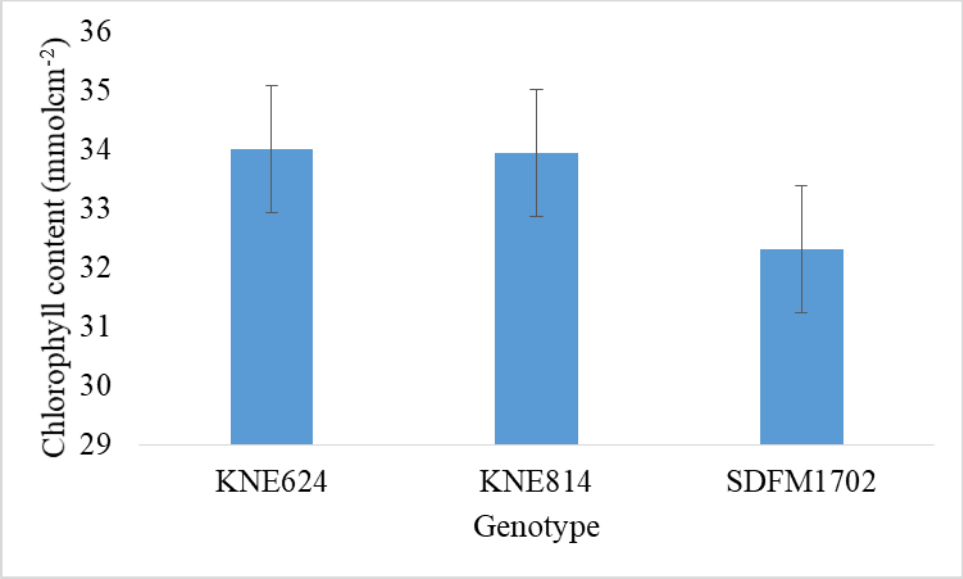

Figure 4.6 Response of finger millet genotypes to *S. asiatica* parasitism on chlorophyll content (mmolcm^{-2}) under glasshouse conditions at the University of Zimbabwe in the 2018-2019 crop growing season. Error bars represent lsd at $p<0.05$.

4.1.4 Chlorophyll fluorescence

The time x genotype x *Striga* and *Striga* x genotype interactions were not significant ($p>0.05$) on chlorophyll fluorescence. Finger millet genotypes significantly ($p<0.05$) differed from each other in terms of chlorophyll fluorescence. Genotype SDMF1702 recorded significantly lower chlorophyll fluorescence than KNE624 and KNe814 which did not significantly differ from each other (Figure 4.7). *Striga* infestation did not significantly ($p>0.05$) affect the chlorophyll fluorescence (Fv/Fm) of finger millet genotypes KNE614, KNE814 and SDMF1702 (Figure 4.8).

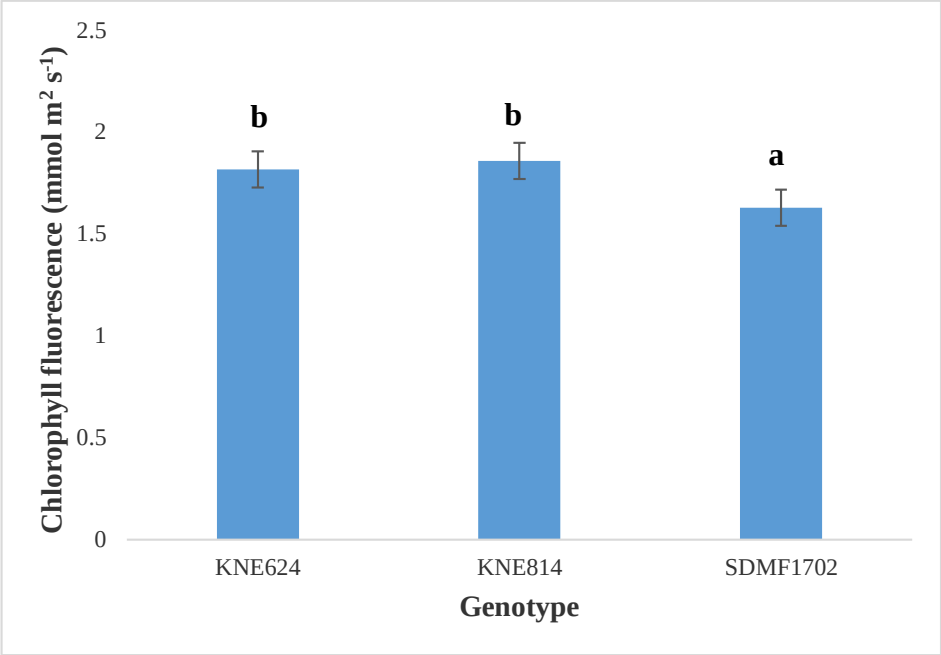

Figure 4.7 Effect of finger millet genotype on chlorophyll fluorescence (mmolm^{2}s^{-1}) of three finger millet varieties grown in pots under glasshouse environment at the University of Zimbabwe in the 2018-2019 crop growing season. Error bars represent lsd at $p<0.05$.

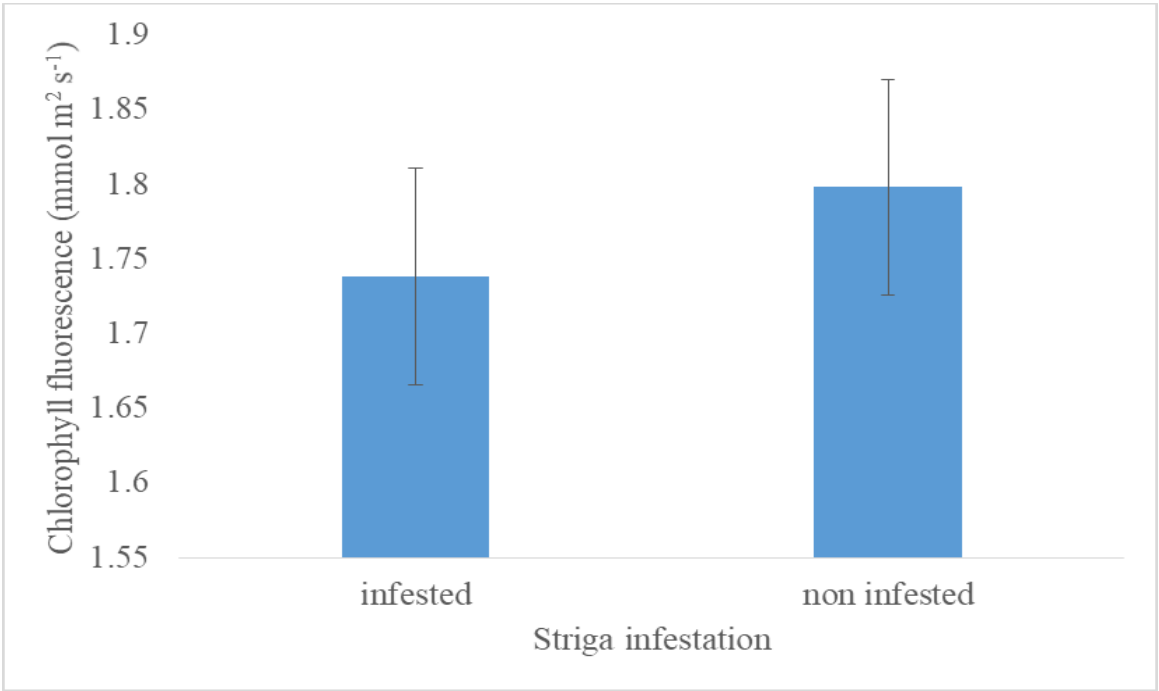

Figure 4.8 Effect of *S. asiatica* on chlorophyll fluorescence (mmolm^{2}s^{-1}) of three finger millet varieties grown in pots under glasshouse environment at the University of Zimbabwe in the 2018-2019 crop growing season. Error bars represent lsd at $p<0.05$.

4.1.5 Stem biomass

The infection x genotype interaction was significant ($p<0.05$) on stem biomass of finger millet. *Striga asiatica* infection significantly ($p<0.05$) reduced stem biomass of all finger millet genotypes (Figure 4.9). KNE624 produced significantly higher above ground biomass for the uninfected compared to genotypes KNE 814 and SDFM 1702.

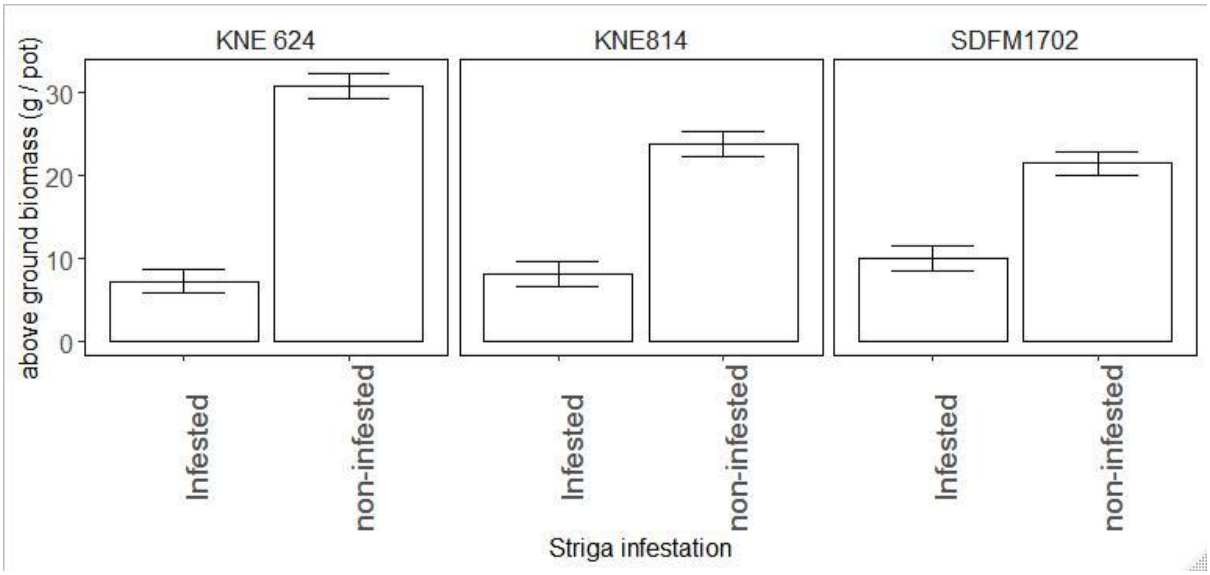

Figure 4.9 Effect of *S. asiatica* infection on stem biomass (g pot^{-1}) of three finger millet genotypes. Error bars represent lsd at $p<0.05$.

4.1.6 Leaf biomass

The *Striga* infection x genotype interaction was not significant ($p>0.05$) on leaf biomass of finger millet. *Striga asiatica* infested finger millet genotypes had significantly ($p<0.05$) lower leaf biomass than those grown in *Striga* free soils (Figure 4.10). There were no significant ($p>0.05$) differences in leaf biomass among the finger millet genotypes (Figure 4.11).

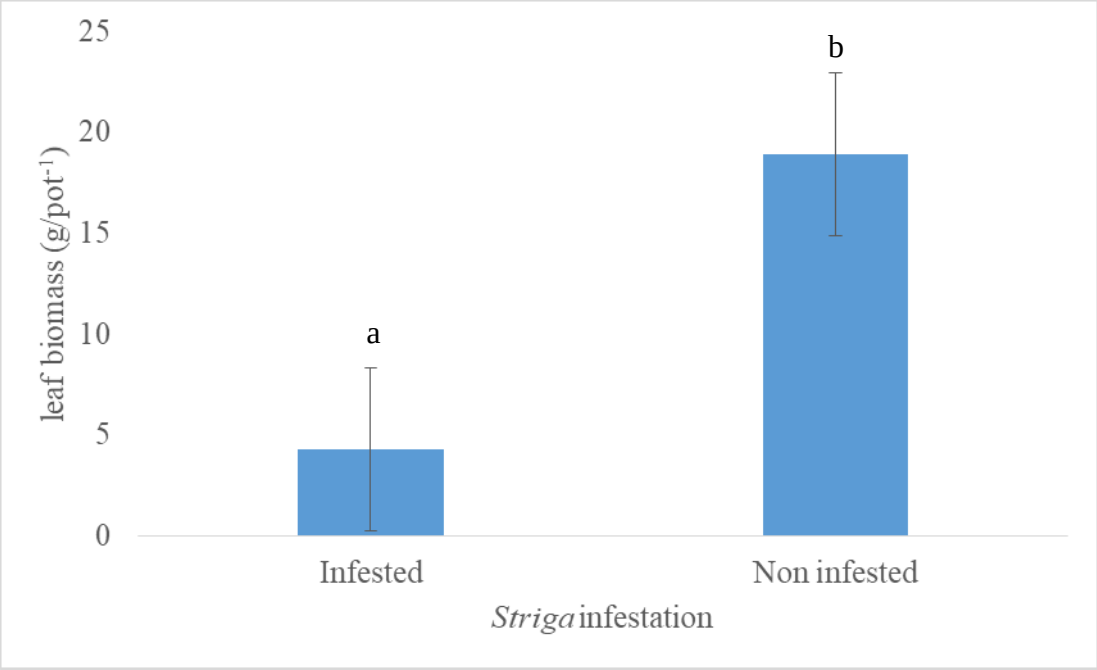

Figure 4.10 Effect of *S. asiatica* infection on leaf biomass (g pot^{-1}) of finger millet genotypes grown under greenhouse conditions at the University of Zimbabwe in the 2018/19 growing season. Error bars represent lsd at p<0.05.

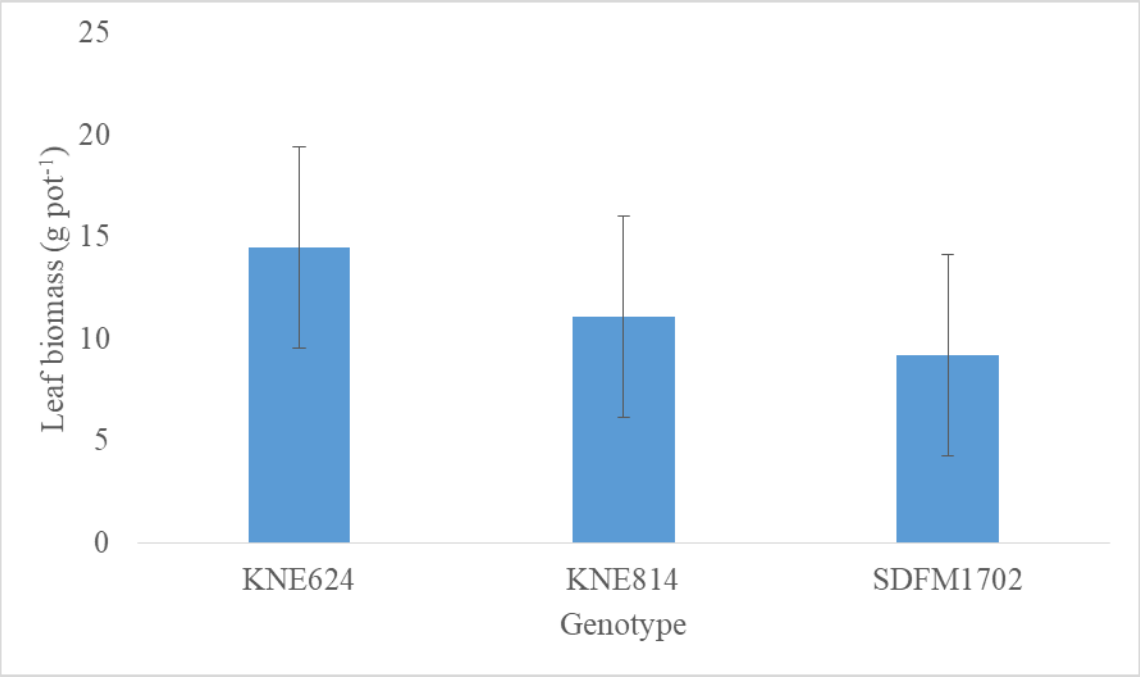

Figure 4.11 Response of finger miller genotypes on leaf biomass (g pot^{-1}) of three finger millet genotypes grown under greenhouse conditions at the University of Zimbabwe in the 2018/19 growing season. Error bars represent lsd at p<0.05.

4.1.7 Total above ground biomass

The *Striga* infection x genotype interaction was significant ($p<0.05$) on total above ground biomass of the three finger millet genotypes. *Striga asiatica* infection significantly reduced the total above ground biomass of all the three finger millet genotypes (Figure 4.12).

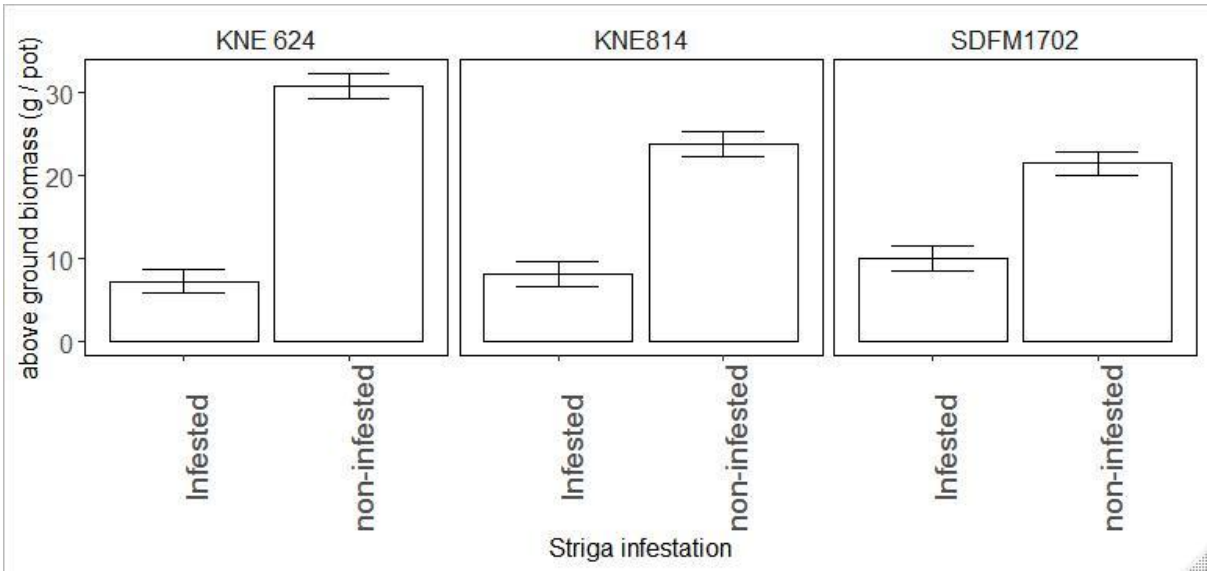

Figure 4.12 Response of above ground biomass (g pot^{-1}) of three finger millet genotypes to *S. asiatica* infection. Error bars represent lsd at $p<0.05$.

4.1.8 Root biomass

The *Striga* infection x genotype interaction was significant ($p<0.05$) on root biomass (Figure 4.13). *Striga asiatica* infection significantly reduced the leaf biomass of the finger millet genotypes KNE624, KNE 814 but not SDMF1702.

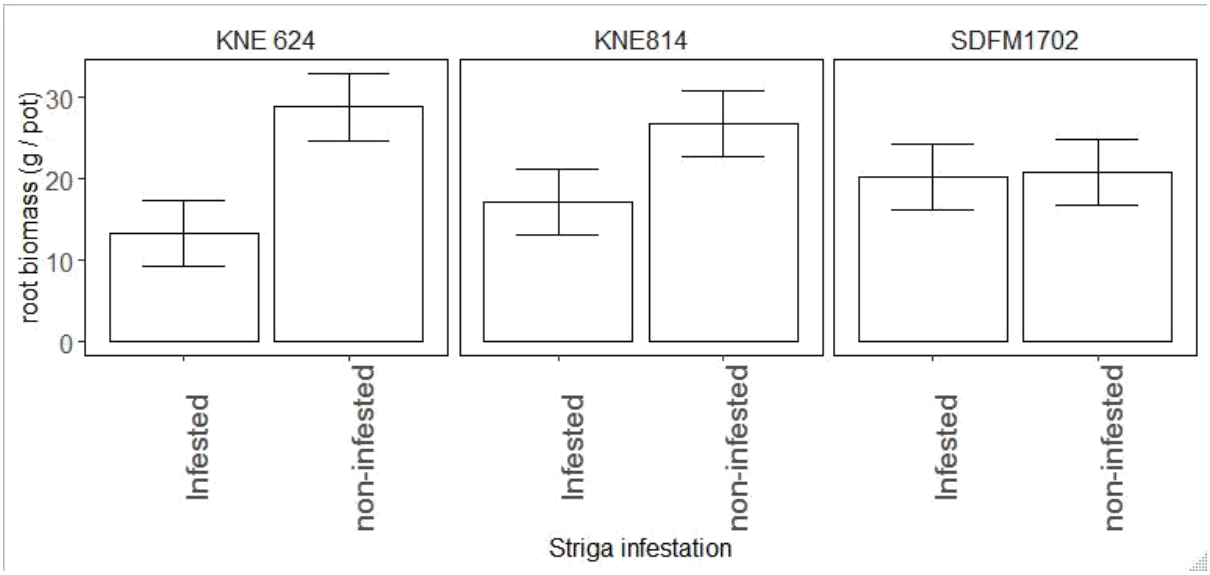

Figure 4.13 Effect of *S. asiatica* infection on the root biomass (g pot^{-1}) of three finger millet genotypes grown under greenhouse conditions at the University of Zimbabwe in the 2018/19 growing season. Error bars represent lsd at $p<0.05$.

4.1.9 Root to shoot ratio

There was no significant interaction between *S. asiatica* infection and genotype ($p>0.05$) on root to shoot ratio of finger millet genotypes. Finger millet genotypes did not significantly ($p>0.05$) differ on root to shoot biomass. However, *S. asiatica* infection significantly ($p<0.05$) reduced the root to shoot ratio of the finger millet genotypes (Figure 4.14).

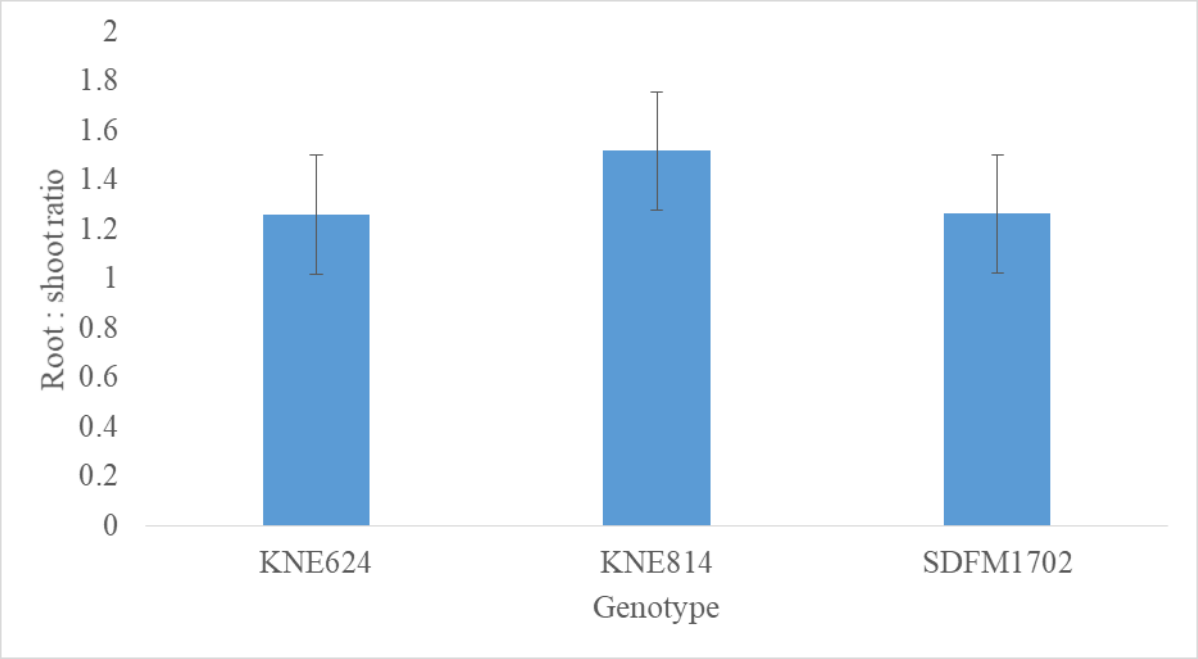

Figure 4.14 Effect of genotype on root to shoot ratio of three finger millet genotypes grown under greenhouse conditions at the University of Zimbabwe in the 2018/19 growing season. Error bars represent lsd at $p<0.05$.

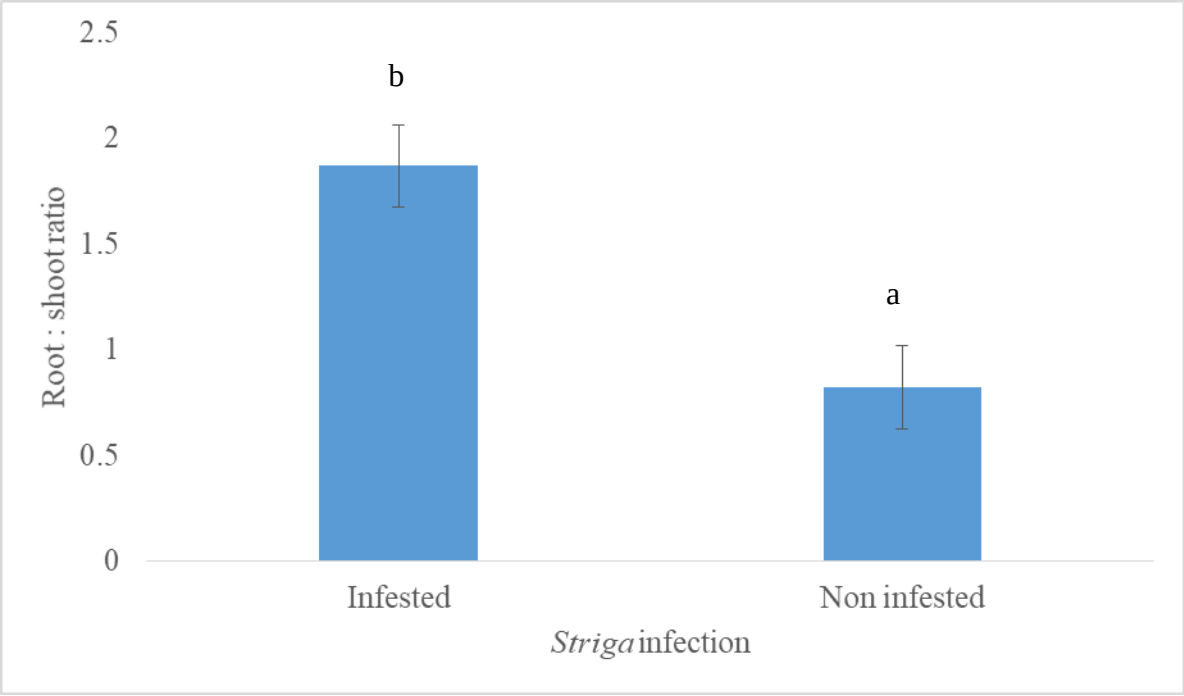

Figure 4.15 Effect of *S. asiatica* infection on root to shoot ratio of three finger millet genotypes grown under greenhouse conditions at the University of Zimbabwe in the 2018/19 growing season. Error bars represent lsd at $p<0.05$.

4.1.10 Number of haustoria

There was a significant ($p<0.05$) difference in the number of haustoria on the roots of different finger millet genotypes (Figure 4.15). Genotype SDFM1702 supported significantly fewer attachments than the other genotypes. On the other hand KNE supported significantly more *Striga* attachments than the other genotypes.

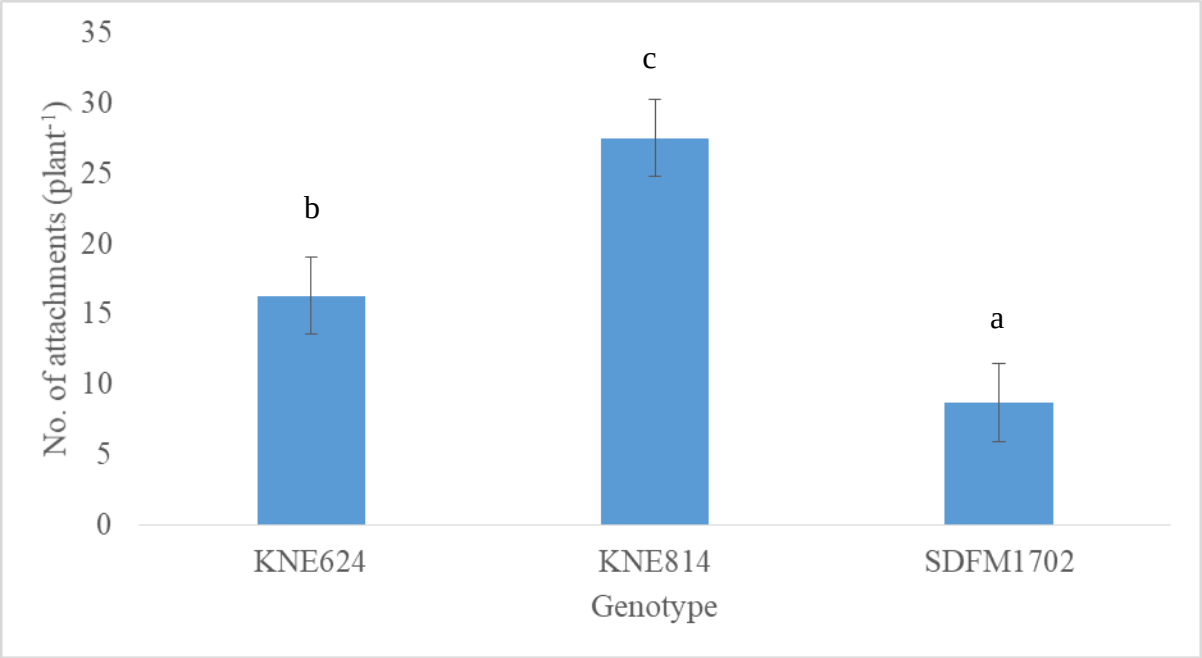

Figure 4.16 Effect of genotype of the number of haustoria (per plant) of three finger millet genotypes grown under glasshouse conditions during 2018/19 season. Error bars represent lsd at $p<0.05$.

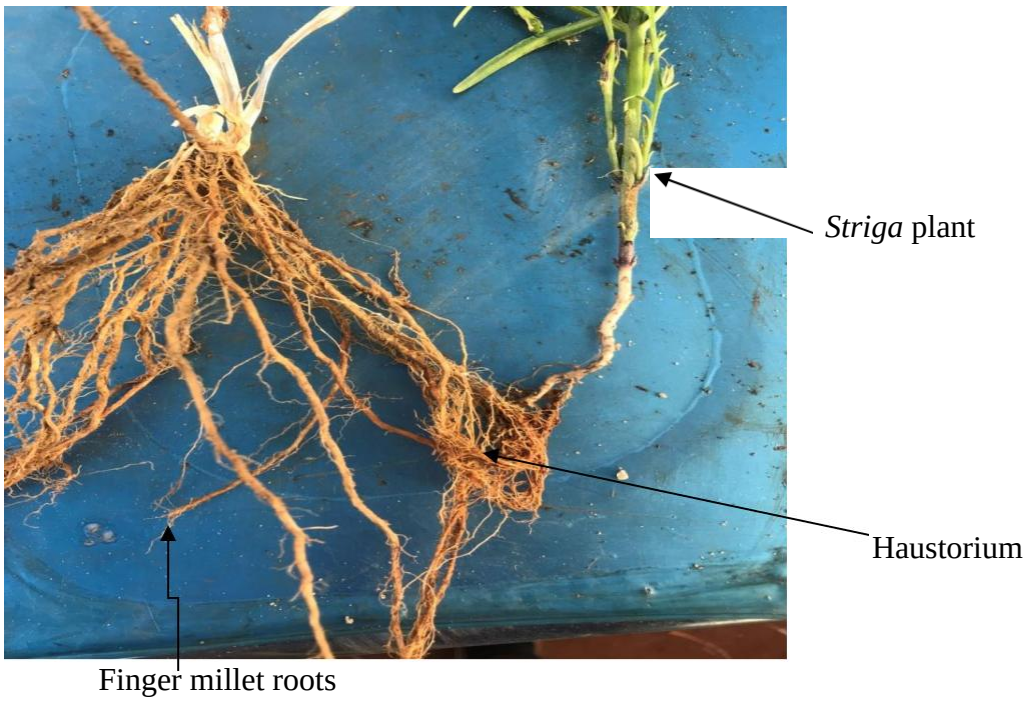

Figure 4.17 *Striga* plant and haustoria attachment to finger millet crop. Picture was taken by Makani(14/05/19).

4.1.11 Grain yield

The *Striga* infection x genotype interaction was significant ($p<0.001$) on grain yield of finger millet genotypes. *Striga* infection significantly reduced the grain yield of all three finger millet genotypes (Figure 4.17).

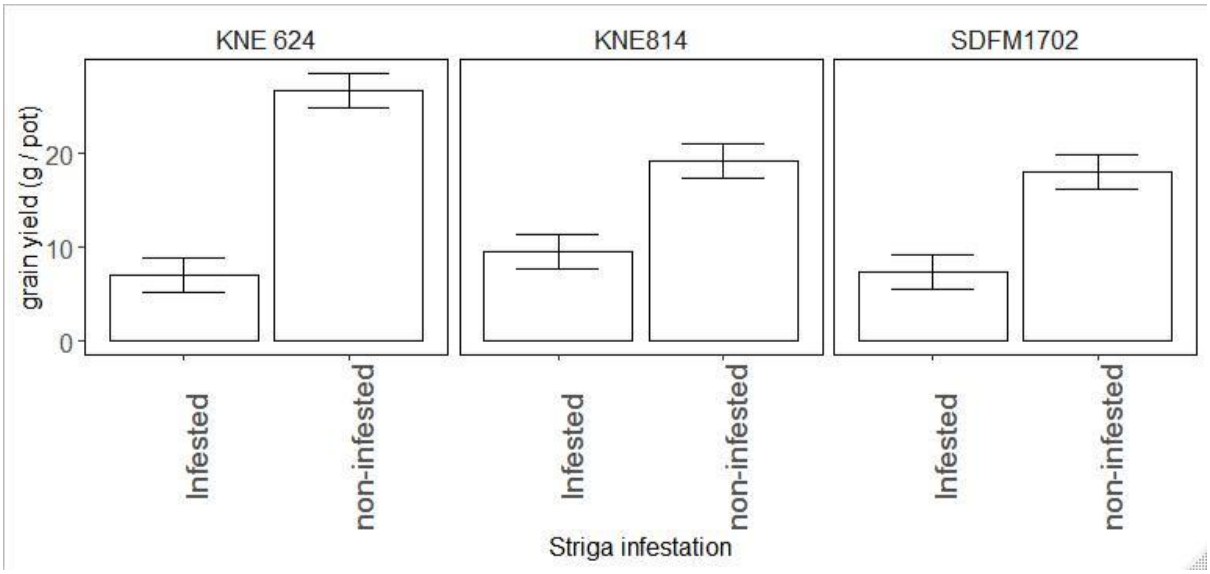

Figure 4.18 Effect of *S. asiatica* infection on the total grain yield (pot^{-1}) of three finger millet genotypes grown under glasshouse conditions at the University of Zimbabwe during 2018/19 season. Error bars represent lsd at $p<0.05$.

4.2 Ager gel assay: Effect of finger millet genotypes on the germination percentage and furthest germination distance of *S. asiatica*

4.2.1 Germination percentage

There were significant ($p<0.05$) differences among genotypes on the germination percentage at day 3, 7 and 10. SDFM1702 recorded significantly lower germination than the other genotypes at days 7 and 10. (Table 4.1).

4.2.2 Furthest germination distance

There was a significant ($p<0.05$) difference on the furthest germination distance of the three finger millet genotypes. SDMF1702 had significantly lower germination distance than KNE624 and KNE814 which performed the same (Table 4.1).

Table 4. 1 **Effect of finger millet genotypes on germination percentage and furthest germination distance of *S. asiatica***

Finger millet Genotype	Germination % (Day 3)	Germination % (Day 7)	Germination % (Day 10)	Furthest distance (mm)
KNE624	1.65^{ab}	5.18^{b}	8.15^{b}	1.420^{b}
KNE814	2.03^{b}	4.89^{b}	8.34^{b}	1.567^{b}
SDFM1702	1.08^{a}	2.2^{a}	5.37^{a}	0.985^{a}
p-value	**0.009**	**<0.001**	**0.028**	**<0.01**
Lsd	**0.589**	**0.544**	**0.47**	**0.2419**
CV%	**40.4**	**26.9**	**22**	**19.9**

Means followed by the different letters in the same column are significantly different at p<0.05.

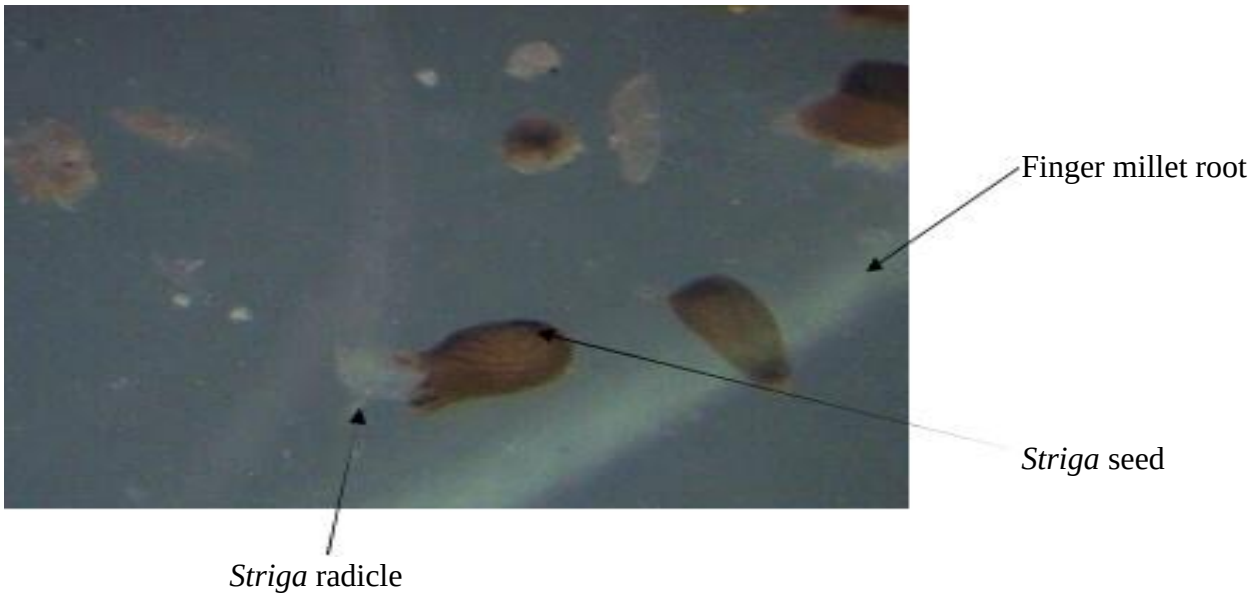

Figure 4.19 *Striga* seed, *Striga* germination and finger millet root in the Petri dish (x40 magnification). Picture taken by Kudzai Makani (6/05/19).

CHAPTER FIVE

DISCUSSION

5.1 Evaluating the effect of *Striga asiatica* infection in finger millet growth and productivity under glasshouse conditions

Striga asiatica infection reduced height of finger millet genotypes. The reduction in plant height can be attributed to stunted growth in response to *Striga* infection due to partitioning of assimilates (Berner and Singh, 1995). According to Mabasa (2003) plant height is one of the most sensitive parameters to *S. asiatica* infection. In this study, genotype KNE624 had the shortest plants. Richard *et al.* (2006) asserted that each genotype is affected differently by *Striga* depending on the environment that the plant has been exposed to. The differences in the plant height because of *Striga* infection could also be due to changes in the growth regulators produced by the host (Frost *et al.,* 1997). Frost *et al.* (1997) and Taylor *et al.* (1996) reported that the increase in abscisic acid (ABA) in *Striga* infected crops may result in the closing of the stoma leading to a reduction in photosynthesis and consequently plant growth.

Finger millet genotypes KNE624 and KNE814 maintained the same plant height until week 10 when *Striga* had emerged from the ground. The difference in height can be attributed to partitioning of assimilates where the *Striga* plant will be the sink for the nutrients (Gurney *et al.,* 2002; Cechin and Press,1993, Smith *et al.*,1995).

Striga asiatica plants continuously emerged from the ground from week 11 onwards in all the genotypes. This means that the host crop continuously produced sufficient strigolactones to support germination, attachment and emergence of *S. asiatica* from the ground. In a study that was carried out by Sun *et al.* (2007) and Jamil *et al.* (2011) the germination and emergence of *S.*

asiatica from the ground was highly dependent on the quality and quantity of strigolactones that were produced by the host plant. In this case, KNE814 produced the highest number of *S. asiatica* plants, followed by KNE624 and SDFM1702 which were the same. This suggests that KNE624 and SDFM1702 are low producers of strigolactones as this is shown by the germination of few *S. asiatica* plants. For the three genotypes, there was a significant difference with regards to number of haustoria. This was also an indicator of the quality and quantity of strigolactones produced by the crop.

Striga asiatica infection reduced chlorophyll content in all the three genotypes that were inoculated with the parasitic weed. However, the chlorophyll content in KNE814 and SDMF1702 was not significantly affected. This is similar to the result that was attained by Gurney *et al.* (2004) who reported that some cereal crops have the capacity to maintain their chlorophyll content even when infected by *Striga.* The chlorophyll concentration within the plant is very important as it indicates the photosynthetic functioning as well as the potential carbon dioxide (CO2) fixation rates. According to Mandumbu (2017) genotypes that are tolerant have the capacity to adjust the chlorophyll content so that they can independently keep the process of photosynthesis at the optimal levels. Chlorophyll content is a very important parameter in plant growth as it is responsible for the plant's canopy and also carbon assimilation. The chlorophyll content for KNE624 was low. According to Sun *et al.* (2007). *Striga* affects the production of carbon in the host crops, and this is believed to limit the assimilation of nitrogen hence resulting in reduced chlorophyll synthesis.

Striga asiatica infection also reduced the chlorophyll fluorescence (Fv/Fm) of all the three genotypes from week 14 to week 15. *Striga* infection reduces chlorophyll fluorescence of infected finger millet plants because of *Striga*-induced photo-inhibition (Mauromicale *et al.*, 2008; Vrbničanin *et al.*, 2013). Photo-inhibition is whereby the photo-system II photochemistry

reaction centre which causes a reduction in rates of photosynthesis is inactivated (Gurney *et al.*, 2002).

Striga infection significantly reduced stem biomass of all the three genotypes. The biomass of the stem appeared to be a very sensitive parameter to infection by *S. asiatica*. According to Mabasa, (1994) similar results were reported for *Striga* effects in other cereals such as maize (*Zea mays* L.) In addition, the leaf biomass of all the genotypes was affected by *Striga* parasitism. However, Mabasa (1994) concluded that different arrangements of leaves within the plant have complications on the use of leaf biomass as a parameter for indicating *Striga* tolerance in plants. For example, the leaf packing which is caused by *Striga* could result in leaf shading leading to reduced photosynthesis and internodes hence resulting in lower dry matter production. High leaf biomass could also mean that there was high photosynthetic area hence leading to additional photo assimilates for the host plant. According to Poorter *et al.* (2011), during plant growing process, the plant balances the allocation of assimilates to the roots, leaves and stems in such a way that works hand in hand with the physiological activities and functions of these plant organs.

Root biomass differed amongst all the three genotypes with KNE624 having a higher root biomass in the non-infected plants than in infected ones. Plants infected with *S. asiatica* lose carbon to the parasite as a result of disruption of photosynthesis by the parasite which then reduces the biomass of the plants (Těšitel *et al.*, 2010). Root to shoot ratio is the ratio of dry mass of below ground structure (roots) against the above ground structures (Oswald, 2005). According to Oswald and Ransom (2001) plants that are affected by *Striga* respond to infection by allocating dry matter to below ground parts rather than above ground parts hence leading to higher root to shoot ratio in infected plants. In this study, infection by *Striga* lowered the grain yield in all the three genotypes. This result is supported by Swabrick *et al.* (2008) who reported

that different genotypes have different capacities to tolerate the pathological and physiological effects that are inflicted by *Striga*. Reduced grain yield in infected crops indicates that there was reduced translocation of assimilates to the head. According to Cechin and Press (1993) the reduction in grain yield may have been due to the parasite acting as a sink for assimilates such as water, carbon and inorganic solutes as well as reduced carbon gain by the infected cereal crop. The parasite has the capacity to develop metabolic sink as compared to the host, hence enabling it to channel the flow of nutrients and water to itself at the expense of the host crop.

However, the different finger millet genotypes still managed to produce grain yield even when they were under *Striga* infection. This result was due the ability of the finger millet genotypes to maintain high levels of photosynthesis even when exposed to unfavourable conditions (Gurney *et al.,* 2002).

5.2 Screening finger millet genotypes for pre-attachment resistance to *S. asiatica*

The study revealed the ability of the three finger millet genotypes to support *S. asiatica* germination. The result is similar to Ibikunle *et al.* (2008) who concluded that cereal crops were significantly different in relation to the germinating percentage and susceptibility to infection. The highest germination percentage was recorded in KNE814 and KNE624 whereas SDFM1702 had the least germination percentage. This implies that all the genotypes used in this study are not resistant to *Striga*. According to Chitagu *et al.* (2014) and Bebawi *et al*. (1984), resistant genotypes do not have the capacity to produce strigolactones that support the germination of *Striga* seeds. High germination percentage of parasitic weed seeds suggests that the genotypes had high *S. asiatica* strigolactone production (Pierce *et al*., 2003). *Striga* seed germination is triggered by the production of strigolactones, whilst the production of strigolactones is governed by the low germination stimulants (LGS) genes which are associated with pre-attachment resistance to *S. asiatica.* Germination distance differed amongst all the genotypes. SDFM1702

had the shortest germination distance compared to KNE624 and KNE814. SDMF1702 had the least germination percentage shortest germination distance. The laboratory findings complement findings from pot study where SDMF1702 supported significantly lower *Striga* attachments than the other genotypes.

CHAPTER SIX

CONCLUSSIONS AND RECCOMMENDATIONS

6.1 Conclusion

All the finger millet genotypes used in this study are not resistant to *Striga* because they supported seed germination and attachment. However, based on results on plant height, *Striga* count, chlorophyll content, chlorophyll fluorescence, leaf biomass and root biomass)it can be concluded that the genotype SDFM1702 is tolerant to *S. asiatica* infection. Genotypes KNE624 and KNE814 are susceptible to *Striga* infection.

6.2 Recommendations

This study was carried out under artificial conditions, hence there is need to carry out research with these genotypes under field conditions. Further screening of *S. asiatica*'s effect in finger millet under different geographical locations is recommended because there is a possibility of *Striga* having variations in strains depending on the location.

REFERENCES

Agbaje, S.A., Badu-Apraku, B. and Fakorede, M.A.B. (2008). Heterotic patterns of early maturing maize inbred lines in *Striga*-free and *Striga*-infested environments. *Maydica* 53: 87-92.

Ahom, R. and Magani, I. (2010). Response of the parasitic plant (*Striga hermonthica*) seeds to different germination stimulants produced by sesame and pigeon pea varieties. *Agriculture and biology journal of North America* 1: 1199-1205.

Amudavi, D., Khan, Z. and Pickett, J. (2007). Enhancing the Push-Pull strategy. *LEISA Magazine* 23**:** 4-6.

Anjorin, B. (2013). Testing of *Striga* resistant composite maize varieties for response to two levels of nitrogen fertilizer up-take. *African Journal of Plant Sciences*7**:** 432-437.

Atera, E.A., Itoh, K., Azuma, T. and Ishii, T. (2012). Response of NERICA rice to *Striga hermonthica* infections in western Kenya. *International Journal of Agriculture and Biology* 14**:** 271-275.

Atera, E.A., Ishii, T., Onyango, J.C., Itoh, K. and Azuma, T. (2013). *Striga* Infestation in Kenya: Status, distribution and management options. *Sustainable Agriculture Research* 2**:** 99-101.

Bebawi, F.F., Eplee, R.E., Harris, C.E. and Norris, R.S. (1984). Longevity of witch weed (*Striga asiatica*) seed. *Weed Science* 32: 494-497.

Beyene, Y., Mugo, S., Gakunga, J., Karaya, H., Mutinda, C., Tefera, T., Njoka, S., Chepkesis, D., Shuma, J.M. and Tende, R. (2013). Combining ability of maize (*Zea mays* L.) inbred ines resistant to stem borers. *African Journal of Biotechnology* 10: 4759-4766.

Berner, D. and Singh, B. (1995). *Striga* research and control. A perspective from Africa. *Plant Disease* 79**:** 652-660.

Bouwmeester, H.J., Matusova, R., Zhongkui, S. and Beale, M.H. (2003). Secondary metabolite signalling in host-parasitic plant interactions. *Current Opinion in Plant Biology* 6**:** 358-364.

Cechin, I. and Press, M.C. (1993). Nitrogen relations of the *Striga hermonthica* host parasite associations: growth and photosynthesis. *Plant cell and environment* 16: 237-247.

Chitagu, M., Rugare, J.T. and Mabasa, S. (2014). Screening Maize (*Zea mays* L.) genotypes for tolerance to witchweed (*Striga asiatica* L. Kuntze) Infection. *Journal of Agricultural Science* 6: 160-167.

De Groote, H., Wangare, L., Kanampiu, F., Odendo, M., Diallo, A., Karaya, H. and Friesen, D. (2008). The potential of a herbicide resistant maize technology for *Striga* control in *Africa. Agricultural Systems* 97: 83-94.

Ejeta, G. and Butler, L.G. (1993). Host-parasite interactions throughout the *Striga* life cycle, and their contributions to *Striga* resistance. *African Crop Science Journal* 1: 75-80.

Elzein, A. and Kroschel, J. (2004). *Fusarium oxysporum* shows potential to control both *Striga hermonthica* and *Striga asiatica*. *Weed Research* 44: 433-438.

Esilaba, A.O. (2006). Options for *Striga* management in Kenya, *Agricultural Systems* 97**:** 83-94.

FAO. (2014).*FAO production year book*, 2014, Rome, Italy.

FAO. (2006). Fertilizer use by crop in Zimbabwe. Rome, Italy.

Fernández-Aparicio, M., Westwood, J.H. and Rubiales, D. (2011). Agronomic, breeding, and biotechnological approaches to parasitic plant management through manipulation of germination stimulant levels in agricultural soils. *Botany* 89: 813-826.

Frost, D., Gurney, A., Press, M. and Scholes, J. (1997). *Striga hermonthica* reduces photosynthesis in sorghum: the importance of stomatal limitations and a potential role for ABA? *Plant, Cell and Environment* 20**:** 483-492.

Gressel, J., Hanafi, A., Head, G., Marasas, W., Obilana, A.B., Ochanda, J. and Tzotzos, G. (2004). Major heretofore intractable biotic constraints to African food security that may be amenable to novel biotechnological solutions. *Crop Protection* 23**:** 661-689.

Gurney, A., Grimanelli, D., Kanampiu, F., Hoisington, D., Scholes, J. and Press, M. (2003). Novel sources of resistance to *Striga hermonthica* in *Tripsacum dactyloides*, a wild relative of maize. *New Phytologist* 160**:** 557-568.

Gurney, A., Press, M. and Scholes, J. (2002). Can wild relatives of sorghum provide new sources of resistance or tolerance against *Striga* species? *Weed research* 42**:** 317-324.

Haussmann, B.I.G., Hess, D.E., Welz, H.G. and Geiger, H.H. (2000). Improved methodologies for breeding *Striga*-resistant Sorghums. *Field Crops Research* 66**:** 195-211

Hess, D.E., Ejeta, G. and Butler, L., G. (1992). Selecting sorghum genotypes expressing a quantitative biosynthetic trait that confers resistance to *Striga. Phytochemistry* 31**:** 493-497.

Ibikunle, O.A., Menkir, A., Kamara, A.Y., Ajeigbe, H.A. and Smith, M.A.K. (2008). Evaluation of artificial field infestation techniques with *Striga hermonthica* for resistance screening in maize (*Zea mays* L.). *Maydica* 53: 97-100.

Ifie, B.E. (2013). Genetic analysis of *Striga* resistance and low soil nitrogen tolerance in early maturing maize (*Zea mays* L.) inbred lines. PhD Thesis. University of Ghana.

Ishida, J. K., Yoshida, S. and Shirasu, K. (2017). Haustorium Induction Assay of the Parasitic Plant *Phtheirospermum Japonicum*. *Bio-protocol* 7: 20-24.

Jamil, M., Charnikhova, T., Houshani, B., van Ast, A. and Boumeester, H.J. (2011). Genetic variation in strigolactone production and tillering in rice and its effects on *Striga hermonthica* infection. *Planta* 253: 473-484.

Jamil, M., Van-Mourik, T.A., Carnikhova, T. and Bouwmeester, H.J. (2012). Effect of diammonium phosphate application on strigolactone production and *Striga hermonthica* infection in three sorghum cultivars. *Weed Research* 3**:** 121-130.

Kabambe, V.H., Kauwa, A.E. and Nambuzi, S.C. (2008). Role of herbicide (metalachlor) and fertilizer application in integrated management of *Striga asiatica* in maize in Malawi. *Africa Journal of Agricultural Research* 3: 140-146.

Karaya, H., Njoroge, K., Mugo, S., Ariga, E.S., Kanampiu, F. and Nderitu, J. (2014). Combining ability of maize (*Zea mays*) inbred lines resistant to *Striga hermonthica* (Del.) Benth evaluated under artificial Striga infestation. *Africa Journal of Agriculture Research* 9: 1287-1295.

Kayeke, J., Sibuga, P.K., Msaky, J.J. and Mbwaga, A. (2007). Green manure and inorganic fertiliser as management strategies for witch weed and upland rice. *Africa Crop Science Journal* 15**:** 220-230.

Khan, Z.R., Pickett, J.A., Wadhams, L.J., Hassanali, A. and Midega, C.A.O. (2006). Combined control of *Striga hermonthica* and stemborers by maize-*Desmodium* spp. intercrops. *Crop Protection* 25: 989-995.

Mabasa, S. (1994). *Striga* activity in Zimbabwe. Pp 143-146. In Lagoke, S.T.O., Hoevers, R., M'boob, S.S. and Traboulsi (Eds). Imporoving *Striga* management in Africa. Proceedings of the second general workshop of the pan African Striga control netqwork (PASCON). 23-29 June, 1991), Nairobi, Kenya, Accra. FAO. West Africa: A review', *Experimental Agriculture* 51**:** 501-521.

MacOpiyo, L., Vitale, J., and Sanders, J. (2010). An ex-ante assessment of a *Striga* control programme in East Africa. *Sustainable Agriculture Research* 8: 6-25.

Mahmoud, B.A., Hamma, I.L., Abdullahi, S.S. and Adam, Y. (2013). Common *Striga* control methods in Nigeria: A review. *International Journal of Agronomy and Agricultural Research* 3: 26-29.

Mandumbu, R. Mutengwa, C., Mabasa, S. and Mwenje, E. (2018). Challenges to the exploitation of host plant resistance for Striga management in cereals and legumes by farmers in sub-Saharan Africa : a review, *Acta Agriculturae Scandinavica, Section B - Soil and Plant Science* 3: 1-7.

Mandumbu, R., Mutengwa, C., Mabasa, S., Mwenje, E., Gotosa, J. and Munyati, V. (2017). The parasitic weeds scourge in northern Zimbabwe: Effects of soil degradation, hosts and food security implications to rural farmers. *Scientia* 20**:** 86-91.

Mason, S.C., Maman, N. and Palé, S. (2015). Pearl millet production practices in semi-arid West Africa: A Review. *Experimental Agriculture* 51: 501-521.

Mauromicale, G., Monaco, A. L. and Longo, A. M. (2008). Effect of branched broomrape (*Orobanche ramosa*) infection on the growth and photosynthesis of tomato. *Weed Science* 56**:** 574-581.

Mohamed, K.I., Papes, M., Williams, R., Benz, B.W. and Peterson, A.T. (2003) Global invasive potential of 10 parasitic witch weeds and related Orobanchaceae. *Ambio* 35**:** 281-288.

Mohamed, K.I., Musselman, L.J., Riches, C.R. (2001). The Genus *Striga* (Scrophulariaceae) in Africa. *Annals of the Missouri Botanical Garden* 88**:** 60-103.

Moyo, S. (2000). *Zimbabwe environmental dilemma: balancing resource inequities.* Harare, Zimbabwe Environmental Research Organization ed. pp 161 Vincent, V. & Thomas, R.G. 1961. *An agro-ecological survey of Southern Rhodesia: Part I agro-ecological survey.* Salisbury, Government Printers.

Mwakaboko, A.S. (2015). Synthesis and biological evaluation of new strigolactone analogues as germination stimulants for the seeds of the parasitic weeds *Striga* and *Orobanche* spp. Radbound Repository theses.

Nail, K., Kriticos, D.J., Scott, J.K., Yonow, T. and Ota, N. (2014). *Striga asiatica* (Witchweed). *Harvest Choice Pest Geography* 2**:** 1-6.

Nickrent, D.L. and Musselman, L.J. (2004). Introduction to Parasitic Flowering Plants [WWW Document].URLhttps://www.apsnet.org/edcenter/intropp/PathogenGroups/ Pages/ParasiticPlants.aspx (accessed 15.09.18).

Nyakurwa, C. S., Gasura, E., Setimela, P. S., Mabasa, S., Rugare, J. T. and Mutsvanga, S. (2018). Reaction of new quality protein maize genotypes to *Striga asiatica*. *Crop Science* 58**:** 1201-1218.

Oswald, A. and Ransom, J.K. (2001). *Striga* control and improved farm productivity using crop rotation. *Crop protection* 20**:** 113-120.

Oswald, A. (2005). *Striga* control-technologies and their dissemination. *Crop Protection* 24**:** 333-342.

Parker, C. and Riches, C.R. (1993). *Parasitic weeds of the world – biology and control*. CAB International, Wallingford, UK, pp332.

Parker, C. (2009). Observations on the current status of *Orobanche* and *Striga* problems worldwide. *Pest Management Science* 65**:** 453-459.

Parker, C. (2012). Parasitic weeds: a world challenge. *Weed Science* 60: 269-276.

Poorter, H., Niklas, K.J., Reich, P.B., Olekysyn, J., Poot, P. And Mommer, L. (2011). Biomass allocation to leaves, stems and roots: Meta-analysis of inter-specific variation and environmental control. *New Phytologist* 193: 30-50.

Pierce, S., Mbwaga, A.M., Press, M.C., Scholes, J.D. (2003). Xenognosin production and tolerance to *Striga asiatica* infection of high-yielding maize cultivars. *Weed Research* 43**:** 139-145.

Reda, F., Butler, L., Ejeta, G. and Ransom, K. (1994). Screening of maize genotypes for low *Striga asiatica* stimulant production using the ‘agar gel technique'. *African Crop Science Journal* 2: 173-177.

Richard, C.L., Bossdorf, O., Muth, N.Z., Gurevitch, J. And Pigliucci. (2006). Jack of all trades, master of some? On the role of phenotypic plasticity in plant invasions. *Ecology letters* 9: 981-993.

Roden, P., Abraha, N., Debessai, M., Ghebreselassie, M., Beraki, H., and Kohler, T. (2007). farmers’ appraisal of pearl millet varieties in Eritrea. *Geographica Bernensia*, pp47.

Scholes, J.D. and Press, M.C. (2008). *Striga* infestation of cereal crops-an unsolved problem in resource limited agriculture. *Current Opinion Plant Biology* 11**:** 180-186.

Sikwese, M., Mloza-Banda, H.R. and Phombeya, V.K.H. (2003). The potential of multi-purpose tree species in the inter-grated management of *Striga* in maize fields in Malawi, in: *African crop science Conference Proceedings* 47**:** 233-137.

Smith, L.H., Keys, A.J. and Evans, M.C.W. (1995). *Striga hermonthica* decreases photosynthesis in *Zea mays* through effects on leaf cell structure. *Journal of Experimental Botany* 46: 759–765.

Spallek, T., Mutuku, M. and Shirasu, K. (2013). The genus *Striga* : a witch profile: Profile of *Striga,* the witchweed. *Molecular plant pathology* 14**:** 861–869.

Sun, Z., Matusva, R. and Bouwmeester, H. (2007). Germination of *Striga* and chemical signalling involved; a target for control methods. Integrating new technologies for Striga control towards ending the witch hunt. World Scientific Publishing Co, Hackensack.

Swabrick, P.J., Huang, K. and Liu, G. (2008). Global patterns of gene expressions in rice cultivars undergoing a susceptible or resistant interaction with the parasitic *Striga hermonthica*. *New Phytologist* 179: 515-529.

Taylor, A., Martin, J. and Seel, W.E. (1996). Physiology of the parasitic association between maize and witch weed (*Striga hermonthica*): is ABA involved? *Journal of experimental botany* 47:1057-1065.

Taylor, J.R.N. (2009). Developments in Africa's cereal crops - potential resources for breeding in tropical and sub-tropical countries. Institute of brewing and distilling sect. - 12th Scientific and Technical convention.

Těšitel, J., Plavcová, L. and Cameron, D.D. (2010). Heterotrophic carbon gain by the root hemiparasites, *Rhinanthus minor* and *Euphrasia rostkoviana* (Orobanchaceae). *Planta* 231: 1137-1144.

Timko, M.P., Huang, K. and Lis, K.E. (2012). Host resistance and parasite virulence in *Striga*–host plant interactions: A shifting balance of power. *Weed Science* 60**:** 307-315.

Umehara, M. (2011). Strigolactone, a key regulator of nutrient allocation in plants. *Plant Biotechnology* 28**:** 429-437.

United Nations Population Division. (2007). World Population Prospects: The 2006 revision population database. Retrieved from http://esa.un.org/unpp (accessed 15 October 2018)

Van Ast, A. and Bastiaans, L. (2006). The role of infection time in the differential response of sorghum cultivars to *Striga hermonthica* infection. *Weed research* 46**:** 264-274. Vrbničanin, S., Sarić-Krsmanović, M. and Ožić, D. (2013). The effect of field dodder (*Cuscuta campestris* Yunck.) on morphological and fluorescence parameters of giant ragweed (*Ambrosia trifida* L.). *Pesticidiifito medicina* 28**:** 57-62.

Wageningen University. (2001). Improved *Striga* control in maize and sorghum (ISCIMAS). A European Commission funded INCO-project [WWW Document]. URL http://www.plant.wageningen-ur.nl/projects/striga/introduction.htm (accessed 4.16.19).

Westwood, J.H., dePamphilis, C.W., Das, M., Fernández-Aparicio, M., Honaas, L.A., Timko, M.P., Wafula, E.K., Wickett, N.J., Yoder, J.I. (2012). The Parasitic plant genome project: New tools for understanding the biology of *Orobanche* and *Striga*. *Weed Science* 60**:** 295-306.

Woomer, P.L. and Savala, C.N. (2007). *Striga* management through herbicide resistance: A Public- Private Partnership in Action, in: AAAE Conference Proceedings: 489

APPENDICES

Appendix 1: Analysis of variance for finger millet height

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	1712.44	342.49	1.23	
Striga	1	1552.36	1552.36	5.57	0.026
Variety	2	17580.48	8790.24	31.53	<.001
Striga*Variety	2	175.24	87.62	0.31	0.733
Residual	25	6970.39	278.82	6.46	
Time	8	159197.38	19899.67	460.85	<.001
Time*Striga	8	562.71	70.34	1.63	0.199
Time*Variety	16	398.27	24.89	0.58	0.708
Time*Striga*Variety	240	10363.27	43.18		
Residual	l240	10363.27	43.18		
Total	323	205488.20			

Appendix 2: Analysis of variance for *Striga* count

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	3347.33	669.47	0.83	
Variety	2	2827.40	1413.70	1.75	0.222
Residual	10	8062.07	806.21	37.64	
Total	89	16080.00			

Appendix 3: Analysis of variance for chlorophyll content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	508.78	101.76	1.92	
Striga	1	231.04	231.04	4.36	0.047
Variety	2	178.07	89.04	1.68	0.207
Striga*Variety	2	157.21	78.60	1.48	0.246
Residual	25	1324.76	52.99	4.42	
Time	7	3558.01	508.29	42.96	<.001
Time*Striga	7	276.47	39.50	3.34	0.016
Time*Variety	14	346.41	24.74	2.09	0.050
Time*Striga*Variety	14	140.15	10.01	0.85	0.553
Residual	210	2484.70	11.83		
Total	287	9205.59			

Appendix 4: Analysis of variance for chlorophyll fluorescence

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	3.2117	0.6423	7.21	
Striga	1	0.0654	0.0654	0.73	0.400
Variety	2	0.7210	0.3605	4.05	0.030
Striga*Variety	2	0.0696	0.0348	0.39	0.681
Residual	25	2.2280	0.0891	0.57	
Time	1	0.0000	0.0000	0.00	1.000
Time*Striga	1	0.4734	0.4734	3.04	0.092
Time*Variety	2	0.9631	0.4815	3.09	0.060
Time*Striga*Variety	2	0.0551	0.0275	0.18	0.839
Residual	30	4.6781	0.1559		
Total	71	12.4653			

Appendix 5: Analysis of variance for stem biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	178.92	35.78	2.81	
Infection	1	1332.25	1332.25	104.65	<.001
Variety	2	378.17	189.08	14.85	<.001
Infection*Variety	2	141.17	70.58	5.54	0.010
Residual	25	318.25	12.73		
Total	35	2348.75			

Appendix 6: Analysis of variance for leaf biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	588.2	117.6	0.86	
Infection	1	1906.8	1906.8	13.90	<.001
Variety	2	170.4	85.2	0.62	0.546
Infection.Variety	2	341.1	170.5	1.24	0.306
Residual	25	3430.1	137.2		
Total	35	6436.6			

Appendix 7: Analysis of variance for total above ground biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	15.556	3.111	0.49	
Infection	1	2567.111	2567.111	406.76	<.001
Variety	2	82.722	41.361	6.55	0.005
Infection*Variety	2	222.722	111.361	17.65	<.001
Residual	25	157.778	6.311		
Total	35	3045.889			

Appendix 8: Analysis of variance for root biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	132.67	26.53	0.57	
Infection	1	658.78	658.78	14.04	<.001
Variety	2	12.17	6.08	0.13	0.879
Infection*Variety	2	334.06	167.03	3.56	0.044
Residual	25	1173.33	46.93		
Total	35	2311.00			

Appendix 9: Analysis of variance for root to shoot ratio

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	2.9213	0.5843	1.79	
Infection	1	9.8849	9.8849	30.34	<.001
Variety	2	0.5226	0.2613	0.80	0.460
Infection*Variety	2	0.2641	0.1320	0.41	0.671
Residual	25	8.1452	0.3258		
Total	35	21.7381			

Appendix 10: Analysis of variance for haustoria attachments

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	115.83	23.17	1.27	
Variety	2	1076.33	538.17	29.52	<.001
Residual	10	182.33	18.23		
Total	17	1374.50			

Appendix 11: Analysis of variance for grain yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	5	47.222	9.444	1.00	
Infection	1	1600.000	1600.000	169.65	<.001
Variety	2	105.556	52.778	5.60	0.010
Infection.Variety	2	182.000	91.000	9.65	<.001
Residual	25	235.778	9.431		
Total	35	2170.556			

Appendix 12: Analysis of variance for germination percent (day 3)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Variety	2	4.5868	2.2934	5.57	0.009
Residual	27	11.1081	0.4114		
Total	29	15.6949			

Appendix 13: Analysis of variance for germination percent (day 7)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Variety	2	53.942	26.971	22.29	<.001
Residual	27	32.672	1.210		
Total	29	86.614			

Appendix 14: Analysis of variance for germination percent (day 10)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Variety	2	55.495	27.747	10.82	<.001
Residual	27	69.230	2.564		
Total	29	124.725			

Appendix 15: Analysis of variance for furthest germination distance.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Variety	2	1.83429	0.91715	13.20	<.001
Residual	27	1.87631	0.06949		
Total	29	3.71060			