ASSESSING MANAGEMENT STRATEGIES TO CONTROL MAJOR INSECT PESTS OF STORED SORGHUM GRAIN

by

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ABSTRACT

Occurrence and diversity of insect pests of stored sorghum, *Sorghum bicolor* (L.) Moench, were monitored in Niger. Efficacy of botanicals was evaluated to control red flour beetle, *Tribolium castaneum* Herbst, in Niger and maize weevil, *Sitophilus zeamais* Motschulsky, in Texas. Hermetic storage methods to control insect pests were assessed in Niger. Cost-benefit analysis determined measures of project worth, Net Present Value and Benefit-Cost Ratio, for benefit from investing in hermetic storage methods.

Monitoring by sieving 200 g of infested grain found means of 15 to 17 red flour beetles in three improved sorghum varieties. Three traps detected as many as 10 insect pests in storage facilities in Niger. A water bottle trap caught 60% of the storage species trapped by a 'Dome' Pheromone trap and 85% of the species in the sticky glue trap.

Four botanicals were effective in controlling red flour beetles in sorghum grain in Niger. Means of 1.5-2.0 adults died with 0.0125 and 0.025 g of kernels of neem, *Azadirachta indica* A. Juss. African locust beans, *Parkia biglobosa* Jacq., hibiscus, *Hibiscus sabdariffa* L., and baobab pulp, *Adansonia digitata* L. were less effective after 7 days. The cumulative number of beetles dead was 3.2 at 35 days after infestation with 0.05 g of neem. Damage scores were low (1.3-2.6 on a 1-5 scale) for sorghum treated with ≥0.1 g of botanical powder compared to a 3.9 score for the check (not treated).

With three botanicals assessed, less than 0.1 g of milkweed, *Asclepias speciosa* J. Torrey, killed 1.3-1.8 maize weevils by Day 2, while mesquite, *Prosopis glandulosa* J. Torrey, killed 1.5 adult by Day 4. Few adults (≤0.8) were killed by neem bark. Two to 2.3 weevils were killed by 0.1 and 0.2 g of neem and 2.0 were killed by 0.2 g of milkweed by Day 6. Neem bark acted slowly for 14 days and killed 2.0 maize weevil adults when grain was treated with 0.05 g of powder.

The cumulative percentage (94 and 91) of dead red flour beetles was greatest with 0.2 g of milkweed or mesquite. With 0.1 g, mesquite killed 87.5% compared to milkweed (78%) and or bark (65.6%).

Percent mortality of beetles (78%) was greatest on sorghum grain treated with 0.2 g of neem compared to 0.05 and 0.1 g that killed 62.5 and 66%. Percent corrected mortality was 75-93% when maize weevils were fed sorghum treated with milkweed or mesquite at >0.1 g. Percent corrected mortality was 86% with 0.1 g of mesquite. Neem at 0.2 g lessened the grain damage score by weevils to 25.5%. Any botanical at any dose reduced damage to less than the mean of 3.5 for the check.

Correlation coefficients showed that an increase in percentage of adult mortality was followed by an increase in percent corrected mortality. When percent mortality or corrected mortality increased, percentages of grain damage and weight loss and the damage score decreased. Percentage of grain damage was very correlated with weight loss and damage score. Regression (Probit) analysis of the cumulative mean number of dead maize weevils was used to calculate LD_{50} and LD_{90} lethal doses of 0.02 and 0.2 g of mesquite or milkweed were required to kill 50 and 90% of maize weevils. More neem was required for lethal doses of 0.26 and 1.27 g to kill 90 and 99% of maize weevils.

Hermetic storage methods assessed to control insect pests of sorghum grain showed that triple and double bagging killed 7.6 and 8.0 red flour beetles by the 7th day. Means were greater than the 1.2 red flour beetle killed when a polypropylene bag was used as a check and greater than the overall mean of 5.2. Means of 10.6, 9.0, and 8.2 storage insects were killed when a double bag, triple bag, and clear plastic bucket, respectively, were used for 7 days. Means were greater than overall means of 6.8 (Day 7) and 8.1 (Day 14) rice moths killed. At 28 and 35 days, few (2.2 and 0.4) moths were dead in the polypropylene check, but 2.5 moths were dead in the double bag at 35 days.

Fewer red flour beetles than rice moths survived in hermetic storage. With polypropylene and polyethylene bags, 8.0 and 25.2 red flour beetles and 21.6 and 33.2 rice moths were alive in sorghum stored 35 days. Overall, double bagging lessened

survival of both storage insect species, with 3.4 red flour beetles and 9.6 rice moths alive. Mean weight losses were 8.5 and 3.2% when polypropylene and polyethylene bags were used, compared with 1.4% with other storage methods.

Cost-benefit analysis assessing project worth by Net Present Value and Benefit-Cost Ratio showed that for any hermetic storage method, percentage weight loss increased during time, especially after 6 months. Simple linear regression analysis showed that for all alternative hermetic storage methods, coefficients were less than for the polypropylene bag (check). Storage costs per ton were $15.00 for a polyethylene bag, $20.00 for a double bag, and $34.60 for a triple bag for 1 year. Benefit gained from any hermetic storage method increased linearly during time. At a discount rate of 4.5% and 10-year investment period, Net Present Value was positive (Year 1-10) for all hermetic storage methods. Overall, greater Net Present Value was calculated for triple bagging ($4,344.81), followed by double bagging ($4,343.22). The Net Present Value for a polyethylene bag ($4,186.55) was $158.26 less than for a triple bag. Benefit-Cost Ratio for the three hermetic storage methods differed slightly, with 1.19 for polyethylene and 1.20 for double and triple bagging of 1 ton of sorghum stored 1 year. Sensitivity analysis using discount rates of 4.5, 6.5, or 8.5% with varying 2-year increment period during 10 years of investment found hermetic storage methods had Benefit-Cost Ratio >1, indicating the alternatives were good investments. For double and triple bagging, Benefit-Cost Ratio ≥1.20 was calculated with all discounting rates at Year 8-10, but less with the polyethylene bag. Hermetic storage methods (triple and double bags) can be used as alternatives to traditional polypropylene bags to preserve more sorghum grain of greater quality.

Monitoring storage insect pests was effective and key to deciding when to apply integrated pest management strategies. Botanicals and hermetic storage methods are alternatives to insecticides and polypropylene bags, and can be used to safeguard large quantities of sorghum to retain grain quality and generate more revenue.

DEDICATION

I dedicate this work to:

My late parents, Abdou Kadi Kadi Malam Saley and Absatou Mato, for the gift of life they gave me through the grace of “Allah”, their overwhelming support, and the encouragement they showed me. Both did not have the chance to see the completion of this work; they passed away on 6 June 2011 and 14 November 2014, respectively. May their souls rest in peace. Amen.

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CHAPTER I

INTRODUCTION

Sorghum, *Sorghum bicolor* (L.) Moench, is one of the most important cereals in the semi-arid tropics (ICRISAT and FAO 1996). Worldwide, >50% of sorghum is produced as a cash crop for domestic consumption or is used for animal feed. However, in some regions, particularly sub-Saharan Africa, sorghum is produced mostly for human food because it is the staple crop for the poorest and most food-insecure people in the world. Although sorghum provides food, feed and forage, grain yields at the farm level generally are low, partly because of damage by insect pests.

Sorghum is adapted for production in areas with warm climates. From 2006 through 2008, average annual sorghum production was 61.7 million tons, of which 25.6 million tons were grown in Africa on 4% of arable land (CTA.ORG 2011). Output in Africa increased from 18.41 million tons in 2000 to 27.16 million tons in 2009, partly because of 54% increase in yield (from 700 to 1,100 kg/ha). Together with Asia, mostly China and India, Africa accounts for more than 95% of sorghum used as food. Output from developed countries (13.6 million tons) is used mostly as animal feed.

Agriculture in southern Niger is dependent on rainfall, and production is limited by harsh environmental conditions (INS 2014, Ministère de l'Agriculture 2014). Most cereal grains are for subsistence by households. Local landraces of sorghum and pearl millet, *Pennisetum glaucum* (L.) R. Br., are the main cereal crops produced by Niger farmers. Yields are low, with a national average of 500 kg/ha ranging from 150 to 4,000 kg/ha depending on growing conditions and inputs (Adamou et al. 1985). In Niger, major constraints to crop production are land degradation and deforestation, demographic pressure, decrease in land holdings, unpredictable drought, and flooding (INS 2014). Other production constraints include limited rainfall (200-600 mm), infertile soil, few external inputs, low investment in irrigated agriculture, long maturity period of landraces with low grain yield potential, drought, witchweed or *Striga* (Adamou et al. 1985), and numerous insect pests including shootfly, *Atherigona soccata* Rondani; spittle bug, *Poophilus costalis* (Walker); panicle bug, *Eurystylys marginatus* Odhiambo; sorghum midge, *Stenodiplosis sorghicola* (Coquillett) (Ajayi and Ratnadass 1998, Ministere de l'Agriculture 2014) and storage insect pests (Kadi Kadi et al. 2013).

Adamou et al. (1985) pointed out that despite the importance of cereal grain as a food source, increased production through increased yield per unit area of land in recent years has been modest at best because abiotic and biotic stresses limit potential grain yield. Post-harvest damage by stored-product insect pests reduces cereal grain quality and quantity in Niger and West Africa. Insecticides often are used to manage stored-grain insect pests (Kadi Kadi et al. 2013). Insecticide residues in grain may be harmful to consumers, and over-dependence on insecticides increases the potential to select resistant strains of insect pests. Alternative methods of insect pest management in stored grain are practiced independent of or in combination with gaseous insecticides (INTSORMIL 2012).

One of the most important constraints to food availability is post-harvest preservation of grain quality and quantity. Insect pests at different developmental stages feed and cause low yield and decreased grain quality in Niger (Kadi Kadi 2009). Farmers identified eight insect pests that damaged stored products in two regions of Niger (Kadi Kadi et al. 2013). Among insect pests, beetles and moths cause serious damage to stored grain (Schulten 1975). Red flour beetle, *Tibolium castaneum* Herbst (Coleoptera: Tenebrionidae), and rice moth, *Corcyra cephalonica* Stainton (Lepidoptera: Pyralidae), were the dominant insect pests that infested grain in different storage facilities in Niger (Kadi Kadi and Pendleton 2017). To control storage insect pests, most farmers relied on insecticides, hermetic bagging, and application of botanical products without scientifically based formulations (INTSORMIL 2012). But, insecticides are costly and toxic to living organisms and the environment. Increasing concern over the amount of insecticide residues in food has encouraged researchers to look for alternatives to synthetic insecticides. Ecologically sound strategies are needed to effectively manage stored-product insect pests and protect non-target organisms, and the environment.

The overall goal of the research was to evaluate different management strategies for suppression of major insect pests of stored sorghum grain. Specific objectives of the study were to: 1) assess diversity and monitor occurrence of storage insect pests of sorghum grain at different storage settings (facilities, markets, etc.); 2) determine an optimal hermetic storage method among multiple available low-cost methods; 3) assess efficacy of botanical products to suppress stored-grain insect pests without sacrificing grain yield and quality, and 4) assess cost-benefit analysis of using low-cost hermetic bagging technology for control of storage insect pests infesting sorghum grain.

CHAPTER II

LITERATURE REVIEW

Importance of Sorghum

The centers of origin and domestication of cultivated sorghum were reported to be northeastern regions of Africa (Ethiopia and Sudan) where cultivation began approximately 4,000-3,000 BC (Dillon et al. 2007). According to Doggett (1988), early domestication occurred by a process of disruptive selection where several traits advantageous to cultivation were favored. Current cultivated sorghums arose from wild *Sorghum bicolor* subsp. *arundinaceum*.

The genus *Sorghum* belongs to the grass family *Poaceae*, subfamily Panicoideae, tribe *Andropogoneae*, and subtribe *Sorghinae* (Clayton and Renvoize 1986). The genus consists of 25 recognized species classified morphologically into five subgenera (USDA ARS 2018). Cultivated sorghum belongs to the subgenus *Eusorghum*. *Eusorghum* contains three species: *S. halepense* (L.) Pers., commonly known as Johnsongrass, a weed species; *S. propinquum*; and *S. bicolor* (de Wet 1978).

Sorghum is an important staple food in the diets of more than 500 million people in 30 countries of Africa and Asia (ICRISAT 2018). In Africa, sorghum undergirds food security because of its drought tolerance and ability to withstand periods of warm temperatures and water logging. Sorghum is well suited to semi-arid and sub-tropical climatic conditions of much of Africa where intense rainfall often occurs during short periods of time (Doggett 1988). Most cultivation in Africa is by subsistence agricultural systems as opposed to industrialized production methods used in most other regions of the world.

Globally, sorghum is the fifth most widely cultivated cereal after maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and barley (*Hordeum vulgare* L.), and is the most important cereal in terms of production and area planted (FAO 2018). According to recent estimates by USDA (2018), countries that annually produce the most sorghum are the United States (9.2 million tons), Nigeria (6.8 million tons), India and Mexico (each 4.6 million tons), Ethiopia (4.1 million tons), and Sudan (4.0 million tons). Of the total 57.6 million tons of sorghum produced worldwide in 2017, 47.2% or 27.2 million tons of grain were produced on the African continent where the crop is harvested from larger areas than on other continents (FAO 2018). Sorghum has a wide range of uses, including human food, animal feed, and production of alcoholic beverages and biofuel.

Sorghum is a warm-weather crop that requires warm temperatures for good germination and growth (DAFF 2010). The minimum temperature for germination varies from 7 to 10°C. At 15°C, 80% of seeds germinate within 10 to 12 days. The best time to plant is when there is enough water in the soil and the soil temperature is 15°C or warmer at a depth of 10 cm. Temperature plays an important role in sorghum growth and development after germination. A temperature of 27 to 30°C is required for optimum growth and development. However, the temperature can be as cool as 21°C without a drastic effect on growth and yield. Day-time temperatures can be as cool as 21°C and as warm as 36°C without drastic effect on growth and yield when night-time temperatures are cool (19°C). Night-time temperature affects sorghum development, with a warm night temperature of about 31°C reducing yield (Downes 1972).

Nutritionists categorize sorghum as very healthy, because it is rich in essential nutrients significant in the bodies of humans and animals (World Atlas 2018). Considering its nutritional and increasing commercial value, many regions of the world are involved in large-scale production of sorghum.

Niger is the fifth largest producer of sorghum in Africa, after Nigeria, Ethiopia, Sudan, and Burkina Faso (USDA 2018). Niger is ranked 12th in sorghum production worldwide, with 1.9 million tons of sorghum grain produced annually. In Niger, sorghum is the second most important crop after pearl millet. Sorghum grain is used for human nutrition and animal feed (INS 2017). Sorghum is grown on sandy and clay soils in the southern part of the country. Local sorghum mostly is grown by using traditional methods. Local and improved sorghum varieties and hybrids are cultivated according to modern agronomic practices. Climatic conditions, low soil fertility, degraded genetic material, traditional cultural techniques used in the field, and pests (insects, diseases, weeds, and birds) are the limiting factors in sorghum production in Sahelian countries.

Changes induced by infestation by insects in a storage environment might cause warm, moist “hotspots” that provide suitable conditions for growth of storage fungi that cause further losses (Jacobson 1982, Ahmed and Grainge 1986). More than 20,000 species of field and storage pests are estimated to destroy approximately one-third of food produced in the world, valued annually at more than $100 billion among which the greatest losses (43%) occur in developing countries. Quantitative and qualitative damage caused by insect pests to stored grain and grain products can amount to 20-30% in the tropics and 5-10% in the temperate zone (Talukder 2006, Rajendran and Sriranjini 2008). Control and removal of stored grain pests from food commodities has long been a goal of entomologists throughout the world.

Origin of Insect Pests in Storage

Since the advent of agriculture, humans began to produce and store large quantities of food products such as grain, fiber, and skins (Rees 2004). The dry foods of animal and plant origin attracted large numbers of insects that fed on them. The insects came from a variety of natural habitats including bark of trees, seeds, leaf litter, dead and ripening fruits, wood, shoot and tuber borers, fungi and mold, carrion and dead animals, nests of wasps, birds and mammals.

Common insect pests in stored cereals and legumes are numerous in Africa (Abate et al. 2000). Traditionally, grain weevils (*Sitophilus* spp.) and Angoumois grain moth, *Sitotroga cerealella* (Olivier), on cereals, and three genera of bruchids (*Acanthoscelides* sp., *Callosobruchus* sp., and *Zabrotes* sp.) on pulses were the most important pests of stored grain in Africa. Wheat and sorghum in storage were attacked by Angoumois grain moth; *Sitophilus* spp.; confused flour beetle, *Tribolium confusum* Jacquelin du Val; sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.); and mites (Haile 2006). In Niger, according to farmers surveyed in two regions, storage insect pests that damage grain or seeds are principally *Sitotroga cereallella*, *Tribolium confusum*, *Tribolium castaneum* Herbst, *Rhyzopertha dominica* Fabricius, *Trogoderma granarium* Everts, and *Ephestia kuehniella* Zell. (INTSORMIL 2012).

Major Insect Pests of Stored Sorghum Grain

Beetles and moths are the most important insect pests of stored sorghum grain (Teetes and Pendleton 2000). Most of the insects have short developmental times, high rates of development, and long lives. Most damage is done by larvae. Damage and control of storage pests can be expensive. Insects that attack stored sorghum grain are either primary pests that damage and develop inside whole kernels, or secondary pests that feed on cracked or broken kernels, grain dust, or molds that grow on grain in storage.

Three insects are the most important and destructive insect pests of stored sorghum grain. The maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae), is the most destructive insect pest of stored sorghum in the world. It infests a large variety of stored grains and is cosmopolitan in distribution, but is more destructive in warm, humid countries (Teetes et al 1983, Teetes and Pendleton 2000, Rees 2004). Both the adults and larvae feed on grain, which often can be damaged beyond use (Teetes et al. 1983).

For a long time referred to as the larger strain or race of the rice weevil, the maize weevil now is recognized as a distinct species (Rees 2004). Although slightly larger, as much as 13 mm long, and darker than a rice weevil adult, the degree of variation within each species makes maize and rice weevils difficult to distinguish. Adult weevils of both species are reddish brown, about 4 mm long, and have four light reddish or yellow spots on the wings (Teetes et al. 1983, Teetes and Pendleton 2000).

Maize weevils infest grain in the field and in storage. An adult female bores a hole into a kernel, deposits an egg, and covers it with a gelatinous substance (Teetes et al.

1983, Teetes and Pendleton 2000). She lays 300-500 eggs during her 4-5 months of life. The life cycle and early life stages are the same as those of the rice weevil (Rees 2004). Eggs hatch in 3 days. The larva is legless, short, stout, and whitish with a brown head, and matures in 3-6 days. There may be five to seven generations a year. Weevils can be managed by storing grain in dry, clean conditions in insect-proof containers (Teetes et al. 1983). If grain moisture content is less than 9%, the insect is unable to breed. If keeping the grain dry is not practical, fumigation might be the only feasible protection.

The red flour beetle, *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae), is a cosmopolitan insect found mostly infesting stored grain, seeds, flour, dried fruit, nuts, museum insects, and stuffed animal specimens (Rees 2004). Beetle adults can be easily observed by the tunnels they construct when they move through flour or other grain products. The insect is especially serious in processed rice and other stored products. Beetle adults cause very serious damage to grain products. When attack is severe, the products turn grayish yellow and become moldy (Teetes et al. 1983). In addition to damage it causes by feeding, the insect imparts a nauseous smell and taste to the material it infests (Rees 2004). The red flour beetle is primarily a pest of milled products and attacks only grain dust and the surfaces of broken grains. It frequently is associated with the confused flour beetle and has similar feeding and breeding habits.

The red flour beetle is almost identical in appearance to the closely related confused flour beetle (Rees 2004). The segments of the antenna of a confused flout beetle gradually increase in size from the base to the tip, whereas the last few distal segments of the antenna of a red flour beetle are abruptly much larger than the other segments, forming an enlarged tip. The margins of the head of the confused flour beetle are expanded and notched at the eyes, with a ridge over the eye. The head margins of the red flour beetle are nearly continuous at the eyes and do not have a ridge over the eye.

The adult red flour beetle is about 3-4 mm long, flattened, oblong, and chestnut brown (Teetes et al. 1983, Teetes and Pendleton 2000). The red flour beetle lays as many as 450 eggs in stored products. The egg is minute, cylindrical, and white. The incubation period is 5-12 days. The yellowish, white, cylindrical larva is covered with hair and becomes fully grown in 27-29 days. The pupa is naked, and adults emerge in 3-7 days. Depending on weather conditions, there can be 4-7 generations a year, and one generation takes 1-4 months. Optimum conditions for development of the pest are 36°C and 70% relative humidity. Beetles can breed throughout the year in warm areas. The life cycle requires 40-90 days, and the adult can live for 3 years. All life stages may be found at the same time in infested grain products (Rees 2004). The red flour beetle can be managed by storing products in sealed containers. Fumigants also are effective (Teetes et al. 1983).

The rice moth, *Corcyra cephalonica*, Stainton (Lepidoptera: Pyralidae), is cosmopolitan and an economically important insect pest of sorghum, rice, flour, dried vegetable material, dried fruit, chocolate, biscuits, and oil cakes (Teetes et al. 1983). Rees (2004) reported that damage by the pest, as by all moth pests, is by the larva, which is a general feeder. When feeding on grains, larvae spin dense silken tubes and web kernels into the walls of the tubes. Larvae produce a dense webbing as they become fully grown, and infested stored products are extensively webbed.

A rice moth adult has a wingspan of about 13 mm and is pale grayish brown (Teetes et al. 1983, Teetes and Pendleton 2000, Rees 2004). A tuft of scales projects from the head. When fully grown, the larva is about 13 mm long and varies in color from white to dirty, slightly bluish gray with occasional tints of green. Adults are short lived. Females lay as many as 200 spherical, white, and loose eggs in food material. The eggs hatch in 3-5 days. The larvae use silken threads to web together particles of food and frass into galleries in which they live and feed. The larval period is 20-30 days, and the pupal period lasts 9-10 days. For control of the storage pest, Teetes et al. (1983) recommended that stored commodities should be well dried, proper sanitation measures should be used for storage, and common fumigants are useful.

Abiotic and Biotic Factors Causing Outbreaks

Typical African traditional storage facilities expose grain to attack by insect pests and favorable climatic conditions that cause proliferation of insect pests, microorganisms, and rodents (FAO 1994). A major weakness is a single orifice for loading and removing grain, which also serves as an entry port for pests into the storage facility (Ngamo 2000). The facilities generally are not hermetically sealed, enabling pests to enter the structures. When constructed of plant material, rodents easily destroy structures and enable other sources of infestation (CIRAD 2002).

Humidity is the principal climatic element in a storage system. Traditional storage cribs, for example, limit air circulation, and when grain is not very dry, moisture content of grain in the structure increases (CIRAD 2002). Biological activity of a pest occurs only when moisture is present. Therefore, moisture content of the product itself, as well as the moisture in the surrounding air, is important for storage (Hayma 2003). Stored products, as well as the organisms attacking stored products are living, breathing organisms. According to Kadi Kadi et al. (2013), storage constraints cited by farmers were humidity, mold, rats, mice, and birds.

Storage Periods and Facilities

Throughout Africa, grain usually is stored for 3 to 12 months. The length of the storage period depends on the agro-ecological zone, ethnic group, quantity of commodity stored, storage conditions, and crop variety (Hell et al. 2000, Ngamo et al. 2007). Storage periods tend to be longer in drier areas of Africa. Ngamo et al. (2007) reported an increase in the length of storage from 3 to 8 months in the Sudano-Guinean Agro-ecology Zone, to more than 24 months in the Sudano-Sahelian Zone of Cameroon. Maize usually is stored between 3 and 8 months in the Northern Guinea Savanna of Benin and 7 to 12 months in the Sudan Savanna (Hell et al. 2000). A few farmers store maize for more than 12 months. In the area, dominated by the "Mina" ethnic group, the size of maize stores is used to assess wealth and social prestige of owners, and maize might be stored for as many as 3 years (Smith 1991).

Storage periods of 5 to 12 months are common for sorghum and pearl millet grains in the Tahoua and Maradi regions of Niger (INTSORMIL 2012, Kadi Kadi et al. 2013). The length of grain storage in the Sudan and Guinea Savanna of Nigeria is between 5 and 12 months, except for soybean, *Glycine max* (L.) Merr., that usually is stored less than 5 months because of high demand (Ivbijaro 1989). A maximum storage period of 7 to 10 years for sorghum and millet in the Sudan Savanna was reported by Adejumo and Raji (2007).

Many publications reported on traditional storage structures in Africa (Gilman and Boxal 1974, Youdeowei and Service 1986, FAO 1994, Adejumo and Raji 2007, Kadi Kadi et al. 2013). Storage facilities are made of local materials (plants and soil) and constructed by villagers. Some structures are used for temporary storage (mostly intended for drying the harvested crop), while others are for long-term storage (FAO 1994). Temporary methods are categorized as aerial storage (maize cobs, sorghum panicles, or pearl millet spikes sometimes are tied in bundles suspended from tree branches, posts, or tight lines on or inside the house), storage on the ground, or on drying floors and open timber platforms.

Long-term methods include storage structures (crib or thatched rhombus) made exclusively of plant materials, calabashes, gourds, earthenware pots, jars, solid wall bins (mud rhombus), and underground storage (FAO 1994). Kadi Kadi et al. (2013) reported long-term storage methods of barrels, burlap bags, plastic bags, and storage houses used by farmers in Niger. Grain stores usually are associated with dry weather conditions in which it is possible to reduce the moisture content of harvested grain to a satisfactory amount simply by drying in the sun (FAO 1994). Storage bins with solid walls are traditional in the Sahel region of Africa and in southern African countries bordering the Kalahari Desert. Underground pits used in Sahelian countries and southern Africa are in dry regions where the water table (low) does not endanger the stored contents. Constructed for long-term storage, pits vary in capacity (from a few hundred kilograms to 200 tons).

Grain Damage and Loss

Loss of food grain to insect pests during storage is a major problem, especially in developing countries (Dubey et al. 2008, Talukder et al. 2008). Losses include not only direct consumption of kernels by insects, but also accumulation of their exuviae, webbing, and cadavers. Large amounts of insect detritus may result in grain that is unfit for human consumption and loss of the food commodities, both in terms of quality and quantity. Many authors reported the major cause of loss in traditional granaries was lack of hygiene (Bell 1996, Ngamo 2000, Hoogland and Holen 2001). At the time of filling the storage facility with newly harvested grain, residues of old grain are not always completely removed and serve as the source of infestation of new grain. Living organisms like insects, rodents, birds (on-farm storage), and microorganisms are serious constraints to traditional storage systems in Africa (Nukenine et al. 2002). Among living organisms, insects are responsible for the greatest storage losses in cereals and pulses. Average grain weight loss for cereals and pulses in Africa is 20% (Youdeowei and Service 1986, Philips and Throne 2010). The range of grain damage and loss throughout Africa is great. Traditional storage structures in Africa expose grain to serious infestations by insect pests. Grain loss also can include non-storage losses (harvesting and drying, threshing and shelling, winnowing, and transportation), as well as loss in storage. Additionally, all small-scale African farmers rely on sunlight to dry their crop products sufficiently for storage (FAO 1980, 1994). Magnitudes of losses in the food supply chain vary greatly among crops, areas, and economies. In developing countries, people try to make the best use of the food produced, but a significant amount is lost after harvest because of inadequate knowledge, technology, and/or infrastructure for storage. On the contrary, in developed countries, food loss in the middle stages of the supply chain is relatively low because of availability of advanced technologies and efficient crop handling and storage systems.

According to Rosegrant et al. (2015), numerous published articles on post-harvest losses are mostly on four aspects of: estimating the magnitude of loss, assessing economic impact of loss in general but also on poor and hungry people, using alternatives to reduce loss through transfer of both new and traditional technologies, and evaluating economic costs of losses as well as remedies. Food losses can be quantitative as measured by decreased weight or volume, or qualitative, such as reduced nutrient value and unwanted changes in taste, color, texture, or cosmetic features of food (Buzby and Hyman 2012).

Quantitative food loss can be defined as reduction in weight of edible grain or food available for human consumption (Boxall 1986). Quantitative loss is caused by reduction in weight because of factors such as spillage, consumption by pests, physical changes in temperature and moisture content, and chemical changes (FAO 1980). Qualitative loss can occur because of insect pests, mites, rodents, and birds, or from handling, physical or chemical changes in fat, carbohydrates, and protein, and by contamination with mycotoxins, pesticide residues, insect fragments, or excreta of rodents and birds and their dead bodies (FAO 1980). Qualitative deterioration that makes food unfit and rejected for human consumption contributes to food loss.

Losses can be categorized broadly as loss of quality, weight because of spoilage, nutrition, seed viability, and commercial loss (Boxall 1986). A critical step in reducing losses is to understand the influence of biological and environmental factors, as well as handling practices on product deterioration, and of post-harvest technologies and practices to reduce the process and maintain quality and safety of the product (World Bank 2011).

Monitoring Storage Insect Pests

A key element of a grain storage integrated pest management (IPM) system is the ability to monitor for arthropod pests and detect them reliably, as early as possible, and at low abundance (Wakefield 2006). Considerable progress has been made in developing traps for monitoring storage insect pests and mites, and progress also has been made in developing and validating attractant lures to augment traps and improve sensitivity. During the past few decades, a range of traps and monitoring devices have been designed and validated for monitoring the presence of insects in the commodity itself (e.g., Loschiavo and Atkinson 1967, Cogan et al. 1990) and in associated buildings (Mullen 1992, Collins and Chambers 2003).

Stored grain is at risk of infestation by a range of stored-product insects and mites. Effective detection of pests is essential for protecting harvested crops, revealing whether control is necessary and whether, once implemented, it was successful. Monitoring for beetle, moth, and mite pests is a key requirement of IPM strategies for stored grain (Wakefield 2006). However, research has shown that monitoring devices still detect only a small percentage of the arthropod pests present. There is need to increase the sensitivity of traps and monitors. Aggregation pheromones, which act as attractants, have been identified for the principal storage beetles. In general, pheromones attract only one species, consist of more than one compound, and are difficult to synthesize on a cost-effective basis. Use of a lure based on food attractants is promising as a basis for a multi-species lure and allows expansion of the number of target species to include those for which attractant pheromones are unknown. Food attractants are complex and less well understood than pheromones (Chambers 2002). Research on behavioral effects of food volatiles on stored-product pest insects was reviewed by Cox and Collins (2002). A food attractant for the foreign grain beetle *Ahasverus advena* (Waltl.) was simplified by Wakefield et al. (2005).

Strategies to Control Storage Insect Pests

***Traditional methods*.** Originally, storage structures in Africa were made of only plant materials and mud. Most research in the late 1960s to the 1970s focused on assessment of the prototypes of storage structures (Gilman and Boxall 1974). Later research to date focused on improving traditional granaries for better durability and air tightness (Adetunji 2007). Results of a survey at the farm level (INTSORMIL 2012, Kadi Kadi et al. 2013) found that facilities used for storing dry pearl millet spikes and sorghum panicles were various types of granaries; stalks of *Andropogon gayanus* Kunth. or cereal crops were used to make a cylindrical granary covered with a grassy roof at Maradi, Niger, and mud and bricks were used to create a cylindrical granary with a grassy roof at Tahoua. To control storage insect pests in Niger, farmers used different inert substances such as ash, fine sand, and salt.

Use of traditional stored-product protection methods is popular among small-scale farmers in Africa. Traditional methods are numerous, diverse, and widespread on the

African continent, with regional and country particularities. Belmain and Stevenson (2001) listed 16 plants commonly used by farmers to protect stored products in northern Ghana. In Niger, during the conservation and storage period, traditional methods mainly were used by farmers to control insect pests damaging grain or seeds (Kadi Kadi et al. 2013). The traditional methods consisted of repairing and cleaning granaries before conserving cereal grain and seeds. To control or repel storage insect pests, farmers used different tactics of mixing dried or fresh plant parts with commodities within granaries. Spiny fruit of *Cenchrus biflorus* Roxb., also is used on the pathway of rodents to prevent access into granaries.

In tropical regions, sun is a powerful and reliable source of energy, and simple technologies make use of this free resource (Langyintou et al. 2003). Appropriate exposure of kernels such as cowpea, *Vigna unguiculata* (L.) Walp., to sun can help increase temperature to kill most if not all life stages (eggs, larvae, and adults) of insect pests on and inside kernels (Mishili et al. 2011). A method developed at Purdue University used black plastic sheeting for drying grain in the sun. Natural heat from the sun is collected in a man-made prototype heater and used to increase the temperature of the grain to the thermal death point necessary to kill all stages of cowpea weevil, *Callosobruchus maculatus* (Fabricius) (Murdock et al. 2003, Mishili et al. 2011). Farmers commented on the extra labor required for solar disinfestation, compared to hermetic storage. Output is a simple but effective solarization technique that harnesses the power of sunlight to reduce the amount of pest damage of stored cowpea to acceptable amounts. Germination tests showed that grain stored for seed remained viable (Baributsa et al. 2012).

Chemical control. Damage to stored grain and grain products can range from 5-10% in temperate countries, but 20-30% in the tropical zone (Nakakita 1998). Managing infestation of stored grain is achieved primarily by using synthetic gaseous insecticides such as methyl bromide and phosphine. In several countries including India, mixing any synthetic insecticide with stored grain is not permitted. Because of environmental concerns and human health hazards, several chemical insecticides have either been banned or restricted for use (Subramanyam and Hagstrum 1995, Tapondjou et al. 2002). Because of resistance to insecticides, there is urgent need for more durable alternatives to conventional chemical insecticides especially from natural sources for protection of grain against infestation by insect pests. Considering all aspects of grain protection and problems, the urgent need to develop newer eco-friendly safer and effective stored-product insecticides was emphasized. Very successful and currently used synthetic pyrethroids were originally derived from the flowers of pyrethrum (Casida et al. 1975).

Use of chemical insecticides in the form of sprays, fumigants, or dusts against grain pests is common on large-scale farms. In some areas of Ethiopia (Tadesse and Eticha 2000), Benin (Hell et al. 2000), Cameroon (Nukenine et al. 2002), and Eritrea (Haile 2006), 70, 50, 23, and 12% of the farmers, respectively, treated their grain with synthetic insecticides. Kadi Kadi et al. (2013) reported that for chemical control of storage insect pests in Niger, all farmers surveyed used phostoxin (tablet) or actellic powder (2%). According to Wilbur and Mills (1985), after granaries and bins had been swept and old grain disposed of in preparation for reception of new grain, stored grain insects might remain in double walls, cracks and crevices, and chandelle tunnels. The insects cannot be reached by brooms or vacuums. The authors stated that if approved residual insecticide was sprayed on the walls and floor about 3 weeks before the new grain was added to the storage bin, many of the insects would emerge from their hiding places, walk to the treated area, and be exposed to a lethal amount of chemical.

Other types of insecticides used against stored-product insects are grain protectants that are formulations of chemicals having residual toxicity, repellent action, or both, that are applied directly to grain to prevent damage by grain-infesting insects. Stored-product insects vary considerably in susceptibility to insecticides. It sometimes is difficult to compare experimental results with the same insect because different methodologies and test conditions were used. However, some general trends can be discussed regarding the susceptibility of individual species (Arthur and Peckman 2006). *Tribolium* species are more difficult to kill with residual insecticide than are other stored-product beetles. Williams et al. (1983) stated that when organophosphorus and pyrethroid insecticides were applied to concrete, wood, or iron, the red flour beetle was less susceptible than either the lesser grain borer, *Rhyzopertha dominica* (Fabricius), or rice weevil on concrete or wood. Also, Arthur (1997) reported that the confused flour beetle was less susceptible than the lesser grain borer to deltamethrin dust. Variation between species, even closely related species, in susceptibility to insecticides emphasizes the importance of accurate identification of species and of selecting insecticides based on treatment strategies for target pests (Arthur and Peckman 2006).

Azadiraechtin, the active ingredient in the plant *Azadiraechta indica* (Indian neem), is an antifeedant and insect growth regulator but lacks contact toxicity (Isman et al. 1990, Islam and Talukder 2005). Currently, no botanical insecticide is available to replace pyrethrum for protection of stored grain against infestation by insect pests.

Bioinsecticides of plant origin often have selectivity against insect species, are biodegradable, have a good chance of acceptability and, therefore, plants could be the best source of newer chemical structures for development of new, eco-friendly, safer agents to control insect pests (Saxena et al. 1992).

Hermetically sealed bags. Hermetic storage has been used since ancient times for preservation of grain (De Lima 1990). The technology relies on creation of unfavorable storage atmospheres by one of three distinct forms of vacuum hermetic fumigation, gas hermetic fumigation, or bio-generated modified atmosphere (Anankware et al. 2012). Hermetic bags work on the principle that kernels release carbon dioxide that rapidly replaces the oxygen in the sealed container (Taruvinga et al. 2014). Once oxygen is exhausted, pests are killed, and fungi cannot spread. Hermetic bags work effectively and are suitable because they can be sealed airtight to ensure a stable condition suitable for maintenance of grain in storage. Villers et al. (2010) described recent evolution of pesticide-free post-harvest hermetic storage for dry commodities that now is used in 38 countries. The authors discussed and illustrated current application for storage of grain and other commodities. As a result of more than 10 years of extensive studies at the International Rice Research Institute (IRRI) (Rickman and Aquino 2004 and 2007) and PhilRice (Sabio et al. 2006), the benefits of storing rice and rice kernels in hermetic storage now are well understood and used widely, especially in Asia (Villers et al. 2006).

In Cameroon, on-farm tests validated the effectiveness of “triple plastic bagging” methodology, the Purdue Improved Cowpea Storage (PICS) bag (Murdock et al. (2003). The recommended procedure consists of filling a plastic bag with infested cowpea grain, tying the opening of the bag shut, enclosing the bag completely within a second bag, tightly securing that, then repeating the procedure using a third bag. The third bag was added as an insurance measure. The method is simple, uses readily available materials, and is low cost. Seck et al. (1996) said that the likely mechanism of triple plastic bagging involved oxygen depletion and increased amounts of carbon dioxide, as occurs with storage of grain in a sealed drum.

The Purdue Improved Crops Storage (PICS) method is based on a bio-generated modified atmosphere. It applies a two-layer envelope of ultra-thick (80-micron) high-density polyethylene liner inside an outer bag of woven polypropylene to create a low permeability seal (Murdock et al. 2003). Once the crop product is packed and the multilayer bag is closed, the amount of oxygen in the bag decreases drastically because of insect, fungal, and seed respiration, while the amount of carbon dioxide increases. The high-density polyethylene liner hinders exchange of gases between the stored product and environment, ensuring the modified atmosphere is sustained (Moreno-Martinez et al. 2000). When the amount of oxygen becomes sufficiently depleted, insects in the bag stop feeding, become inactive, and eventually die of asphyxiation.

Other hermetic storage methods include use of plastic containers such as volcanic cubes and grain cocoons, small containers of plastic or steel, or even clay water pots. The size of containers ranges from 25 liters to 300 metric tons (Gummert et al. 2004). The hermetic storage system can be used for rice paddy, milled rice, and other cereal crops such as maize. Hermetic storage preserves grain quality and seed viability by maintaining the original moisture content of the grain and reducing damage by pests. Once a container is hermetically sealed, the moisture content of the grain will be controlled. Seed viability of only 6 months can be increased to 12 months in topical environments. For maize seed, Moreno et al. (1988) found that at 14-14.5% moisture content, hermetic storage did not have a detrimental effect on seed germination.

Respiration by grain and insects inside a storage container change the inter-granular atmosphere by consuming oxygen and producing carbon dioxide. Sealed storage controls insect pests that use available oxygen during respiration and expire carbon dioxide (for example, amounts of oxygen can be reduced from 21% to less than 5% in 10-21 days (Murdock et al. 2003). With scarce oxygen, insect activity is minimal and reproduction ceases. Depending on the number of insects and type and size of the system, the amount of oxygen will be reduced from 21% to less than 10% within a short period of time. At an oxygen level <10%, insects are curtailed, and viability of grain is ensured. Because it minimizes biological activity inside the storage container, hermetic storage also helps maintain milling quality (Gummert et al. 2004). Rodents and birds also are not attracted to grain in storage containers, possibly because they are unable to smell the grain.

Botanical insecticides. Plants with insecticidal properties, commonly referred to as botanicals, have been used traditionally for generations throughout the world. Botanical pesticides are naturally occurring chemicals extracted from plants (Regnault-Roger et al. 2005, Regnault-Roger and Philogène 2008). Botanical products are available as an alternative to synthetic chemical insecticides, but are not necessarily less toxic to humans. Some of the most deadly, fast-acting toxins and potent carcinogens occur naturally Botanicals, because of their usually low toxicity, show undesirable effects on the environment and non-target organisms (Grainge and Ahmed 1986) compared with many conventional insecticides. If applied even in very low quantities, biochemicals efficiently reduce abundance of pests.

Botanicals are characterized favorably for low acute toxicity and ready dissipation in nature (Soloway 1976). They can be used in low quantity to prepare combined insecticidal formulations for controlling pests in storage. Botanical treatments are especially relevant during post-harvest storage of commodities by small-scale farmers (Proctor 1994, Dales 1996). In developing countries, botanicals have advantages over synthetic pesticides because they are collected locally and can provide inexpensive pest control during storage. Botanicals are one of the most important locally available, biodegradable, and inexpensive methods for controlling stored-grain pests (Mishra et al. 2012a, b). The main advantage of botanicals is that they are produced easily by farmers and small-scale industries and are potentially less expensive (Nikkon et al. 2009).

Utilization of botanical insecticides to protect stored products is promising, mostly because of the possibility of improving environmental conditions inside storage units and maximizing the insecticidal effect (Guzzo et al. 2006). The natural botanical product can be used as powder, extract, or oil in storage facilities. Moreover, use of plant materials to protect grain in storage is sustainable; the plants can be continuously propagated year after year. Botanicals are biodegradable, and do not have a negative impact on the environment if care is taken to avoid propagation of plants from foreign ecosystems that might become established as weeds. Nevertheless, many plants commonly regarded as safe contain noxious compounds that might render them unsafe for animals and humans to consume (Golob et al. 1999, Suthisut et al. 2011). These are biodegradable and impose low residue risks to food crops, drinking water, soil flora and fauna (Manasaray 2000, Ottaway 2001).

In Niger, a survey of farmers to assess their knowledge of storage pests and control methods revealed the farmers used eight plants with insecticidal effects as alternatives to synthetic insecticides (Kadi Kadi et al. 2013). Many botanicals, with few exceptions, are very toxic to insects but less or moderately toxic to mammals (Soloway 1976). If used with natural diet or used by applying any control method, botanical insecticides primarily cause harmful effects to insect pests and do less harm to beneficial insects. Hence, naturally occurring insecticides are characterized favorably for low toxicity to non-target organisms and ready dissipation naturally. Bioorganic products can be used in poison baits to minimize human exposure and health risks.

Cost-Benefit Analysis of Using Low-Cost Hermetic Storage Methods to Control Storage Insect Pests of Sorghum Grain

Post-harvest loss is an often-forgotten factor that exacerbates food insecurity in developing countries (World Bank 2011). Post-harvest loss can and does occur all along the chain from farm to fork, which reduces real income for all consumers. This especially affects poor people because a large percentage of disposable income is spent to purchase staple foods. Interest in reducing post-harvest losses is not new. In 1975, the United Nations brought post-harvest storage losses into international focus when it declared that “further reduction of postharvest food losses in developing countries should be undertaken as a matter of priority” (FAO 1980). Less food loss improves food security by increasing real income for all consumers (World Bank 2011). In addition, crop production contributes a significant proportion of typical income in certain regions of the world (70% in Sub-Saharan Africa), and reducing food loss can directly increase the real income of producers.

According to the World Bank (2011), the primary role of an effective post-harvest system is ensuring that harvested products reach the consumer while fulfilling market/ consumer expectations in terms of volume, quality, and transaction attributes, including nutrition, food security, and product safety. Once harvested, products are subject to a biological deterioration rate influenced by factors and practices that increase product exposure along the chain, including extreme temperatures, excessive rainfall, contamination by microorganisms, mechanical damage, and contamination by chemicals. Storage is important to food security in developing countries. This is especially important because most cereals, including sorghum, are produced on a seasonal basis; the only harvest per year might fail to yield (Proctor 1994). Seasonal production leads to fluctuating supplies at international, regional, national, and household levels. Storage helps even out fluctuations in market supply, both from one season to the next and from 1 year to the next.

During storage, beetle and moth pests destroy an average of 5-35% of stored grain worldwide, but stored-product pests destroy 40% or more in developing countries of the tropics and subtropics (Schulten 1975). Post-harvest losses of cereals such as sorghum and pearl millet are a major problem throughout West Africa. In Niger, a survey evaluated sorghum and millet storage facilities, pests, and controls (Kadi Kadi 2009). Results indicated that farmers identified the major pests that include six species of storage insect pests, rats, mice, birds, mold, and humidity (INTSORMIL 2012). During conservation and storage, solutions to eliminate major pests of stored grain and seeds were mostly chemicals (with misuse).

Because pesticides can poison non-target organisms, pollute the environment, and result in development and selection of resistant strains of insect pests, alternatives are needed. Farmers also use traditional methods alternatively or in combination with pesticides to protect stored grain. Farmers use inert substances (ash, sand, and salt) and plant parts to manage insect pests of stored sorghum and millet (INTSORMIL 2012, Kadi Kadi et al. 2013). Storage technologies included actellic super (a mixture of 1.6% pirimiphos-methyl and 0.3% permethrin), multiple-layer hermetic bagging, and botanical products from plants to control storage insects.

Hermetic storage techniques have been used in many locations around the world. Plastic bags (Villers et al. 2010, Yakubu et al. 2011) and steel drums (Murdock et al. 1997) have been used extensively to hermetically store cowpeas and other products in Africa. Both containers can be effective in preventing damage by insect pests during storage. Plastic bagging can protect grain in one to three layers of polyethylene protected by an exterior woven bag. Purdue Improved Cowpea Storage (PICS) bags (Purdue 2019) and GrainPro bags (GrainPro 2016) now are used in developing countries. However, they are not effective against rodents, and some insects can bore through the bags, rendering them ineffective for hermetic storage. A steel drum is rodent-proof and has a long life, but costs more initially. Based on initial costs and projected useful life, estimated annual storage costs $20 per megagram for a plastic bag and $16 per megagram for a steel drum (Moussa et al. 2011). Thus, a steel drum might be a more effective strategy for long-term storage.

Very little research has been done on economics of grain storage and conditioning. Most literature on the topic involves marketing considerations and calculation of the carrying cost. Anderson (1988) referenced the opportunity cost of grain storage as the grain price multiplied by the interest rate and the storage time. Anderson et al. (1995) noted that the one primary reason for storing grain was to increase net return. Unless the market produces enough to cover storage costs, even best management practices will result in net loss. There is need for cost-benefit analysis of hermetic storage methods for controlling storage insect pests before recommending the methods for greater use at the farm level and to other end-users. In developing countries, resources are scarce and planners must decide their optimum use. Therefore, economic appraisal of a project is vital to assess its usefulness from the broader framework of the economy of a country (Shukla 1997).

Boardman et al. (2006) defined cost-benefit analysis as a policy (project) assessment method that attempts or purports to quantify in monetary terms the value of all consequences of a policy to all members of society. In simple terms, cost-benefit analysis can be a tool for analyzing alternatives in decision making. According to Price (1989) cited by Shukla (1997), cost-benefit analysis is used primarily to appraise projects. Cost-benefit analysis is defined as "an economic appraisal of the costs and benefits of alternative courses of action, whether those costs and benefits are marketed or not, to whomsoever they accrue, both in present and future time, the costs and benefits being measured as far as possible in a common unit of value." Cost-benefit analysis supports a comprehensive model to provide a rational choice for decision makers. The basic concept of rational choice is action that will be taken to provide greater benefits compared to costs (Pearce 1983). Good decision making about complex issues requires good analysis. Through analysis, decision makers can develop options and make decisions (Bridgman and Davis 1998). Among many tools, cost-benefit analysis is one that can be used to assist the decision-making process. Cost-benefit analysis is an example of rational analysis and reduces the chance that an important option will be overlooked. It supports the wider search for options, rather than extensive search for only a few options (Klein 1998). As noted by Price (1988) cited by Shukla (1997), the selection of a suitable discount rate is an issue in applying cost-benefit analysis for appraisal of projects because effects more than anything else determine the viability and profitability of projects.

Additional assessment of project attractiveness when analyzing economics is using sensitivity analysis to identify comparative advantages of new technologies rather than the commonly used method. Sensitivity analysis is the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in input to the model. It is considered by some as a prerequisite for building models in any setting, whether diagnostic or prognostic, and in any field where models are used (Saltelli 2002).

In addition to studies to assess efficacy of botanicals to control storage insect pests as alternatives to insecticides, the research evaluated the costs and benefits of using hermetic storage methods as compared to common polypropylene bags. Cost-benefit analysis determined the Net Present Value and Benefit-Cost Ratio that will make any better alternative hermetic storage method a viable option in which to invest.

CHAPTER III

MATERIALS AND METHODS

Monitoring Occurrence and Diversity of Storage Insect Pests of Sorghum Grain in Niger

Sorghum grains infested with storage pests were collected from storage facilities - 'Grinkan' sorghum at Bengou (11° 98' N; 3° 60' E) and 'SSD-35' and 'Mota Maradi' at Konni (11° 79' N; 5° 25' E) in Niger (West Africa). Two samples of "red" and "white" sorghum were purchased from cereal markets at Niamey (13° 51' N; 2° 12' E), Niger. A sample of 200 g of sorghum grain of each variety (treatment) was replicated four times in a completely randomized block design. Samples of each kind of sorghum were sieved through a size-10 sieve (0.2-cm aperture) that is commonly used for small grains. A light-colored surface and strong light (40- or 60-watt bulb) were used to examine insect pests in sorghum grain that was sieved. Heat and light from the light bulb caused any live insects to move, making detection easier. A plastic plate containing sieved adults was put into a chilling bucket containing ice to help cool the adults for easy counting.

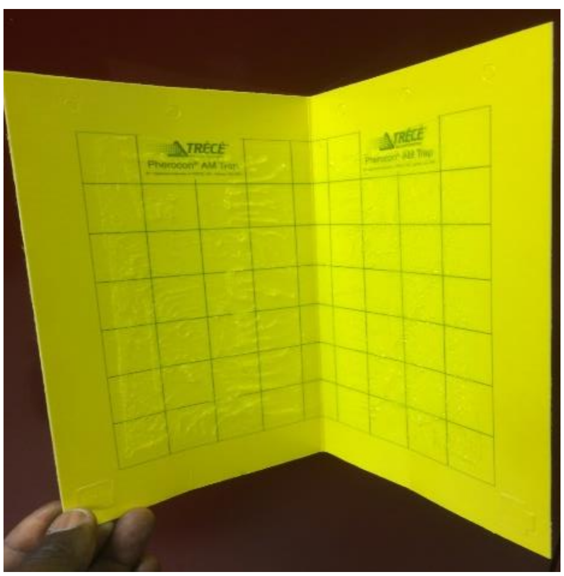
Data were recorded weekly for 1 month, and storage insect species found were counted, removed, and identified. Identification was made possible using keys to families of insects by Delvare and Aberlenc (1989) and Rees (2004), an identification handbook of sorghum insect pests (Teetes et al. 1983), and an identification key for insects of stored products in the Sub-Saharan region by Delobel and Tran (1993).

In a second experiment, three traps - sticky glue, water bottle, and 'Dome' pheromone (Fig. 1) were used to determine the diversity of storage insect pests in storage facilities. A trap made from a simple water bottle (0.5 liter) with holes (4 x 4 cm) pierced on two sides was placed in a storage facility to capture storage insect pests in the grain. The humidity around the bottle and the need for the insect pests to come close to the trap made them fall into the trap. A sticky glue trap was made of yellow paper (23 x 28 cm; Pherocon AM no-bait trap, Trécé Inc., Adair, OK) with the inner surface coated with Tanglefoot® Tangle-trap® insect-trapping adhesive. The sticky glue traps were placed in storage facilities to capture flying storage insects. 'Dome' pheromone traps (Storgard®, Trécé Inc., Adair, OK) are circular with an interior diameter of 10.5 cm and an exterior cover (11.5-cm diameter) and baited with pheromone. The 'Dome" traps lure and trap more than 25 species of storage insects when placed under wooden pallets or supports.

The traps were arranged in and around storage facilities. The experiment was a completely randomized block with three treatments (traps) and blocks (storage facilities), with four replications. The traps were placed at least 10 m apart in a storage facility. The species of storage insects trapped were recorded. All species were identified by using the keys and taxonomic handbooks described previously.

Data from sieving and trapping were compiled and analyzed using SAS (SAS Institute 2018) to calculate mean numbers of storage insect species per sorghum variety and kind of trap. Microsoft Excel (2013) was used to graph the means of each species by sorghum variety and kind of trap.

a.



b.

c.

Fig. 1. Traps tested to capture insect pests in stored sorghum grain: a) 'Dome' pheromone trap, b) sticky glue trap, and c) water bottle trap.

Assessing Efficacy of Botanicals to Control Red Flour Beetles in Stored Sorghum Grain

The experiment was done at Centre Régional de la Recherche Agronomique (CERRA) of Institut National de la Recherche Agronomique du Niger (INRAN) at Niamey. Conditions in the laboratory were room temperature (28-30^{0}C) and 70 ± 5% relative humidity.

Red flour beetles were collected initially from infested Grinkan sorghum grain sampled at Bengou research station in Niger. Beetle adults were reared in four 0.95-liter glass jars in a laboratory. The top of each jar was covered by a piece of organdy cloth screwed over the top by a metal rim. Rearing helped ensure that enough newly emerged beetle adults were available to infest sorghum kernels treated with botanical powder. Rearing jars were kept on a shelf in the laboratory, and water was added frequently to maintain humidity at 70%. Sorghum kernels were added regularly to each jar to ensure enough food was available for the beetles to survive.

Leaves, kernels, fruit pulp, and pericarp of four plants known to have some natural toxicity were collected and/or purchased at markets at Niamey, Niger. Plant parts were washed with distilled water, allowed to dry at room temperature, and blended to fine powder by using an Oster® blender at 1,000 watts. Powders were stored in sealed polyethylene bags to prevent loss of quality.

Botanicals tested were neem kernel, *Azadirachta indica* A. Juss; African locust bean fruit pulp, Pa*rkia biglobosa* Jacq. Benth; hibiscus fruit pericarp, *Hibiscus sabdariffa* L.; and baobab fruit pulp, *Adansonia digitata* L. (Table 1). The experimental design was completely randomized, with four replications of each plant powder and a check. Powder

Table 1. Botanicals Evaluated for Efficacy to Control Insect Pests in Stored Sorghum Grain

<table>
<tr><th>Common name</th><th>Scientific name and author</th><th>Family</th><th>Part used</th><th>Tested against</th></tr>
<tr><td>Neem</td><td>Azadirachta indica A. Juss</td><td>Meliaceae</td><td>kernel</td><td rowspan="4">Red flour beetle, Tribolium castaneum Herbst</td></tr>
<tr><td>African locust bean</td><td>Parkia biglobosa Jacq. Benth</td><td>Fabaceae</td><td>fruit pulp</td></tr>
<tr><td>Hibiscus</td><td>Hibiscus sabdariffa L.</td><td>Meliaceae</td><td>fruit pericarp</td></tr>
<tr><td>Baobab</td><td>Adansonia digitata L.</td><td>Malvaceae</td><td>fruit pulp</td></tr>
<tr><td>Neem</td><td>Azadirachta indica A. Juss</td><td>Meliaceae</td><td>bark</td><td rowspan="3">Maize weevil, Sitophilus zeamais Motchulsky</td></tr>
<tr><td>Mesquite</td><td>Prosopis glandulosa J. Torrey</td><td>Fabaceae</td><td>bean pod</td></tr>
<tr><td>Milkweed</td><td>Asclepias speciosa J. Torrey</td><td>Apocynaceae</td><td>leaves</td></tr>
</table>

of each botanical at five doses of 0.0125, 0.025, 0.05, 0.1, and 0.2 g were individually mixed with 5 g of ‘SSD-35’ sorghum kernels and put into small, clear-plastic cups (3-cm bottom width x 5-cm diameter x 7-cm height). Additional cups with no plant powder were prepared as checks. Each cup containing treated sorghum kernels and beetles was closed with a small piece of organdy cloth affixed over the top of the cup by a rubber band. During manipulation of live red flour beetles, a large bucket containing ice was used to cool the rearing jar to make the beetles immobile and easy to transfer into the cups.

Five newly emerged red flour beetle adults (2 ♂:3 ♀) were put into each plastic cup containing sorghum kernels treated with botanical powder. Dead adults were counted every 7 days for 35 days, and cumulative numbers of dead beetles were recorded. At the end of the experiment, red flour beetles and sorghum kernels were poured into Petri dishes on ice to collect and record numbers of dead and live adult beetles. A small camel-hair bush was used to separate the beetles from the kernels. Kernels were put into a Petri dish and examined with the aid of a dissecting microscope to score and record damage to kernels treated with each dose of botanical. A scale of 1 to 5 was used to assess damage by red flour beetles to sorghum kernels, where 1 = no damage to kernels, 2 = 1-25% damaged kernels showing some feeding such as one hole on the surface but not all the way through the kernel, 3 = 26-50% damaged kernels with two tunnels through the kernel, 4 = 51-75% damaged kernels and/or with more than two tunnels, and 5 = 76-100% damage with many feeding tunnels in the kernels.

Data recorded (number of dead adults, cumulative number of dead adults, and damage score) were subjected to statistical analysis of variance (ANOVA). Mean numbers of insects counted were analyzed using PROC Mixed of SAS (SAS Institute 2018). Numbers of dead weevil adults and damage scores were transformed to log-base 10 before analysis (Sokal and Rohf 1995) to reduce variance. Means were transformed back before being reported. Means were separated and compared by using least significant difference (LSD) to assess significant differences among treatments and doses at a 5% level of significance.

Assessing Efficacy of Botanicals to Control Maize Weevils in Stored Sorghum Grain

The experiment was done at room temperature (27-28^{0}C), 70 ± 5% relative humidity, and a photoperiod of 14:10 light:dark hours at the Entomology Laboratory at West Texas A&M University, Canyon (34° 98’ N; -101° 92’ E), Texas. The powders (leaves and/or bark) of plants known to have some natural toxicity were purchased from commercial botanical gardens through the Internet. The powders were stored in polyethylene bags sealed to prevent quality loss.

A colony of maize weevil adults was maintained in multiple 0.95-liter glass jars in the laboratory. The rearing procedure used the same process described for red flour beetles in previous experiments. Rearing helped ensure enough newly emerged weevil adults were available for use in all experiments in the laboratory. Rearing jars were kept in a plastic cage (Bug Dorm, BioQuip Products, Rancho Dominguez, CA) in the laboratory, with water added to maintain humidity at about 70%. Popcorn kernels were added regularly to each jar to ensure enough food was available for weevils to survive.

To obtain live maize weevils for infestation, the contents of a rearing jar were poured into a sieve that allowed the weevils to pass through the holes in the sieve. Adults from the sieve were collected in a plastic bucket set on a chilling table (Chill Table #1431, BioQuip Products, Rancho Dominguez, CA) that cooled the weevils, preventing them from flying away. The chilled weevils were immobile for easy transfer into Petri dishes.

In the experiment, four treatments were a check (no plant material) and powder of three botanicals (neem bark, mesquite, and milkweed) (Table 1). The experiment was a completely randomized design with four replications of each plant powder, and a check. Eight unsexed newly emerged maize weevil adults from the colony were released into each Petri dish (10-cm diameter x 1.5-cm height) containing 5 g of 'Malisor-84' sorghum grain treated with powder of a botanical at one of the three doses of 0.05, 0.1, or 0.2 g. An additional Petri dish for a check was prepared with no plant powder. Each covered Petri dish containing treated sorghum kernels and weevil adults was closed securely with a rubber band.

Numbers of dead weevils in the presence or absence of botanicals were counted every 2 days for a total of 18 days, and the cumulative numbers of dead weevils were recorded. At the end of the experiment, a small camel-hair bush was used to separate weevil adults from the sorghum kernels. Maize weevils and sorghum kernels in Petri dishes were put onto ice to immobilize and collect then record live and dead adults. Kernels were put into a separate Petri dish and examined with the aid of a dissecting microscope to score damage for each botanical and dose tested. Damage was scored on a 1 to 5 scale as described for the experiment on efficacy of botanicals against *T. castaneum*. Other data recorded included the number and weight of damaged grains and the number and weight of nondamaged grains. The number of adult weevils that died in each replication was expressed as a percentage of the initial total number of adult weevils.

Abbott's (1925) correction formula was used to calculate mortality by using Equation 1:

$$CM\% = \frac{(\%T - \%C)}{(100 - \%C)} \times 100 \qquad (1)$$

where CM is corrected mortality, T is mortality in treated sorghum grain, and C is the number of dead weevils in the check (not treated).

Grain damaged expressed as a percentage was the ratio of the total number of damaged grains per the total number of grains used in each replication and was computed using Equation 2:

$$GD\% = \frac{\text{Number of damaged grains}}{\text{Total number of grains}} \times 100 \qquad (2)$$

Grain weight loss was calculated using the count and weight method of Gwinner et al. (1996) as expressed in Equation 3:

$$WL\% = \frac{(Wu * Nd) - (Wd * Nu)}{(Wu * (Nd + Nu)} \times 100 \qquad (3)$$

where Wu = weight of nondamaged grains, Wd = weight of damaged grains, Nu = number of nondamaged grains, and Nd = number of damaged grains.

Before statistical analysis, the data for the number of dead adults over time, and damage scores were log-10 transformed to reduce variance. Means and SE were transformed back before reporting. Percentage of mortality, percentage of damaged grains, and percentage of grain weight loss were not transformed before analysis.

Correlation analysis at a 1% level of significance was used to determine relationships between the variables. Regression (Probit) analysis of data for numbers of dead weevil adults compared to the check was used to determine different lethal doses of the botanicals evaluated.

All data collected and/or computed (numbers of dead weevils by time, cumulative numbers of dead weevils, damage score of sorghum grains, corrected mortality of weevils, percentage of grains damaged, and percentage of grain weight loss) were analyzed by analysis of variance (ANOVA). PROC Mixed of SAS (SAS Institute 2018) was used for ANOVA. When significant differences were found between treatments and doses, means were separated by using Tukey's Studentized Test at a 5% level of significance. Means for treatments and doses were compared for each variable by time.

Evaluating Hermetic Storage Methods to Control Storage Insect Pests of Sorghum

Five hermetic storage methods were evaluated in a laboratory at CERRA Kollo (13° 18' N; 2° 18' E) in Niger (West Africa). The experimental design was completely randomized with five replications of each treatment. With each treatment, 200 g of Grinkan sorghum was used. Treatments were a woven polypropylene bag (check) commonly used during storage in Niger; 25-µ polyethylene bag; 15 x 20 x 30-cm clear-plastic bucket; double bag consisting of one 80-µ bag of high-density polypropylene fitted inside a polypropylene bag; and triple bag consisting of two 80-µ high-density polyethylene bags fitted inside a polypropylene bag. Each bag (polypropylene, polyethylene, double, or triple bag) were 0.6 x 0.5 cm to accommodate the quantity of sorghum grain used in the experiments, easily handle the contents (sorghum grain and live weevils) in the bags, and record data. A step-by-step process of how-to-use PICS technology (Purdue n.d.) to tie the bags was adopted to hermetically seal the bags in the treatments and ensure airtight storage.

To infest sorghum grain in the bags, adults and larvae were obtained from the same colony reared for the botanical study as described previously. Using the same procedure and steps to rear red flour beetles and maize weevils, a colony of rice moths (*C. cephalonica*) was maintained in the laboratory.

Five newly emerged *T. castaneum* adults were put with sorghum grain in a container. In another experiment, five newly emerged larvae of *C. cephalonica* were put with sorghum grain in a container. Red flour beetles and rice moths were the dominant insects found infesting sorghum grain at different storage facilities in Niger (Kadi Kadi and Pendleton 2017). Sequential counts of dead adults were recorded every 7 days for 35 days; dead and live adults were counted until the end of the experiment. Grain weight was recorded for each treatment, and data were used to compute the percentage of weight loss caused by red flour beetles.

Data recorded were subjected to analysis of variance (ANOVA), and mean numbers of insects were compared using PROC Mixed of SAS (SAS Institute 2018). The numbers of insects were transformed to log-base 10 to reduce variance before analysis (Sokal and Rohf 1995). When significant differences were found among treatments and doses, means were separated by using least significant difference (LSD) at a 5% level of significance. Hermetic methods were compared to each other and to the check, so efficacy could be determined.

Cost-Benefit Analysis of Using Low-Cost Hermetic Storage Methods to Control Storage Insect Pests of Sorghum Grain

An experiment was done at the farm station at INRAN/CERRA Kollo, Niger. Four treatments were a polyethylene bag, double bag, triple bag, and a woven polypropylene bag as a check. A polypropylene bag was used as the check because it is the common storage bag used by farmers, traders, and medium- and large-sized facilities for storing grain in Niger. The size of the bags was the same as the ones used in the previous experiment. Live *T. castaneum* adults were obtained from a colony reared in the laboratory. Live red flour beetles were handled according to the procedures and steps described in the previous studies of botanicals and hermetic storage.

The experiment was a completely randomized design with five replications of each treatment. For each treatment, 200 g of Grinkan sorghum was used. Sorghum grains in the bags were artificially infested with five newly emerged red four beetles.

Microsoft® Excel Spreadsheet was used to calculate means of different variables for the cost-benefit analysis study. Data on grain weight loss were collected for 3 months, and the experiment ended when some treatments were severely infested and stored grains were not withstanding damage by storage insects or heat conditions in the laboratory. For each treatment, the percentage of grain weight loss was calculated by using initial and ending weights during a period of 6 months.

Using SAS (SAS Institute 2018), simple linear regression analysis was used to assess the interactive effect of treatment over time on weight of sorghum grain to obtain Equation 4:

$$\%L_t = \beta_2 t + u_t \tag{4}$$

where $\%L_t$ = average grain weight loss over time t, β_2 = regression coefficient/slope coefficient, t = time variable (month), and u = error term.

For each treatment, the previous analysis helped determine the percentage of grain weight loss per month as expressed by the regression coefficient/slope coefficient during time. The equations were expected to indicate a linear trend of weight loss during time.

For the hermetic storage methods, benefits and costs were calculated as the loss abated compared to that in a polypropylene bag (check). Incremental costs and benefits were calculated based on a method to store 1 ton of Grinkan sorghum grain for 1 year. Grinkan sorghum is a certified variety produced by INRAN and sold to private seed producers and farmers who can afford to buy the seeds. The estimated cost (production, storage, and marketing) of 1 ton of Grinkan sorghum grain was $3,466.20 (1 kg sells for $3.47 and an exchange rate of West African Franc CFA (Communauté Financière Africaine) to dollar estimated at 577 to 1).

Measures of project worth, the Net Present Value (NPV) and Benefit-Cost Ratio (BCR), were used to analyze benefits expected from investing in hermetic bagging methods at a given discount rate for a projected investment period. For discounting costs and benefits of hermetic storage methods, Net Present Value and Benefit-Cost Ratio were used as the basis to compare benefits of investing in each hermetic storage method for attractiveness or not for future decisions. The Net Present Value is the current value of all net benefits of the project. The value of net benefits during any period is the benefit (B) minus the cost (C). According to Gittinger (1982) cited by Shively (2012), to calculate discounted values of each, Net Present Value can be computed by using Equation 5, and Benefit-Cost Ratio can be calculated using Equation 6:

$$NPV = \sum_{t=0}^{T} \frac{(Bt - C_t)}{(1+r)^t} \quad (5)$$

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \quad (6)$$

where *Bt* is benefit at time *t*, *Ct* is the measure of costs at time *t*, and *r* is the discount rate.

A discount rate of 4.5% obtained from BCEAO (Central Bank of West African States) was used. It is the average discount rate applicable for change in consumer price index. A model for discounting costs and benefits was developed using Microsoft® Excel Spreadsheet as presented in Table 2. The model was used to determine the Net Present Value and Benefit-Cost Ratio of each hermetic storage method. After inputting the variables into the model, Net Present Value and Benefit-Cost Ratio were calculated with Excel built-in formulas 1 and 2 in corresponding cells C6 and C8.

NPV = C12 = +NPV(discount rate,D10:M10)+C10

= +NPV(C16,D10:M10)+C10 (1)

BCR = C14 = +NPV(discount rate,D9:M9)/(NPV(discount rate,D8:M8)+C8)

= +NPV(C16,D9:M9)/(NPV(C16,D2:M8)+C8) (2)

The same formulas were used to calculate Net Present Value and Benefit-Cost Ratio by varying the benefits and costs in appropriate cells for double bagging and triple bagging hermetic storage methods.

Sensitivity analysis was done using three discount rates (4.5, 6.5 and 8.5%) for Benefit-Cost Ratio with varying 2-year increments during 10 years of investment. For computation of Benefit-Cost Ratio, at the discounted rates and during the periods chosen, a sensitivity analysis model (Table 3) was developed using Microsoft® Excel

Table 2. Model of Cost-Benefit Analysis for Discounting Benefits at 4.5% for the Hermetic Polyethylene Bag Storage Method Tested for Production, Storage and Sale of Grinkan Sorghum Seeds in Niger

A	B	C	D	E	F	G	H	I	J	K	L	M
7	year	0	1	2	3	4	5	6	7	8	9	10
8	Total costs	550	3149.16	3149.16	3149.16	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2
9	Total benefits		3734.12	3734.12	3734.12	3734.12	3734.12	3734.12	3734.12	3734.12	3734.12	3734.12
10	Cash-flow (Benefit-cost)	-550	585	585	585	585	585	585	585	585	585	585
11												
12	NPV	4078.62										
13												
14	BCR	1.19										
15												
16	Discount rate	4.5%										

Table 3. Model for Sensitivity Analysis of Benefit-Cost Ratio for Polyethylene Bagging of Grinkan Sorghum Seeds Produced, Stored and Sold in Niger

A	B	C (Changing variables)	D	E	F	G	H	I	J	K	L	M	N	O	P
7	Farming tools	250		year	0	1	2	3	4	5	6	7	8	9	10
8	Irrigation equipment	300		Total costs	550	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2	3149.2
9	Salary (part-time)	1525.12		Farming tools	250										
10	Land preparation	208		Irrigation equipment	300										
11	Farm inputs	570.2		Salary (part-time)		1525.12	1525.12	1525.12	1525.12	1525.12	1525.12	1525.12	1525.12	1525.12	1525.12
12	Field laborers	668.8		Land preparation		208	208	208	208	208	208	208	208	208	208
13	Cost of bags	15		Farm inputs		570.2	570.2	570.2	570.2	570.2	570.2	570.2	570.2	570.2	570.2
14	Other storage costs	`100.52		Field laborers		668.8	668.8	668.8	668.8	668.8	668.8	668.8	668.8	668.8	668.8
15	Additional costs	148.61		Cost of 30 bags ($1.30/bag)		15	15	15	15	15	15	15	15	15	15
16	Seed sold (year 1)	0.908		Additional storage costs		100.52	100.52	100.52	100.52	100.52	100.52	100.52	100.52	100.52	100.52
17	Seeds sold (year 2)	0.908		Other costs		148.61	148.61	148.61	148.61	148.61	148.61	148.61	148.61	148.61	148.61
18	Seeds sold (year 3-10)	0.908		Total benefits	0	3745.7096	3745.7096	3745.7096	3745.7096	3745.7096	3745.7096	3745.7096	3745.7096	3745.7096	3745.7096
19	Seed price (USD/t)	3466.2		Value ($) of seeds sold		3147.3096	3147.3096	3147.3096	3147.3096	3147.3096	3147.3096	3147.3096	3147.3096	3147.3096	3147.3096
20	Tax	598.4		Tax		598.4	598.4	598.4	598.4	598.4	598.4	598.4	598.4	598.4	598.4
21	Discount rate	4.5%		Cash-flow (Benefit-cost)	-550	596.5096	596.5096	596.5096	596.5096	596.5096	596.5096	596.5096	596.5096	596.5096	596.5096
22				NPV (4.5%)	4170.01										
23				BCR	1.18942										

Spreadsheet. After inputting the variables into the model, Net Present Value and Benefit-Cost Ratio were calculated with the Excel built-in formulas 3 and 4 in the model.

F22 = NPV (4.5%) = +NPV(discount rate,G20:P20)+F20

= +NPV(C20,G20:P20)+F20 (3)

F23 = BCR = +NPV(discount rate, G17:P17)/(NPV(C20,G8:P8)+F8)

= +NPV(C20, G18:P18)/(NPV(C20,G8:P8)+F8) (4)

The same formulas were used to calculate Net Present Value and Benefit-Cost Ratio for double bagging and triple bagging hermetic storage methods by varying the benefits and costs with the syntaxes in appropriate cells.

CHAPTER IV

RESULTS AND DISCUSSION

Monitoring Occurrence and Diversity of Storage Insect Pests of Sorghum Grain in Niger

Occurrence of insect pests in stored sorghum grain. Results of monitoring by sieving infested sorghum kernels for insect pests commonly found in stored products in Niger are shown in Fig. 2. Red flour beetle was the dominant pest in all sorghum varieties sieved. Means of 16.9, 15.2, and 14.9 beetles per 200 g were found in kernels of SSD-35, Mota Maradi, and Grinkan. These improved sorghum varieties are grown for resistance to sorghum midge or for large yields. About 12.6 and 7.9 *T. castaneum* adults were found in sorghums with white and red kernels sold in local markets. Means of three or four *T. confusum* adults were counted per 200 g of each of the three sorghum varieties, with the greatest mean of four beetles in Grinkan sorghum. No *T. confusum* adults were found in the white sorghum or the red sorghum.

Means of 1.9 (Grinkan) and 5.1 (SSD-35 and Mota Maradi) adult rice moths per 200 g were found only in the three improved varieties (Fig. 2). Means of 9.9, 8.4, and 8.1 *S. cerealella*, *T. granarium*, and *R. dominica*, respectively, were in 200 g of red sorghum, and 9.9 *S. cerealella* and 4.4 each of *T. granarium* and *R. dominica* adults were in white sorghum. As many as 10 *R. dominica* were in Mota Maradi. *S. cerealella* was the only species in the two local red and white sorghums but not in the improved varieties.

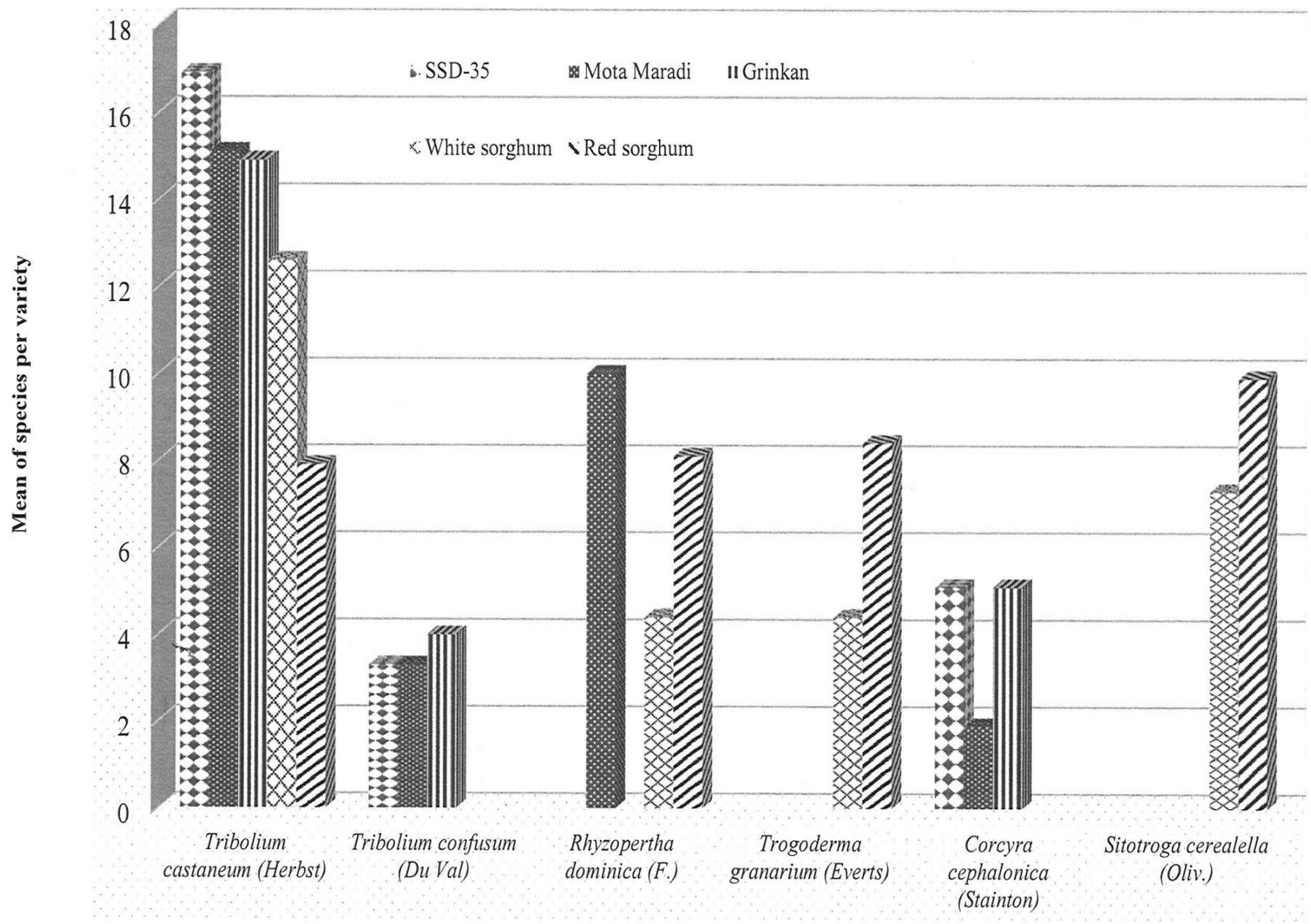


Fig. 2. Mean numbers of storage insects in 200 g of grain of different sorghum varieties, Niamey, Niger.

Six species of storage insects recorded in the study were identified previously by farmers as the eight major insect pests of stored grain in Niger (Kadi Kadi et al. 2013). Of the six species, four were weevils and beetles (Coleoptera) and two were moths (Lepidoptera). Farmers mentioned that infestation by these insect species in stored products reduced grain quantity and quality.

Sieving infested sorghum grain helped monitor and record six storage insect pests. According to Wakefield (2008), stored grain is at risk for infestation by a range of insects and mites. Effective detection of pests is essential for protecting harvested crops, indicating if control is necessary, and once implemented, whether control has been successful. Sieving is commonly used to separate grains from insect pests and residue of damaged grains. It can be labor intensive and costly if large amounts need to be sieved to clean the grain. Therefore, it cannot be recommended as a method to use to assess the amount of infestation in a storage facility, but can be used to monitor the presence of storage insect pests so appropriate measures can be taken to reduce grain loss.

Diversity of storage insect species. Three traps used to monitor and detect diversity of storage insects captured 10 species (Fig. 3). Ten species of storage insects were captured in the 'Dome' Pheromone trap. The largest mean numbers of 12.9, 10.0, and 6.0 *T. castaneum*, *S. cerealella*, and *S. oryzae* adults, respectively, were trapped in the 'Dome' Pheromone trap. Mean numbers ranged from 0.6-3.6 individuals of other species trapped in the 'Dome' Pheromone trap. Seven species were caught in the sticky glue trap, with means of 8.8 each of *S. cerealella* and *T. confusum*, and 7.3 *T. castaneum* adults. Only six species were caught in the water bottle trap, with 5.4, 5.3, 5.1, and 4.9 *T.*

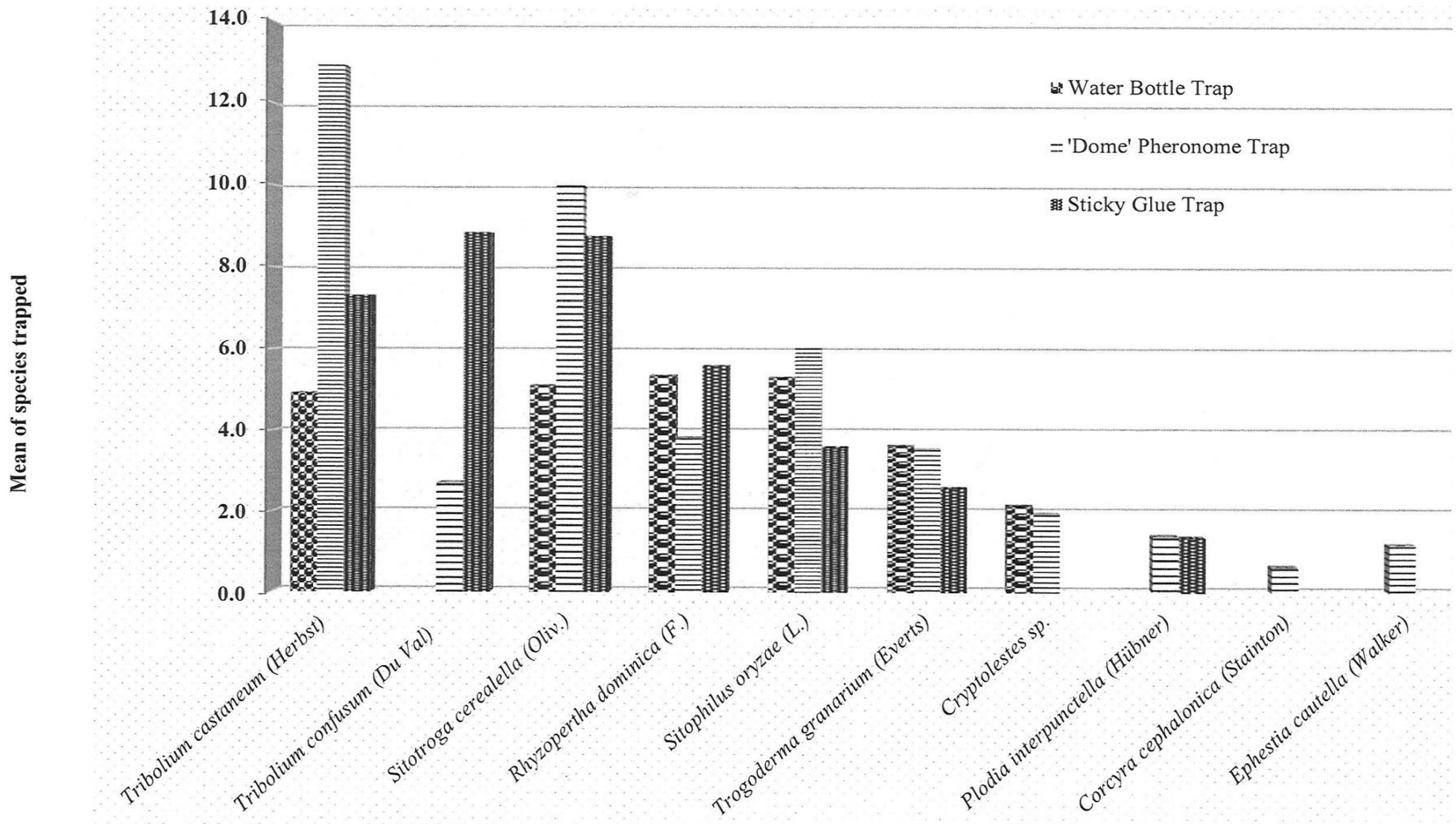


Fig. 3. Mean numbers of storage insect pests caught in different kinds of traps, Niamey, Niger.

castaneum, *R. dominica*, *S. cerealella*, and *S. oryzae* adults, respectively. No lepidopteran pests were collected in the water bottle trap.

Results of the research revealed that traps were effective in detecting diversity of as many as 10 insect pests in storage facilities. The species were six weevils or beetles and four moths. Eight of the 10 insect species were previously reported as infesting stored cereal grain in Niger (INSORMIL 2012). Raoul et al. (2013) reported that among 12 species recorded, eight attacked cereals, with five being primary pests, and five of 12 species of insects were harmful to stored foodstuff, in the Logone Valley of Cameroon, Central Africa Republic, and Western Chad. Ten species were coleopterans and only two were lepidopterans. Coleopterans are harmful to legume seeds, with only one secondary pest. But it should be noted that Ngamo and Hance (2007) in a review paper listed 18 insect species that attack stored products in Northern Cameroon. In Burkina Faso, Waonga et al. (2015) found more species (14 species in eight coleopteran and lepidopteran families) associated with stored sorghum than were recorded in our study.

Results of the study can serve as a basis for making decisions to apply measures to prevent or reduce grain loss. Our study supports the findings of other authors such as Wakefield (2008) who stated that monitoring the presence of beetle, moth, and mite pests is a tool or key requirement of IPM strategies for stored grain. The study also added more information about different traps and monitoring devices designed and validated for monitoring the presence of insect pests in the commodity (Cogan et al. 1990) and storage facilities (Mullen 1992, Collins and Chambers 2003).

The water bottle trap collected 60% of insect species caught with the 'Dome' Pheromone trap and 85% of the species in the sticky glue trap. The water bottle trap can be an effective monitoring tool for certain stored-product insects because bottles are readily accessible, relatively inexpensive, and easy to use. Use of a water bottle trap provides the additional benefit of attracting males and females of the pest species. Unlike sex pheromones, a water bottle trap collects species inside the storage unit and will not attract other species from outside a storage facility.

The 'Dome' Pheromone trap is expensive and not readily available. The trap type is species specific, limiting the range of pest species that can be monitored, and usually is attractive to only adult males of the target species. A sticky glue trap cannot be placed in direct contact with grain, thereby limiting its effectiveness to storage insects that fly.

Results of the study coupled with those obtained from storage insect pests monitored by sieving helped clearly identify the dominant species of insects in storage facilities in Niger. The results served as a baseline for determining species on which to focus studies to develop and assess alternative strategies to manage storage insect pests of sorghum and other cereal grains. Knowledge of diversity and application of simple monitoring devices for storage insect pests are keys to recommending control strategies.

Assessing Efficacy of Botanicals to Control Red Flour Beetles in Stored Sorghum Grain

Mortality over time. In Table 4, means of weekly numbers of red flour beetles killed by botanicals differed significantly at days 7 ($F = 16.8$; df = 4,239; $p < 0.0001$) and 14 ($F = 22.7$; df = 3,239; $p < 0.0001$). Means of 1.5-2.0 red flour adults were killed when 0.0125 or 0.025 g of powder of neem kernel, African locust bean, or hibiscus were applied to sorghum grains, but 1.0-1.5 adult was killed when baobab pulp was used.

Table 4. Mean Numbers (± SE) of Dead *Tribolium castaneum* Fed Sorghum Grains Treated with Botanical Powders at Three Doses and a Check

		Day after infestation				
Botanical	Dose	7	14	21	28	35
Neem kernel	0.0125	1.5 ± 0.2c	1.0 ± 0.1f	2.5 ± 0.5d	3.0 ± 1.0c	3.0 ± 1.0d
	0.025	1.5 ± 0.3c	2.0 ± 0.2d	3.5 ± 0.5b	3.5 ± 0.5b	3.0 ± 1.0d
	0.05	2.0 ± 0.5b	2.5 ± 0.5c	3.5 ± 0.5b	4.0 ± 1.0a	3.5 ± 0.5c
	0.1	2.5 ± 0.5a	2.5 ± 0.5c	4.0 ± 1.0a	3.5 ± 0.5b	4.0 ± 1.0b
	0.2	2.5 ± 0.5a	2.5 ± 0.5c	4.0 ± 1.0a	4.0 ± 1.0a	4.5 ± 0.5a
African locust bean	0.0125	1.5 ± 0.5c	2.5 ± 0.5c	2.0 ± 0.9e	1.5 ± 0.5f	2.0 ± 0.4f
	0.025	2.0 ± 0.5b	2.5 ± 0.5c	2.5 ± 0.2c	2.0 ± 0.5e	2.5 ± 0.4d
	0.05	2.0 ± 0.5b	2.5 ± 0.5c	3.0 ± 0.5c	3.0 ± 0.5c	3.0 ± 0.5d
	0.1	2.5 ± 0.5a	3.0 ± 0.5b	3.0 ± 0.5c	3.5 ± 0.5b	3.0 ± 0.5d
	0.2	2.5 ± 0.5a	3.5 ± 0.5a	3.0 ± 0.5c	3.5 ± 0.5b	3.0 ± 0.5d
Hibiscus	0.0125	1.5 ± 0.2c	2.0 ± 0.9d	1.5 ± 0.5f	1.5 ± 0.5f	1.5 ± 0.5
	0.025	2.0 ± 0.4b	2.5 ± 0.2c	2.0 ± 0.2e	2.0 ± 0.4e	2.0 ± 0.4f
	0.05	2.0 ± 0.4b	3.0 ± 1.0b	2.0 ± 0.2e	2.0 ± 0.2e	2.5 ± 0.4e
	0.1	2.5 ± 0.5a	3.5 ± 0.5a	2.5 ± 0.2d	2.5 ± 0.3d	2.5 ± 0.5e
	0.2	2.5 ± 0.5a	3.5 ± 0.5a	2.5 ± 0.5d	2.5 ± 0.4d	3.5 ± 0.5c
Baobab pulp	0.0125	1.0 ± 0.2d	1.0 ± 0.5f	1.5 ± 0.2e	1.0 ± 0.3f	1.0 ± 0.3g
	0.025	1.5 ± 0.5c	1.0 ± 0.2f	1.5 ± 0.3f	1.0 ± 0.2f	1.0 ± 0.2g
	0.05	2.0 ± 0.7b	2.0 ± 0.4d	2.0 ± 0.5e	2.0 ± 0.6e	2.0 ± 0.3f
	0.1	2.0 ± 0.5b	2.5 ± 0.5c	2.5 ± 0.5d	2.0 ± 0.5e	2.5 ± 0.5e
	0.2	2.5 ± 0.9a	3.0 ± 1.1b	2.5 ± 0.5d	2.5 ± 0.5d	2.5 ± 0.5e
Check	0.0	0.9 ± 0.2e	1.5 ± 0.2d	1.2 ± 0.3f	1.2 ± 0.3f	1.5 ± 0.3g
Mean	-	1.8 ± 0.1	2.5 ± 0.1	2.4 ± 0.1	2.4 ± 0.1	2.4 ± 0.1
F		16.8	22.7	22.8	22.1	22.2
P		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Means followed by the same letter in a column are not significantly different ($P < 0.05$).

With each botanical at a dose of 0.5 g, a mean of 2 adults was killed. With 0.1 and 0.2 g of powdered neem kernels, 2.5 red flour beetle adults were dead at days 7 and 14, but for sorghum grains treated with locust bean powder, means of red flour beetles dead were 3.0 (Day 7) and 3.5 (Day14), which were greater than overall means of 1.8 (7 days) and 2.5 (14 days), respectively. A large mean of 3.5 was observed when hibiscus at doses of 0.1 or 0.2 g was applied to sorghum grain. The mean number of beetle adults killed was 3 when baobab pulp was used. After 14 days of exposure, powder of neem kernels killed fewer adults compared to other botanicals. With non-treated sorghum grains, the means were 0.9 and 1.5 adult killed.

Mean numbers of red flour beetles killed when exposed to botanical powders were significantly different at days 21 ($F = 22.8$; df = 4,239; $p < 0.0001$) and 28 ($F = 22.1$; df = 4,239; $p < 0.0001$). At days 21 and 28, when 0.1 and 0.2 g of baobab pulp powder was applied to sorghum grains, 3.5-4.0 red flour beetle adults were killed (Table 4). At low doses of 0.0125 and 0.25 g, neem kernel and locust bean powders on sorghum grains killed 2.5-3.5 and 3.0-3.5 flour beetle adults by 21 and 28 days, respectively. The mean numbers were greater than with powder of hibiscus or baobab pulp at a dose of 0.1 or 0.2 g that killed 2.0-2.5 beetles by 21 and 28 days. With hibiscus or baobab pulp during the same number of days, 1.5 red flour beetle adult was killed, which was the same statistically as the 1.2 adult that died in nontreated sorghum but less than the overall mean of 2.4 dead adults.

At 35 days, there was a statistically significant difference ($F = 22.2$; df = 4,239; $p < 0.0001$) among botanical powders in numbers of red flour beetles dead. With 0.1 and 0.2 g of neem kernel powder applied to sorghum grain, greatest mean numbers of 4.0 and

4.5 red flour beetles were dead (Table 4). At doses >0.05 g of locust bean powder, 3.0 adult beetles were killed. Hibiscus powder killed 3.5 beetles when 0.2 g of powder was applied to sorghum grain.

With 0.025 to 0.1 g of hibiscus and baobab pulp powders, 2.0-2.5 adults were killed, which were fewer than with neem kernels or locust beans (Table 4). But doses of 0.0125 and 0.025 g of baobab pulp powder killed only 1.0 beetle adult, which was less than the mean for any other botanical tested and much less than the overall mean of 2.4 beetles. Overall, with the check (no botanical powder), mean numbers of adults killed were 0.9-1.5 over time and less than the overall mean at any time period.

The study showed that during time, botanical powders had different toxicity against red flour beetles. Neem kernel powder tended to act slowly at the beginning of the experiment until Day 14, but killed more beetle adults as time passed. At 21 or more days, with doses of 0.1 or 0.2 g, neem kernel and locust bean powder killed more beetles compared to hibiscus or baobab pulp at the same doses.

***Cumulative mortality and damage scores*.** Means of cumulative numbers of red flour beetles dead after 35 days of feeding on sorghum grain treated with five doses of three botanicals are shown in Fig. 4. Powder of neem kernels and African locust beans at ≤0.1 g killed >2.5 red flour beetle adults in sorghum grain. Kadi Kadi and Pendleton (2016) also found that <0.05 g of neem leaf powder killed most maize weevils. The most beetles (3.2) killed was by neem kernels at 0.05 g. As the dose increased from 0.05 to 0.1 g, neem kernel and African locust bean powders showed different potency in killing red flour beetles. While means of adults killed increased as the dose of African locust bean powder increased, neem kernel powder killed fewer adults as the dose increased. This

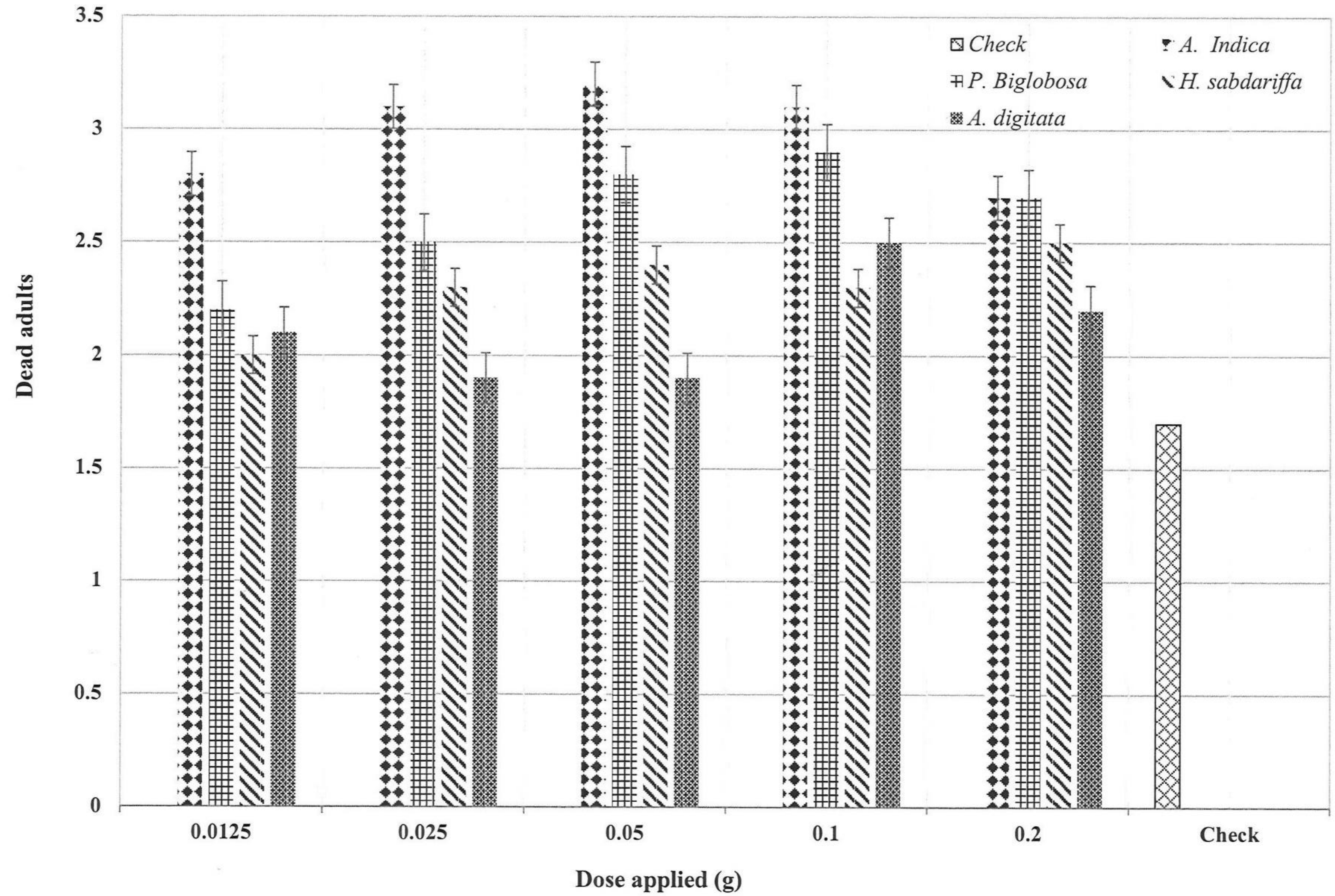


Fig. 4. Mean numbers of *Tribolium castaneum* killed per treatment and dose of botanicals, Niamey, Niger.

suggested that toxicity of neem kernel powder at a greater dose induced avoidance or anti-feeding behavior by red flour beetles. Thus, reapplication of neem kernel powder might be needed to kill more adults. Except for locust bean, powders of other botanicals at 0.2 g sharply decreased to 2.2-2.7 the number of beetle adults killed. The botanicals elicited an anti-feeding or avoidance behavior by *Tribolium*. At doses of 0.0125, 0.1, and 0.2 g, powders of hibiscus and baobab pulp tended to have similar toxicity against adult T. *castaneum*. At 0.2 g, powder of hibiscus and baobab powders killed 2.5 and 2.0 adults, respectively. Cumulative mortality of adults was less for the check (nontreated sorghum); 1.7 adults were dead.

In Fig. 5 are mean damage scores for red flour beetles fed sorghum grain treated with three botanicals at five doses for 35 days. Damage scores were low (1.3-2.6) for sorghum treated with ≥0.1 g of botanical powder compared to the check (3.9). Damage by red flour beetles was scored 3.3 on a 1-5 scale in sorghum treated with 0.05 g of baobab pulp powder; but at doses of only 0.0125 and 0.025 g, damage scores were 2.8 and 2.7, respectively. With only 0.0125 g of neem kernel and African locust bean, damage scores were 1.6 and 1.7, respectively. In general, neem and African locust bean resulted in much lower damage scores for sorghum treated at any dose compared to the other two plant products and check. Plant powders might have toxic effects on life history characteristics (longevity, fecundity, etc.) of red flour beetle exposed to the botanicals. Results of the research were similar to those of Adarkwah et al. (2017) who showed that more adults of three beetle species (*S. granarius*, *T. castaneum*, and *A. obtectus*) died with increasing dose and exposure to botanicals. The study showed the potential of using botanicals to reduce grain damage and weight loss during storage.

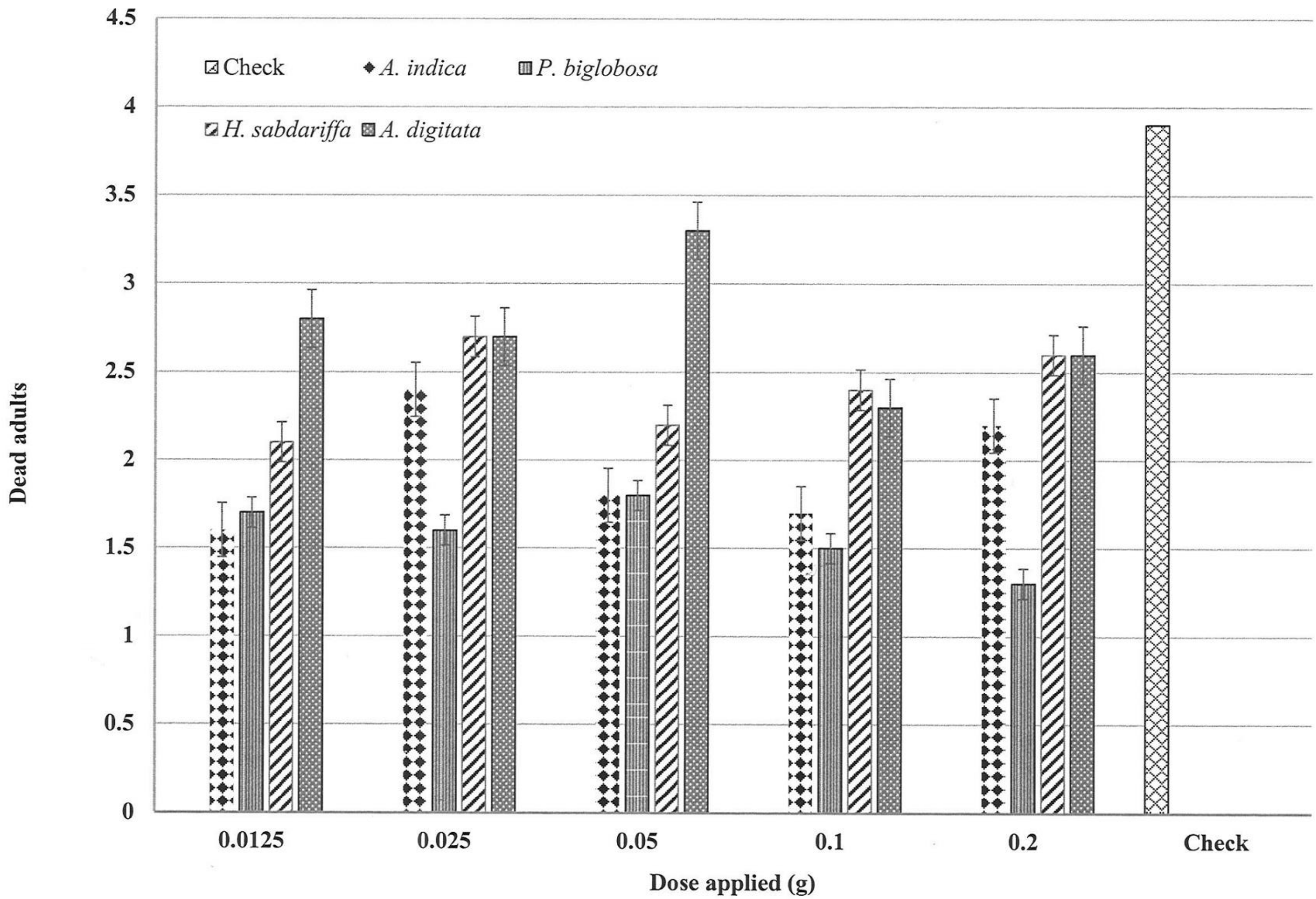


Fig. 5. Mean damage scores of sorghum grain treated with botanicals fed to *Tribolium castaneum*, Niamey, Niger.

Botanicals, which are readily available, safe to apply, and affordable for farmers with limited resources, are an effective option for controlling numerous stored-product pests. Use of botanicals as grain protectants is an eco-friendly and economical approach to suppress stored-product pests evaluated in the current research. Isman (2008) and Mukanga et al. (2010) said the principal advantage of botanicals was that farmers could supply their own protectants. Plants with insecticidal properties are a cost-effective and sustainable alternative to synthetic insecticides, store design, fumigation, and thermal distribution methods. They can be an abundant source of locally available pest control agents. Botanicals used in the study were effective for suppressing target insect pests and have the added benefit of low mammalian toxicity, making them an important part of an integrated pest management program.

Assessing Efficacy of Botanicals to Control Maize Weevils in Stored Sorghum Grain

Mortality of maize weevils over time. Periodic counts of maize weevils killed by botanicals showed significant differences at days 2 and 4 ($F = 5.9$; df = 3,169; $p < 0.0001$), with 0.2 g of powder of mesquite or milkweed most effective compared to other botanicals (Table 5). Mesquite and milkweed powder at doses of 0.2 g killed 1.5-2.8 maize weevils. With ≤0.1 g, milkweed powder killed 1.3-1.8 maize adults at Day 2, with 0.2 g of powder of mesquite and milkweed most effective compared to other botanicals. Mesquite and milkweed powder at doses of 0.2 g killed 1.5-2.8 maize weevils. With ≤0.1 g, milkweed powder killed 1.3-1.8 maize adults at Day 2, while it was not until Day 4 that mesquite powder killed 1.5 adult. At days 2 and 4, few adults (≤0.8) were killed by neem bark at any dose.

Table 5. Mean Number (± SE) of Maize Weevil Adults Killed per Botanical Treatment by Dose during Time, Canyon, Texas

Botanical	Dose (g)	Day after treatment 2	4	6	8	10	12	14	16	18
Mesquite	0.05	0.8 ± 0.2c	1.8 ± 0.3b	1.0 ± 0.2c	0.5 ± 0.2c	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0e	0.0 ± 0.0	0.0 ± 0.0b
	0.1	0.8 ± 0.1c	1.5 ± 0.9c	0.5 ± 0.2d	0.0 ± 0.0e	0.0 ± 0.0	0.5 ± 0.2	0.5 ± 0.2c	0.3 ± 0.1	0.0 ± 0.0b
	0.2	1.8 ± 0.4a	2.8 ± 1.1a	1.0 ± 0.1c	0.7 ± 0.3b	0.0 ± 0.0	0.3 ± 0.1	0.0 ± 0.0e	0.0 ± 0.0	0.0 ± 0.0b
Milkweed	0.05	1.3 ± 0.4b	0.8 ± 0.4d	0.5 ± 0.3d	0.3 ± 0.1d	0.5 ± 0.2	0.3 ± 0.1	0.0 ± 0.0e	0.3 ± 0.2	0.3 ± 0.1a
	0.1	1.8 ± 0.3a	0.8 ± 0.4d	1.0 ± 0.4c	0.8 ± 0.2b	0.3 ± 0.1	0.8 ± 0.2	0.8 ± 0.3d	0.3 ± 0.1	0.0 ±0 .0b
	0.2	1.8 ± 0.5a	1.5 ± 0.3c	2.0 ± 0.5b	0.5 ± 0.2c	0.3 ± 0.1	0.7 ± 0.2	0.0 ± 0.0e	0.0 ± 0.0	0.0 ± 0.0b
Neem	0.05	0.3 ± 0.1d	0.8 ± 0.2d	0.3 ± 0.1de	0.3 ± 0.1d	0.0 ± 0.0	0.0 ± 0.0	2.0± 0.8a	0.5 ± 0.2	0.0 ± 0.0b
	0.1	0.0 ± 0.0e	0.3 ± 0.1ef	2.0 ± 0.8b	1.3 ± 0.6a	0.5 ± 0.3	0.5 ± 0.3	1.0 ± 0.4b	0.0 ± 0.0	0.0 ± 0.0b
	0.2	0.3 ± 0.1d	0.0 ± 0.0g	2.3 ± 0.9a	0.8 ± 0.4b	0.0 ± 0.0	0.8 ± 0.2	0.8 ± 0.3d	0.0 ± 0.0	0.0 ± 0.0b
Check	-	0.0 ± 0.0e	0.5 ± 0.2de	0.3 ± 0.1de	0.5 ± 0.1c	0.0 ± 0.0	1.0 ± 0.2	0.8 ± 0.1d	0.5 ± 0.2	0.3 ± 0.1a
Mean		1.0 ± 0.2	1.0 ± 0.2	0.7 ± 0.01	0.3 ± 0.01	0.1 ± 0.01	0.4 ± 0.01	0.8 ± 0.03	0.2 ± 0.01	0.0 ± 0.0
F	-	5.9	5.9	4.8	1.9	0.5	2.0	4.7	1.1	
P		<0.0001	<0.0001	<0.0001	<0.0001	0.06	0.05	<0.0001	0.3	

Means followed by the same letter in a column are not significantly different ($P < 0.05$).

Mean numbers of maize weevils dead were significantly different at days 6 (F = 4.8; df = 3,169; $p < 0.0001$) and 8 (F = 1.9; df = 3,169; $p < 0.0001$) (Table 5). Mortality of maize weevils ranged from 2.0 to 2.3 at 6 days after applying neem bark powder to sorghum grain at doses of 0.1 and 0.2 g, respectively. At Day 6, 2.0 adults were dead when 0.2 g of milkweed powder was applied to sorghum grain. Mean numbers of adults killed were less with any dose of mesquite or milkweed at Day 8, but 1.3 adult was killed when sorghum grain was treated with 0.1 g of neem bark. At Day 10, there was no significant difference (F = 0.5; df = 3,169; $p = 0.06$) in mean numbers of maize weevils killed by botanical treatments at any dose. With mesquite at any dose, no weevil was killed, and only 0.5 adult was killed when 0.1 g of neem bark was applied to the sorghum grain. At Day 10, any dose of milkweed powder was more effective than the other botanicals. With 0.05 g of milkweed powder, 0.5 adult was killed, and only 0.3 adult was killed when sorghum grain was treated with 0.1 or 0.2 g of powder.

For any botanical, no significant difference (F = 2.0; df = 3,169; $p = 0.05$) was recorded for dead weevils at Day 12. Milkweed powder at doses of 0.1 and 0.2 g killed 0.8 and 0.7 adult weevils, respectively (Table 5). Fewer weevils were killed by mesquite powder compared to neem bark at doses of 0.1 and 0.2 g that killed 0.5 and 0.8 weevils, respectively. At 14 days, there was a significant difference (F = 4.7; df = 3,169; $p < 0.0001$) in the number of weevils killed by botanical powders; few maize weevils were alive in any treatment. Neem bark seemed to act slowly and killed 2.0 maize weevil adults when sorghum grain was treated with 0.05 g of powder. Overall, few adults of the check were killed, and only 1 and 0.8 adult was dead at days 12 and 14, respectively.

Percent mortality (PM%) and corrected mortality (CM%) of maize weevils. Table 6 shows results for mortality (PM%) and corrected mortality (CM%) of maize weevil adults fed sorghum grain treated with powders of mesquite, milkweed, and neem bark at three doses and the check. The number of weevils killed was significantly different (F = 2.36; df = 3,35; p = 0.11) and tended to increase as the dose of the botanical increased. On sorghum grain treated with milkweed or mesquite at a dose of 0.2 g, the percentages of maize weevils were 93.8 and 90.6%, respectively. At a dose of 0.1 g, mesquite powder killed 87.5% of maize weevil adults, while milkweed killed 78.1%, and neem bark killed 65.6%. When 0.2 g of powder of neem bark was applied to sorghum grain, the percentage killed was greater (78.1%) compared to 0.05 and 0.1 g, with 62.5 and 65.6%, respectively.

At the three doses, any botanical killed more weevils than did the check. When sorghum grains were treated with >0.1 g of milkweed or mesquite powder, the percentage corrected mortality was large at 75.0 to 92.9%. Percentage corrected mortality was 85.6% when sorghum grain was treated with 0.1 g of mesquite powder. Corrected mortality was only 76.8% when the greatest dose of 0.2 g of neem bark powder was applied to sorghum grain. Least corrected mortality (51.1%) was with neem bark at a dose of 0.05 g.

Grain damage (GD%), weight loss (WL%) and damage score by maize weevils. Maize weevils fed sorghum treated with powder of mesquite, milkweed, or neem bark had no effect on grain damage (F = 4.6; df = 3,35; p = 0.12) or weight loss (F = 1.7; df = 3,35; p = 0.2) (Table 7). Both grain damage and weight loss were inversely proportional to the dose of botanical applied. Grain damage (49.7-59.5%) was greater on sorghum

Table 6. Mean (± SE) Percent Mortality and Percent Corrected Mortality for Maize Weevils Fed Sorghum Grains Treated with Botanical Powders, Canyon, Texas

Botanical	Dose (g)	% mortality	% corrected mortality
	0.05	68.8 ± 7.6e	64.3 ± 9.1e
Mesquite	0.1	87.5 ± 5.1ab	85.6 ± 5.8b
	0.2	90.6 ± 6.0a	89.3 ± 6.7a
	0.05	71.9 ± 8.9e	67.9 ± 9.3de
Milkweed	0.1	78.1 ± 5.9c	75.0 ± 8.5c
	0.2	93.8 ± 3.6a	92.9 ± 4.1a
	0.05	62.5 ± 6.3f	51.1 ± 6.7g
Neem bark	0.1	65.6 ± 6.0f	60.7 ± 6.8f
	0.2	78.1 ± 3.1c	76.8 ± 3.1c
Check	0.0	12.5 ± 2.3g	_
Mean	_	77.4	74.4
F		2.4	2.2
P		0.11	0.13

Means followed by the same letter in a column are not significantly different ($P < 0.05$).

Table 7. Percentages of Sorghum Grains Damaged and Grain Weight Loss and Scores of Damage by Maize Weevils, Canyon, Texas

Botanical	Dose (g)	% grains damage	% weight loss	Damage score (1-5)
Mesquite	0.05	40.8 ± 5.2d	2.1 ± 1.8c	3.0 ± 0.8b
	0.1	36.7 ± 5.0e	1.5 ± 0.8c	2.5 ± 0.6c
	0.2	35.2 ± 5.9e	0.8 ± 0.2d	1.5 ± 0.6f
Milkweed	0.05	57.6 ± 1.9b	1.6 ± 0.9c	3.0 ± 0.8b
	0.1	49.7 ± 3.7c	1.0 ± 0.3d	2.5 ± 0.6c
	0.2	34.0 ± 4.7e	0.8 ± 0.1d	1.8 ± 0.5de
Neem bark	0.05	59.5 ± 3.1b	3.6 ± 0.9a	3.1 ± 0.8b
	0.1	52.0 ± 8.0c	2.8 ± 0.9b	2.7 ± 0.6c
	0.2	25.5 ± 2.3f	1.4 ± 0.2c	2.0 ± 0.6d
Check	0.0	68.4 ± 3.5a	3.9 ± 0.3a	3.5 ± 0.5a
Mean		48.0	1.7	2.5
F		4.6	1.7	0.7
P		0.12	0.20	0.53

Means (± SE) followed by the same letter in a column are not significantly different ($P < 0.05$).

grain treated with ≤0.1 g of powder of milkweed or neem bark. Neem bark powder at 0.2 g resulted in less grain damage caused by maize weevils -- only 25.5% compared to 35.2 and 34.0%, respectively, at the same dose. When weevils were fed nontreated sorghum, grain damage and weight loss were 68.6 and 3.9%, respectively, more than the means of any botanical powder used at any dose. For sorghum treated with neem bark powder at a dose of ≤0.1 g, grain weight losses were more (2.8-3.6%) compared to 1.0-2.1% for mesquite and milkweed at the same dose. Only 0.8% weight loss occurred when maize weevils were fed mesquite or milkweed at a dose of 0.2 g.

From Table 7, it should be noted that powder of mesquite or milkweed at 0.2 g was more effective than neem or the check at killing maize weevil adults (>90%) and reducing grain damage (34-35.2%) and weight loss (0.8%). About 78.1% of maize weevil adults were killed with milkweed at 0.1 g and neem bark at 0.2 g. But neem bark powder at a dose of 0.05 g was slow acting, and mortality of 62.5%, percent grain damage of 59.5%, and grain weight loss of 3.6% were greater. The results proved that botanicals can effectively be used as an alternative method to control maize weevils in stored sorghum grain.

After maize weevil adults fed on treated sorghum grain, damage scores were significantly different ($F = 0.7$; df = 3.35; $p = 0.53$) between botanical treatments at the three doses (Table 7). On sorghum grain treated with 0.05 and 0.1 g of mesquite and milkweed, mean damage scores were 3.0 and 2.5, respectively. With neem bark powder at the same doses, damage scores were 4.0 and 2.7. At a dose of 0.2 g, mean damage scores were 1.5 and 1.8 when mesquite and milkweed, respectively, were applied to the sorghum grain. Any botanical applied at any dose considerably reduced the damage score to less than the mean damage score of 3.5 of the check.

At any dose tested, botanicals significantly killed more weevil adults and reduced grain damage, grain weight loss, and damage score compared to the check (no plant powder). But the amount of control differed among the botanicals when maize weevils were fed sorghum grain treated with powder at different doses.

***Correlation and regression (Probit) analysis*.** Results of simple linear correlation analysis to determine the relationship among the variables of percentage adult mortality, corrected mortality, grain damaged, grain weight loss, and damage score by maize weevils fed sorghum grain treated with botanical powders are shown in Table 8. The Pearson correlation coefficient between variables was interpreted according to Hinkle et al. (2003). The percentage of maize weevil adults killed was very positively correlated with percentage corrected mortality (r = 0.99, $p < 0.001$). But the percentage of adults killed was low negatively correlated with percentage of grain damage (r = -0.19, p = 0.24), percentage of grain weight loss (r = -0.13, p = 0.44), and damage score (r = -0.47, p = 0.46). The percentage corrected mortality followed the same trend as the percentage of adult mortality and was low negatively correlated with the percentage of grain damage (r = -0.19, p = 0.24), percentage of grain weight loss (r = -0.13, p = 0.44), and damage score (r = -0.47, p = 0.46). The percentage corrected mortality followed the same trend as the percentage of adult mortality and was low negatively correlated with the percentage of grain damage (r = -0.19, p = 0.24), percentage of grain weight loss (r = -0.13, p = 0.44), and damage score (r = -0.47, p = 0.46). However, the percentage of grain damage was low positively correlated with the percentage of grain weight loss (r = 0.42,

Table 8. Pearson Correlation Coefficients among Variables (Percent Mortality-PM (%), Percent Corrected Mortality-CM (%), Percent Grain Damaged-GD (%), Percent Grain Weight Loss-WL (%), and Damage Score-DS) for *Sitophilus zeamais* Fed Sorghum Grain Treated with Powder of Botanicals

Variable	PM (%)	CM (%)	GD (%)	WL (%)	DS
PM (%)	1				
CM (%)	0.99**	1			
GD (%)	-0.19	-0.21	1		
WL (%)	-0.13	-0.13	0.42**	1	
DS	-0.45	-0.47	0.52**	0.27**	1

**ns: Correlation significant at α = 0.05

$p = 0.01$) and damage score ($r = 0.52$, $p = 0.0001$). The correlation between the percentage of grain weight loss and damage score ($r = 0.27$, $p = 0.11$) could be classified as low positive.

Linear correlation analysis showed that an increase in percentage of adults killed was correlated with an increase in percentage corrected mortality. When either percent adult mortality or percent corrected mortality increased, percent grain damage, percent grain weight loss, and damage score tended to decrease. An increase in percent grain damage was correlated with an increase in percent weight loss and damage score. Increasing percent weight loss led to increasing damage scores.

Lethal doses calculated by regression (Probit) analysis of the cumulative mean number of *S. zeamais* adults killed showed that mesquite and milkweed powders had similar potency, with almost the same LD_{50} and LD_{90} to kill 50 and 90% of maize weevil adults with 0.02 and 0.2 g of powder (Table 9). But, doses of mesquite and milkweed powders needed to kill 99% of maize weevils were slightly different, with LD_{99} of 0.83 and 0.89 g, respectively. More neem bark powder was required to be effective as lethal doses of 0.04, 0.26, and 1.27 g to kill 50, 90, and 99%, respectively, of maize weevil adults. The three botanicals killed more than did basil powder tested by Mwangangi and Mutisya (2013). Our results showed that lower doses (0.02-1.27 g) were needed to kill 50% (LD_{50}) and 99% (LD_{99}) of maize weevils, but 0.68-0.78 and 1.60-3.07 g were required to obtain the same LD_{50} and LD_{99} values for basil as reported by Mwangangi and Mutisya.

Results of the study indicated that efficacy of the botanicals decreased during time as shown by fewer weevils dead at Day 12 (Table 5). Botanicals for continuous

Table 9. Probit Analysis of Cumulative Numbers of *Sitophilus zeamais* Killed by Amounts (LD_{50}, $LD_{90,}$ and LD_{99}) of Botanical Powders

		LD_{50}, LD_{90} and LD_{99}	95% confidence limit	
Botanical	Probit	Amount (g)	Lower	Upper
Mesquite	0.50	0.02	$1.40\ 10^{-6}$	0.04
	0.90	0.16	0.10	12.10
	0.99	0.83	0.27	3.67
Milkweed	0.50	0.02	$1.47\ 10^{-6}$	0.05
	0.90	0.17	0.10	24.21
	0.99	0.89	0.28	5.02
Neem bark	0.50	0.04	0.002	0.06
	0.90	0.26	0.15	10.55
	0.99	1.27	0.38	9.73

All values were significant at $\alpha = 0.05$.

protection against maize weevils might need to be reapplied as indicated by Golob (2000) and BioSafe® Systems (M. Campos personal communication) that concluded the need for reapplication of botanicals in their studies. Use of the three botanicals killed many weevil adults in our study because the powder might have been a physical barrier between weevils and grains. According to Mulungu et al. (2007), the powder had a tendency to block the spiracles of the insects, thereby impairing respiration and leading to death of parents and F_1 progeny.

Local plant materials were reported to have insecticidal and antifeedant properties that might inhibit pest activities of *S. zeamais* (Owusu 2000). Other earlier reports with similar trends as our study showed that insecticidal, repellent, or antifeedant effects of various plant parts and products on inhibiting *S. zeamais* had varying degrees of success (Obeng-Ofori and Amiteye 2005). Powdered plant extracts act by dehydrating, suffocating, and reducing movement of weevils, thereby resulting in less grain damage and weight loss (Hall 1990, Parwada et al. 2012).

Assessing efficacy of botanicals showed good potential insecticidal activity against red flour beetle and maize weevil. Both target insects showed anti-feeding or avoidance behavior against feeding on sorghum grains treated with powder of botanicals at greater doses. According to Araya and Emana (2009), insecticidal activities of plant powders are variable, broad, and dependent on different factors such as the presence of bioactive chemicals that need to be identified, isolated, and manufactured for use in pest management. Botanicals applied at larger doses could be an eco-friendly alternative to toxic insecticides to protect and guarantee quantity and quality of cereal grains for end-users.

Evaluating Hermetic Storage Methods to Control Storage Insect Pests of Sorghum

Mortality of red flour beetles. Mean numbers of red flour beetles killed using hermetic storage methods differed significantly after 7 days ($F = 11.3$; df = 4,125; $p < 0.0001$) (Table 10). When the double bag and triple bag were used, means of 8.0 and 7.6 red flour beetle adults were killed. The means were greater than the 1.2 red flour beetle dead in the polypropylene bag (check). Compared to polypropylene, slightly more adults were killed, 5.2 and 3.0, respectively, when a clear plastic bucket and polyethylene bag were used.

Mean numbers of dead red flour beetles differed significantly at days 14 ($F = 7.1$; df = 4,125; $p < 0.0001$) and 21 ($F = 7.2$; df = 4,125; $p < 0.0001$). At days 14 and 21, 3.8 adults were dead with triple bagging, which was the same as the overall mean during time (Table 10). For polyethylene bags at the same periods, 3.6 and 3.0 beetle adults were dead. Greater means of 4.2 and 6.2 adults were dead at 14 and 21 days, respectively, with double bagging. Lower means of 2.4 and 1.4 dead weevils were found in polypropylene bags at 14 and 21 days, respectively.

Means were significantly different at 28 days ($F = 6.1$; df = 4,125; $p < 0.0001$) and 35 days ($F = 4.4$; df = 4,125; $p < 0.0001$) with hermetic bagging (Table 10). Greater means of 5.4 and 3.0 were calculated with the double bag and clear plastic bucket after 28 days. Three adults were dead at 35 days when the polyethylene bag was used. Only 1.2-2.2 adults were dead at 28 and 35 days with other storage methods.

Mortality of rice moths. Mean numbers of rice moths dead after 35 days of hermetic storage by five methods are shown in Table 11. Mean numbers of dead rice moths differed significantly through sequential counts at 7 ($F = 7.6$; df = 4,125; $p <$

Table 10. Mean Number (± SE) of *Tribolium castaneum* Adults Dead 35 Days after Hermetic Storage of Sorghum Grain, Kollo, Niger

Method	Day after infestation					Mean
	7	14	21	28	35	*F* and *P*
Double bag	8.0 ± 2.1a	4.2 ± 0.6a	6.2 ± 1.2a	5.4 ± 1.4a	2.4 ± 0.4b	5.2 ± 1.2 5.8 *P*<0.0001
Triple bag	7.6 ± 1.0a	3.8 ± 1.2ab	3.8 ± 1.3b	2.2 ± 0.7c	1.6 ± 0.5c	3.8 ± 1.1 3.8 *P*<0.0001
Clear plastic bucket	5.2 ± 1.1b	3.6 ± 0.6b	3.0 ± 0.9bc	3.0 ± 1.1b	1.5 ± 1.3c	3.2 ± 0.2 8.3 *P*<0.0001
Polyethylene	3.0 ± 0.5c	3.0 ± 0.5c	2.0 ± 0.7d	2.2 ± 1.0c	3.0 ± 1.0a	2.6 ± 0.4 11.5 *P*<0.0001
Polypropylene - Check	1.2 ± 0.1d	2.4 ± 0.6d	1.4 ± 0.5e	1.2 ± 0.4d	1.6 ± 0.6c	1.7 ± 0.2 7.1 *P*=0.0003
Mean	5.2 ± 0.3	3.4 ± 0.2	3.3 ± 0.1	2.8 ± 0.4	2.0 ± 0.2	
F	11.3	7.5	7.2	6.1	4.4	
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	

Means followed by the same letter in a column are not significantly different ($P < 0.05$).

Table 11. Mean Number (± SE) of *Corcyra cephalonica* Adults Dead 35 Days after Hermetic Storage of Sorghum Grain, Kollo, Niger

	Day after infestation					
Method	7	14	21	28	35	Mean
Double bag	10.6 ± 2.6a	10.8 ± 2.7a	4.6 ± 1.1ab	3.2 ± 1.0b	2.5 ± 0.6a	6.3 ± 1.3
						4.2
						P<0.0001
Triple bag	8.2 ± 3.4ab	7.0 ± 0.6b	5.0 ± 1.0a	3.8 ± 1.9a	1.6 ± 0.7c	5.1 ± 1.1
						2.7
						P<0.0001
Clear plastic bucket	9.0 ± 3.1ab	11.0 ± 2.2a	6.8 ± 2.1a	2.2 ± 1.1c	2.2 ± 0.9ab	6.2 ± 0.2
						7.0
						P<0.0001
Polyethylene	4.8 ± 2.1c	6.0 ± 1.4b	2.8 ± 0.9c	2.4 ± 0.8c	2.7 ± 1.1a	3.7 ± 0.3
						7.1
						P<0.0001
Polypropylene -Check	1.2 ± 0.7d	5.6 ± 1.1c	2.4 ± 0.8d	2.2 ± 0.6c	0.4 ± 0.2d	2.4 ± 0.8
						5.8
						P=0.009
Mean	6.8 ± 0.8	8.1 ± 1.2	4.3 ± 0.8	2.8 ± 0.5	1.8 ± 0.2	
F	7.6	9.1	4.9	3.1	2.1	
P	< 0.0001	< 0.0001	< 0.0001	0.003	0.041	

Means followed by the same letter in a column are not significantly different ($P < 0.05$).

0.0001) and 14 days ($F = 9.1$; df = 4,125; $p < 0.0001$). Many (8.2, 10.6, and 9.0) rice moth adults were dead at 7 days when the triple bag, double bag, and clear plastic bucket were used for hermetic storage of sorghum grain (Table 11). Mean numbers dead also were large at 14 days, when 7.0, 10.8, and 11.0 adults were killed by the triple bag, double bag, and the clear plastic bucket, respectively.

Means were comparatively greater than overall means of 6.8 (7 days) and 8.1 (14 days) rice moths killed. Also, the means were greater than the 4.8 and 1.2 adults killed at 7 days when polyethylene and polypropylene bags were used. After 14 days of testing the polyethylene and polypropylene bags, mean numbers of 2.8 and 2.4 rice moth adults killed were less than the overall mean of 8.1. The mean numbers of adults killed differed significantly ($F = 6.9$; df = 4,125; $p < 0.0001$) among methods at 21 days. As compared to 7 and 14 days, fewer adults were dead at 21 days, 5.0, 4.6 and 6.8 when a triple bag, double bag, and clear plastic bucket were used. After 21 days of using polyethylene and polypropylene bags, 2.8 and 2.4 rice moth adults were dead, which was less than the overall mean of 4.3.

Mean numbers of rice moth adults killed were significantly different at days 28 ($F = 3.1$; df = 4,125; $p < 0.003$) and 35 ($F = 2.1$; df = 4,125; $p < 0.041$). After 28 days, mean numbers of 3.8 and 3.2 adults were killed when triple bagging and double bagging were used (Table 11). After 35 days, 2.5 adults were killed in a double bag. For the clear plastic basket and polyethylene bag, the means were 2.2-2.7 adults killed after 28 and 35 days. At days 28 and 35, only 2.2 and 0.4 adults were killed when a polypropylene bag was used.

Survival of the two storage insects. The mean numbers of adults that survived were significantly different for red flour beetle (F = 6.7; df = 4,24; p = 0.06) and rice moth (F = 2.0; df = 4,24; p = 0.14) in hermetically sealed bags (Table 12). When polypropylene and polyethylene bags were used, means of 8.0 and 25.2 red flour beetles and 21.6 and 33.2 rice moths survived on sorghum stored for 35 days. Large numbers of moths also survived in the triple bag (21.8) and clear plastic bucket (28.6). Overall, the double bag killed more of both storage insect species, with means of 3.4 red flour beetles and 9.6 rice moths alive after 35 days in hermetic storage. Compared to the red flour beetle, more rice moths survived with any hermetic storage method. A mean of 4.6 adults surviving was less than the mean number of adults in polyethylene or polypropylene bags.

Percentage of weight loss by red flour beetles. Mean percentage of weight loss caused by red flour beetle was significantly different (F = 1.8; df = 4,24; p = 0.2) among the hermetic storage methods tested (Fig. 6). Mean weight loss was 8.5 and 3.2% when polypropylene and polyethylene bags were used. For the other hermetic storage methods tested, mean weight loss was 1.4%. Results showed that hermetic storage would be a useful way to decrease survival of insect pests and grain weight loss during storage.

Results of hermetic storage methods showed more adults killed, less survival, and the less percentage of grain weight loss. Grain weight loss was less with triple or double bagging. Survival of both species of storage insect pests was greater in polypropylene bags compared to other hermetic storage methods. Our results confirmed the report by Ognakossan et al. (2013) that more insects died in a hermetic grain bag compared to a woven polypropylene bag used to store maize. Like all aerobic organisms, development

Table 12. Mean Numbers (± SE) of Adult Insects Alive 35 Days after Hermetic Storage of Sorghum Grain, Kollo, Niger

Method	*Tribolium castaneum*	*Corcyra cephalonica*
Triple bagging	2.2 ± 0.5d	21.8 ± 3.2bc
Double bagging	3.4 ± 0.5e	9.6 ± 2.3d
Clear plastic basket	4.6 ± 1.2c	28.6 ± 7.7b
Polyethylene	8.0 ± 2.4b	21.6 ± 8.7bc
Polypropylene -check	25.2 ± 7.7a	33.2 ± 7.5a
Mean	8.7 ± 2.3	23.0 ± 6.4
F	6.7	2.0
P	0.06	0.14

Means followed by the same letter in a column are not significantly different ($P < 0.05$).

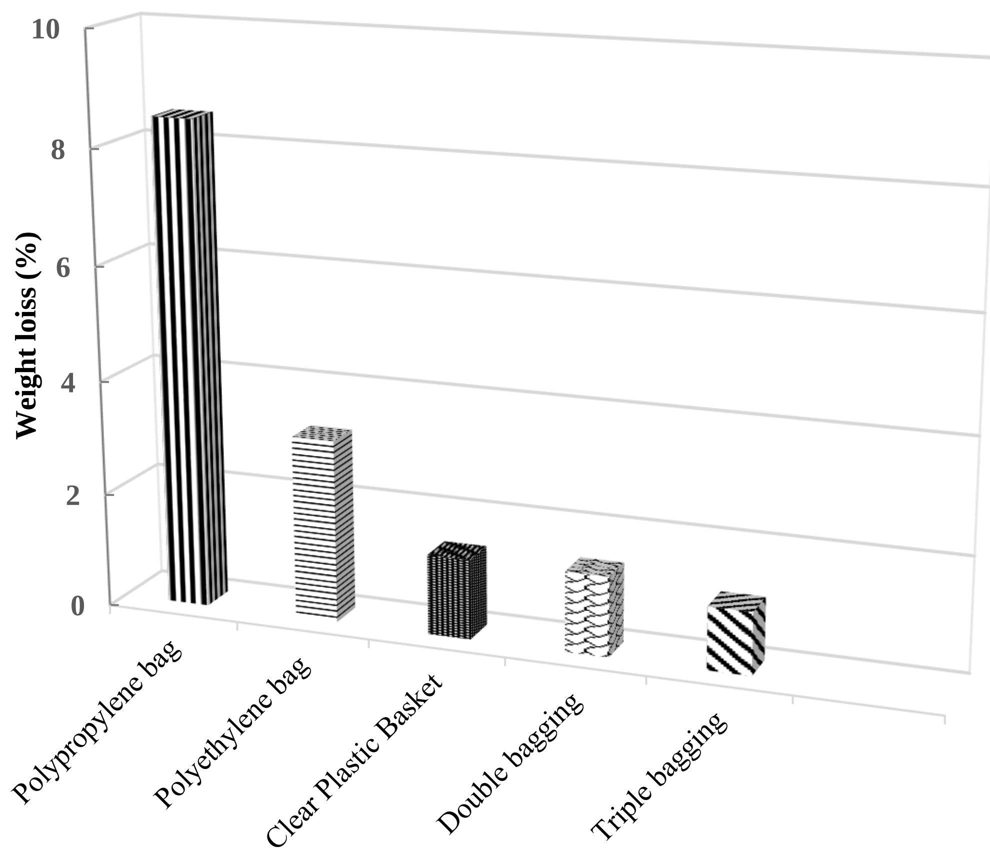


Fig 6. Percentage of weight loss caused by *Tribolium castaneum* to sorghum grain stored by hermetic storage methods, Kollo, Niger.

and survival of insects are correlated with the amount of oxygen, so in hermetic storage, insect development ceases (Donahaye and Navarro 2000) and insects perish if oxygen is less than 2-3% (Moreno-Martinez et al. 2000). Bailey and Banks (1980) said that hermetic conditions delayed insect development, impaired metamorphosis, and altered fecundity.

Our results complement past research on simple hermetic storage technologies developed and validated for several commodities. The effectiveness of the hermetic storage technologies was validated by on-farm tests in Cameroon, and the technology was adopted widely in West Africa (Murdock et al. 2003). Baributsa et al. (2010) noted that because of its effectiveness and ease of use, small-scale farmers and organizations quickly adopted Purdue Improved Cowpea Storage (PICS) technology. The International Rice Research Institute (IRRI) super-bag was used to control post-harvest problems on rice in Asia (Rickman and Aquino 2004 and 2007). Also, PhilRice (Sabio et al. 2006) showed benefits of storing rice and rice seeds in hermetic storage that are well understood and widespread especially in Asian countries as reported by Villers et al. (2006).

In the future, simple hermetic storage can be useful to sorghum farmers following successes achieved by Purdue Improved Cowpea Storage (PICS) in West Africa and diffusion of the IRRI super-bag for storage of rice in Asia. Results from this study can serve as a baseline for evaluating at the farm level and promoting use of hermetic bags to control primary and secondary storage insect pests of sorghum grain. Hermetic storage of sorghum can be advantageous to farmers and the public by reducing direct losses caused by insect pests that attack grain, allowing farmers to store grain with expected good quantity and quality for later sale rather than earlier at harvest.

Cost-Benefit Analysis of Using Low-Cost Hermetic Storage Methods to Control Storage Insect Pests of Sorghum Grain

Data from the experiments of hermetic storage methods were evaluated by cost-benefit analysis. Analysis focused on production, storage, and marketing of Grinkan sorghum seeds. The estimated cost per ton of sorghum grain was $3,466.20 (1 kg sold for $3.47 and a monetary exchange rate of West African CFA estimated at 577 per 1 dollar). Costs and benefits from hermetic storage methods were calculated as differences from a polypropylene bag (check).

Percentage of grain weight loss with effects of treatment over time. Regression coefficients for each hermetic storage method represent the monthly percentage of weight. For any hermetic storage method, the coefficient was less than the coefficient for the polypropylene bag (Table 13). The linear trend equations had positive slope coefficients that indicated noticeable increases in percentage of grain weight loss during time. For the equations, R^2 = 0.96-0.99 (96-99% of the time determined variation in the percentage of grain weight loss). The R^2 varied between hermetic methods, thus the differences in percentage weight loss observed. It was the same (0.99) for the polyethylene bag and double bag, but differed by 2% between the polypropylene bag and triple bag. Grain weight loss per month was 0.81, 0.77, 0.72, and 0.69% for the polypropylene bag (check), polyethylene bag, double bag, and triple bag, respectively. As compared to using a polypropylene bag, the monthly percentage of grain weight loss was 0.04 for a polyethylene bag, 0.09 for a double bag, and 0.12 for a triple bag. Results showed that hermetic storage could be a valuable alternative method compared to polypropylene bagging that resulted in more loss during storage.

Table 13. Linear Regression Analysis of Percentage Loss of Sorghum Grain with Effects of Treatment during Time for Each Hermetic Storage Method

	Polypropylene bag	Polyethylene bag	Double bag	Triple bag
Coefficient	0.81	0.77	0.72	0.69
Standard error	0.20	0.18	0.04	0.006
P	< 0.001	< 0.001	< 0.01	< 0.01
Regression equation	%L = 0.81 t	%L = 0.77 t	%L = 0.72 t	%L = 0.69 t
	R^2 = 0.98	R^2 = 0.99	R^2 = 0.99	R^2 = 0.96

Monthly incremental grain weight loss. The monthly incremental grain weight loss (kg) of Grinkan seeds during a period of 12 months is shown in Table 14. Weight losses were calculated using linear equations previously mentioned. For any hermetic bagging method, the incremental grain weight loss increased during time and was more after 12 months. The monthly incremental increases in grain weight losses were greater for the polypropylene bag (8.10) and polyethylene bag (7.70). With the polypropylene bag, grain weight losses tended to be greater than with other hermetic storage methods. Weight losses were reduced to 6.20 and 6.90 kg with double bagging and triple bagging, respectively. With a polyethylene bag, grain weight loss was 92.40 kg after 1 year of storage. After 1 and 6 months, when a double bag was used, grain weight loss was less by 0.50 and 3.00 kg than with a polyethylene bag. Triple bagging greatly reduced grain weight loss by 3.60 and 10.80 kg as compared to a polypropylene bag used for storage for 3 and 9 months. Weight loss of stored grain was less by 10.80 kg with double bagging and 14.40 kg with triple bagging compared to a polypropylene bag, after 12 months. Overall, alternative storage methods reduced weight loss from the initial quantity of sorghum grain compared to using a polypropylene bag during time.

Costs and benefits of hermetic storage methods. Costs of bags used for hermetic storage were calculated based on 1 ton of Grinkan seeds stored during a period of 1 year (Fig. 7). For any storage method, the cost considers using a method to store 1 ton of Grinkan sorghum grain for 1 year. When a polyethylene bag was used, the incremental cost per ton was $15.00, with extra charges for using 10 replacement bags after 4 and 8 months of storage because of damage by *T. castaneum* and/or heat in the storage facility. The cost was $20.00 per ton for a double bag. For a triple bag, the cost was $34.60 after

Table 14. Monthly Incremental Weight Loss (kg) of Grinkan Sorghum Seeds Stored in Hermetic Bags for 1 Year

Month	Polypropylene bag	Polyethylene bag	Double bag	Triple bag
1	8.10	7.70	7.20	6.90
2	16.20	15.40	14.40	13.80
3	24.30	23.10	21.60	20.70
4	32.40	30.80	28.80	27.60
5	40.50	38.50	36.00	34.50
6	48.60	46.20	43.20	41.40
7	56.70	53.90	50.40	48.30
8	64.80	61.60	57.60	55.20
9	72.90	69.30	64.80	62.10
10	81.00	77.00	72.00	69.00
11	89.10	84.70	79.20	75.90
12	97.20	92.40	86.40	82.80

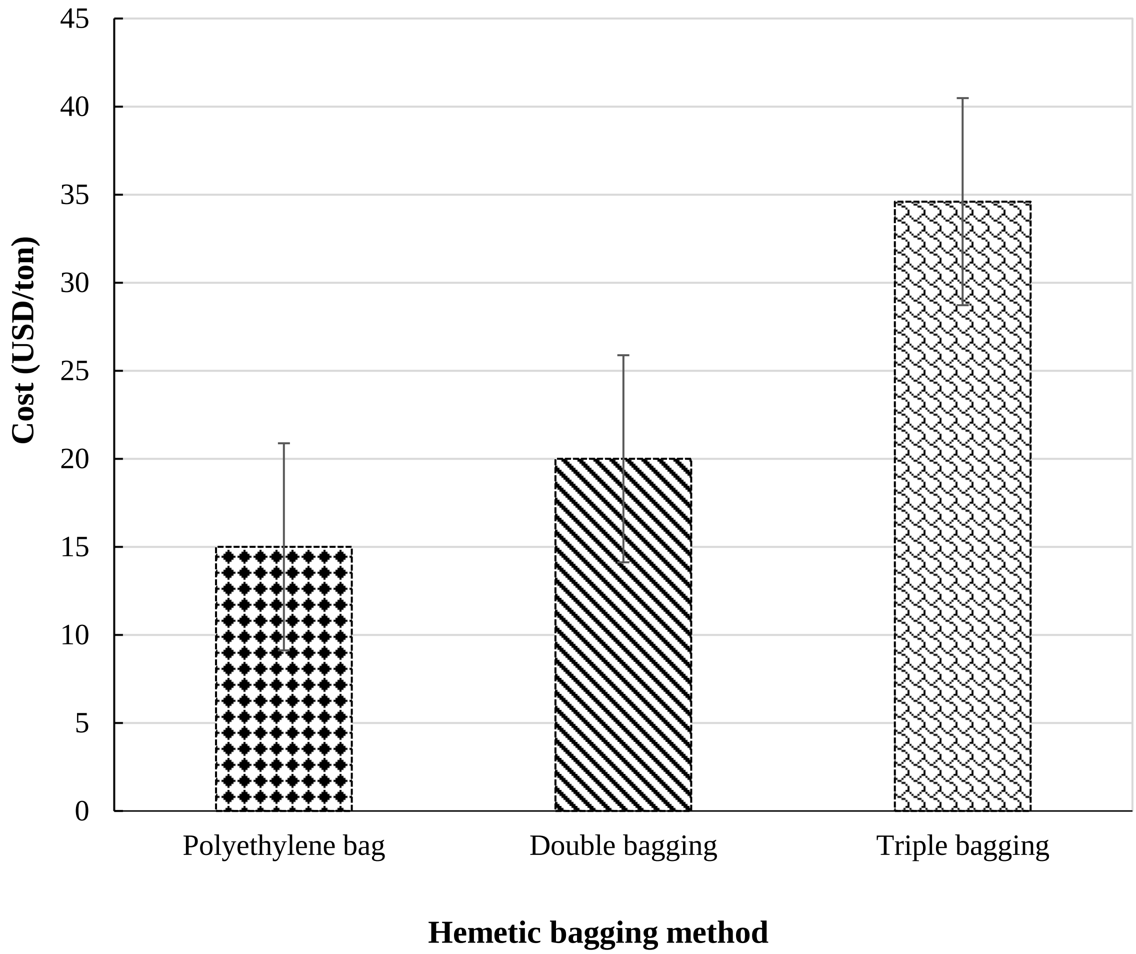


Fig. 7. Cost incurred (US dollars per ton) for each hermetic bagging method for stored sorghum grain.

1 ton of sorghum was stored for 1 year. The difference in cost of bags was based on the price of a hermetic bag compared with a polyethylene bag that cost $0.50 for a total of 20 bags, with the initial 10 bags replaced twice to store 1 ton of Grinkan seeds per year (Table 15). A double bag was assumed to cost the same ($1.00) as a super-bag used to store rice in Asia, and a triple bag cost $1.73. Ten bags for each method were replaced once during the year.

Quantity (kg) of Grinkan sorghum seeds obtained after using the three alternative hermetic storage methods are presented in Table 15. The quantity that can be sold was greater with a triple bag (917.20 kg), followed by a double bag (913.60 kg). When a polyethylene bag was used, the quantity was 907.30 kg, and with a polypropylene bag, only 902.20 kg of sorghum grain were preserved and marketable. The difference in quantity of sorghum seeds obtained was not significantly different because weight loss differed by only 0.30-0.80 kg between storage methods.

Monetary value ($) varied among the hermetic methods used to store 1 ton of Grinkan sorghum seeds for 1 year (Table 15). When the sorghum was produced at a research station, the value of the seeds in a polyethylene bag was $3,149.37. Only $3,132.70 can be generated when a polypropylene bag was used as the storage method. A greater value of $3,182.68 was calculated when a triple bag was used, which was $12.49 more than by using a double bag. When any hermetic storage method was used to store sorghum grain produced at a farm, the monetary value generated was about 11.0% as compared to a research station selling Grinkan certified sorghum seeds ($3.47 per kg), because 1 kg sells for only $0.38. Monetary values for the stored sorghum grain were $348.54 and 347.17 when double and triple bags were used. But sorghum grain stored in

Table 15. Costs of Hermetic Bags and Quantity and Value ($) of Grinkan Sorghum Seeds Sold after Hermetic Storage per Year

Method	Unit price of bag ($)	Total cost of bags	Quantity (kg)	Value ($)	
				Research	Farm
Polypropylene bag	0.50	15.00[a]	902.20	3132.70	342.84
Polyethylene bag	0.50	15.00[a]	907.30	3149.37	344.89
Double bag	1.00	20.00[b]	913.60	3170.19	347.17
Triple bag	1.73	34.60[b]	917.20	3182.68	348.54

NB: [a]polypropylene (check) and polyethylene bags replaced twice and [b]double and triple bags replaced once during 1 year of hermetic storage.

the polypropylene bag and the polyethylene bag can be sold for only $342.84 and 344.89, respectively.

In Fig. 8 are presented benefits accrued from using each hermetic storage method calculated using monthly incremental weight losses presented in Table 14. The benefit from using each hermetic storage method increased during time. With a triple bag, the benefit increased from $23.90 after 1 month to $143.70 and 287.30 after 6 and 12 months, respectively. This meant that if triple bagging was used, a user would gain $287.30 compared with the amount of loss of grain (0.81% per month) stored in a polypropylene bag. With double bagging of sorghum grain, the benefit accrued would increase from $24.98 (1 month) to $149.90 and 299.80 after storage for 6 and 12 months, respectively. With a polyethylene bag, the benefit was $26.70 after 1 month of storage. Benefits were $160.30 and 320.60, after 6 and 12 months, respectively.

The results as a matrix of benefits in terms of different hermetic methods used to store Grinkan sorghum seeds for 1 year are presented in Table 16. With a triple bag to hermetically store 1 ton of sorghum, the benefit was $52.10 compared to using a polypropylene bag. With a polyethylene bag and a double bag, benefits accrued were $17.70 and 39.60, respectively, compared to using a polypropylene bag. Benefits were $21.90 and 34.35 for a double bag and a triple bag, respectively, as compared to a polyethylene bag. A triple bag provided a benefit of $12.49 more than a double bag for hermetic storage. Hermetic methods help preserve sorghum grain and generate more benefits compared to polypropylene bags for storage that resulted in greater loss.

Discounted costs and benefits of hermetic storage methods and Benefit-Cost Ratio sensitivity analysis. The variables, Net Present Value (NPV) and Benefit-Cost

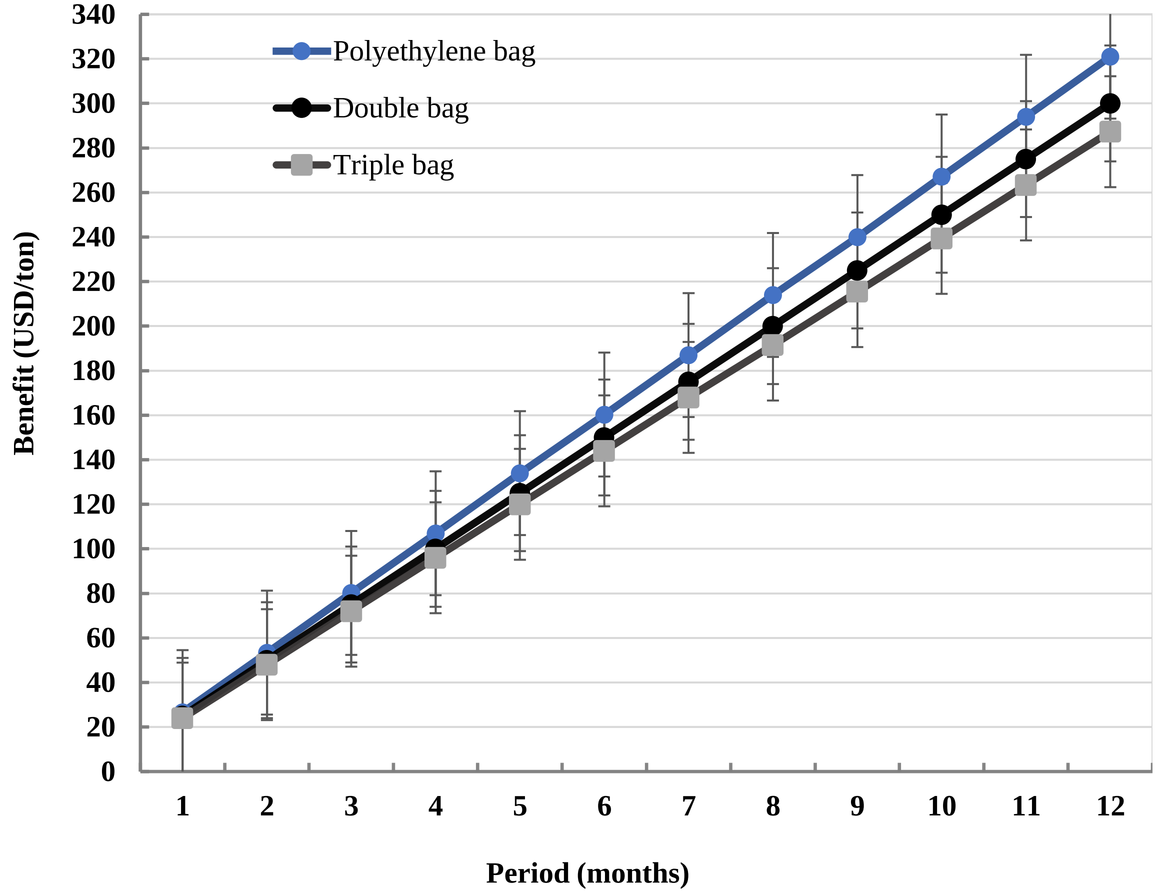


Fig. 8. Benefit accrued (US dollars per ton) from each hermetic bagging method for stored sorghum grain.

Table 16. Matrix of Benefits in Terms of Different Hermetic Storage Methods Used to Store Grinkan Sorghum Seeds

Method	Cost of bags*	Polypropylene bag 15.00	Polyethylene bag 15.00	Double bag 20.00	Triple bag 34.60
Polypropylene bag (check)	15.00	0	17.70	39.60	52.10
Polyethylene bag	15.00		0	21.90	34.35
Double bag	20.00			0	12.49
Triple bag	34.60				0

*Cost of bags to store 1 ton of sorghum per year.

Ratio (BCR), were used as the basis to compare benefits of each hermetic storage method for future decisions about attractiveness or not. The Net Present Value is the current value of all project net benefits. The value of net benefits in any period of time is the benefit (*B*) minus the cost (*C*) and is computed by the following formulas:

$$NPV = \sum_{t=0}^{T} \frac{(Bt - C_t)}{(1+r)^t} \quad (1)$$

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \quad (2)$$

where Bt is benefit at time t, Ct is the measure of cost at time t, and r is discount rate.

Net Present Value and Benefit-Cost Ratio were analyzed based on production, storage, and marketing of Grinkan sorghum seeds. Costs and benefits from hermetic methods were calculated from costs of applying the storage methods and the quantity of sorghum seeds. The estimated cost per ton of sorghum grain was $3,466.20 (1 kg selling at $3.47 and a monetary exchange rate of West African CFA estimated at 577 per 1 dollar). The discount rate used for the analysis was obtained from the BCEAO (Central Bank of West African States). The average discount rate applicable for change in the consumer price index was 4.5%.

Models for discounting costs and benefits were developed using Microsoft® Excel Spreadsheet. The models were used to determine the Net Present Value and Benefit Cost Ratio calculated with built-in Excel formulas for the model. Costs were calculated based on producing 1 ton of seed of the sorghum variety on 1 ha of land. Benefits were accrued from the sale of 1 ton of sorghum grain after storage with hermetic technology versus the check.

Results of discounted costs of the three hermetic storage methods (polyethylene bag, double bag, and triple bag) are shown in Table 17. Because of possible damage to polyethylene bags by *T. castaneum* and/or heat in a storage facility, an extra charge was added for replacing bags after 4 and 8 months in storage. For the analysis, the cost of 1 ton of sorghum seeds was calculated to be $3,466.20. For the 10 years used for cost and benefit discounting, all three hermetic storage methods had positive Net Present Value. Greater Net Present Value was calculated with triple bagging ($4,344.81) followed by double bagging ($4,343.22). The Net Present Value for a polyethylene bag ($4,186.55) was $158.26 less than using a triple bag for storage. At any period and 4.5% discount rate, any of the hermetic storage methods had positive Net Present Value that suggested they would be better than a polypropylene bag.

The estimated Benefit-Cost Ratios for the three hermetic storage methods were slightly different, with 1.19 for the polyethylene bag and 1.20 for double or triple bagging of 1 ton of sorghum stored for 1 year. A Benefit-Cost Ratio of ≥ 1 was assumed for determining the best alternative hermetic storage method. Cost-Benefit Analysis using positive Net Present Value and Benefit-Cost Ratio of ≥ 1 showed hermetic storage methods could be more acceptable than using a polypropylene bag. But the polyethylene bag could not be recommended as an alternative hermetic method if large quantities of seeds needed to be stored. Polyethylene bags tend to be damaged by *Tribolium* and conditions in a storage facility; therefore, extra costs are needed to replace the bags during the time the grain is stored. The other two hermetic storage methods (double bag and triple bag) can be used, because they sustain stacking and are less damaged during storage.

Table 17. Net Present Value (US dollars) and Benefit-Cost Ratio Calculated at 4.5% Discounted Rate during 10 Years for Production, Storage and Sale of Grinkan Sorghum Seeds

Year	Polyethylene bag	Double bag	Triple bag
0	-550.00	-550.00	-550.00
1	572.82	591.77	591.96
2	548.16	566.29	566.47
3	524.55	541.90	542.08
4	501.96	518.57	518.73
5	480.35	496.24	496.40
6	459.66	474.87	475.02
7	439.87	454.42	454.56
8	420.93	434.85	434.99
9	402.80	416.12	416.26
10	385.46	398.20	398.33
NPV (4.5%)	4186.55	4343.22	4344.81
BCR	1.19	1.20	1.20

A sensitivity analysis was done for the Benefit-Cost Ratio using three discount rates (4.5, 6.5, and 8.5%) with a varying 2-year increment period during 10 years of investment. Models using Microsoft® Excel Spreadsheet were developed for computation of the Benefit-Cost Ratio at the discounted rates and during the period chosen. After inputting the variables into the model, Net Present Value and Benefit-Cost Ratio were calculated with the Excel built-in formulas below the model. A user of any hermetic storage method was assumed not to invest for more than 10 years, because long-term investment is not common in the zone of study. A target Benefit-Cost Ratio >1 was used for any hermetic bagging method to be considered a good option.

At Year 2 to 4, the polyethylene bag tended to have the lowest Benefit-Cost Ratio of 1.17 to 1.18 (Table 18), but this should be considered cautiously before recommending a polyethylene bag as a viable alternative because of fragility of the plastic to withstand heat and handling. For all the periods of 6-10 years with all discount rates used, hermetic bagging methods had Benefit-Cost Ratio >1, and thus, investing in alternative hermetic bagging was good. A triple bag would be considered as the best option to choose followed by a double bag.

At Year 8 and 10 and with all discount rates, investing in hermetic bags for storage was good because the Benefit-Cost Ratio was >1.20. Double and triple bags tended to have almost the same Benefit-Cost Ratio for any period and discount rate. For double and triple bagging after Year 6, the greatest Benefit-Cost Ratio of ≥1.20 was calculated with any discounting rate. Based on Benefit-Cost Ratio sensitivity analysis, triple and double bags are good alternatives to polypropylene bags.

Table 18. Sensitivity Analysis of Benefit-Cost Ratio at Different Discount Rates during Time for Production, Storage and Sale of Grinkan Sorghum Seeds

Year	Discount rate	Polyethylene bag	Double bag	Triple bag
2		1.17	1.18	1.18
4		1.18	1.19	1.18
6	4.5	1.18	1.19	1.18
8		1.19	1.20	1.19
10		1.19	1.20	1.20
2		1.17	1.18	1.18
4		1.18	1.19	1.18
6	6.5	1.18	1.19	1.19
8		1.19	1.20	1.20
10		1.20	1.20	1.20
2		1.18	1.18	1.18
4		1.18	1.19	1.18
6	8.5	1.19	1.20	1.19
8		1.20	1.20	1.20
10		1.20	1.20	1.20

The present cost-benefit analysis of hermetic storage methods is the first of its kind in integrated pest management technology available in Niger. In summary, the analysis determined which method(s) might be more suitable to store sorghum seeds for improved quantity, quality, and revenue. Simple linear regression determined grain weight loss per month was 0.81% in a polypropylene bag (check), 0.77% for a polyethylene bag, 0.72% for double bagging, and 0.69% for triple bagging. Linear trend equations had positive slope coefficients that indicated noticeable increases in percentage of grain weight loss during time. For the equations, $R^2 = 0.96\text{-}0.99$ (meaning that 96-99% of the time the trend determined the variation in percentage of weight loss). Results of analysis of experimental data showed that for all hermetic bagging methods, the incremental grain weight loss increased during time and was more after 12 months. Monthly incremental increases in weight loss were 8.10, 7.70, 7.20, and 6.90 kg for polypropylene, polyethylene, double, and triple bags, respectively. When the double bag and triple bag were used, the weight loss was less (≤87 kg) than when polyethylene bags were used for storage.

Costs incurred from hermetic storage were calculated as the incremental cost of each method to store 1 ton of Grinkan sorghum seed for 1 year compared to a polypropylene bag (check). When a polyethylene bag was used, the incurred cost per ton was $15.00, assuming 1 year of storage. The incurred cost was greater and reached $34.60 per ton when triple bagging was used. For double bagging, the cost was $20.00 when 1 ton of sorghum grain was stored for 1 year.

The quantity of sorghum grain that can be sold was greater with a triple bag (917.20 kg), followed by a double bag (913.60 kg). When a polyethylene bag was used, the quantity of grain was only 907.30 kg. The quantity of sorghum seeds preserved was not significantly different because weight loss differed only by 0.30-0.80 kg between storage methods. Monetary value ($) of seeds varied between the hermetic storage methods used for 1 ton of Grinkan sorghum seeds for 1 year. When sorghum was produced at a research station, the value of seeds was less ($3,149.37) for a polyethylene bag. The greatest value of $3,182.68 was calculated when a triple bag was used, which was $12.49 more than by using a double bag.

The benefit of using each hermetic storage method increased during time. When triple bagging was used, the benefit increased from $23.90 after 1 month to $143.70 and 287.30 after 6 and 12 months, respectively, of hermetic storage. With double bagging of sorghum grain, the benefit accrued would increase from $24.98 (1 month) to $149.90 and 299.80 after storage for 6 and 12 months, respectively. With a polyethylene bag, the benefit was $26.70 after 1 month of storage. Benefits were $160.30 and 320.60 after 6 and 12 months, respectively, of storage.

A matrix of benefits in terms of different hermetic methods helped to determine that with a triple bag as storage method, the benefit of $52.10 was obtained as compared to using a polypropylene bag. Benefits accrued of $17.70 for a polyethylene bag and 39.60 for a double bag, over using a polypropylene bag. A triple bag provided a benefit of $12.49 more than a double bag for hermetic storage. Compared to polypropylene bags, tested hermetic storage methods help preserve sorghum grain and generate considerable benefits.

Measures of project worth, Net Present Value and Benefit-Cost Ratio, were used to analyze expected benefits from investing in a hermetic storage method. Using a discount rate of 4.5% and 10 years of investment, the incremental Net Present Value from any hermetic bagging method was positive. A target Benefit-Cost Ratio >1 was set for any hermetic bagging method to be considered a good option. At Year 1 to 3, the polyethylene bag tended to have the least Net Present Value decrease from $572.82 to 524.53, but this should be considered cautiously before recommending it as an alternative because of the fragility of the plastic to sustain heat and handling. For all the periods of 6-10 years with all discount rates, the hermetic bagging methods had Benefit-Cost Ratio >1, and thus, the alternatives were good investments. Double and triple bagging tended to have the same Benefit-Cost Ratio for all periods and discount rates. For double and triple bagging after Year 6, the greatest Benefit-Cost Ratio of ≥1.2 was calculated with any discounting rate.

A sensitivity analysis was done for Benefit-Cost Ratio using three discount rates (4.5, 6.5, and 8.5%) with varying 2-year increment period during 10 years of investment. At Year 2 to 4, the polyethylene bag tended to have the lowest Benefit-Cost Ratio of 1.17 to 1.18, but this should be considered cautiously before recommending it as a viable alternative because of fragility of the plastic to sustain heat and handling. For all the periods of 6-10 years with all discount rates used, the hermetic bagging methods had Benefit-Cost Ratio >1, and thus, the alternatives were good in which to invest. At Year 8 and 10 and with all the discount rates, hermetic bags for storage were good alternatives in which to invest because the Benefit-Cost Ratio was >1.20. Double and triple bagging tended to have the same Benefit-Cost Ratio for all periods and discount rates. Results showed that hermetic storage methods could be used as alternatives to polypropylene bags for reducing weight loss.

Benefit-Cost Analysis showed that hermetic storage methods would be more acceptable to use than a polypropylene bag. Based on Benefit-Cost Ratio sensitivity analysis, triple bagging can be considered a good alternative to polypropylene bags. But, polyethylene bags cannot be used as an alternative if large quantities of sorghum grain must be stored. Hermetic methods (triple and double bags) were good alternatives to polypropylene bags, thus ensuring that large quantities of grain can be stored, resulting in more sorghum grain with good quality and generation of more revenue.

CHAPTER V

SUMMARY AND CONCLUSIONS

Beetles and moths damage 5-35% of stored products, especially in tropical countries. Control of storage insect pests relies on insecticide that causes human and environmental hazards, thus alternatives such as botanicals and hermetic storage are needed to effectively manage the pests. Research assessed strategies to better manage insect pests of stored sorghum grain.

Monitoring and sieving infested sorghum samples helped determine the occurrence of stored insect pests. Red flour beetles were dominant in all sorghum varieties sieved, with means of 14.9-16.9 beetles in three improved varieties of sorghum. *S. cerealella* was the only species in the two local red and white sorghums but was not in the other varieties. Traps evaluated were effective in detecting 10 insect pests in storage facilities. The 'Dome' Pheromone trap captured all 10 species, with largest means of 13, 10.0, and 6.0, respectively, for *T. castaneum*, *S. cerealella*, and *S. oryzae*. Compared to other traps, the water bottle trap caught 60% of the 10 storage species trapped in the 'Dome' Pheromone trap and 85% of the seven species in the sticky glue trap, respectively. Surveying the presence and using traps to assess diversity of storage insect pests are required to apply appropriate methods to prevent loss of stored grain.

Four botanicals were effective in controlling red flour beetles fed treated sorghum grain in Niger. Means of 1.5-2.0 adults died with 0.0125 and 0.025 g of powder of neem kernels, African locust bean, and hibiscus, but powder of baobab pulp was less effective after 7 days. A mean of 2.0 adults was killed by any botanical at a dose of 0.5 g. With 0.1 and 0.2 g of powder of neem, 2.5 red flour beetle adults were dead at 7 and 14 days. But 3.0 (Day 7) and 3.5 (Day 14) red flour beetles were killed by locust beans, which was greater than overall means of 1.8 and 2.5 at 7 and 14 days, respectively. At days 21 and 28 when 0.1 and 0.2 g of baobab pulp was applied to sorghum grain, greatest means of 3.5-4.0 red flour beetles were dead. With 0.1 and 0.2 g of neem applied to sorghum grain, the largest mean numbers of 4.0 and 4.5 red flour beetles were dead at 35 days. With nontreated sorghum, 0.9-1.5 adults were killed during time.

The greatest cumulative mean number of red flour beetles was 3.2 when neem kernel powder at a dose of 0.05 g was applied. As the dose increased from 0.05 to 0.1 g, neem kernel and African locust bean powders differed in potency for killing red flour beetles. Mean damage scores by red flour beetles were low (1.3-2.6 on a 1-5 scale) for botanical powder applied to sorghum grain compared to ≥0.1 g with a damage score of 3.9 for the check. With only 0.0125 g of neem and African locust beans, damage scores were 1.6 and 1.7, respectively. Overall, the number of beetles killed was proportional to the dose of any botanical applied.

Efficacies of three botanicals were assessed to control maize weevils fed sorghum grain. Periodic counts of dead maize weevils differed significantly at days 2 and 4. With ≤0.1g, milkweed powder killed 1.3-1.8 maize weevils at Day 2, while mesquite killed only 1.5 by Day 4. At days 2 and 4, few weevils (≤0.8) died when neem bark was used.

Two to 2.3 weevils were killed by 0.1 and 0.2 g of neem bark at Day 6, and 2.0 were killed when 0.2 g of milkweed was applied. With 0.1 g of neem bark, 1.3 adult was killed, but fewer adults were dead with any dose of mesquite or milkweed at Day 8. At Day 10, only 0.5 adult was killed when 0.1 g of neem bark was applied to sorghum grain. At any dose, milkweed was more effective than any other botanical.

By Day 12, milkweed at 0.1 and 0.2 g killed 0.8 and 0.7 weevil. For mesquite, fewer adults were killed than by neem bark that killed 0.5 and 0.8 weevil at doses of 0.1 and 0.2 g. One and 0.8 weevil were dead at days 12 and 14 in the check. Until 14 days, neem bark acted slowly and killed 2.0 maize weevils when sorghum grain was treated with 0.05 g of powder.

The percentage of maize weevils killed differed and tended to be greater as the dose of any botanical increased. Cumulative percentages (93.8 and 90.6) of dead maize weevils were greatest with 0.2 g of milkweed and mesquite. With 0.1 g of mesquite, 87.5% adults were killed compared to milkweed (78.1%) or neem bark (65.6%). Percent mortality of weevils (78.1%) was greatest when sorghum grain was treated with 0.2 g of neem compared to doses of 0.05 and 0.1 g that killed 62.5 and 65.6%, respectively. Any dose of mesquite tended to kill more weevil adults fed sorghum grain. At any dose, the botanicals killed more than the check (12.5%).

When sorghum grain was treated with ≥0.1 g of milkweed or mesquite, the corrected mortality was 75.0 to 92.9%, respectively, of maize weevils killed compared to the check. Percent corrected mortality was 85.6% with 0.1 g of mesquite applied. Least corrected mortality (51.1%) was with 0.05 g of neem bark.

Significantly different amounts of grain damage and weight loss were calculated with all doses of botanicals. Both grain damage and weight loss were inversely proportional to the dose of botanical applied. Grain damage was greatest (50-60%) on sorghum grain treated with ≤0.1 g of milkweed or neem bark. Neem bark at 0.2 g reduced grain damage to 25.5% compared to 35.2 and 34.0% for mesquite and milkweed, respectively. On nontreated sorghum, grain damage of 68.6% was greater than for any treated sorghum.

For sorghum treated with neem bark at a dose of ≤0.1 g, grain weight loss was more (3-4%) than the 1.0-2.1% for mesquite and milkweed at the same dose. Grain weight loss was only 0.8% when maize weevils were fed 0.2 g of mesquite or milkweed. Percentages of grain damage and weight loss were 68.4 and 3.9% for the nontreated check.

Damage scores differed significantly among botanicals at the three doses. On sorghum grain treated with 0.05 and 0.1 g of mesquite and milkweed, mean damage scores were 3.0 and 2.5, respectively, while neem bark at the same doses resulted in large damage scores of 4.0 and 2.7. At a dose of 0.2 g, mean damage scores were 1.5 and 1.8 when mesquite and milkweed were applied to sorghum grain. Any botanical applied at any dose considerably reduced damage scores to less than the mean score of 3.5 for the check.

With Pearson correlation coefficients calculated by simple linear correlation analysis, the relationships among variables (percentages of adult mortality, corrected mortality, grain damage, grain weight loss, and damage score) were classified. Correlation coefficients showed that an increase in percentage of adult mortality was followed by an increase in percent corrected mortality. When more weevils died, the greater percentage of adult mortality and percentage of corrected mortality resulted in less percentages of grain damage and weight loss and damage score. An increase in the percentage of grain damage caused an increase in the percentage of grain weight loss and damage score. An increasing percentage of grain weight loss led to an increased damage score.

Regression (Probit) analysis of the cumulative mean number of maize weevils killed was used to calculate similar lethal doses of 0.02 (LD_{50}) and 0.2 g (LD_{90}) for mesquite and milkweed required to kill 50 and 90% of maize weevils. But, doses of mesquite and milkweed needed to kill 99% of maize weevils were slightly different, with LD_{99} of 0.83 and 0.89 g, respectively. More neem was required for effective lethal doses of 0.04, 0.26, and 1.27 g to kill 50, 90, and 99% of maize weevil adults.

Assessing better hermetic storage methods showed that after 7 days, means of about 8.0 red flour beetles were killed when triple or double bags were used. The means were greater than the 1.2 red flour beetle when a polypropylene bag was used and less than the overall mean of 5.2. Mean numbers of 10.6, 9.0, and 8.2 rice moths were killed when a double bag, clear plastic bucket, and triple bag were used for 7 days. Means were greater than the overall means of 6.8 (Day 7) and 8.1 (Day 14) rice moths killed. When a triple bag was used for 14 and 21 days, 3.8 adults were killed, which was the same as the overall mean for the same period. For a polyethylene bag, means of 3.6 and 3.0 beetles were killed compared to greater means of 4.2 and 6.2 adults dead in double bags after 14 and 21 days.

Fewer rice moths were dead at 21 days, with 6.8, 5.0, and 4.6 dead in the clear plastic bucket, triple bag, and double bag. At 28 days, 3.8 and 3.2 adults were dead in the triple and double bags. At 28 and 35 days, few (2.2 and 0.4) moths were dead in the polypropylene check. When a polyethylene bag was used, 3.0 adults were dead at 35 days, while only 1.2-2.2 adults were dead at 28 or 35 days in other storage methods. At 35 days, 2.5 rice moths were dead in the double bag. For the clear plastic bucket and polyethylene bag, 2.2-2.7 moths were dead at 28 and 35 days.

Means of surviving adults differed significantly for red flour beetles and rice moths in hermetic storage. With polypropylene and polyethylene bags, 8.0 and 25.2 red flour beetles and 21.6 and 33.2 rice moths were alive on sorghum stored 35 days. Many moths survived in the triple bag (21.8) and clear plastic bucket (28.6). Overall, double bagging resulted in less survival of both storage insect species, with means of 3.4 live red flour beetles and 9.6 rice moths surviving. Few adults survived in polypropylene or polyethylene bags.

A cost-benefit analysis assessed measures of project worth, Net Present Value and Benefit-Cost Ratio, to determine expected benefits from investing in hermetic storage. Simple linear regression determined grain weight loss per month was 0.81% for the polypropylene bag (check), 0.77% for a polyethylene bag, 0.72% for a double bag, and 0.69% for a triple bag. Linear trend equations had positive slope coefficients that indicated noticeable increases in percentage of grain weight loss during time.

Results of analysis of experimental data showed that for any hermetic bagging method, the incremental grain weight loss increased during time and was more after 12 months. The monthly incremental increase in grain weight loss was greater for the polypropylene bag (8.10) and polyethylene bag (7.70). Weight losses were reduced to 6.20 and 6.90 kg with double bagging and triple bagging, respectively. Overall, any alternative hermetic method reduced grain weight loss as compared to the commonly used polypropylene bags used to store sorghum grain.

Costs incurred from hermetic storage methods were calculated as the incremental cost of each method to store 1 ton of Grinkan sorghum seed for 1 year. When a polyethylene bag was used, the cost incurred per ton of sorghum grain was $15.00. Costs were $34.60 and $20.00 for triple bagging and double bagging methods, respectively.

The quantity of sorghum grain preserved and marketable was greater in a triple bag (917.20 kg), followed by a double bag (913.60 kg). With polypropylene and polyethylene bags, only 907.30 and 902.20 kg, respectively, were obtained. Monetary value ($) varied among the hermetic methods used to store 1 ton of Grinkan sorghum seeds for 1 year. When polypropylene and polyethylene bags were used, only $3,132.70 and $3,149.37, respectively, were generated. The triple bag preserved more sorghum grain and generated $3,182.68, which was $12.49 more than a double bag. Storing sorghum grain produced at the farm level helped generate only about 11.0% of revenue compared to marketing Grinkan sorghum seeds produced and stored at a research station.

Benefits differed among alternative hermetic storage methods and increased during time. When triple bagging was used, the benefit increased from $23.90 after 1 month to about $143.70 and 287.30 after 6 and 12 months, respectively, of storage. With double bagging of sorghum grain, the benefit accrued increased from $24.98 (1 month) to about $149.90 and 299.80 after storage for 6 and 12 months, respectively. With a polyethylene bag for storage, the benefit was $26.70 after 1 month. Benefits were $160.30 and 320.60, after 6 and 12 months respectively.

As compared to a polypropylene bag to store 1 ton of sorghum seeds, using a triple bag generated $52.10 as the greatest benefit. Instead of using a polypropylene bag, with a polyethylene bag and double bag, the benefits were $17.70 and 39.60, respectively. Benefits were $21.90 and 34.35 for the double bag and triple bag, respectively, as compared to a polyethylene bag. The benefit of a triple bag was $12.49 more than when a double bag was used for storage. Alternative hermetic methods helped generate more benefits than if common polypropylene bags were used for storage of sorghum grain.

Using a discount rate of 4.5% and 10-year investment period, the incremental Net Present Value from any hermetic bagging method was positive. The measures of project worth, Net Present Value and Benefit-Cost Ratio, were used to analyze expected benefits from investing in a hermetic storage method. A target Benefit-Cost Ratio >1 was set for any hermetic bagging method to be considered a good option. At Year 1 to 3, the polyethylene bag tended to have the least Net Present Value that decreased from $572.82 to 524.16, but this should be considered with caution when recommending it as an alternative because of fragility of the plastic to sustain heat and handling in storage. For all periods of 6-10 years with all discount rates used, the hermetic bagging methods had Benefit-Cost Ratio >1, and thus, the alternatives were good investments. The double and triple bagging methods tended to have the same Benefit-Cost Ratio for all periods and discount rates. For double and triple bagging after Year 6, the greatest Benefit-Cost Ratio of ≥1.2 was estimated with all discounting rates.

A sensitivity analysis was done for Benefit-Cost Ratio using three discount rates (4.5, 6.5, and 8.5%) with varying 2-year increment period during 10 years of investment. At Year 2 to 4, a polyethylene bag tended to have the lowest Benefit-Cost Ratio of 1.17 to 1.18, but this should be considered cautiously before recommending it as a good alternative because of fragility of the plastic to sustain heat and handling in storage. For all the periods of 6-10 years with all discounts rates used, the hermetic bagging methods had Benefit-Cost Ratio >1, and thus, the alternatives were good investments. At Year 8 and 10 and with all discount rates, hermetic bags for storage were good alternatives in which to invest because the Benefit-Cost Ratio was greater than 1.20. The double and triple bagging methods tended to have the same Benefit-Cost Ratio for all periods and discount rates. Results showed that hermetic storage methods could be alternatives to reduce weight loss compared to polypropylene bags that resulted in more loss in weight of sorghum grain during storage. The triple bag that resulted in greater Net Present Value at 4.5% discount and a Benefit-Cost Ratio of >1, seemed to be a good alternative to polypropylene bags. The triple bag was followed by the double bag that had the second-best Net Present Value and Benefit-Cost Ratio almost the same as that of a triple bag.

Results from the research indicated that valuable strategies exist and can be effective in controlling insect pests of stored sorghum grain. Botanicals and hermetic bags would be valuable for killing more adults and reducing survival of storage insects and grain weight loss to guarantee better grain quantity and quality.

A cost-benefit analysis assessed measures of project worth for producing, storing, and marketing Grinkan certified sorghum seed. Any hermetic method reduced grain weight loss, preserved more sorghum seeds/grains, and generated more benefits and revenue compared to commonly used polypropylene bags to store sorghum grain. Net Present Value and Benefit-Cost Ratio determined expected benefits from investing in triple bagging as the most viable alternative storage method. Additional research can complement the results, with possible topics identified in the following section.

Future Research

Monitoring and sieving infested sorghum samples helped determine the occurrence of six stored insect pests, with red flour beetle the dominant species. Results of evaluating three traps revealed they were effective in detecting diversity of as many as 10 insect pests in storage facilities. A water bottle trap caught 60% of 10 species of storage insect pests caught in a 'Dome' Pheromone trap and 85% of the seven species caught in a sticky glue trap. From the study, we suggest assessing more traps in different areas and recommend adopting the water bottle trap at the farm level.

Research on assessing efficacy of botanicals applied to sorghum grain controlled red flour beetles in Niger and maize weevils in Texas. Although the botanicals controlled stored insect pests, the powders tended to lose potency over time and might need to be reapplied. It is important to investigate the duration of toxicity and when to reapply botanical products. Other botanicals also should be evaluated for controlling insect pests infesting stored grain products. Plant-based extracts and/or oils need to be isolated and assessed for controlling storage insects. For powders and plant-based extracts/oils, it is important to study the biology (including longevity, fecundity, and reproduction) of storage insects fed treated sorghum grain. Studies should determine the properties of active ingredients and modes of action of botanicals. Other alternatives such as inert substances (ash, sand, and salt) should be tested to determine efficacy for controlling storage insect pests.

Hermetic storage methods assessed were effective in killing storage insect pests; fewer insects survived and grain weight loss was less. Results obtained can serve as a baseline for testing at the farm level and promoting use of hermetic bags to control primary and secondary storage insect pests of sorghum grain.

Other available simple hermetic storage methods should be tested for use by sorghum farmers. With hermetic storage methods tested, viability of seeds should be evaluated. Study of effects of environmental conditions should be included when testing hermetic storage methods.

Cost-benefit analysis assessed measures of project worth of production, storage, and marketing of Grinkan sorghum grain. Alternative hermetic storage methods, especially the triple bag reduced grain weight loss. Economic analysis showed hermetic storage had greater Benefit-Cost Ratio that suggested it is worth investing in using hermetic bagging instead of traditional polypropylene bags. More studies are needed using other storage methods to confirm the results obtained and extend economic analysis to sorghum produced and marketed by farmers.

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