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Efficacy of Selected Botanical Powders to Control Maize Weevil, *Sitophilus zeamais* Motschulsky in Stored Sorghum Grain

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Abstract

Increasing concern over the amount of insecticide residues in food has encouraged research for ecologically sound strategies to effectively manage stored-product insect pests and protect living organisms and the environment. Botanicals were evaluated as potential alternatives to control maize weevil, *Sitophilus zeamais* Motschulsky, in stored sorghum, *Sorghum bicolor* (L.) Moench. Beetles and moths of stored grain at farm and consumer levels damage 5 - 35% worldwide and >40% in tropical countries. Maize weevil is the most damaging storage insect of sorghum grain. Management of storage insects relies on insecticides that leave residues in food and the environment. Treatments were powders of neem bark, *Azadirachta indica*; mesquite pods, *Prosopis glandulosa*; milkweed leaves, *Asclepias speciosa*; and a check (no botanical powder). Eight newly emerged maize weevils were provided 5 g of Malisor-84 grain treated with three doses of each plant powder. Every 2 days, data were recorded on the number of adults killed by each treatment. Percentage killed was calculated by dose per treatment and compared with the check. Grain loss was calculated based on initial and final weights. LD_{50} was determined by probit analysis, and associations between variables were assessed by simple linear correlation. Powder of mesquite and milkweed at 0.2 g were more effective than neem or the check in killing *S. zeamais* (>90%) and reducing grain damage (34 - 35.2%) and weight loss (0.8%). Milkweed at 0.1 g and neem at 0.2 g killed 78.1% of weevils. Neem at 0.05 g was slow acting, resulting in 62.5% dead and more grain damage (59.5%) and weight loss (3.6%). Botanicals at low doses (LD_{50} = 0.2 - 0.4 g) showed efficacy in controlling maize weevils and are recommended alternatives to guarantee quantity and quality of stored cereal grains.

Keywords

Sorghum, Grain, Botanical Plants, Powder, Maize Weevil, *Sitophilus zeamais*, Lethal Dose

1. Introduction

Worldwide, >50% of sorghum, *Sorghum bicolor* (L.) Moench, is produced as a cash crop for domestic consumption or is used for animal feed [1]. However, in some regions, particularly in the semi-arid tropics and sub-Saharan Africa, sorghum is produced mostly for human food because it is the staple crop for the most food-insecure people in the world [2]. According to recent estimates by [3], 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 [4]. Although sorghum has a wide range of uses, including human food, animal feed, and production of alcoholic beverages and biofuel, grain yields at the farm level generally are low, partly because of damage by insect pests.

Beetles and moths are the most important insect pests of stored sorghum grain [5]. Most of the insects have short developmental times, high rates of development, and long lives. Damage is done by larvae, and controlling the costs 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.

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 [5]-[7]. Both the adults and larvae feed on grain, which often can be damaged beyond use [6]. Maize weevil adults are reddish brown, about 4 mm long, and have four light reddish or yellow spots on the wings [5] [6]. *S. zeamais* adults 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. She lays 300 - 500 eggs during her 4 - 5 months of life. The life Weevils can be managed by storing grain in dry, clean conditions in insect-proof containers [6]. Eggs hatch in 3 days. The larva is legless, short, stout, and whitish with a brown head, and matures in 3 - 6 days. There is five to seven generations a year. 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. cycle and early life stages are the same as those of the rice weevil [7].

Post-harvest damage by stored-product insect pests reduces cereal grain quality and quantity in Niger and West Africa [8]. Alternative methods of insect pest management in stored grain are practiced independently of or in combination with gaseous insecticides. Quantitative and qualitative damage caused by insect pests to the stored grain and the grain products can amount to 20% - 30% in the tropics and 5% - 10% in the temperate zone [9] [10]. To control storage insect pests, most farmers relied on insecticides, hermetic bagging, and application of botanical products without scientifically based formulations. Increasing concern over the amount of insecticide residues in food has encouraged researchers to look for alternatives to synthetic insecticides. Generally, insecticides are used to manage stored-grain insect pests [11]. But insecticides are costly and toxic to living organisms and the environment. Insecticide residues in grain may be harmful to consumers, and over-dependence on insecticides increases the potential to select resistant strains of insect pests. Ecologically sound strategies are needed to effectively manage stored-product insect pests and protect non-target organisms, and the environment.

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 [12]. 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.

The objective of this study was to assess the efficacy of selected botanical plant powders as alternative for 0 control of maize weevil in stored sorghum grain to obtain quantity, high quality of stored cereal grains and earn more revenues with low investment in control strategy.

2. Materials and Methods

The experiment was done at room temperature (27 - 28˚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 botanical plants known to have some natural toxicities were purchased from commercial botanical gardens through the Internet. The powders were stored in polyethylene bags that were sealed to prevent quality loss.

A colony of maize weevil adults was maintained in multiple 0.95-liter glass jars in the 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 weevil adults were available to infest sorghum kernels treated with botanical powder. 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 powder) and powder of three botanicals (neem bark, mesquite pods, and milkweed leaves). The experimental setup 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 × 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, 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 *S. zeamais* 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.

Other data recorded included the number and weight of damaged grains and the number and weight of non-damaged 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 correction formula was used to calculate mortality by using Equation (1) [13].

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

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).

Damaged grain 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):

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

Grain weight loss was calculated using the count and weight method of [14] as expressed in Equation (3):

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

where Wu = weight of non-damaged grains, Wd = weight of damaged grains, Nu = number of non-damaged 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 [15] 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.

3. Results and Discussion

3.1. 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 1**). 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 on 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 on Day 2, while it was not until Day 4 that mesquite powder killed 1.5 adult. On days 2 and 4, few adults (≤0.8) were killed by neem bark at any dose.

Mean numbers of dead maize weevils 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 1**). 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. On 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 on Day 8, but 1.3 adult was killed when sorghum grain was treated with 0.1 g of neem bark. On 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. On 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.

Table 1. Means ± SE of maize weevil adults killed per treatment by dose over time, Canyon, Texas.

		Days after treatment								
Botanicals	Dose (g)	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 ± 0.0c	0.0 ± 0.0e	0.0 ± 0.0e	0.0 ± 0.0c	0.0 ± 0.0b
	0.1	0.8 ± 0.1c	1.5 ± 0.9c	0.5 ± 0.2d	0.0 ± 0.0e	0.0 ± 0.0c	0.5 ± 0.2c	0.5 ± 0.2c	0.3 ± 0.1ab	0.0 ± 0.0b
	0.2	1.8 ± 0.4a	2.8 ± 1.1a	1.0 ± 0.1c	0.7 ± 0.3b	0.0 ± 0.0c	0.3 ± 0.1	0.0 ± 0.0e	0.0 ± 0.0c	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 ± 0.2a	0.3 ± 0.1d	0.0 ± 0.0e	0.3 ± 0.2ab	0.3 ± 0.1a
	0.1	1.8 ± 0.3a	0.8 ± 0.4d	1.0 ± 0.4c	0.8 ± 0.2b	0.3 ± 0.1ab	0.8 ± 0.2b	0.8 ± 0.3d	0.3 ± 0.1ab	0.0 ± 0.0b
	0.2	1.8 ± 0.5a	1.5 ± 0.3c	2.0 ± 0.5b	0.5 ± 0.2c	0.3 ± 0.1ab	0.7 ± 0.2b	0.0 ± 0.0e	0.0 ± 0.0c	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 ± 0.0c	0.0 ± 0.0e	2.0 ± 0.8a	0.5 ± 0.2a	0.0 ± 0.0b
	0.1	0.0 ± 0.0e	0.3 ± 0.1ef	2.0 ± 0.8b	1.3 ± 0.6a	0.5 ± 6.3a	0.5 ± 0.3c	1.0 ± 0.4b	0.0 ± 0.0c	0.0 ± 0.0b
	0.2	0.3 ± 0.1d	0.0 ± 0.0g	2.3± 0.9a	0.8 ± 0.4b	0.0 ± 0.0c	0.8 ± 0.2b	0.8 ± 0.3d	0.0 ± 0.0c	0.0 ± 0.0b
Check	-	0.0 ± 0.0e	0.5 ± 0.2de	0.3 ± 0.1de	0.5 ± 0.1c	0.0 ± 0.0c	1.0 ± 0.2a	0.8 ± 0.1d	0.5 ± 0.2a	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 (± SE) with same letter in the same column are not significantly different ($P < 0.05$).

For any botanical, no significant difference ($F = 2.0$; df = 3,169; $p = 0.05$) was recorded for dead weevils on Day 12. Milkweed powder at doses of 0.1 and 0.2 g killed 0.8 and 0.7 adult weevils, respectively (Table 1). 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 were dead on days 12 and 14, respectively.

3.2. Percent Mortality (PM%) and Corrected Mortality (CM%) of Maize Weevils

Table 2 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.

Table 2. 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 ($P < 0.05$).

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%. The percentage of corrected mortality was 85.6% when sorghum grain was treated with 0.1 g of mesquite powder (Table 2). 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.

3.3. 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 3). Both grain damage and weight loss were inversely proportional to the botanical dose applied. Grain damage (49.7% - 59.5%) was greater on sorghum 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.

Table 3. 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 ($P < 0.05$).

From Table 3, 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 3**). 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.

3.4. 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 4**. The Pearson correlation coefficient between variables was interpreted according to [16]. 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 and 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 of 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 of 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 ($r = 0.42$, $p = 0.01$) 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 of 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.

Table 4. 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.

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 5**). 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 results obtained showed that lower doses (0.02 - 1.27 g) were needed to kill 50% (LD_{50}) and 99% (LD_{99}) of maize weevils.

Table 5. Probit analysis of cumulative numbers of *Sitophilus zeamais* killed by amounts (LD_{50}, $LD_{90,}$ and LD_{99}) of botanical powders.

Botanical	Probit	LD_{50}, LD_{90} and LD_{99} amount (g)	95% confidence limit	
			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 $\alpha = 0.05$.

4. Discussion

Results of the study indicated that efficacy of the botanical powders decreased over time, as shown by fewer dead weevils on Day 12. Use of the three botanicals killed many weevil adults in our study because the powder might have acted as a physical barrier between weevils and grains. This supported farmers' statements as reported by many authors that applied botanical plant materials served as protection to prevent storage insects from causing damage to stored products or foods. According to [17], the powder tended 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* [18]. 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 [19]. The main advantage of botanicals is that they are produced easily by farmers and small-scale industries and are potentially less expensive [20]. Powdered plant extracts act by dehydrating, suffocating, and reducing movement of weevils, thereby resulting in less grain damage and weight loss [21] [22]. According to [20], 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 are one of the most important locally available, biodegradable, and inexpensive methods for controlling stored-grain pests [23].

The study assessing the efficacy of botanical powders showed good potential insecticidal activity against maize weevil. Targeted insects showed anti-feeding or avoidance behavior against feeding on sorghum grains treated with powder of botanicals at greater doses. This is in accordance with the reports by [23] and [24] that 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. Many plants are biodegradable and impose low residue risks to food crops, drinking water, soil flora and fauna. Botanicals for continuous protection against maize weevils might need to be reapplied as indicated by [25] and by BioSafe® Systems (M. Campos personal communication in 2019 that concluded the need for reapplication of botanicals in their studies. 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. 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.

The three botanicals killed more than did basil powder tested by [26]. 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 [26].

In this study, 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. [27] and [28] reported that botanical treatments are especially relevant during post-harvest storage of commodities by small-scale farmers. They implied that, in developing countries, botanicals have advantages over synthetic pesticides because they are collected locally and can provide inexpensive pest control during storage.

5. Conclusion

To control the storage of insect pests, most farmers relied on insecticides, hermetic bagging, and the application of botanical products without scientifically based formulations, as reported in [8]. Insecticides were known to be costly and toxic to living organisms and the environment, whereas botanical products when applied in very low quantities are biochemicals that efficiently reduce abundance of pests. The results obtained in this study helped to reach the overall research goal of evaluating the efficacy of botanical powders as an alternative and effective for the control of maize weevil in stored sorghum grain. This could contribute to environmental protection, which is meaningful to humans. Further study is needed to evaluate the active substances contained within the tested botanicals and synthesize them as oils or other sub-products (powder, extract) to be used in controlling storage insect pests to obtain quantity, high quality of stored cereal grains and earn more revenues with low investment in the control strategy.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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