

Review

## Control strategies and breeding efforts in sorghum for resistance to storage weevils

Maletsema Alina, Mofokeng

Agricultural Research Council-Grain Crops Institute, Private Bag X1251, Potchefstroom, 2520, South Africa.

Received 29 April, 2016; Accepted 2 June, 2016

**Sorghum (*Sorghum bicolor* L. Moench) is one of the main staple cereal crops grown worldwide. It is used for food, feed, fodder and bio-ethanol. Biotic and abiotic challenges are the major constraints of the crop. Among the biotic constraints, weevil attack is the most devastating causing yield reduction ranging between 15 and 77%. This paper highlights control strategies and progresses of breeding sorghum towards improved yield and weevil resistance. The use of resistant varieties is an economically feasible, technically easy and environmentally friendly alternative to minimize losses due to storage insect pests. Breeding for post-harvest insect pest resistance is the most important component to improve yield and reduce the impact of weevils. Also to combine resistance to post-harvest insect pests with other desirable plant characters such as high yield, and good quality to provide the basic foundation on which to build an integrated pest management system. Estimation of combining ability to resistance to weevils in sorghum helps in selection of good combiners, and the nature of gene action involved. Marker assisted breeding could have a complementary role in sorghum breeding for introgression of resistance genes and their fast enhancement in succeeding generations in the breeding programmes. This review provides theoretical bases on the progress of breeding sorghum for weevil resistance and control strategies.**

**Key words:** Breeding, insect pests, resistance, sorghum, weevils.

### INTRODUCTION

Sorghum, a diploid and a C4 plant belonging to the grass family Gramineae, is one of the most important cereal crops grown in the tropics and sub-tropics of the world. It ranks fifth after maize, rice, wheat and barley (FAO, 2012). It performs well in areas considered marginal for other cereal crops such as maize. It has an ability to withstand harsh conditions including drought and water logging. The sorghum crop is used for food, feed, fodder

and bio-ethanol. It is the main source of calories and protein in some regions of Africa and Asia (Waniska and Rooney, 2000). However, its production is hindered by biotic and abiotic constraints. Among the biotic constraints, post-harvest insect pests are the major devastating insect pests attacking the grains during storage. The weevil infestation is encountered on-farm storage where it causes high loss in grain weight in

\*Corresponding author. E-mail: MofokengA@arc.agric.za. Tel: +27 72 1222 369.

Author(s) agree that this article remain permanently open access under the terms of the [Creative Commons Attribution License 4.0 International License](http://creativecommons.org/licenses/by/4.0/)

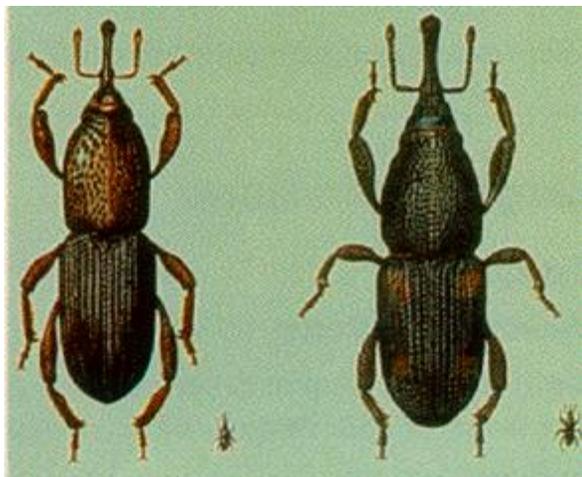


Figure 1. Maize weevil (*S. zeamais*).

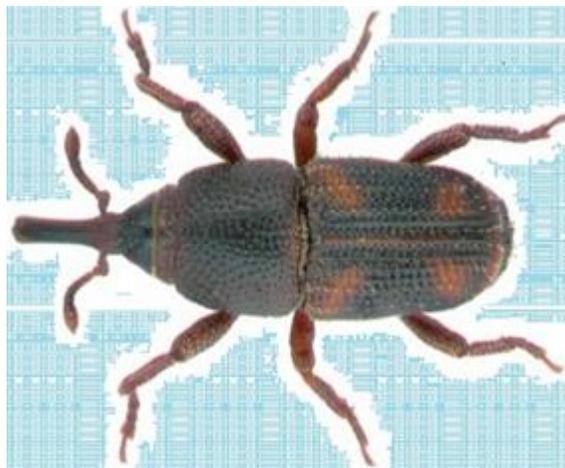


Figure 2. Rice weevil (*S. oryzae*).

addition to deterioration in quality (Giga et al., 1991).

According to Rounet (1992), a huge post-harvest losses and deterioration in quality is one of the major obstacles to achieving food security in developing and under developed countries. Effective control of the weevils would improve the market quality and quantity of sorghum. Various control strategies were employed, and these control strategies include modern and traditional control methods. The methods involved cultural, physical, biological, and chemical controls, as well as host plant resistance. Although the use of chemicals is one of the most common control strategies, it is expensive to smallholder farmers and environmentally undesirable. Host plant resistance is more sustainable and is a major component of integrated pest management which is cheaper and ecologically safer (Abebe et al., 2009; Tefera et al., 2011).

This study seeks to highlight the progresses of breeding sorghum towards improved yield and weevil resistance. Further, the potential and limitations of the conventional and non-conventional breeding methods for sorghum improvement have been reviewed.

### Sorghum production constraints

As mentioned earlier, sorghum production and productivity is limited by abiotic and biotic constraints. Abiotic constraints include drought, cold injury and aluminium toxicity among others. Biotic constraints in sorghum include foliar, panicle and grain diseases, weeds, as well as pre- and post-harvest insect pests. The major insect pests of sorghum include stem borers, maize and sorghum aphids, panicle feeding bugs, beetles, bollworms, wireworms, cutworms, shootfly, sorghum midge, armoured cricket, larger grain borer and weevils (Dogget, 1988; Van den Berg and Drinkwater, 1997).

### Post-harvest insect pests in sorghum

The post-harvest insect pests that attack sorghum during storage include larger grain borer (*Prostephanus truncates* Horn), rice weevil (*Sitophilus oryzae*) and maize weevil (*Sitophilus zeamais*) (Boxal, 2002; Teetes and Pendleton, 2000). The larger grain borer adults are black or brown and cylindrical in shape with heads facing down. They are larger than 3 to 4 mm and have two strong lateral ridges with sharp edges. The *S. zeamais* is a small snout beetle with adults reaching lengths of between 3 to 3.5 mm and it is capable of flight (Figure 1). The maize weevil has reddish yellow blotches on the wing case. The *S. oryzae* is a small (4 mm) snout reddish brown beetle with faint yellow or red patterns on the wings. It has deep irregular pits behind the head and the snouts can grow up to 1 mm (Figure 2).

The *S. zeamais* and *S. oryzae* occur throughout the warmer, more humid regions of the world, especially where maize is grown (Longstaff, 1981). They have been reported to attack a wide range of crops including wheat, barley, maize, sorghum and other cereal and fruit crops particularly when moisture contents are above 20°C (Anonymous, 2009). The biology of *S. zeamais* and *S. oryzae* has been reviewed in detail by Longstaff (1981). The adults are long-lived. Eggs are laid throughout most of the adult life, although 50% maybe laid in the first 4 to 5 weeks; each female may lay up to 150 eggs. The eggs are laid individually in small cavities chewed into cereal grains by the female; each cavity is sealed, thus protecting the egg, by a waxy secretion produced by the female. The incubation period of eggs are about 6 days at 25°C (Howe, 1952). Eggs are laid at temperatures between 15 and 35°C (with an optimum around 25°C) and at grain moisture contents over 10%. However, rates of oviposition are very low below 20°C or above 32°C, and below 12% moisture content (Birch, 1944). Upon



**Figure 3.** Weevil damage on sorghum grain.

hatching, the larva begins to feed inside the grain, excavating a tunnel as it develops. The actual length of the life cycle also depends upon the type and quality of grain being infested: for instance, in different varieties of maize, mean development periods of *S. zeamais* at 27°C, and 70% RH have been shown to vary from 31 to 37 days.

### Effects of weevils on sorghum

Weevils infest sorghum while still in the field, and deposit eggs in the stored grains and once the larval stage is reached, the larvae feeds on the grains and cause damage (Demissie et al., 2008). The grains are mostly damaged inside and are full of holes (Figure 3). The significant damage happens during grain storage. The damaged grain has reduced nutritional value, low percent germination and reduced weight and market value. Weevil damage leads to quantitative and qualitative deterioration of the grain (Goftishu and Belete, 2014). These losses could be influenced by the storage time and population of insects involved in the infestation. The qualitative loss is attributed to change in biochemical components such as carbohydrates, starch contents and proteins (Danjumba et al., 2009). The commercial value of the infested grain is reduced by contamination with uric acid, insect body fragments, and other toxic substances (Borikar and Tayde, 1979; Gupta et al., 2000). It also predisposes the seeds to attack by storage fungi (Subramanyan et al., 1992). Weevils cause direct damage to the stored grains and also affect their viability and successful planting by smallholder farmers. Globally, yields are affected from a range of 15 to 77% grain losses of insecticide untreated sorghum (Ramputh et al., 1999). Upadhyaya and Ahmad (2011) reported an annual loss of about 10 to 45% annually worldwide.

### Strategies for weevil control

The losses of the grain yield can be prevented in various ways including chemical and non-chemical control

methods as shown in Table 1 (Hagstrum and Subramanyam, 2006).

### Chemical control

The chemical control refers to the application of insecticides before or during storage. Fumigation with chemicals such as Malathion was recommended (Navi et al., 2006). A surface dressing with an insecticide can be applied to prevent insects from entering bins where the grain will be stored. Grain can also be treated with inert dusts, or sprays of synergized pyrethrins. Friction of inert dusts and the weevil's cuticle can cause desiccation and hampers the development of the insect pest (Golob, 1997). The inert dusts, silica gel and aerosol kill insects through physical contact.

### Physical control

Sorghum grain can be placed in a low oxygen and CO<sub>2</sub> enriched atmosphere in order to reduce weevil numbers via reduced respiration. Additionally, grain can be placed in a store room with a temperature ranging between 55 to 65°C for 12 h (Upadhyaya and Ahmad, 2011). High temperatures of 55 to 65°C can kill the insect pest's life stages in a life cycle in store houses. Low temperatures also plays a significant role in controlling the insect pests. Temperatures below 12°C makes the weevil inactive and reduces the insect development and kills all immature stages in the life cycle. Keeping grain in store houses with low temperatures provides a long term seed storage and high mortality of insect pests.

### Cultural control

The cultural control method involves keeping the store warehouses clean at all times, for example removal of cracked seeds, egg shells and dead larvae. Store houses should be kept clean between the harvests and infested residues must be removed and burned. Further, the crop can be harvested early, immediately after maturity. Selections of only un-infested material should be made for grain storage. The clean grain should be stored in containers that are fitted with insect proof glass, or refrigeration or deep freeze. In addition, the storage should be ventilated to get rid of any moisture as the insect pests reproduce rapidly in moist areas. The moisture of the seed should be 12% or less during storage. This will help to reduce insect pest numbers and their survival and development will be hindered.

### Biological control

The biological control includes the use of parasitoids

**Table 1.** Strategies used to control storage weevil infestation.

Techniques/strategies	References
Malathion application	Navi et al. (2006)
Inert dusts	Golob (1997)
<i>Bacillus thuringiensis</i>	Abdel-Razek (2002)
Growth regulators: Methropene and hydropene	Mian and Mulla (1982)
Host resistance	Borikar and Tayde (1979), Shazali (1982), Fademula and Horber (1984), Wongo and Pedersen (1990)
Low aeration	Maier et al. (2002), Reed and Authur (1998)
Wood ash	De Groot (2004)
Extracts	Karthikeyan et al. (2009)
Plant parts	Karthikeyan et al. (2009)
Plant powders	Suleiman et al. (2012), Danjumma et al. (2009), Mukherjee and Joseph (2000)
Natural oils	Koul et al. (2008), Mollalei et al. (2011)
Volatile substances: Methyl salicylate	Jayasekara et al. (2005), Liu et al. (2006)

which must be introduced early in the storage facility to outnumber the insect pests. These parasitoids include species such as *Anisopteromalus calandrae*, *Cephalomia tarsalis*, *Lanophagus distinguendus* and *Theocola xelegans* to feed on the insect pests. *Beauveria bassiana* and *Bacillus thuringiensis* can also be used as biological insecticides for control of maize weevil. The *B. thuringiensis* produces Bt toxins that are harmful to the insect pests. Sometimes *B. thuringiensis* is mixed with some botanicals such as plant essential oils and their chemical constituents and results in killing of insect pests in higher rates. The essential oils of many plant species are known to have repellent and insecticidal activities (Koul et al., 2008; Mollalei et al., 2011). *Bacillus thuringiensis* strains are also used to control Coleopteran pests of stored wheat (Abdel-Razek, 2002). Moreover, insect growth regulators such as methropene and hydropene can be used to reduce insect pest populations of *S. oryzae* (Mian and Mulla, 1982).

### Host plant resistance

The use of varieties resistant to storage weevils is another strategy for preventing yield losses due to storage weevils. In areas where storage facilities are inadequate, stored grain resistance might be used alone or as an adjunct to chemical control to protect yields. Pramod et al. (2002) reported presence of resistance to rice weevil (*S. oryzae*) when using A/B lines, R lines, commercial varieties, germplasms, mutants and locals. The study showed a need to increase the levels of resistance among parental lines and hybrids to ensure a better protection from rice weevil infestation in stored sorghum. Resistance to *S. oryzae* was also reported in sorghum by Prasad et al. (2015) and Kudachi and Balikai (2014). Various researchers studied and reported

resistance of sorghum to storage weevils (Mannechoti, 1974; White, 1975, Doraiswamy et al., 1976; Borikar and Tayde, 1979; Shazali, 1982; Fademula and Horber, 1984; Wongo and Pedersen, 1990). Some sorghum genotypes were found to possess variable degrees of resistance viz. progeny emergence (Borikar and Tayde, 1979), low larval penetration (Shazali, 1982; Wongo and Persen, 1990), increased progeny emergence (Adentuji, 1988) and low loss in seed weight (M'bata, 1992). Combining early planting with early harvest with resistant varieties proved to be effective for management of maize weevils in the stores in Niger Delta-agro-ecological zone (Zakka et al., 2015).

### Integrated pest management (IPM)

Integrated pest management strategies can manage to control insect pests in bulk grain (Hagstrum et al., 1999). Once the grain is stored, the biophysical conditions in the bin can be monitored and modified for insect control by:

1. Removing grain samples and counting the number of live and/or dead insects
2. Using insect traps to estimate insect population
3. Using automatic insect traps to detect insect activity at different spots in the grain mass
4. Using temperature sensors and data loggers to collect hourly temperature measurements at different spots in the grain mass.

Based on the monitoring outcome, one or a combination of control strategies can be implemented appropriately. For instance, using low aeration to control the biophysical conditions in the storage bin to control insect population growth rate (Maier et al., 2002; Reed and Arthur, 1998). The grain can be kept at lower temperatures, for example



**Figure 4.** Farmer's traditional granary for grain storage.

16°C which is the lowest temperature limit for survival, development and reproduction of the storage pests. Development and use of improved grain cultivars with resistance to storage pests and pre-harvest pests will provide a key elementary control in IPM.

#### **Farmer's traditional control strategies of weevils**

Traditionally farmers in rural areas in some parts of India and Africa use traditional granaries to store their grains (Figure 4). The granaries are found not to be very effective against storage pests. Hence, a need for suitable storage facilities and management technologies following the cultural control methods. This lack somehow forces farmers to sell their grain immediately after harvest. As a result, farmers receive low market prices for any surplus grain they may produce due to storage weevil damage (Kimenju et al., 2009).

#### **Physical control**

Traditionally, farmers apply wood ash (*Acacia* and *Casuariana* spp.) (De Groot, 2004), or clay to stored grain in order to cause insects to die from desiccation. Farmers believed that ash prevent grain losses up to an extent of 80% (Karthikeyan et al., 2009). Farmers using the ash strategy stored sorghum grains for 6 months without any storage pests' problems. Farmers further use sands and soil components on seed grain to control storage pests. The grain will be covered by sand particles which forms a protective layer of the stored grain (Golab and Webley, 1980). For instance, treating *Vigna radiata* with inert clay before storage lead to 100% mortality of *Callosobruchus chinensis* within 24 h. The inert clay coat can control insect pests up to twelve months under ambient conditions (Babu et al., 1989). Smallholder farmers store their grains in bags and put them in holes dug inside the cattle kraal and cover with the cow dung. This strategy seemed to be effective against storage

pests as the ammonia from the faeces repelled the weevils. According to Karthikeyan et al. (2009) farmers preferred jute gunny bags for short term storage of grain to be used as seed materials for future sowing. The gunny bags were treated with neem seed kernel extract. The practice involved preparation of neem seed kernel extract (NSKE) and then treating the gunny bags with the extract before storage by soaking them in the solution (Karthikeyan et al., 2009). In addition, fresh pungam (*Pongamia glabra*) leaves were placed in layers between the gunny bags arranged one above the other in the storerooms. The strong odour from the leaves acts as a repellent against the weevils. Farmers also use paddy husks to store grain. For instance, the paddy grains (*Oryza sativa*) were stored in earthen pods and placed paddy husk in top layer (5 cm) above it. The storage pests did not prefer the grain stored with paddy husk. Lastly, farmers made traditional mud pots of different capacity and sizes with the clay soil. Firstly the grain were sun dried and cleaned before storing in pots. Farmers placed a circular ring-like structure made with paddy straws on the floor. Above the ring, mud pots filled with grain are placed and then arranged one on top of the other and the top most pots were closed with the lead. This is usually in the house at the corner. The grains were kept for about six months, and then were sun dried and again re-stored in the mud pots for control of storage insect pests.

#### **Use of plant powders**

Non-chemical control of weevils refers to the use of physical, cultural and biological control methods. Danjumma et al. (2009) used plant powders of *Nicotiana tabacum*, *Alliumsativum*, and *Zingiber officinale* to control maize weevils. Suleiman et al. (2012) reported powders of *Jatropha curcas*, *Euphorbia balsamifera*L., *Lawsonia iners*L. and *Leptadenia hastate* L. collected from the bushes to control weevil infestation on sorghum grains. The Japanese mint (*Mentha arvensis*) oil was found effective as fumigant against *Sitophilus oryzae* in sorghum (Mukherjee and Joseph, 2000). *Inula graveolens* and soap berry are mixed with grain to protect grains against weevils (De Groot, 2004). Sweet flag (*Acorus calamus*) is one of the indigenous methods used as a plant powder mixed with grain and the grain can be protected for up to six months. This strategy was used for more than 40 years to store seeds of pulses, cereals and oil crops. In the study by Bhanderi et al. (2015) sweet flag powder, custard apple seed powder and neem seed kernel powder were the most effective powders in controlling populations of weevils in sorghum.

#### **Natural oils**

The essential oils of many plant species have repellent

and insecticidal activities (Koul et al., 2008; Mollalei et al., 2011). Natural products show little detrimental effects on the environment and non-target organisms and is continuously evaluated for their pesticidal effects (Matthews, 1993). These oils have shown an effect on the oviposition and growth inhibitory activity (Triphati et al., 2001).

### **Volatile substances**

In addition, volatile constituents, such as methyl salicylate from *Securidacalanga pedunculata* exhibited repellent and toxic properties against *S. zeamais* and *Rhizopertha dominica* (Jayasekara et al., 2005). The active component from leaves of *Artimisia princepi* and seeds of *Cinnamomum camphora* (L.) have shown repellent and insecticidal activity against *S. oryzae* and *Bruchus rugimanus* (Liu et al., 2006). The volatile constituent, di-n-propyl disulphide extracted from the seed of neem, *Azadirachta indica*, is toxic when applied as a fumigant to *Tribolium castaneum* adults and larvae of *S. oryzae* adults. These plant products show toxicity against pests of stored grain and furthermore, provide prolonged protection to seeds that may be due to high mortality of adult insect besides the effect on oviposition and low hatching (Huang and Subramanyam, 2004).

### **Conventional breeding for weevil resistance in sorghum**

There is little progress in developing insect-resistant high yielding sorghum varieties for cultivation by the farmers. This is largely because of the lack of knowledge on inheritance of the agronomic and morphological characteristics associated with insect resistance and grain yield (Sharma et al., 2005; Riyazaddin et al., 2015). Traditional breeding methods such as germplasm evaluation and enhancement, backcrossing, pedigree selection, and recurrent selection continue to play an important role in developing insect-resistant cultivars with major resistance genes (Huang et al., 2013). In such breeding approaches, sorghum breeders search for genetic variability for insect resistance and then incorporate the desired gene into breeding lines, leading to the development of resistant commercial cultivars or hybrids. Since sorghum is a self-pollinated crop, most breeding methodologies are based on the production of segregating populations followed by selection in segregating population. The selections are usually allowed to self-pollinate during selection to produce homozygous uniform lines (pure lines). In hybrid breeding programmes, these lines will be test crossed to measure their value as parental lines. Although the aforementioned breeding methods are employed in breeding for insect pest resistance pest resistance, there is still limited breeding studies conducted on resistance to weevil damage in sorghum *per se*.

Other studies on breeding for resistance to weevils using traditional breeding methods have been reported on maize but limited on sorghum. Kasozi et al. (2015) used two cycles of modified S1 recurrent selection to study resistance to maize weevil in maize. The authors found that the modified S1 recurrent selection was effective in improving Longe5 for maize weevil resistance.

### **Marker assisted breeding**

Genetic resistance in sorghum, where possible, should be combined with other desirable plant characters such as high yield and good quality grain providing a basic foundation on which to build integrated pest management systems. A promising strategy should be based on gene pyramiding and development of cultivars with multiple resistances to insect pests. Many studies were conducted in identifying the quantitative trait loci (QTL) regions of different traits associated with insect resistance as well as the morphological and agronomic traits (Satish et al., 2009; Srinivas et al., 2009; Aruna et al., 2011; Nagaraja Reddy et al., 2013, 2014).

Based on the present inheritance studies of the agronomic and morphological traits and as well as the QTL information available, one can effectively plan suitable breeding strategies for sorghum improvement. In contrast to the conventional approaches that takes about six to eight generation to transfer a trait within a species into high yielding, locally adapted cultivars, and the non-conventional breeding approaches such as marker-assisted selection (MAS) allows rapid introgression of the resistance genes and ultimately gene pyramiding into the high-yielding varieties and hybrids. It further allows early selection of breeding materials and cloning of the important resistance genes for sorghum improvement via map-cloning method. Use of DNA markers for indirect selection offers great potential gains for quantitative traits with low heritability, as these are the most difficult traits to work with in the field using direct phenotypic selection. However, little work has been done on the use of molecular markers on weevil resistance gene mapping and transfer to the locally adapted high yielding sorghum varieties.

Nonetheless, Silverio et al. (2009) mapped the QTLs associated with resistance to maize weevil in maize using 151 RFLP markers, and further found that the genetic effects were mainly dominant for grain damage, grain weight losses and maize weevil susceptibility index, and additive for number of adult progeny. Castro-Alvarez et al. (2015) identified a total of 15 QTLs for maize weevil resistance parameters located on six chromosomes in a RIL maize population using SSR markers.

### **The genetics of weevil resistance in sorghum**

Information on inheritance of agronomic and morphological traits is useful for improving genotypic

performance across environments. An understanding of the inheritance of morphological and agronomic traits will be helpful in combining the genes for insect resistance and desirable agronomic traits and grain characteristics to increase production and productivity of sorghum. The genetic effect can either be additive, dominant or epistatic and in rare case over dominance. According to Griffing (1956), general combining ability (GCA) and specific combining ability (SCA) are used to estimate gene effects. The GCA is used to estimate additive genetic effects while SCA estimates the non-additive components.

Mohammed et al. (2015) studied the genetic analysis of agronomic and morphological traits in sorghum in relation to insect resistance. The authors found that the GCA/SCA, and the predictability ratios indicated predominance of additive gene effects for majority of the traits studied. The significance of reciprocal combining ability effects for days to 50% flowering, plant height and 100 seed weight, suggested maternal effects for inheritance of these traits. Plant height and grain yield across seasons, days to 50% flowering, inflorescence exertion, and panicle shape in the post-rainy season showed greater specific combining ability variance, indicating the predominance of non-additive type of gene action/epistatic interactions in controlling the expression of these traits.

Additive gene action in the rainy season, and dominance in the post-rainy season for days to 50% flowering and plant height suggested genotype by environment interactions for these traits. Other authors reported high GCA/SCA and predictability ratios for 100 seed weight in the post-rainy season indicated the predominance of additive gene action, whereas both additive and non-additive gene action was observed in the rainy season. Grain yield exhibited higher SCA variance suggesting the predominance of dominance (non-additive) type of gene action (Hovny et al., 2000; Umakanth et al., 2002; Girma et al., 2010).

However, the importance of both additive and non-additive gene action was observed for 100 seed weight by Toure et al. (1996). The combining ability analysis is useful for understanding of the nature of gene action, and has been used by breeders for selection of suitable parents for the crossing programmes.

### Effects of genotype by environment interaction on weevil resistance in sorghum

Studies on the effects of genotype by environment interaction on the resistance of maize and rice weevils in sorghum are not yet documented. Sorghum improvement efforts in the development of cultivars and hybrids with high grain yield under diverse environmental conditions are needed. Osiru et al. (2009) suggested that knowledge of genotype performance in different agro-ecologies is critical in cultivar development. Selecting genotypes that

interact less with the environments in which they are grown would be beneficial. Maize hybrids were tested in nine environments in Kenya and Ethiopia for resistance to weevils, larger grain borer and other foliar diseases (Tefera et al., 2013).

The results indicated that the performances of the hybrids were not consistent across environments for all traits tested as evident from the significant genotype by environment interactions and two hybrids were showed resistance to larger grain borer and maize weevil (Tefera et al., 2013). A study involving inbred lines and ten top best crosses was reported in maize for combining ability gene action and resistance to weevils in maize (Gafishi et al. 2010). The inbred lines and the crosses were tested in two environments where the across site analysis of genotype by environment for yield revealed that the testcrosses were environment specific. It is possible to identify genetic variability within an environment although stable performance is required.

## CONCLUSION AND RECOMMENDATIONS

Postharvest insect pests such as maize and rice weevils are the major limiting factor in sustainable production of sorghum. Host plant resistance is one of the more effective control strategies of postharvest insects without the undesirable effects of pesticides. Continuous research efforts on the identification of new sources of resistance to these pests and breeding should be the major objectives of breeding programmes. A promising strategy for sorghum improvement should be based on gene pyramiding and development of cultivars with multiple resistance to insect pests. Also to combine resistance to post-harvest insect pests with other desirable plant characters such as high yield, and grain quality to provide the basic foundation on which to build integrated pest management system. There is an urgent need for transfer of various insect resistance genes into cytoplasmic male sterile, maintainer, and restore lines so as to develop hybrids with increased levels and diverse mechanisms of resistance to target pests. Furthermore, there is a need for genotypes that show good combining ability effects for weevil resistance, yield and other agronomic characters, as well as selection of genotypes that interact less with the environment in which they are grown.

### Conflict of Interests

The authors have not declared any conflict of interests.

### REFERENCES

- Abdel-Razek AS (2002). Comparative study on the effect of two *Bacillus thuringiensis* strains of the same serotype on three Coleopteran pests of stored wheat. J. Egypt Soc. Parasitol. 84.32(2):415-424.

- Abebe F, Tefara T, Mugo S, Beyene Y, Vidal S (2009). Resistance of maize varieties to the maize weevil *Sitophilus zeamais* (Motsch.) (Coleoptera: Curculionidae). *Afr. J. Biotechnol.* 8:5937-5943.
- Adentuji JF (1988). A study of the resistance of some sorghum seed cultivars to *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae). *J. Stored Prod. Res.* 24:67-71.
- Anonymous (2009). Maize weevil *Sitophilus zeamais* (Motsch.) Canadian Grain Commission.
- Aruna C, Bhagwat V, Madhusudhana R, Sharma V, Hussain T, Ghorade RB, Khandalkar HG, Audilakshmi S, Seetharama N (2011). Identification and validation of genomic regions that affect shootfly resistance in sorghum [*Sorghum bicolor* (L.) Moench]. *Theor. Appl. Genet.* 122:1617-1630.
- Babu TR, Reddy VS, Hussaini SH (1989). Effect of edible and non-edible oils on the development of the pulse beetle (*Callosobruchus chinensis* L.) and on viability and yield of mung bean (*Vignaradiata* L.)Wilczek. *Trop. Sci.* 29:215-220.
- Bhandari GR, Radadia GG, Patel DR (2015). Ecofriendly management of rice weevil *Sitophilus oryzae* (Linnaeus) in sorghum. *Indian J. Entomol.* 77(3):210-213.
- Birch LC (1944). Two strains of *Calandra oryzae* L. (Coleoptera). *Aust. J. Exp. Biol. Med. Sci.* 22:271-275.
- Borikar PS, Tayde DS (1979). Resistance in sorghum to *Sitophilus oryzae* Linn. *Proc. Indian Acad. Sci.* 88B:273-276.
- Boxal RA (2002). Damage and loss caused by the larger grain borer *Prostephanus truncatus*. *Int. Pest Manage. Rev.* 7:105-121.
- Castro-Alvarez FF, William M, Bergvinson DJ, Garcia-Lara S (2015). Genetic mapping of QTL for maize weevil resistance in a RIL population of tropical maize. *Theor. Appl. Genet.* 128:411-419.
- Danjumma BJ, Majeed Q, Manga SB, Yabaya A, Dike MC, Bamaayi L (2009). Effect of some plants powders in the control of *Sitophilus zeamais* Motsch (Coleoptera: Curculionidae) infestation on maize grains. *Am. Eur. J. Sci. Res.* 4(4):313-316.
- De Groot I (2004). Protection of stored grains and pulses. *Agrodok* 18. Agromisa Foundation. Wageningen.
- Demissie G, Tefera T, Tadesse A (2008). Importance of husk covering on field infestation of maize by *Sitophilus zeamais* Motsch. (Coleoptera: Curculionidae) at Bako, Western Ethiopia. *Afr. J. Biotechnol.* 7:3774-3779.
- Dogget HD (1988). *Sorghum*. 2nd ed. Longman Group UK, Green and Co. Ltd, London, Harlow, England.
- Doraiswamy V, Subramanian TR, Dakshinamurthy A (1976). Varietal preference in sorghum for the weevil, *Sitophilus oryzae* L. *Bull. Grain Technol.* 14:107-110.
- Fademula A, Horber E (1984). Resistance of sorghum varieties to *Sitophilus oryzae* and *Sitotroga carealella*. In: *Proc 3<sup>rd</sup> Intl. Working Conf. Stored-Product Entomology 23-28 October*. Kansas State University, Manhattan, Kansas, USA. pp. 418-434.
- Gafishi MK, Tumutegereize JK, Asea G (2010). Inheritance of resistance to maize weevil *Sitophilus zeamais* (Motschulsky) in maize inbred lines and determination of their heterotic grouping. Second RUFORUM Biennial Meeting 20-24 September, Entebbe, Uganda.
- Giga DP, Mutumeerwa S, Moya G, Neeley D (1991). Assessment and control of losses caused by insect pests in small farmer's stores in Zimbabwe. *Crop Prot.* 10:287-292.
- Girma M, Amsalu A, Ketema B (2010). Combining ability for yield and its components in Ethiopian sorghum [*Sorghum bicolor* (L.) Moench] landraces. *East Afr. J. Sci.* 4:34-40.
- Goftishu M, Belete K (2014). Susceptibility of sorghum varieties to the maize weevil *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae). *Afr. J. Agric. Res.* 9(31):2419-2426.
- Golab P, Webley DJ (1980). The use of plants and minerals as protectants of stored product. *Tropical product Institute G138. Post-harvest Pest and Quality Section Natural Resource Institute*. Cathan, U.K. p. 32.
- Golob P (1997). Current status and future perspectives for inert dusts for control of stored product insects. *J. Econ. Entomol.* 33:69-79.
- Griffing B (1956). Concept of general and specific combining ability in relation to diallel crossing system. *Aust. J. Biol. Sci.* 9:463-493.
- Gupta AK, Bahal SR, Awashi BK, Verma RA (2000). Reaction protein, starch and ash constituent of different varieties of maize on growth and development of *Sitophilus oryzae* L. *Indian J. Entomol.* 62:375-381.
- Hagstrum DW, Subramanyam BH (2006). Fundamentals of stored product. *Entomology*, American Association of Cereal Chemists (AACC). St. Paul, Minnesota.
- Hagstrum DW, Reed C, Kenkel P (1999). Management of stored wheat insect pests in the USA. *Int. Pest Manage. Rev.* 4:127-142.
- Hovny MRA, El-Naggouly OO, Hassaballa EA (2000). Combining ability and heterosis in grain sorghum [*Sorghum bicolor* (L.) Moench]. *Assiut J. Agric. Sci.* 31:1-16.
- Howe RW (1952). The biology of the rice weevil, *Calandra oryzae* (L.). *Ann. Appl. Biol.* 39(1):68-180.
- Huang F, Subramanyam B (2004). Responses of *Corcyra cephalonica* (Stainton) to primiphos-methyl, spinosad and combinations of pirimiphosmethyl and synergized pyrethrins. *Pest Manage. Sci.* 60(2):191-198.
- Huang Y, Sharma HC, Dhillon MK (2013). Bridging conventional and molecular genetics of sorghum insect resistance. In: Paterson A.H. (Ed.) *Genomics of the saccharine*, Plant Genetics and Genomics: Crops and Models. Springer Science+ Business Media, New York. pp. 367-389.
- Jayasekara TK, Stevenson PC, Hall DR, Belmain SR (2005). Effect of volatile constituents from *Securidaca long pedunculata* on insect pests of stored grain. *J. Chem. Ecol.* 31(2):303-313.
- Karthikeyan C, Veeraravathatham D, Karpagam D, Ayisha Firdouse S (2009). Traditional storage practices. *Indian J. Trad. Knowl.* 8(4):564-568.
- Kasozzi LC, Derera J, Tongoona P (2015). Response of maize population "Longe5" to two cycles of modified S<sub>1</sub> recurrent selection for resistance to maize weevil. *Euphytica* 204(3):587-598.
- Kimenu SC, De Groote H, Hellin H (2009). Preliminary Economic Analysis: Cost effectiveness of the use of improved storage methods by small scale farmers in east and southern Africa countries. *International Maize and Wheat Improvement Centre (CIMMYT)*. P. 17.
- Koul O, Walia S, Dhaliwal GS (2008). Essential oils as green pesticides: Potential and Constraints. *Biopestic. Int.* 4(1):63-84.
- Kudachi DC, Balikai RA (2014). Evaluation of *rabi* sorghum genotypes against rice weevil, *Sitophilus oryzae* in storage. *Indian J. Entomol.* 76(2):87-91.
- Liu CH, Mishar AK, Tan RX, Yang H, Shen YF (2006). Repellent and insecticidal activities of essential oils from *Artemisia princeps* and *Cinnamomum camphora* and their effect on seed germination of wheat and broad bean. *Technol. Bioresour.* 97(15):1969-1973.
- Longstaff BC (1981). Biology of the grain pest species of the genus *Sitophilus* (Coleoptera: Curculionidae): A critical review. *Protect. Ecol.* 2:83-130.
- M'bata GN (1992). Egg distribution on seeds by *Callosobruchus subinnotatus* (Pic.) (Coleoptera: Bruchidae). *J. Stored Prod. Res.* 28:301-319.
- Maier DE, Illeji KE, Woloshuk CP, Szabela DA (2002). The effect of temperature management on *Sitophilus zeamais*, *Tribolium castaneum* and *Plodia interpunctella* in maize: Summer 2001 Pilot Bin Trials. In: Careland, P.F., D.M. Armitage, C.H. Bell, P.M. Cogan and E. Highley (eds) *Advances in stored product protection*. Proceedings of 8<sup>th</sup> International Working Conference on Stored Product Protection. York, U.K. CAB International, Willingford, UK.
- Mannechoti P (1974). Studies of resistance of 92 sorghum and 38 maize cultivars to four species of stored product insects. MSc thesis. Kansas State University, Manhattan, Kansas.
- Mian LS, Mulla MS (1982). Biological and environmental dynamics of insect growth regulators (IGRs) environmental and health impacts of juvenile hormone analogue, methoprene used against Diptera of public health importance. In: Gunther, F.A. (ed.) *In Residue Reviews*. pp. 27-112.
- Mollaei M, Izadi H, Hossein D, Majid A, Reza RK (2011). Bioactivity of essential oil from *Satureja hortensis* (Lamiaceae) against three stored product insect species. *Afr. J. Biotechnol.* 10(34):6620-6627.
- Mukherjee SN, Joseph M (2000). Medicinal plant extracts influencing insect growth and reproduction. *J. Med. Arom. Plant Sci.* 22(1):38.
- Nagaraja RR, Madhusudhana R, Murali Mohan S, Chakravarthy DVN, Mehtre SP, Seetharama N, Patil JV (2013). Mapping QTL for grain yield and other agronomic traits in post-rainy sorghum [*Sorghum*

- bicolor* (L.) Moench]. *Theor. Appl. Genet.* 126:1921-1939.
- Nagaraja RR, Madhusudhana R, Murali Mohan S, Seetharama N, Jagannatha Vishnu P (2014). Detection and validation of stay-green QTL in post-rainy sorghum involving widely adapted cultivar, M35-1 and a popular stay-green genotype B35. *BMC Genomics* 15:909.
- Navi SS, Deshpande VK, Kulloli SD (2006). Influence of seed colouring on rice weevil infestation during storability of hybrid sorghum. *Karnataka J. Agric. Sci.* 19(2):287-290.
- Osiru MO, Olanya OM, Adipala E, Kapinga R, Lemaga B (2009). Yield stability analysis of *Ipomoea batatas* L. cultivars in diverse environments. *Aust. J. Crop Sci.* 3(4):213-220.
- Pramod KKR, Singh BU, Dharma R (2002). Sorghum resistance to the rice weevil, *Sitophilus oryzae* (L.): Antixenosis. *Insect Sci. Appl.* 22(1):9-19.
- Prasad GS, Babu KS, Sreedhar M, Padmaja PG, Subbarayudu B, Kalaisekar A, Patil JV (2015). Resistance in sorghum to *Sitophilus oryzae* (L.) and its association with grain parameters. *Phytoparasitica* 43:391-399.
- Ramputh A, Techome A, Bergvinson DJ, Nozzolillo C, Arnason JT (1999). Soluble phenolic content as an indicator of sorghum grain resistance to *Sitophilus oryzae* (Coleoptera: Curculionidae). *J. Stored Prod. Res.* 35:57-64.
- Reed C, Arthur F (1998). Conditioning practices and their effects on quality of corn stored on Kansas Farms. *Appl. Eng. Agric.* 14:623-630.
- Riyazaddin MD, KaviKishor PB, Ashok Kumar A, Belum Reddy VS, Rajendra SM, Sharma HC (2015). Mechanisms and diversity of resistance to sorghum shoot fly, *Atherigona soccata*. *Plant Breed.* 134:423-436.
- Rounet G (1992). *Maize. The tropical agriculturist.* CTA, Macmillan, London.
- Satish K, Srinivas G, Madhusudhana R, Padmaja PG, Nagaraja Reddy R, Murali Mohan S, Seetharama N (2009). Identification of quantitative trait loci for resistance to shoot fly in sorghum [*Sorghum bicolor* (L.) Moench]. *Theor. Appl. Genet.* 119:1425-1439.
- Sharma HC, Reddy BVS, Dhillon MK, Venkateswaran K, Singh BU, Pampapathy G, Folkerstma RT, Hash CT, Sharma KK (2005). Host plant resistance to insects in sorghum: present status and need for future research. *Int. Sorghum Millets Newsllett.* 46:36-43.
- Shazali MEH (1982). The biology and population ecology of four insect pests of stored sorghum with particular reference to competition and succession. PhD thesis, University of Reading, Reading, UK.
- Silverio G, Mirelle MK, Mateo V, David JB (2009). Mapping of QTL associated with maize weevil resistance in tropical maize. *Crop Sci.* 49(1):139-149.
- Srinivas G, Satish K, Madhusudhana R, Nagaraja Reddy R, Murali Mohan S, Seetharama N (2009). Identification of quantitative trait loci for agronomically important traits and their association with genic-microsatellite markers in sorghum. *Theor. Appl. Genet.* 118:1439-1454.
- Subramanyay B, Wright VF, Fleming EE (1992). Laboratory evaluation of food habits for their relative ability to retain three species of stored product beetles. *J. Agric. Entomol.* 9:117-127.
- Suleiman M, Ibrahim ND, Majeed Q (2012). Control of *Sitophilus zeamais* (Motsch) [Coleoptera: Curculionadae] on sorghum using some plant powders. *Int. J. Agric. For.* 2(1):53-57.
- Teetes GL, Pendleton BB (2000). Insect pests of sorghum. In: Smith, CW and Frederikson, RA (eds.), *Sorghum: Origin, history, technology, and production.* Wiley Series in Crop Science, New York. . pp. 443-495.
- Tefera T, Mugo S, Beyene Y, Karaya H, Gakunga J, Demissie G (2013). Postharvest insect pest and foliar disease resistance and agronomic performance of new maize hybrids in East Africa. *Int. J. Plant Breed. Genet.* 7(2):92-104.
- Tefera T, Mugo S, Likhayo P (2011). Effects of insect population density and storage time on grain damage and weight loss in maize due to the maize weevil *Sitophilus zeamais* and larger grain borer *Protephanus truncates*. *J. Agric. Res.* 6:2249-2254.
- Toure A, Miller FR, Rosenow DT (1996). Heterosis and combining ability for grain yield and yield components in guinea sorghums. *J. Afr. Crop Sci.* 4:383-391.
- Tripathi AK, Prajapati V, Aggarwa KK, Kumar S (2001). Insecticidal ovicidal activity of the essential oil of *Anethum sowa* Kurz against *Callosobruchus maculatus* F. (Coleoptera:Bruchidae). *Insect Sci. Appl.* 31(1):61-66.
- Umakanth AV, Madhusudhana K, MadhaviLatha P, Hema K, Kaul S (2002). Genetic architecture of yield and its contributing characters in post rainy season sorghum. *Int. Sorghum Millets Newsllett.* 43:37-40.
- Upadhyay RK, Ahmad S (2011). Management strategies for control of stored grain insect pests in farmer stores and public ware houses. *World J. Agric. Sci.* 7(5):527-549.
- Van den Berg J, Drinkwater TW (1997). Field guide to identification of sorghum pests in Southern Africa. Agricultural Research Council-Grain Crops Institute, Potchefstroom, South Africa.
- Waniska RD, Rooney LW (2000). Structure and chemistry of the sorghum caryopsis. In: Smith, C.W., and R.A. Frederiksen (Eds.), *Sorghum: origin, history, technology, and production.* Wiley, New York, USA. pp. 649-688.
- White SC (1975). Laboratory studies on levels and causes of insect resistance in stored sorghum varieties. MSc Thesis. Kansas State University, Manhattan, Kansas, USA.
- Wongo LE, Pedersen JR (1990). Effect of threshing different sorghum cultivars on *Sitotroga cerealella* (Oliv.) and *Sitophilus oryzae* (L.) (Lepidoptera: Gelechiidae and Coleoptera: Curculionidae). *J. Stored Prod. Res.* 26(2):89-96.
- Zakka U, Lale NES, Umeozor OC (2015). Efficacy of combining varietal resistance with harvest time and planting date for the management of *Sitophilus zeamais* Motschulsky infestation in stored maize. *J. Stored Prod. Res.* 60:31-35.