Integrated management of *Striga hermonthica* and *S. asiatica* in sorghum: A review

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ABSTRACT

Potential yield of sorghum [*Sorghum biocolor* (L.) Moench] in the semi-arid agro-ecologies of East Africa is curtailed by several biotic, abiotic and socio-economic constraints. *Striga* is one of the major biotic constraints that causes up to 90% yield losses in sorghum in the region. In these regions *Striga hermonthica* and *S. asiatica*, are widely distributed, and severely affecting sorghum production and productivity. Several *Striga* management strategies are available that can be integrated to synergistically combat the weed. The use of resistant sorghum genotypes that are compatible with *Fusarium oxysporum* f.sp. *strigae* (*FOS*), a biocontrol agent of *Striga,* together with host plant resistance could promote integrated *Striga* management (ISM). This strategy is yet to be explored in most SSA countries where sorghum serves as a staple food crop for millions of households. This review discusses the management options available to control *S. hermonthica* and *S. asiatica* in sorghum. Breeding sorghum for *Striga* resistance and compatibility to *FOS* are highlighted as key components of integrated *Striga* management*.*

Keywords: *Fusarium oxysporum* f.sp. *strigae*, gene action, integrated *Striga* management, *Striga* resistance, sorghum.
Abbreviations: *FOS_Fusarium oxysporum* f.sp. *strigae*; ICRISAT_International Crop Research Institute for the Semi_arid Tropics; ISM_integrated *Striga* management; MGD_maximum germination distance; *Sa_Striga asiatica; Sh_Striga hermonthica*; SSA_sub_Sharan Africa.

Introduction

Sorghum (*Sorghum bicolor* L.] Moench., 2n=2x=20) is a multi-purpose cereal crop serving as an important source of food, feed and bioenergy (Doggett, 1988). It thrives well under harsh growing conditions in the arid and semi-arid regions, characterised by low soil fertility and high temperature, conditions not suitable for other major crops such as maize and wheat (Blum, 2004; Rwebugisa, 2008). Sorghum is ranked as the fifth leading cereal crop in the world in terms of total production and consumption after wheat (*Triticumae stivum*), rice (*Oryza sativum,* L.), maize (*Zea mays* L.) and barley (*Hordeum vulgae*) (Blum, 2004). An estimated area of 42 million ha of agricultural land is devoted to sorghum production globally, providing about 61.5 million tonnes of grain annually, of which 80% is produced in Africa and Asia (FAOSTAT, 2014). Sorghum production is affected by abiotic stresses, particularly poor soil fertility and drought, as well as biotic stresses such as infestations by *Striga*, stem borers, and shoot fly (*Atherigona soccata*)] (Wortmann et al., 2006; Roose, 1994). Lack of access to production inputs such as fertilizers, insecticides, fungicides and herbicides are among the major production constrains of sorghum in the semi-arid regions including in Tanzania (Lamboll et al., 2001; Mrema et al., 2017a).
In sub-Saharan Africa sorghum is cultivated under dryland condition on soils of poor fertility levels often heavily infested by *Striga* spp [*Striga hermonthica* (Del.) Benth (*Sh*)

and *S. asiatica* (L.) Kuntze (*Sa*)] (Johnson et al., 1997). Therefore, improved farming technologies that enhance soil fertility are critically required to boost sorghum yields and to minimize damage caused by *Striga*. Yield improvement in sorghum fields infested by *Striga* can be realised through application of recommended levels of inorganic fertilizers based on soil tests. However, inorganic fertilizers are inaccessible and unaffordable to smallholder farmers, suggesting the need of innovative solutions to boost sorghum productivity under smallholder farming systems by controlling the *Striga* damage. This review, therefore, discusses integrated *Striga* management options in Sorghum, with particular emphasis on breeding and biocontrol using *Fusarium oxysporum* f.sp. *strigae* to achieve potential yields of the crop

Distribution of *Striga* species

Striga is among the main biotic constraints affecting sorghum yields in the semi-arid regions of the world (Riches, 2003; Gethi et al., 2005; Mrema et al., 2016). The distribution of *Striga* species of economic importance and their corresponding yield losses are presented in Table 1. Yield losses of up to 100% occur in areas with high *Striga* infestation (Table 1). Tanzania, faces yield losses of up to 90% due to heavy infestation by *S. hermonthica* and *S.*

asiatica (Riches, 2003). The two weed species (Figure 1) are persistently present in cereal fields in the Tabora, Mwanza and Shinyanga regions of Tanzania (Mrema et al., 2016).

Striga parasitism

Striga species are distributed in most sorghum fields in the semi-arid regions of East Africa. *Striga* spread efficiently owing to their ability to produce 10,000 to 500,000 seeds per plant that remain viable in dry soils for 15 to 20 years (Koichi et al., 2010). *Striga* seeds can easily be dispersed by wind, water, livestock and man (Enserin, 1995). Their germination is often stimulated by the host plant, though some non-host species have been reported to produce stimulus for germination of *Striga* seed (Matusova et al., 2005). For instance, roots of cotton, a non-host plant, releases strigol, which induces germination of *Striga* seeds (Garcia-Garrido et al., 2009). Sorgolactone and alectrol are analogs of strigol produced by sorghum and cowpea roots, respectively, and induce *Striga* germination (Matusova et al., 2005). Ethylene initiates *Striga* seed germination and can be used as a *Striga* management technology where pre- or post-emergent herbicides cannot be applied to control the weed. Following stimulation of germination, *Striga* seedlings die back owing to a lack of host plants (Parker and Riches, 1993). The seed germinates after a period of primary dormancy followed by seed preconditioning under warm temperatures (25-35°C) and moderate humidity levels (30 to 50 %) for about two weeks (Parker and Riches, 1993). Secondary metabolites (xenognosins) released in form of root exudates by host plants are also required for *Striga* seed germination (Yoder, 2001). These metabolites direct the radicle of *Striga* seedlings towards the host root (Williams, 1961a, b).

The amount and effects of exudates produced by sorghum genotypes can be studied using agar-gel assays developed by Hess et al. (1992). This involves preconditioning of *Striga* seeds followed by growing them in agar in petri dishes. After 5 days the maximum germination distance (MGD) between the sorghum seed and a distantly germinated *Striga* plant is measured. Genotypes with an MGD below 10 mm are classified as *Striga* resistant owing to their capacity to supress *Striga* germination. This technique is useful in screening sorghum genotypes for *Striga* resistance.

Striga is an obligate parasite that requires host-synthesized nutrients for survival (Mohamed et al., 2001). After the *Striga* seed germination is initiated by the host plant exudates, the radicle of the parasite seedling contacts the host root and enlarges to form a haustorium. This structure provides attachment and establishes a channel for extracting nutrients and metabolites from the host tissue (Mohamed et al., 2001). Failure of haustorium formation or its development leads to death of the parasite due to lack of water, mineral nutrients and synthesized photosythetes (Stewart et al., 1991). The transpiration rate of *Striga* that is greater than that of the host, speeds up the flow of food, water and nutrients into the parasite (Stewart et al., 1991). *Striga* also produces allelopathic toxins that retards growth and development of sorghum (Stewart et al., 1991). Production of the toxin is associated with decreased cytokinin and gibberellin concentrations and a substantial increase in abscisic acid levels in damaged host tissues causing a reduction in the rate of ribulose biphosphate

carboxylation (Stewart et al., 1991). Ultimately, *Striga* invasion in sorghum fields decreases the crop's growth rate and causes yellowing and wilting of the host plant. This results in poor plant growth and development and leading to a failure of panicle formation and yield loss. Understanding the conditions required for *Striga* seed dispersal, germination, infestation, and parasitism will allow plant breeders to develop suitable crop varieties. Knowledge of the association of the parasite with the host and non-host species will also help in designing cropping patterns and crop choices.

Management of *Striga* in sorghum

Several *Striga* management options are available including cultural practices, chemical control, use of biological agents or natural enemies and host plant resistance. Table 3 summarises the opportunities and challenges associated with different *Striga* control methods. However, their adoption depends on the availability of resources and skills among smallholder farming communities. *Striga* control options are briefly described below.

Cultural practices

Several cultural control methods have been recommended to manage *Striga* in sorghum fields (Table 2). The techniques help to reduce the *Striga* seed banks in the soil, and to improve soil fertility (Udom et al., 2007). Cultural practices improve sorghum growth rate, and retard parasite seed germination and seedling development (Udom et al., 2007). These practices include crop rotation (Oswald and Ransom, 2001); mixed cropping (Udom et al., 2007; Oswald et al., 2001); water management (Udom et al., 2007), fertilization (Jamil et al., 2011) and weeding (Ransom, 2000). Early planting following the main rains minimizes *Striga* in the semi-arid regions because it allows escape from heavy *Striga* infestation, which often happens almost two months after planting (Mrema et al., 2016). Cultural methods of *Striga* management are poorly adopted by smallholder farmers due to limited accessibility and knowledge. Further, their implementation is costly in terms of resources, time and labour. Adoption of proper fertiliser application, rates and timing remains a challenge among sorghum growers in developing countries. Development of a viable integrated *Striga* management program aimed at minimizing *Striga* infestation and improving sorghum yield will require an understanding of the potential and limitations of the currently available management approaches.

Chemical control

Several herbicides are available for controlling *Striga* infestation in sorghum (Kanampiu et al. 2003). Among selective herbicides reported are 2,4-D and MCPA (2-methyl-4-chlorophenoxyacetic acid) (Ejeta et al., 1996). Selective herbicides that kill the weed before attachment to the host would be extremely valuable for controlling the weed (Kanampiu et al., 2003). A study conducted on sorghum and maize shows that treatment of seeds with 2,4-D provides effective control of *Striga* (Dembele et al., 2005). Development of transgenic herbicide resistant sorghum genotypes is an alternative approach that will allow the use

of herbicides without damaging the crop (Kanampiu et al., 2003). They reported the effectiveness of sulfosulfuron herbicide seed coating applied to mutant sorghum lines in controlling *Striga*. Seed coating with herbicides is a low cost treatment due to the requirement of only a small quantity of the herbicide for seed dressing. However, this approach is poorly adopted in the semi-arid regions of Tanzania. The high prices of herbicides, their limited availability, and the lack of technical knowledge on the use of agrochemicals for weed and pest management are among the main reasons for their limited use in sorghum production (Mrema et al., 2017a). To improve sorghum yield under smallholder farmers' conditions, there is a need to develop a *Striga* management programme that is cheap enough for the farmers to adopt.

Biological control

Natural enemies useful in suppressing parasitic weeds including *Striga* species are available in the ecosystems (Templeton, 1982). Among the biological agents, microbes are often host specific, highly aggressive, easy to mass produce and show maximum diversity (Ciotola et al., 2000). A biological agent has no residual effect in the soil or plant system unlike chemical control (Abbasher et al., 1998). Studies on the potential of soil microbes in *Striga* management found various *Fusarium. oxysporum* isolates to be highly pathogenic against *Striga* (Abbasher et al., 1998). The isolates are often overwinter in the soil even inthe absence of their host by colonizing crop debris and producing chlamydospores, which are the dormant resting propagules (Ciotola et al., 2000). In this form microbesare able to withstand extreme environmental conditions (Ciotola et al., 2000). Among *Fusarium oxysporum* isolates, *Fusarium oxysporum* f.sp. *strigae* (*FOS*) is reported to control *Striga* infestation in sorghum offering about 90% *Striga* control (Ciotola et al., 2000). *FOS* grows in the rhizosphere of the sorghum plants, parasitizes, and inhibits the germination, emergence and development of *Striga* (Mrema et al., 2017c). The biocontrol fungus destroys *Striga* plants before they penetrate sorghum roots. Recent studies have indicated significant reduction in *Striga* numbers as well as the number of days to flowering and maturity in sorghum seeds coated with *FOS* (Rebeka et al., 2013; Mrema et al., 2017a). Use of *FOS* in *Striga* management in sorghum fields in East Africa is not yet reported and implemented. Therefore, there is a need for integrated management of the parasite through host resistance and application of *FOS* to enhance production and productivity of sorghum and related cereals affected by *Striga.* There are no reports of negative effects of *FOS* on sorghum or related cereal crops. In fact, *FOS* has been reported to promote the abundance of arbuscular mycorrhizal fungi in the rhizospheres of sorghum resulting in enhanced crop growth and development (Rebeka et al. 2013; Mrema et al. 2017b). Further, *FOS* has a very narrow host range, which is restricted to *S. hermonthica*, *S. asiatica* and *S. gesneroides* (Rebeka et al. 2013).

Host resistance

Stiga management through the use of resistant cultivars was reported in several crops including sorghum (Ejeta et al.,

1992). Resistant cultivars reduce *Striga* emergence and *Striga* seed production. These genotypes support fewer *Striga* plants and yield better than their susceptible counterparts under *Striga* infestation (Doggett, 1988; Ejeta et al., 1992).

The gene action, source and the mode of *Striga* resistance of wild and domesticated sorghum genotypes are presented in Table 2. Several resistance mechanisms have reported to control *Striga* in sorghum, among them includes low production of germination stimulant, mechanical barriers, inhibition of germ tube exoenzymes by root exudates, phytoalexine synthesis, incompatibility, antibiosis, insensitivity to *Striga* toxin and avoidance through root growth habit (Wegmann,1996). In additions to these resistance strategies, hypersensitive reaction or necrotic tissue development and phytoalexin production by sorghum plants also confer *Striga* resistance. Tissue surrounding the point of attachment of the parasite form necrotic spots that limits food, water and nutrients supply to the parasite. Necrosis is reported to accompany phytoalexin secretion that kills the parasite (Patrick et al., 2004). Genes for hypersensitive response and phytoalexin production under *Striga* attack are reported in some sorghum genotypes (Mohamed, 2002). A wild sorghum genotype, P47121, has been reported to have better hypersensitive response to *Striga* infestation than cultivated sorghum genotypes and could be a useful genetic resource for resistance breeding (Mohamed et al., 2003).

Incompatibility to *Striga* has been reported in some sorghum genotypes under *Striga* infestation (Ejeta, 2007). Incompatible genotypes do not show any response to *Striga* infestation and the parasite dissociates from the host immediately after penetration (Grenier et al., 2001). In this case, *Striga* seedlings die before formation of the first leaf or show sign of stunted growth and death (Matusova et al., 2005).

Sorghum varieties differ in root morphology and the amount of lignin (Mati et al., 1984), and cellulose deposition (Oliver et al., 1991), and encapsulation (Labrousse et al., 2001). Haustorium fails to penetrate tougher roots of resistant sorghum genotypes than in susceptible cultivars with tender root tissues. Developing sorghum genotype with tougher root systems that act as developmental barriers in addition to other resistance mechanisms reduces *Striga* infestation. Use of low haustorium initiation factors (LHF) present in some sorghum genotypes is an effective methods of supressing *Striga* (Lynn and Chang, 1990). The presence of LHF (sorgolactones) among sorghum genotypes has been reported from agar gel assays (Hess et al., 1992). A recessive gene conditioning LHF was reported in a wild sorghum accession, P47121, of which resistance was manifested before parasite attachment (Mohamed et al., 2003). Haussmann et al. (2000b) reported a set of genes controlling LHF. A single dominant gene was also reported to control LHF by Mohamed (2002). Haustoria do not form when the sorghum root with the LHF gene block the parasite from feeding on the host (Ejeta, 2007). The LHF gene can be introgressed into high yielding and broadly-adapted sorghum cultivars (Ejeta et al., 1997). Exploring the mode of gene action and inheritance of candidate *Striga* resistance genes is imperative to develop promising sorghum genotypes with multiple resistance genes adapted to semi-arid environments of sub-Saharan Africa.

Table 1. Distribution and impact of economic *Striga* species affecting cereals in East African countries.

Country	*Striga* species	Host plants	Reported areas	Infested area (ha)	Yield loss (%)	References
Tanzania	*Striga hermonthica*	Maize, rice, sorghum, pearl millet, finger millet, sugar cane	Mara, Kagera, Tabora and Shinyanga		30 to 90	Mbwaga (1993), Frost (1995); Mrema et al. (2016)
	Striga asiatica	Maize	Tanga, Morogoro, Coast, Lindi, Mtwara, Ruvuma, Singida and Dodoma	963,532		
	Striga forbesii	Maize	Tanga, Morogoro, Coast, Lindi, Mtwara, Ruvuma, Singida and Dodoma			
Kenya	*Striga asiatica*	Maize, rice, sorghum, pearl millet, finger millet	Kilifi, Isiolo, Mathews range, Alupe, DakaChom, Kiunga	342,168	15 to 100	Mohamed et al. (2001); Gethi et al. (2005)
	Striga forbesii	Sorghum, rice, maize	Naivasha, Chyulu hills, Rumbia, Narok, Mara plains, Kipini, Chyulu hills, UasinGishu plateau, Trans Nzoia			
	Striga hermonthica	Maize, rice, sorghum, pearl millet, finger millet	Alupe, Churaimbo, Miwani, Bungoma, Kendu, Migori, Kuria, Nyamira, Siaya, Homabay Sultan Hamud, Kilifi, Mwea			
Uganda	*Striga hermonthica* *Striga asiatica*	Sorghum, millet, and maize	Pallisa and Tororo	107,798	60 to 100	Gethi et al. (2005)
Ethiopia	*Striga hermonthica*	Sorghum	North Shewa,North WelloqndMetekel	550,395	50 to 100	Tesso et al. (2007); FAOSTAT (2014)
Sudan	*Striga hermonthica*	Sorghum	Um-Rawaba, El-Rahad, Kadugli, Khour-Tagat and El Obied	4,859,008	58 to 100	FAOSTAT (2014)

Fig 1. *Striga* affecting sorghum and maize crops in Tanzania. Note: Top: sorghum (left) and maize (right) fields infested by *S. hermonthica* at Mwanagwa village farm of Misungwi District, Mwanza Region in the Lake Victoria Zone of Tanzania. Bottom: sorghum fields infested mostly by *S. asiatica* at Mbutu village farm of Igunga District, Tabora Region in the Western Zone of Tanzania.

Table 2. Summary of genetic sources, candidate genes and mode of gene action controlling *Striga* resistance of sorghum

Source of resistance	Candidate genes or gene action for resistance	Mode of resistance	Reference
Wild genetic resources			
Sorghum versicolor, *Sorghum drummondii*	Single recessive gene	Low production of the germination stimulus	Lane et al. (1995); Ejeta (2000)
Landraces			
654, 672,3993, Bedeno, Gambela, Esmile,, Emahuye, Gobeye, and Redgobe, White America, White Jegurte, Radar,Dobbs, P41, Serena, Najjad, Seredo, MY134, MY183, MY95-Z,L-187, RZI, YG5760, ICSV1002, ICSV1005, ICSV1006, ICSV1007, IS6961, IS7739, SAR29, SAR35, SAR37, 555,N13, IS9830,ICSV1002BF,ICSV1007BF, CS54, CS95, KSV4, SSV6, SRN39,SRN6838,SAR16, SAR19, SAR33, IS1005, IS1006, IS7777, IS1260, IS8140, IS9934, IS14825, IS14829, IS14907, IS14928 and IS15401			Saunders (1942), Riches et al. (1987), Doggett (1953), Ramaiah (1986), Kiriro (1991), Mabasa (1996), Mohamed (2002), Rebeka et al. (2013), Mrema et al. (2017a)
Improved lines and hybrids			
Framida, 555, SRN 39, Hormat, and Birhan,	Single recessive gene		Ramaiah et al. (1990), Vogler et al. (1996)
IS 9830 x E 36 -1	One major gene and several minor genes		Haussmann et al. (1996, 2000a)
555 and Framida	Additive, dominance and additive x additive		Haussmann et al. (1996, 2000a)
675 x 654,1563 x AS436,	Sets of alleles		Mrema et al. (2017c)
1563 x AS436	Dominance x dominance		
3984 x 672	Additive x dominance		Mrema et al. (2017b)
3984×672	additive x dominance		Mrema et al. (2017b)
3984 x 672	Additive x dominance		Mrema et al. (2017b)
Accession P-78 of Sorghum drummondii		Low haustorial initiation stimulant	Olivier et al. (1991), Carsky et al. (1996)
N 13, Framida	Single recessive gene	Mechanical barrier	Olivier et al. (1991)
SRN 39, N 13	Single recessive gene	Antibiosis	
SAR 16, SAR 19, SAR 33, Sorghum versicolor	Single recessive gene	Hypersensitivity	

Table 3. Opportunities and challenges of *Striga* controlling options.

Control options	Mode of action or agent	Opportunity	Challenges	Reference (s)
Cultural practices	Crop rotation Water management Early planting Use of early maturing varieties	• Reduces *Striga* seed banks in the soil • Improves soil fertility • Enhances sorghum growth rate • Retards the parasites seed germination and seedling development	• Poor adoption • Implementation cost are higher • Most of the methods are laborious and expensive • Applicable on large fields	Jamil et al. (2011), Mrema at al. (2017a)
Chemical control	Use of herbicides like 2,4-D-Triclopyr, Dicamba, Chlorsulfuron, Paraquat, Imazaquin, and glyphosate	• Pre- or post-emergent use	• Poor adoption • High prices • Limited availability	Mrema et al. (2016)
Biological control	*Fusariumoxysporumf.sp. strigae (FOS)*	• No residual effect • *Reduces Striga* number • Improves sorghum yield • Reduces days to maturity in sorghum	• Not yet developed commercially for *Striga* management in most countries	Abbasher et al., 1998; Ciotola et al., 2000; Rebeka et al., 2013; Mrema et al., 2017a
Host resistance	Low production of germination stimulant, mechanical barriers, inhibition of germ tube exoenzymes, phytoalexins synthesis, incompatibility, antibiosis, insensitivity to *Striga* toxin, and avoidance	• In expensive • Reduces *Striga* emergence and seed production. • Source of resistance available from wild and cultivated varieties.	• Poor adoption for some resistant varieties • Some genotypes are incompatible, • Resistance break down	Lynn and Chang, 1990; Mohamed, 2002; Ejeta, 2007; Rebeka et al., 2013; Mrema et al., 2017b
ISM	Use of *Striga* resistant sorghum genotypes compatible to *FOS*	• Reduces *Striga* number • Improves grain yield • Cost effective • Easy adoption • Environmentally friendly • •	• The method is yet to be commercialized	Joel, 2000; Hearne, 2009, Rebeka et al., 2013, Mrema et al., 2017a

ISM = Integrated *Striga* management

Breeding sorghum for *Striga* resistance

Striga resistance and compatibility of genotypes with *FOS*
In SSA breeding for *Striga* resistancein sorghum started in 1953 in South Africa (Mohamed, 2002). Several sorghum genotypes that are resistant to *Striga* had been developed (Table 2) (Riches et al., 1987). Screening for *Striga* resistance was also conducted in 1970 at the Institute for Agricultural Research (IAR) in Samaru, Nigeria (Lagoke et al., 1991). In 1991, the International Crop Research Institute for the Semi-arid Tropics (ICRISAT) reported sorghum genotypes that were resistant to *S. hermonthica* in SSA (Obilana and Ramaiah, 1992). ICRISAT released some sorghum varieties with resistance to *S. asiatica*in Botswana, Tanzania and Zimbabwe (Mabasa, 1996; Mrema et al. 2017a). Haussmann et al. (2000a) and Doggett (1953) also reported several genotypes that were resistant to both *S. asiatica*and *S. hermonthica*. Account on sorghum genotypes resistant to *Striga* have also been reported in Ethiopia, Mali, Kenya, Uganda and Sudan (Table 2) (Mohamed et al., 2002; Rebeka et al., 2013). *Striga* resistance breeding efforts were initiated in Tanzania under the East African Regional Sorghum Improvement Program, which started in 1958 (Obilana, 2004). From 1999 to 2003 some preliminary evaluations were conducted on the control of *Striga* infestation through integrating resistant sorghum genotypes with improved soil fertility (Riches, 2000). Two introduced sorghum varieties namely, ''Hakika'' and ''Wahi'' were identified with *Striga* resistance (Riches, 2000). Macia, an introduced and high yielding variety is susceptible under farmers' field condition and in screening trials (Mrema et al. 2016, 2017a). Further research is needed develop sorghum varieties with durable *Striga* resistance and farmer preferred traits.

The need to develop sorghum varieties with a combination of durable *Striga* resistance and compatibility with *FOS* in areas of high *Striga* infestation is crucial. Some sorghum genotypes are compatible with *FOS* (Mrema et al., 2017b). Treating seeds of *FOS* compatible sorghum genotypes cause the parasite to wilt, die or to be terminated from the host immediately after penetration (Grenier et al., 2001). Rebeka et al. (2013) reported several sorghum genotypes that were compatible with *FOS* among a diverse population of sorghum genotypes screened for compatibility in Ethiopia.

Integrated Striga management (ISM)

Striga management using a single control method is less effective (Rebeka et al., 2013). A combination of several options can be efficient and economical with better control of *Striga* (Tesso et al., 2007). Use of trap-cropping, fertilizer application and resistant genotypes are some of the effective tools that need to be integrated for effective *Striga* management (Tesso, et al., 2007). Several *Fusarium* spp. and vesicular arbuscular mycorrhizal (VAM) fungi have been reported to control *Striga* and enhance biomass production of compatible hosts when integrated with resistance genes (Franke et al., 2006). Integrated use of *Striga* resistant sorghum genotypes with *FOS* treatment enhances the effectiveness of the biocontrol agent with ultimate yield benefits (Rebeka et al., 2013). Therefore, ISM should be promoted as an effective way of managing *Striga* under smallholder farming systems. An ISM strategy that combines the use of *Striga* resistant sorghum varieties compatible with

FOS is cost effective, environmentally friendly and can easily be adopted by smallholder farmers (Joel, 2000; Hearne, 2009).

Participatory approach to *Striga* management

Development of sorghum varieties with traits of farmer' preferences require involvement of farmers in any breeding stages. Involvement of farmers' in a breeding program may assist breeders to gather the current constraints affecting sorghum production, trait preferences, and strategies for effective *Striga* management in the major sorghum production areas. Understanding of the current farming systems, including the prevailing farming practices, production constraints and the overall socio-economic aspects is critical when devising strategies of managing the parasite (Rebeka et al., 2013). Successful development, release and adoption of new sorghum varieties arehighly dependent on farmer and stakeholder engagement (Chambers, 1992). It is therefore important to investigate farmers' production constraints and their traits of preference, before variety development is initiated. This will also enable breeders to acquire adapted and *Striga* resistant landraces to incorporate into current breeding programs.

Conclusion

Yields of sorghum in SSA is low due to biotic and abiotic factors including *Striga* parasitism. Several cultural and chemical control measures are available to control *Striga*. However, these strategies are often poorly adopted by smallholder farmers either due to their unavailability or cost. Integrated *Striga* management involving the use of sorghum genotypes with *Striga* resistance and *FOS* compatibility is an important approach of managing *Striga* and improving sorghum yields in the semi-arid areas. Further, participatory variety development is a key component of successful sorghum breeding that allows researchers to address the real problems that the famers face and for ultimate adoption of the newly developed varieties.

Disclosure statement

No potential conflict of interest is expected by the authors.

References

Abbasher AA, Hess DE, Sauerborn J (1998) Fungal pathogens for biological control of *Striga hermonthica* on sorghum and pearl millet in West Africa. African Crop Science Journal. 6:179-188.

Blum A (2004) Sorghum physiology. *In*: Nguyen HT, Blum A (eds), *Physiology and Biotechnology Integration for Plant Breeding*. Marcel Dekker Inc., New York, USA.

Carsky RJ, Ndikawa R, Kenga R, Singh L, Fobasso M, Kamuanga M (1996) Effect of sorghum variety on *Striga hermonthica* parasitism and reproduction. Plant Var Seeds. 9:111-118.

Chambers R (1992) Rural Appraisal: rapid, relaxed and participatory. Institute of Development Studies (IDS), Discussion paper 311. University of Sussex, England.

Ciotola M, Ditommaso A, Watson AK (2000) Chlamydospore production, inoculation methods and pathogenicity of *Fusarium oxysporum* M12-4A, a bio-control agent for *Striga hermonthica*. Biocontrol Science and Technology. 10:129-145.

Dembele B, Dembele D, Westwood JH (2005) Herbicide seed treatment for control of purple witch weed (*Striga hermonthica*) in sorghum and millet. Weed Technology. 19: 629-635.

Doggett H (1953) Sorghum improvement in Tanganyika. East African Agricultural Journal. 18:155-159.

Doggett H (1988) Sorghum 2nd ed. Longman Scientific and Technical, Essex, England.

Ejeta G (2007) Breeding for *Striga* resistance in sorghum: exploitation of an intricate host-parasite biology. Crop Science. 47:216-227.

Ejeta G, Mohammed A, Rich P, Melake-Berhan A, Housley TL, Hess DE (2000). Selection for specific mechanisms of resistance to *Striga* in sorghum. In: Haussmann BIG, Koyama ML, Grivet L, Rattunde HF, Hess DE (Eds.), Breeding for *Striga* Resistance in Cereals. Proceedings of a Workshop, IITA, Ibadan, Nigeria, 18±20 August 1999. Margraf, Weikersheim, Germany, pp. 29±37.

Ejeta G, Babiker AG, Mohamed A (1996) Chemical control of *Striga hermonthica* on sorghum. p. 769-773. *In*: Moreno MT, Cubero JI, Berner D, Joel D, Musselman LJ, Parker C. (eds). Advances in Parasitic Plant research. Proceedings of the 6th International Symposium on Parasitic Weeds, Cordoba, Spain.

Ejeta G, Butler LG, Babiker AG (1992) New approaches to the control of *Striga*. *Striga* Research at Purdue University, Research Bulletin RB-991. Agricultural Experiment Station, Purdue University, West Lafayette, IN.

Ejeta G, Butler LG, Hess DE, Obilana T, Reddy BV (1997) Breeding for *Striga* resistance in sorghum. In: Rosenow et al (eds) Proceedings of International Conference on Genetic Improvement of Sorghum and Pearl Millet. Lubbock, TX, USA

Enserink HJ (1995) Sorghum Agronomy in West Kenya: Investigations from a farming systems perspective. Royal Tropical Institute, Amsterdam.

Food and Agriculture Organization of the United Nations (FAOSTAT) (2014) Databaseavailable from: http://faostat.fao.org/default.aspx. Date Visited 18th January 2018.

Franke AC, Ellis-Jones J, Tarawali G, Schulz S, Hussaini MA, Kureh I, White R, Chikoye D, Douthwaite B, Oyewole BD, Olanrewaju AS (2006) Evaluating and scaling-up integrated *Striga hermonthica* control technologies among farmers in Northern Nigeria. Crop Protection. 25:868-878.

Frost H (1995) *Striga Hermonthica* surveys in Western Kenya, p. 145-150 Brighton Crop Protection Conference - Weeds - 1995, Brighton.

Garcia-Garrido JM, Lendzemo V, Castellanos-Morales V, Steinkellner S, Vierheilig H (2009) Strigolactones, signals for parasitic plants and arbuscular mycorrhizal fungi. Mycorrhiza. 19: 449-459.

Gethi JG, Smith SE, Mitchell SE, Kresovich S (2005) Genetic diversity of *Striga hermonthica* and *Striga asiatica* population in Kenya. Weed Research. 45: 64-73.

Grenier C, Rich PJ, Mohamed A, Ellicott A, Shaner C, Ejeta G (2001) Independent inheritance of LGS and IR genes in sorghum. *In*: Fer et al (ed.) Proceedings of the 7th International Parasitic Wee Symposium, Nantes, France.

Haussmann BIG, Hess DE, Reddy BV, Welz HG, Geiger HH (2000a) Analysis of resistance to *Striga hermonthica* in diallel crosses of sorghum. Euphytica. 116:33-40.

Haussmann BIG, Hess DE, Welz HG, Geiger HH (2000b) Improved methodologies for breeding *Striga*-resistant sorghums. Field Crops Research. 66:195-211.

Haussmann BIG, Hess DE, Reddy BVS, Welz HG, Geiger HH (1996) Quantitative-genetic parameters for resistance to *Striga hermonthica* in sorghum. In: Moreno MT, Cubero JI, Berner D, Joel D, Musselman LJ, Parker C (Eds.), Advances in Parasitic Plant Research. Proceedings of the Sixth International Parasitic Weed Symposium, Cordoba, Spain, 16 - 18 April 1996, pp. 681-688.

Hearne S (2009) Control - the *Striga* conundrum. Pest Management Sciences. 65:603-614.

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

Jamil M, Charnikhova T, Cardoso C, Jamil T, Ueno K, Verstappen F, Asami T, Bouwmeester HJ (2011) Quantification of the relationship between strigolactones and *Striga hermonthica* infection in rice under varying levels of nitrogen and phosphorus. Weed Research. 51: 373-385.

Joel DM (2000) The long-term approach to parasitic weeds control: manipulation of specific developmental mechanisms of the parasite. Crop Protection. 19:753-758.

Johnson DE, Riches CR, Diallo R, Jones MJ (1997) *Striga* on rice in West Africa: crop host range and the potential of host resistance. Crop Protection. 16:153-157.

Kanampiu FK, Kabambe V, Massawe C, Jasi L, Friesen D, Ransom JK, Gressel J (2003) 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. 22: 697-706.

Kiriro FH (1991) The *Striga* problem in Kenya. In: Kim SK (ed.). Proceedings of the International Workshop on Combating *Striga* in Africa, 22-24 August 1988. IITA, Ibadan, Nigeria

Koichi Y, Awad AA, Xiaonan X, Kaori Y, Takeuchi Y (2010) Strigolactones as germination stimulants for root parasitic plants. Plant Cell Physiology. 51:1095–1103.

Labrousse P, Amaud MC, Seryes H, Berville A, Thalouarn P (2001) Several mechanisms are involved in resistance of helianthus to *Orobanchecumana*. Annals of Botany. 88: 859-868.

Lagoke STO, Parkinson V, Agunbiade RM (1991) Parasitic weeds and control methods in Africa. In: Kim SK (ed.), Proceedings of the International Workshop on Combating *Striga* in Africa, 22-24 August 1988. IITA, Ibadan, Nigeria.

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Lane JA, Child DV, Moore THM, Bailey JA (1995) Wild relatives of cereals as new sources of resistance to *Striga*. *In*: Parasitic Plants: Biology and Resistance. International Workshop, IACR-Long Ashton Research Station, Bristol, UK, 30 May±2 June 1995, p. 13.

Lamboll R, Hella J, Riches C, Mbwaga AM, Ley G (2001) Integrated management of *Striga* species on cereal crops in Tanzania: preliminary study of farmer perceptions of soil resources in Central, Lake and Eastern zones. Project R7564, Crop Protection Programme, Department for International Development, UK.

Lynn DG, Chang M (1990) Phenolic signals in cohabitation: implication for plant development. Annual Review of Plant Physiology. 41:497-526.

Mabasa S (1996) Screening sorghum genotypes for resistance to witch weed (*Striga asiatica*) in Zimbabwe. *In*: LeuschnerK, Manthe CS (eds.) Drought tolerant crops for Southern Africa: Proceedings of the SADC/ICRISAT Regional sorghum and pearl millet workshop, 25- 29 July 1994, Gaborone, Botswana.

Mati RK, Ramaiah KV, Bisen SS, Chidley VL (1984) A comparative study of the haustorial development of *Striga asiatica* (L.) Kuntz on sorghum cultivars. Annals of Botany. 54:447-457.

Matusova R, Rani K, Verstappen FWA, Maurice CRF, Beale MH, Bouwmeester HJ. 2005. The Strigolactone germination stimulants of the plant-parasitic *Striga* and Orobanche spp. are derived from the carotenoid pathway. Plant Physiology. 139(2): 920-934.

Mohamed AH (2002) Identification and characterization of genetic variants in sorghum for specific mechanisms of *Striga* resistance. PhD thesis. Purdue University, USA.

Mohamed AA, Ellicott TL, Housley, Ejeta G (2003) Hypersensitive response to *Striga* infection in sorghum. Crop Science. 43: 1320-1324.

Mohamed KI, Musselman LJ, Riches CR (2001) The genus *Striga scrophulariaceae* in Africa. Annals of the Missouri Botanical Garden. 88:60-103.

Mbwaga AM, Obilana AT (1993) Distribution and host specificity *of Striga asiatica* and *S. hermonthica* on cereals in Tanzania: a preliminary study. International Jounal of Pest Management. 39:449-451.

Mrema E, Shimelis H, Laing M, Bucheyeki T (2016) Farmers' perceptions of sorghum production constraints and *Striga* control practices in semi-arid areas of Tanzania, International Journal of Pest Management. DOI:10.1080/09670874.2016.1238115.

Mrema E, Shimelis H, Laing M, Bucheyeki T (2017a) Screening of sorghum genotypes for resistance to *Striga hermonthica* and *S. asiatica* and compatibility with Fusariumoxysporumf.sp. *strigae*. Acta Agriculturae Scandinavica, Section B-Soil and Plant Science. DOI: 10.1080/09064710.2017.1284892.

Mrema E, Shimelis H, Laing M, Mwadzingen L (2017b) Genetic analysis of maximum germination distance of *Striga* under *Fusarium oxysporum* f.sp. *strigae* biocontrol in sorghum. Journal of Integrative Agriculture. DOI10.1016/S2095-3119(17)61790-8.

Mrema E, Shimelis H, Laing M (2017c) Genetic analysis of maximum germination distance of *Striga* under *Fusarium oxysporum* f.sp. *strigae* biocontrol in sorghum. Euphytica. Doi.org/10.1007/s10681-017-2073-3

Ndung"u DK (2009) Mutagenesis and Development of herbicide resistance in sorghum for protection against *Striga*. PhD. Thesis. University of KwaZulu-Natal, South Africa.

Obilana AT, Ramaiah KV (1992) *Striga* (witch weed) in sorghum and millet: Knowledge and future research needs. *In*: deMilliano WAJ, FrederiksonRA, BengstonGD, (eds.) Sorghum and millet diseases, a second world review, ICRISAT. Pp 187-207.

Oliver A, Benhamon N, Leroux GD (1991) Cell surface interactions between sorghum roots and the parasitic weed *Striga hermonthica* cytochemical aspects of cellulose distribution in resistant and susceptible host tissues. Canadian Journal of Botany. 69:1679-1690.

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

Oswald A, Ransom JK, Kroschel J, Saurborn J (2001) Transplanting maize (*Zea mays*) and sorghum (*Sorghum bicolour*) reduces *Striga hermonthica* damage. Weed Science 49: 346-353.

Parker C, Riches CR (1993) Parasitic Weeds of the Worlds: Biology and Control. CAB International, Wallingford, UK.

Patrick JR, Grenier C, Ejeta G (2004) *Striga* resistance in the wild relatives of sorghum. Crop Sci. 44: 2221-2229.

Ramaiah KV, Chidley VL, House LR (1990) Inheritance of *Striga* seed-germination stimulant in sorghum. Euphytica. 45. 33±38.

Ramaiah V (1986) Status of ICRISAT's *Striga* resistance breeding in sorghum and millet in Africa. In: Proceedings of the FAO/OAU All-African Government Consultation on *Striga* Control, 20-24 October 1986, Maroua, Cameroon

Ransom JK (2000) Long term approaches for the control of *Striga* on cereals: field management options. Crop Protection. 19: 759-763.

Rebeka G, Shimelis H, Laing MD, Tongoona P, Mandefro N (2013) Evaluation of sorghum genotypes compatibility with *Fusarium oxysporum* under *Striga* infestation. Crop Science. 53:385-393.

Riches C (2003) Integrated management of *Striga* species on cereal crops in Tanzania. DFID Crop Protection Program, Final technical Report, Project R7564. Natural Resources Institute, University of Greenwich, Chatham, Kent, UK.

Riches CR, de Milliano WAJ, Obilana AT, House LR (1987) Witch weeds (*Striga* spp.) of sorghum and pearl millet in the SADCC region: Distribution and control. *In* proceedings of the third regional SADCC/ICRISAT sorghum and millet improvement, project workshop, Lusaka, Zambia, 20-25 September 1986.

Roose E (1994) Introduction à la gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols (GCES), Bulletin pédologique de la FAO, 70, 14–17.

Rwebugisa RA (2008) Groundwater re-charge assessment in the Makutupora Basin, Dodoma, Tanzania. M.Sc. Thesis. International Institute for Geo-Information Science and Earth Observation, Enschede.

Saunders AR (1942) Field experiments at Potchestroom. A summary of investigations conducted during the period 1903-1940. South African Department of Agriculture and Forestry Science Bulletin 214: 19-31, 49-50.

Stewart GR, Press MC (1990) The physiology and biochemistry of parasitic angiosperms. Plant molecular biology. 41: 127-151.

Stewart GR, Press MC, Graves JD, Nour JJ, Wylde A (1991) Physiological characterization of the Host-Parasite Association between *Sorghum bicolor* and *Striga hermonthica* and its implications for *Striga* control. *In:* Kim SK (ed.), Combating *Striga* in Africa, Proceedings, International Workshop organised by IITA, ICRISAT and IDRC, 22-24 August 1988. IITA, Ibadan, Nigeria. Pp 48-54.

Templeton GE (1982) Status of weed control with plant pathogens. p.29-44, *In*: Charudattan R,Walker HL. (eds). Biological Control of Weeds with Plant Pathogens. Wiley, New York.

Tesso T, Zenbaba G, Aberra D, Ejeta G (2007) An integrated *Striga* management option offers effective control of *Striga* in Ethiopia. P199-212. *In*: Ejeta G, Gressel J (eds). Integrating New Technologies for *Striga* Control: Towards Ending the Witch-hunt. World Scientific Publishing Co., Singapore.

Udom GN, Babatunde FE, Tenebe VA (2007) Suppression of witch-weed (*Striga hermonthica*) in sorghum: cowpea mixture as affected by cowpea varieties and planting patterns. International Journal of Agricultural Research 2: 268-274.

Vogler RK, Ejeta G, Butler LG (1996) Inheritance of low production of *Striga* germination stimulant in sorghum. Crop Sci. 36, 1185±1191.

Wegmann K (1996) Biochemistry of host/parasite relations. Sixth Parasitic Weed Symposium, Cordoba, Spain. Manuscript available from Eberhard-Karls University, Institute of Chemical Plant Physiology, Correnstr. 41, D-72076 TuÈbingen, Germany

Williams CN (1961a) Growth and morphogenesis of *Striga* seedlings. Nature 189: 378-382.

Williams CN (1961b) Tropism and morphogenesis of *Striga* seedlings in the host rhizosphere. Annals of Botany 25: 407-414.

Wortmann CS, Mamo M, Abebe G, Mburu C, Kayuki KC, Letayo E, Xerinda S (2006) The atlas of sorghum production in five countries of Eastern Africa. University of Nebraska-Lincoln, Lincoln, USA.

Yoder JI (2001) Host plant recognition by parasitic scrophulariaceae. Current Opinion in Plant Biology 4: 359-365.