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Efficacy of Filter Cake and Triplex Powders Against Three Internally Developing Stored-product Insect Species

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Abstract: Filter cake and Triplex powders from Ethiopia were applied to maize and wheat in the laboratory to determine efficacy against the lesser grain borer, *Rhyzopertha dominica* (Fabricius) (Coleoptera: Bostrichidae); maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae); and rice weevil, *Sitophilus oryzae* (Linnaeus) (Coleoptera: Curculionidae). These species are major insect pests associated with stored grain in Ethiopia. Efficacy of the two powders was determined by exposing 20 adults of each species to 100 g of maize and wheat treated with 0, 0.3, 0.5, 0.7, 1, 2, 3, 4 and 5 g/kg of filter cake, and 0, 0.5, 0.7, 1, 2, 3, 6, 8 and 10 g/kg of Triplex. Adult mortality was determined 14 d after exposure to untreated and treated grain. Adult progeny production at each species-powder-concentration combination was determined at 42 d. Complete mortality (100%) of *R. dominica* was achieved on maize treated with 3–5 g/kg of filter cake; however, on maize 100% mortality of *S. zeamais*, and *S. oryzae* was not achieved at any of filter cake concentrations. Complete mortality of *R. dominica* adults was observed on wheat treated with 2–3 g/kg of the filter cake. Complete mortality of *S. zeamais* and *S. oryzae* was achieved when adults were exposed to wheat treated with 0.7–3 g/kg of filter cake. Mortality was less than 100% at all Triplex concentrations on maize and wheat for all three species. Adult progeny production of *R. dominica* was wholly suppressed at filter cake concentrations of 1–5 g/kg on maize, whereas progeny production of *S. zeamais* and *S. oryzae* on maize was not entirely suppressed at any of the filter cake concentrations. No progeny of *R. dominica* was observed on wheat treated with 2–3 g/kg of filter cake. Similarly, progeny production of *S. zeamais* and *S. oryzae* was completely suppressed on wheat treated with 3 g/kg of a filter cake. Complete suppression of progeny production of the three species was not achieved at any concentration of Triplex on both maize and wheat. These powders have potential in managing *R. dominica*, *S. zeamais*, and *S. oryzae* infesting maize and wheat.

Keywords: Filter Cake, Triplex, Maize, Wheat, *Rhyzopertha dominica*, *Sitophilus* Species, Efficacy Assessment

1. Introduction

Most of the sub-Saharan African countries store their grains in traditional structures which are not insect proof [1, 2]. Post-harvest losses of dry durable commodities in sub-Saharan Africa are estimated to range from 20-40% [3]. Losses up to 50% in cereals and 100% in pulses have been reported, although average losses stand at about 20% [2]. Grain storage losses in Ethiopia due to insect pests were estimated to be in the range of 10-21% [1], consistent with losses in other sub-Saharan countries. Tefera and his colleagues [4] reported the post-harvest loss in Ethiopia to range from 20 to 30%. Major insects that contribute to post-harvest loss of cereals and pulses in Ethiopia include grain weevils, grain borers, grain beetles, and grain moths [1, 2]. The lesser grain borer, *Rhyzopertha dominica* (Fabricius); maize weevil, *Sitophilus zeamais* Motschulsky; and rice weevil, *Sitophilus oryzae* (Linnaeus) are cosmopolitan insect pests [5], and are considered as primary insect pests of stored grains in Ethiopia [1, 2, 6].

Application of chemical pesticides has been recommended to protect stored grain from insect pests. However, farmers in Ethiopia reported keeping their grains in stores infestationfree was difficult because of the ineffectiveness of pesticides approved for grain treatment [7]. Despite the use of pesticides, Ethiopian smallholder farmers reported that their storages had become severely infested with weevils. In addition, Ethiopian smallholder farmers are confronted with many problems related to unsafe handling and use of pesticides due to improper training in safe use of pesticides, and inadequate infrastructure to regulate safe use of pesticides [8].

Therefore, safe and non-chemical alternatives should be explored for use by smallholder farmers to reduce hazards related to pesticides. New non-chemical technologies such as Purdue Improved Crop Storage (PICS) bags, GrainPro Super bags, plastic drums, and metal silos were introduced in sub-Saharan Africa to protect smallholder farmers' stored commodities [9 – 11]. In addition to these new technologies, some inert dusts such as clay, sand, ground phosphate, ash, diatomaceous earth were in use in Africa [12 – 15]. Inert dusts are dry dusts that are chemically unreactive [15, 16], and are identified as alternatives to chemical pesticides [14]. Protection of stored grain from insect pests using inert dusts such as wood ash, lime, and sand has been practiced in Ethiopia [1]. Inert dusts are classified into different groups based on their physical and chemical composition [14, 17]. The first group consists of clay, sand, paddy husk ash and wood ash. The second group consists of minerals such as dolomite, magnesite, copper oxychloride, calcium hydroxide, calcium carbonate and common salt. The third group consists of dusts that contain synthetic silica (silicon dioxide). The last group consists of natural silica such as diatomaceous earth which are made up of fossilized skeletons of diatoms [14].

Silica based inert dusts exert their lethal effect on insects due to their ability to adsorb lipid from insect's epicuticle leading to death by desiccation [4, 13, 18]. Limited studies investigated different alternatives to chemical pesticides in Ethiopia [1, 19, 20]. Filter cake and Triplex available in Ethiopia were identified as two such alternatives to chemical pesticides. Filter cake and Triplex are by-products of aluminum sulfate and soap factories, respectively [19 – 22]. Filter cake and Triplex have a higher atomic percentage of silicon and oxygen in the form of silicon dioxide [21], and it is possible that the mode of action may be similar to other silica-based inert dusts. Complete mortality of *S. zeamais* adults was observed after exposure of adults for 24 h to 7.5 g/m^2 of filter cake on concrete arenas [21]. Complete mortality of *S. zeamais* and *S. oryzae* adults was reported after a 12 h exposure to 3–8 g/m^2 and 4–8 g/m^2 filter cake, respectively on concrete arenas [23]. Tadesse and Subramanyam reported significantly greater mortality and lower progeny production after exposure of *S. zeamais* and *S. oryzae* adults for 7 and 14 d to 0.1, 0.5, 0.7 and 1g/kg of filter cake or Triplex treated wheat [22]. However, there are limited data on the efficacy of filter cake and Triplex against internally developing stored-product insect pests at a range of concentrations applied to maize and wheat. Unlike our previous study [22], which used four concentrations of filter cake and Triplex (0.1, 0.5, 0.7 and 1g/kg), the present study used a range of filter cake and Triplex concentrations using powders that had particle sizes less than 177 µm applied to maize and wheat to characterize efficacy against *R. dominica*, *S. zeamais*, and *S. oryzae*.

2. Materials and Methods

2.1. Insect Rearing

Organic maize and hard red winter wheat (Heartland Mills, Marienthal, Kansas, USA) were cleaned manually using a 4.76 and 2.38 mm diameter round-holed aluminum sieves, respectively (Seedburo Equipment Company, Des Plaines, Illinois, USA), to remove broken kernels and dockage. The cleaned maize and wheat were frozen at -13°C for five days to kill any live insects present. A 400 g cleaned, untreated maize with a moisture content of 13.5% (wet basis) was transferred to each of the six 0.95 L glass jars. One hundred unsexed adults of mixed ages of laboratory strains of *R. dominica*, *S. zeamais*, and *S. oryzae* were transferred to separate glass jars.

Similarly, 400 g of cleaned organic wheat with a moisture content of 12% (wet basis) was transferred to each of the six 0.95 L glass jars. One hundred unsexed adults of mixed ages of laboratory strains of *R. dominica*, *S. zeamais*, and *S. oryzae* were transferred to separate glass jars. All glass jars containing the grain and insects were covered with filter paper and wire-mesh screen lids to facilitate air diffusion. The originally added adults were removed after 14 d of incubation in an environmental growth chamber (Percival Scientific, Inc., Model I-36VL, Perry, Iowa, USA) maintained at 28°C and 65% r.h. These jars were checked after six weeks to obtain newly emerged adults for use in bioassays.

2.2. Concentration Response Tests

A 100 g of cleaned, untreated maize and wheat with moisture contents 13.5 and 12.5% (wet basis), respectively, were transferred to separate 0.45 L glass jars, and jars were covered with filter paper and wire-mesh screen lids to facilitate air diffusion. A brass frame steel US standard sieve #80 (mesh size of 177 µm) (Seedburo Equipment Company) was used to sift filter cake and Triplex powders. Powders that passed through the sieve were used to treat maize and wheat in glass jars. Filter cake concentrations of 0 (untreated maize), 0.3, 0.5, 0.7, 1, 2, 3, 4 and 5 g/kg were added to separate jars containing maize, and Triplex concentrations of 0 (untreated maize), 1, 2, 3, 6, 8, and 10 g/kg were added to separate jars containing maize. Similarly, filter cake concentrations of 0 (untreated wheat), 0.3, 0.5, 0.7, 1, 2, and 3 g/kg were added to separate jars containing wheat. Triplex concentrations of 0 (untreated wheat), 0.5, 07, 1, 2, and 3 g/kg were added to separate jars containing wheat. Each jar was manually shaken for one minute to ensure uniform distribution of powders on maize and wheat kernels.

2.3. Addition of Insects to Jars

Insects reared on maize were used in all tests using maize, and those reared on wheat were used in all tests using wheat. Twenty unsexed, newly emerged adults of *R. dominica* were transferred to separate jars containing maize treated with 0, 0.3, 0.5, 0.7, 1, 2, 3, 4 and 5 g/kg of filter cake, and 0, 1, 2, 3, 6, 8 and 10 g/kg of Triplex. Another 20 unsexed newly emerged adults of *R. dominica* were transferred to separate jars containing 0, 0.3, 0.5, 0.7, 1, 2 and 3 g/kg of filter cake, and 0, 0.5, 0.7, 1, 2 and 3 g/kg of Triplex treated wheat. Similarly, 20 adults of each of *S. zeamais* or *S. oryzae* were transferred to maize treated with 0, 1, 2, 3, 4, and 5 g/kg of filter cake, and 0, 1, 2, 3, 6, 8 and 10 g/kg of Triplex. Twenty adults of *S. zeamais* or *S. oryzae* were transferred to wheat treated with 0, 0.3, 0.5, 0.7, 1, 2 and 3 g/kg of filter cake, and 0, 0.5, 0.7, 1, 2 and 3 g/kg of Triplex. All jars containing grain and insects were kept at 28°C and 65 % r.h. for 14 d to determine mortality. Separate jars were used for each species-grain-powder-concentration combinations with three replications. After a 14 d exposure, maize and wheat samples from each jar were sifted using a 4.76 and 2.38 mm circular round-holed aluminum sieves, respectively, to separate insects from the grain. Adults that did not respond when gently prodded with a Camel's hair brush were considered dead.

A separate experiment with the same species-grain-powder-concentration combinations as explained above was set up and held in an environmental chamber at 28°C and 65% r.h to determine adult progeny production. The progeny produced was counted from each jar after 42 d.

2.4. Data Analysis

The number of adults that died at 14 d was reported as a percentage. The mean ± SE mortality of *R. dominica* adults on untreated maize was 1.6 ± 1.6 and 0% in tests with filter cake and Triplex, respectively. Mortality of *R. dominica* adults on untreated wheat was 0%. The mean ± SE mortality of *S. zeamais* adults on both untreated maize and wheat was 0 and 1.6 ± 1.6% in tests with filter cake and Triplex, respectively. The mean ± SE mortality of *S. oryzae* adults on untreated maize was 1.6 ± 1.6 and 3.3 ± 3.3% in tests with filter cake and Triplex, respectively. Therefore, in cases where mortality on untreated maize or wheat was higher than 0%, mortality data of each species exposed to filter cake and Triplex treated maize and wheat were corrected for responses in the control treatment [24]. Uncorrected and corrected mortality data were transformed to angular values [25] to normalize heteroscedastic treatment variances. Adult progeny production was determined after subtraction of the 20 added adults initially. Adult progeny production data was transformed to $\log_{10}(x+1)$ scale [26] to normalize heteroscedastic treatment variances. However, untransformed mortality and adult progeny data are presented in tables. Corrected mortality and progeny production data were subjected to three-way analysis of variance (ANOVA) to determine significant differences ($P < 0.05$) of main (concentration, species, and grain), and interactive effects (27). Data on corrected mortality and progeny production were later subjected to one-way ANOVA to determine significant differences ($P < 0.05$) among concentrations and grains, and means were separated by Ryan-Einot-Gabriel-Welsch multiple range test (REGWQ) (27).

3. Results

3.1. Mortality Responses of Insects at Different Concentrations of Filter Cake and Triplex

Three–way ANOVA showed that the mortality due to the main effects of concentration ($F = 7.46$, df = 10, 206) and grain ($F = 49.32$, df = 1, 206) were significant ($P < 0.0001$), whereas significant differences in mortality were not observed among species ($F = 2.88$; df = 2, 206; $P = 0.0588$). The mortality differences due to the associated interactions: concentration × grain ($F = 2.32$; df = 5, 206; $P = 0.0453$) and species × grain ($F = 3.56$; df = 2, 206; $P = 0.0307$) were also significant. All the remaining two and three way interactive effects were not significant (F, range = 0.32 to 1.3; df = 4, 206 and 20, 206; P, range = 0.1762 to 0.8669).

The mean ± SE mortality of *R. dominica* adults exposed to filter cake treated maize ranged from 2.3 ± 1.1 to 100% and those exposed to Triplex treated maize ranged from 0 to 45.0 ± 5.8%. Complete mortality of *R. dominica* was observed when adults were exposed to maize treated with 2–5 g/kg of filter cake. However, mortality of adults was less than 50% at the highest concentration of Triplex (10 g/kg).

The mean ± SE mortality of *R. dominica* adults exposed to filter cake treated wheat ranged from 73.3 ± 4.4 to 100%, and those exposed to Triplex treated wheat ranged from 40.0 ± 10.4 to 83.3 ± 4.4%. Complete mortality of adults was achieved when they were exposed to 2 and 3 g/kg of filter cake treated wheat, whereas the mortality was 83.3% at the highest concentration of Triplex (3 g/kg).

In tests with maize, one-way ANOVA showed significant differences in mortality of *R. dominica* among concentrations of filter cake ($F = 79.69$; df = 7, 23; $P < 0.0001$) and Triplex ($F = 8.78$; df = 5, 17; $P = 0.0011$). In tests with wheat, one–way ANOVA showed significant differences among concentrations of filter cake ($F = 12.47$; df = 5, 17; $P = 0.0002$) and Triplex ($F = 5.78$; df = 4, 14; $P = 0.0113$). Mortality of *R. dominica* adults was significant between maize and wheat treated with 0.3 and 0.5 g/kg of filter cake ($F = 13.55$; df = 1, 5; $P = 0.0212$ at 0.3 g/kg, and $F = 131.38$; df = 1, 5; $P = 0.0003$ at 0.5 g/kg). However, no significant differences were observed in *R. dominica* adult mortality at each of the remaining concentrations between maize and wheat (F, range between grains = 0.58–1.0; df = 1, 5; P, range = 0.3739–0.9955) (Table 1). Significantly greater mortality of *R. dominica* was observed when adults were exposed to Triplex treated wheat at concentrations of 1, 2, and 3 g/kg compared to those exposed to similar concentrations on maize (F, range between grains = 51.89–75.56; df = 1, 5; P, range = 0.0010–0.0020) (Table 2).

The mean ± SE mortality of *S. zeamais* adults exposed to maize treated with filter cake and Triplex ranged from 50.0 ± 2.9 to 90.0 ± 2.9% and 2.8 ± 2.8 to 64.4 ± 2.9%, respectively. Complete mortality was not achieved when adults were exposed to maize treated with all concentrations of filter cake and Triplex. The mean ± SE corrected mortality of *S. zeamais* adults exposed to wheat treated with filter cake and Triplex ranged from 51.7 ± 10.9 to 100% and 57.6 ± 4.5 to 91.5 ± 3.4%, respectively. On wheat 100% mortality was achieved at filter cake concentrations of 0.7–3 g/kg, whereas adult mortality was 91.5% at the highest Triplex concentration of 3 g/kg.

On maize, one–way ANOVA showed significant differences in mortality of *S. zeamais* among concentrations of filter cake (F = 6.80; df = 4, 14; P = 0.0065) and Triplex (F = 31.93; df = 5, 17; P < 0.0001). On wheat one–way ANOVA showed significant differences in mortality among concentrations of filter cake (F = 31.35; df = 5, 17; P < 0.0001) and Triplex (F = 9.89; df = 4, 14; P = 0.0017). Significantly greater mortality of *S. zeamais* adults was observed in 1, 2, and 3 g/kg of filter cake treated wheat compared to those observed at the same concentrations on maize (F, range between grains = 17.23 –737.75; df = 1, 5; P, range < 0.0001 – 0.0143) (Table 1). Significantly greater mortality of *S. zeamais* adults was observed at Triplex concentrations of 1, 2, and 3 g/kg on wheat compared to adults exposed to similar concentrations on maize (F, range between grains = 82.62 – 173.47; df = 1, 5; P, range = 0.0002 – 0.0008) (Table 2).

Table 1. *Mortality of R. dominica, S. zeamais, and S. oryzae adults after a 14 d exposure to filter cake treated maize and wheat.*

Concentration (g/kg)	**Mean ± SE mortality (%) of:** [a, b]					
	R. dominica		***S. zeamais***		***S. oryzae***	
	Maize	**Wheat**	**Maize**	**Wheat**	**Maize**	**Wheat**
0.3	2.3 ± 1.1D,b	73.3 ± 4.4B,a	–[c]	51.7 ± 10.9B	–	41.7 ± 14.8B
0.5	55.9 ± 6.1C,b	80.0 ± 2.9B,a	–	96.7 ± 1.7A	–	93.3 ± 3.3A
0.7	84.7 ± 5.9B	90.0 ± 5.0AB	–	100.0 ± 0.0A	–	100.0 ± 0.0A
1	98.3 ± 1.7A	98.3 ± 1.7A	50.0 ± 2.9B,b	100.0 ± 0.0A,a	69.0 ± 3.0b	100.0 ± 0.0A,a
2	98.3 ± 1.7A	100.0 ± 0.0A	70.0 ± 12.6AB,b	100.0 ± 0.0A,a	79.3 ± 6.0b	100.0 ± 0.0A,a
3	100.0 ± 0.0A	100.0 ± 0.0A	76.7 ± 1.7AB,b	100.0 ± 0.0A,a	82.8 ± 8.6	100.0 ± 0.0A
4	100.0 ± 0.0A	–	85.0 ± 2.9A	–	82.8 ± 6.2	–
5	100.0 ± 0.0A	–	90.0 ± 2.9A	–	91.4 ± 8.6	–

[a] Means among concentrations within a commodity and species followed by different uppercase letters are significantly different (F, range = 6.80–79.69; df = 7, 23 for *R. dominica*; and 4, 14 for *S. zeamais* on maize; and 5, 17 for the remaining grain-species combinations; P, range < 0.0001 – 0.0065; one–way ANOVA with means separated by REGWQ multiple range test).
[b] Means between maize and wheat by species followed by different lowercase letters are significantly different (F, range = 13.55–635.10; df = 1, 5; P, range < 0.0001 – 0.0212; one–way ANOVA with means separated by REGWQ multiple range test).
[c] These concentrations were not tested.

Table 2. *Mortality of R. dominica, S. zeamais, and S. oryzae adults after a 14 d exposure to Triplex treated maize and wheat.*

Concentration (g/kg)	**Mean ± SE mortality (%) of:** [a, b]					
	R. dominica		***S. zeamais***		***S. oryzae***	
	Maize	**Wheat**	**Maize**	**Wheat**	**Maize**	**Wheat**
0.5	–[c]	40.0 ± 10.4B	–	57.6 ± 4.5B	–	56.7 ± 4.4C
0.7	–	41.7 ± 10.1B	–	78.0 ± 4.5A	–	70.0 ± 5.8BC
1	3.3 ± 1.7B,b	55.0 ± 5.8AB,a	2.8 ± 2.8B,b	86.4 ± 4.5A,a	32.2 ± 4.5C,b	85.0 ± 2.9AB,a
2	3.3 ± 1.7B,b	65.0 ± 5.8AB,a	10.2 ± 3.4B,b	88.1 ± 1.7A,a	57.6 ± 6.8BC,b	86.7 ± 6.0AB,a
3	5.0 ± 2.9B, b	83.3 ± 4.4A,a	11.9 ± 4.5B,b	91.5 ± 3.4A,a	57.6 ± 4.5BC,b	90.0 ± 2.9Aa
6	11.7 ± 1.7B	–	57.6 ± 4.5A	–	61.0 ± 4.5BC	–
8	16.7 ± 7.3B	–	61.0 ± 4.5A	–	79.7 ± 5.9B	–
10	45.0 ± 5.8A	–	64.0 ± 2.9A	–	94.9 ± 2.9A	–

[a]Means among concentrations within a commodity and species followed by different uppercase letters are significantly different (F, range = 5.78–31.93; df = 5, 17 for maize, 4, 14 for wheat; P, range < 0.0001 – 0.0113; one–way ANOVA with means separated by REGWQ multiple range test).
[b]Means between maize and wheat by species followed by different lowercase letters are significantly different (F, range = 9.92–173.47; df = 1, 5; P, range < 0.0001 – 0.0345; one–way ANOVA with means separated by REGWQ multiple range test).
[c]These concentrations were not tested.

The mean ± SE mortality of *S. oryzae* adults on maize treated with filter cake ranged from 69.0 ± 3.0 to 91.4 ± 8.6% and mortality of adults exposed to Triplex ranged from 32.2 ± 4.5 to 94.9 ± 2.9%. On maize, irrespective of the powder used, mortality of adults was less than 100% at all concentrations tested.

The mean ± SE mortality of *S. oryzae* adults on wheat treated with filter cake ranged from 41.7 ± 14.8 to 100% and those exposed to Triplex ranged from 56.7 ± 4.4 to 90.0 ± 2.9%. On filter cake treated wheat, 100% mortality was achieved at concentrations of 0.7–3 g/kg. However, the mortality of *S. oryzae* adults was 90.0% at the highest concentration of Triplex (3 g/kg).

On maize one–way ANOVA did not show significant differences in mortality of *S. oryzae* adults among concentrations of filter cake (F = 1.45; df = 4, 14 ; P = 0.2867). However, significant differences in mortality were found among concentrations of Triplex (F = 16.30; df = 5, 17; $P < 0.0001$). On wheat one–way ANOVA showed significant differences in mortality of *S. oryzae* adults among concentrations of filter cake ($F = 20.64$; df = 5, 17; $P < 0.0001$) and Triplex ($F = 8.02$; df = 4, 14; $P = 0.0037$). Significantly greater mortality of *S. oryzae* adult was observed on wheat at filter cake concentrations of 1 and 2 g/kg compared with mortality observed at similar concentrations on maize ($F = 332.02$; df = 1, 5; $P < 0.0001$ at 1 g/kg and $F = 37.03$; df = 1, 5; $P = 0.0037$ at 2 g/kg) (Table 1). Similarly, significantly greater mortality of *S. oryzae* adults on wheat was observed in 1, 2, and 3 g/kg concentrations of Triplex compared with mortality observed on maize at similar concentrations (F, range between grains = 9.92–91.34; df = 1, 5; P, range = 0.0008–0.0345) (Table 2).

3.2. Adult Progeny Production at 42 d

Three–way ANOVA showed that the progeny production was significantly different among concentrations ($F = 32.93$, df = 11, 251, $P < 0.0001$) and species ($F = 85.15$, df = 2, 251, $P < 0.0001$). However, progeny production between the two types of grains was not significant ($F = 1.15$; df = 1, 251; $P = 0.2839$). The concentration × grain interaction ($F = 10.26$; df = 6, 251; $P < 0.0001$) and species × grain interaction ($F = 14.64$; df = 2, 251; $P < 0.0001$) were significant. All of the remaining two way and three way interactive effects were not significant (F, range = 0.63 to 0.56; df = 6, 251 and 22, 251; P, range = 0.7101 to 0.9453).

The mean ± SE number of *R. dominica* adult progeny produced after 42 d of exposure to maize treated with filter cake ranged from 0 to 29.0 ± 9.6 adults per jar and those exposed to Triplex ranged from 1.0 ± 0.6 to 31.3 ± 8.8 adults per jar. More progeny were produced at lower than high concentrations of both powders. On maize, progeny production was not observed when adults were exposed to 1–5 g/kg of filter cake. However, on maize 100% reduction in progeny production was not achieved at any of the Triplex concentrations. The mean ± SE number of progeny of *R. dominica* produced after 42 d of exposure to wheat treated with filter cake ranged from 0 to 204.7 ± 26.1 adults per jar and those exposed to Triplex ranged from 5.3 ± 0.9 to 207.0 ± 10.7 adults per jar. On wheat, progeny production was not observed when adults were exposed to filter cake concentration of 2 and 3 g/kg. However, on wheat 100% reduction in progeny production was not achieved when adults were exposed to all Triplex concentrations.

On maize, one–way ANOVA showed significant differences in number of *R. dominica* adult progeny producted among concentrations of filter cake ($F = 15.77$; df = 8, 26; $P < 0.0001$) and Triplex ($F = 10.04$; df = 9, 29; $P < 0.0001$). On wheat, one–way ANOVA showed significant differences in *R. dominica* progeny production among concentrations of filter cake ($F = 20.96$; df = 6, 20; $P < 0.0001$) and Triplex ($F = 142.44$; df = 5, 17; $P < 0.0001$). Significantly less number of adult progeny of *R. dominica* was produced at higher concentrations of filter cake (Table 3) and Triplex (Table 4) compared to lower concentrations on both grains because of greater mortality at higher concentrations.

The mean ± SE number of *S. zeamais* adult progeny produced after 42 d of exposure to maize treated with filter cake ranged from 26.0 ± 8.7 to 201.0 ± 18.4 adults per jar and those exposed to Triplex ranged from 57.7 ± 3.5 to 192.7 ± 32.5 adults per jar, with the highest number of progeny being produced at lower than higher concentrations. On maize, complete suppression of *S. zeamais* progeny production was not achieved at all filter cake and Triplex concentrations. The mean ± SE number of *S. zeamais* progeny produced after 42 d of exposure to wheat treated with filter cake ranged from 0 to 587.7 ± 124.3 adults per jar and those exposed to Triplex ranged from 15.7 ± 3.2 to 672.0 ± 53.4 adults per jar, with the highest number of progeny being produced at lower than higher concentrations. On wheat, adult progeny production was entirely suppressed when adults were exposed to 3 g/kg of filter cake. However, on wheat, complete suppression of progeny production was not achieved when adults were exposed to all Triplex concentrations.

On maize, one–way ANOVA showed significant differences in *S. zeamais* adult progeny production among concentrations of filter cake ($F = 14.32$; df = 5, 17; $P = 0.0001$) and Triplex ($F = 20.94$; df = 6, 20; $P < 0.0001$). On wheat, one–way ANOVA showed significant differences in *S. zeamais* adult progeny production among concentrations of filter cake ($F = 34.41$; df = 6, 20; $P <0.0001$) and Triplex ($F = 80.81$; df = 5, 17; $P < 0.0001$). Significantly less number of adult progeny of *S. zeamais* were produced at higher than lower concentrations of filter cake (Table 3) and Triplex (Table 4) on both grains.

Table 3. *Number of adult progeny produced by R. dominica, S. zeamais, and S. oryzae after a 42 d exposure to filter cake treated maize and wheat.*

Commodity	Concentration (g/kg)	Mean ± SE number of adult progeny produced[a, b]		
		R. dominica	*S. zeamais*	*S. oryzae*
Maize	0	29.0 ± 9.6A,b	201.0 ± 18.4Aa	131.3 ± 19.7Aa
	0.3	4.7 ± 2.6B	–[c]	–
	0.5	3.0 ± 0.6B	–	–
	0.7	0.3 ± 0.3B	–	–
	1	0.0 ± 0.0B,c	66.7 ± 2.9B,a	20.3 ± 2.8B,b
	2	0.0 ± 0.0B,c	57.0 ± 3.2BC,a	14.3 ± 3.4BC,b
	3	0.0 ± 0.0B,c	34.7 ± 8.3BC,a	13.3 ± 4.8BC,b
	4	0.0 ± 0.0B,c	33.0 ± 7.8BC,a	7.7 ± 3.8BC,b
	5	0.0 ± 0.0B,b	26.0 ± 8.7C,a	5.0 ± 5.0C,b
Wheat	0	204.7 ± 26.1A,b	587.7 ± 124.3A,a	535.7 ± 29.2A,a
	0.3	100.3 ± 60.4AB	169.3 ± 26.3AB	204.0 ± 23.8AB

Commodity	Concentration (g/kg)	Mean ± SE number of adult progeny produced[a, b]		
		R. dominica	***S. zeamais***	***S. oryzae***
	0.5	54.7 ± 14.0AB	57.0 ± 19.5B	102.3 ± 33.2AB
	0.7	13.0 ± 6.2BC	31.3 ± 4.7B	64.3 ± 18.4BC
	1	1.7 ± 1.7CD	5.3 ± 2.7C	13.7 ± 5.4CD
	2	0.0 ± 0.0D	1.3 ± 1.3C	6.0 ± 3.8D
	3	0.0 ± 0.0D	0.0 ± 0.0C	3.7 ± 1.9D

[a] For each species, means among concentrations followed by different uppercase letters are significantly different (F, range = 8.07–34.41; df = 8, 26 for *R. dominica*, 5, 17 for *S. zeamais* and *S. oryzae* in maize, and 6, 20 for all species in wheat; P, range < 0.0001 – 0.0065; one–way ANOVA with means separated by REGWQ multiple range test).
[b] Means among species at each concentration followed by different lowercase letters are significantly different (F, range = 8.25–789.11; df = 2, 8; P, range < 0.0001 – 0.0189; one–way ANOVA with means separated by REGWQ multiple range test).
[c] These concentrations were not tested.

Table 4. *Number of adult progeny produced by R. dominica, S. zeamais, and S. oryzae after a 42 d exposure to Triplex treated maize and wheat.*

Commodity	Concentration (g/kg)	Mean ± SE number of adult progeny produced[a,b]		
		R. dominica	***S. zeamais***	***S. oryzae***
Maize	0	31.3 ± 8.8A,c	192.7 ± 32.5A,a	162.0 ± 2.5A,b
	0.3	17.7 ± 5.8AB	–[c]	–
	0.5	8.0 ± 1.2BC	–	–
	0.7	9.0 ± 2.6BC	–	–
	1	7.3 ± 2.4BC,b	120.7 ± 3.5B,a	77.7 ± 2.6AB,a
	2	6.7 ± 1.8BC,b	119.0 ± 8.9B,a	53.7 ± 24.0B,a
	3	5.3 ± 1.8BCD,c	103.3 ± 2.2BC,a	34.0 ± 9.5B,b
	6	4.3 ± 0.3BCD,c	101.0 ± 2.3BC,a	44.3 ± 3.9B,b
	8	2.0 ± 0.6CD,c	78.3 ± 6.9CD,a	32.3 ± 1.9B,b
	10	1.0 ± 0.6D,c	57.7 ± 3.5D,a	25.7 ± 4.9B,b
Wheat	0	207.0 ± 10.7A,b	672.0 ± 53.4A,a	656.3 ± 182.1A,a
	0.5	95.7 ± 8.1B,c	159.3 ± 10.2B,b	304.3 ± 55.9A,a
	0.7	44.3 ± 5.5C,b	129.6 ± 25.2BC,a	220.7 ± 52.8AB,a
	1	17.7 ± 2.0D,b	72.3 ± 2.0CD,a	81.0 ± 38.3BC,a
	2	8.3 ± 1.5E,b	58.0 ± 8.0D,a	27.7 ± 14.7CDa,b
	3	5.3 ± 0.9E	15.7 ± 3.2E	8.3 ± 2.0D

[a]For each species, means among concentrations followed by different uppercase letters are significantly different (F, range = 5.65–142.44; df = 9, 29 for *R. dominica*, 6, 20 for *S. zeamais* and *S. oryzae* in maize, 5, 17 for all species in wheat; P, range < 0.0001 – 0.0113; ; one–way ANOVA with means separated by REGWQ multiple range test).
[b] Means among species at each concentration followed by different lowercase letters are significantly different (F, range = 6.91–616.35; df = 2, 8; P, range < 0.0001 – 0.0278; ; one–way ANOVA with means separated by REGWQ multiple range test).
[c] These concentrations were not tested.

The mean ± SE number of *S. oryzae* adult progeny produced after 42 d of exposure to maize treated with filter cake ranged from 5.0 ± 5.0 to 131.3 ± 19.7 adults per jar and those exposed to Triplex ranged from 25.7 ± 4.9 to 162.0 ± 2.5 adults per jar, with the highest number of progeny being produced at lower concentrations. On maize, complete suppression of progeny production was not achieved at all concentrations of filter cake and Triplex. The mean ± SE number of *S. oryzae* adult progeny produced after 42 d of exposure to wheat treated with filter cake ranged from 3.7 ± 1.9 to 535.7 ± 29.2 adults per jar and those exposed to Triplex ranged from 8.3 ± 2.0 to 656.3 ± 182.1 adults per jar, with the highest number of progeny being produced at lower concentrations. On wheat, complete suppression of progeny production was not achieved at all filter cake and Triplex concentrations.

On maize, one–way ANOVA showed significant differences in *S. oryzae* adult progeny production among concentrations of filter cake (F = 8.07; df = 5, 17; P = 0.0015) and Triplex (F = 5.65; df = 6, 20; P = 0.0036). On wheat, one–way ANOVA showed significant differences in *S. oryzae* adult progeny production among concentrations of filter cake (F = 18.35; df = 6, 20; P <0.0001) and Triplex (F = 22.81; df = 5, 17; P < 0.0001). Significantly less number of adult progeny of *S. oryzae* was produced at higher than lower concentrations of filter cake (Table 3) and Triplex (Table 4) on both grains.

On maize, one–way ANOVA showed significant differences in adult progeny production among the species at all concentrations of filter cake (F, range among species = 8.25 to 789.11; df = 2, 8; P, range < 0.0001 to 0.0189) and Triplex (F, range among species = 13.40 to 616.35; df = 2, 8; P, range < 0.0001 to 0.0061). On wheat, one–way ANOVA did not show significant differences in adult progeny production among the species at all concentrations of filter cake (F, range among species = 0.83 to 3.62; df = 2, 8; P, range = 0.0794 to 0.4801;). On wheat, one–way ANOVA showed significant differences in adult progeny production among the species at all concentrations of Triplex (F, range among species = 6.91 to 17.31; df = 2, 8; P, range = 0.00032 to 0.0278; one–way ANOVA). In general, *R. dominica* produced less number of progeny on both grains treated with filter cake and Triplex compared to that of *S. oryzae* and *S. zeamais*.

4. Discussion

Our data demonstrated the efficacy of filter cake and Triplex against *R. dominica*, *S. zeamais*, and *S. oryzae* in response to powder concentrations and grain types. Admixing of powder with maize and wheat was done manually, where uneven distribution of powder particles over the maize and wheat kernel surfaces was more likely to occur. Accumulation of powder over the insect's body is directly proportional to the concentration of the powder [28], and insect's behavior such as mobility [29]. The toxicity of such powders will depend on particle accumulation from the maize and wheat on to the insect's body and adsorption of lipid from the insect's cuticle by the powder particles [28, 30]. Therefore, uneven distribution of filter cake and Triplex on maize and wheat might have contributed to unexplained variations in mortality and progeny production responses of the tested species.

We hypothesize that filter cake and Triplex have properties similar to silica-based inert dusts, because of their higher atomic percentage of silicon and oxygen in the form of silicon dioxide [21]. The proportion of silicon and oxygen as silicon dioxide in both filter cake and Triplex was less than that found in diatomaceous earth powders. Therefore, our results cannot be compared directly with the research done on diatomaceous earth powders by numerous researchers [31–36]. However, mortality of all tested species tended to increase with increasing filter cake and Triplex concentrations on maize and wheat. Similar results using diatomaceous earth dusts were reported by Athanassiou et al. [32, 33] and Arthur [31]. Several researchers suggested that the insecticidal efficacy of different diatomaceous earth was affected by grain type [32, 33, 37–40]. For example, Athanassiou et al. [33] reported that the susceptibility of *S. oryzae* to diatomaceous earth was lower in maize than wheat. A similar report indicated that *S. oryzae* adults were less susceptible to the diatomaceous earth SilicoSec® when exposed to treated maize compared to exposure on treated pearled rice and barley [32]. Kavallieratos et al. [38] reported significant differences in the mortality of *R. dominica* adults among eight grain types after a 14 d exposure to the diatomaceous earth dusts Insecto and SilicoSec® treated grains. They reported that mortality of *R. dominica* was higher in Insecto and SilicoSec® treated wheat compared to the rest of the grains. A similar phenomenon was observed in our experiment. We observed significantly higher mortality of *R. dominica*, *S. zeamais*, and *S. oryzae* adults exposed to filter cake and Triplex treated wheat compared to maize. Complete mortality of *R. dominica* adults was observed on maize and wheat treated with 3–5 and 2–3 g/kg of filter cake, respectively. Complete mortality of *S. zeamais* and *S. oryzae* adults was observed when adults were exposed to wheat treated with 0.7–3 g/kg of filter cake. A higher mortality of *R. dominica, S. zeamais* and *S. oryzae* adults was observed on wheat compared to maize at all concentrations of filter cake and Triplex.

Complete suppression of adult progeny production of *R. dominica* was achieved when adults were exposed to maize and wheat treated with 1–5 and 1–3 g/kg of filter cake, respectively. Although adults might have been killed by exposure to filter cake and Triplex some oviposition may still occur as these powders do not kill adults rapidly [22]. Therefore, progeny production was observed mainly at the lower powder concentrations tested. In our experiments, we found that progeny of *R. dominica*, *S. zeamais*, and *S. oryzae* were found dead on both maize and wheat treated with ≥ 1 g/kg of filter cake. However, complete suppression of adult progeny production was not achieved at any of Triplex concentrations on both grains. Adult progeny production tended to decrease with increasing filter cake and Triplex concentrations on both maize and wheat. The higher mortality of *R. dominica*, *S. zeamais*, and *S. oryzae* adults at increasing concentrations of filter cake and Triplex might have caused significant reduction in adult progeny production. A similar phenomenon was reported by Tadesse and Subramanyam [22] after a 42 d exposure of *S. zeamais* and *S. oryzae* adults to filter cake and Triplex treated wheat. Tadesse et al. [23] also reported a decreasing trend of *S. zeamais* and *S. oryzae* adult progeny production with an increase in concentration of filter cake and Triplex on concrete surfaces.

5. Conclusions

The present study showed that filter cake was consistently more efficacious against *R. dominica*, *S. zeamais* and *S. oryzae* compared to Triplex on both maize and wheat. Therefore, including filter cake and Triplex as part of an integrated pest management program in smallholder farmers' traditional storage structures will be useful to protect maize and wheat from *R. dominica*, *S. zeamais*, and *S. oryzae* infestations. Filter cake and Triplex can be used in combination with the Purdue Improved Crop Storage (PICS) bags, GrainPro Super bags, plastic drums, and metal silos. Field studies in Ethiopia need to be conducted in smallholder farmers' traditional storages, which include above-ground structures like gota and gotera, and underground pits to make recommendations to smallholder farmers.

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