Artículos

Post-Harvest Protection Strategies: Comparing Diatomaceous Earth and Spinetoram Against Key Storage Pests

Estrategias de protección poscosecha: Comparación de la tierra de diatomeas y el espinetoram contra las principales plagas del almacenamiento

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Abstract: Stored grain pests significantly threaten food security by causing both quantitative and qualitative losses during post-harvest storage. This study evaluated the insecticidal efficacy of diatomaceous earth (DE) and spinetoram (SPM) against *Trogoderma granarium* Everts (Coleoptera: Dermestidae), *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae), *Sitophilus oryzae* Linnaeus (Coleoptera: Curculionidae), and *Rhyzopertha dominica* Fabricius (Coleoptera: Bostrichidae), on wheat and rice grains under laboratory conditions. Treatments were applied at varying concentrations, and insect mortality was assessed at 1, 2, 7, 14, and 21 days, and progeny suppression was evaluated after 65 days of treatments application. Results revealed that spinetoram, particularly T7 (2.0 ppm), induced rapid and complete mortality (up to 100%) across all species and effectively suppressed progeny emergence. In contrast, DE, though slower in action, still achieved significant efficacy at T4 (300 ppm), reaching up to 86.67% mortality of *T. granarium* in treated wheat samples and caused substantial reductions in progeny production. Comparative analysis highlights spinetoram's superior performance in short-term pest suppression, while DE offeres a slow but more sustainable and environment-friendly pest management option. These findings not only highlight the potential of integrating chemical and non-chemical methods to manage stored grain insect pests but also offer valuable information regarding the selection and application of effective stored grain pest management approaches.

Keywords: Diatomaceous earth, Insect mortality, Integrated pest management, Progeny suppression, Spinetoram, Stored grain.

Resumen: Las plagas de granos causan pérdidas cuantitativas y cualitativas durante el almacenamiento poscosecha lo que amenaza la seguridad alimentaria. Este estudio evaluó la eficacia insecticida de la tierra de diatomeas (TD) y el espinetoram (SPM) contra *Trogoderma granarium* Everts (Coleoptera: Dermestidae), *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae), *Sitophilus oryzae* Linnaeus (Coleoptera: Curculionidae) y *Rhyzopertha dominica* Fabricius (Coleoptera: Bostrichidae), en granos de trigo y arroz en laboratorio. Se evaluó la mortalidad de los insectos a los 1, 2, 7, 14 y 21 días tratados a diferentes concentraciones. A los 65 días se evaluó la supresión de la progenie. Los resultados revelaron que SPM, particularmente en T7 (2,0 ppm), indujo una mortalidad rápida (hasta el 100%) en todas las especies y suprimió la emergencia de la progenie. Por el contrario, TD, de acción más lenta, logró una eficacia significativa en T4 (300 ppm), con un 86,67% de mortalidad de *T. granarium* en muestras de trigo tratadas. Así mismo redujo sustancialmente la producción de la progenie. El SPM suprimió las plagas más que TD a corto plazo. Aunque TD presentó acción más lenta, es más sostenible con el medio ambiente. Estos hallazgos aportaron conocimiento, integrando métodos químicos y no químicos, para la selección y el manejo eficaz de los sistemas de almacenamiento poscosecha.

Palabras clave: Espinetoram, Grano almacenado, Manejo integrado de plagas, Mortalidad de insectos, Supresión de progenie, Tierra de diatomeas.

INTRODUCTION

The damage of stored grains is a major concern globally, largely due to inadequate storage conditions and persistent insect pest infestations during storage and transport. While various pests contribute to this issue, species such as *Rhyzopertha dominica* Fabricius (Bostrichidae: Coleoptera), *Trogoderma granarium* Everts (Dermestidae: Coleoptera), *Tribolium castaneum* Herbst (Tenebrionidae: Coleoptera), and *Sitophilus oryzae* Linnaeus (Curculionidae: Coleoptera) are particularly destructive in stored wheat and rice. These pests are responsible for about 10-25% annual yield losses (Taddese et al., 2020). Commonly, organophosphates and pyrethroids have been primarily used for managing storage pests (Vassilakos & Athanassiou, 2023). Some of these insecticides exert neurotoxic effects by inhibiting acetylcholinesterase (AcHE) and disrupting the sensory function of the insects (Soderlund et al., 2002; Casida & Durkin, 2013). However, long-term reliance on these insecticides has led to the development of substantial resistance in pest populations (Morsy, 2021). Some insects have developed resistance against organophosphates (Wakii et al, 2021a) and pyrethroids (Daglish et al., 2024). Therefore, it is essential to develop and evaluate the efficacy of innovative compounds having diverse modes of action, which could present an alternative to conventional insecticides for better management of storage insect pests.

Among these pest control tactics, grain protectants such as diatomaceous earth (DE) have emerged as an excellent, sustainable, and non-synthetic alternative to chemical insecticides used for the management of stored grain insect pests (Atay et al., 2023). DE is derived from fossilized diatoms and composed of hydrated silica, which acts through physical desiccation of the insect cuticle and causes death by dehydration when it comes in contact with the body of the insects (Wakii et al, 2021b). However, DE can be easily removed from treated grains (Losic & Korunic, 2017) and is usually preferred for its low mammalian toxicity, long residual activity, and compatibility with other integrated pest management (IPM) programs (Zeni et al., 2021). The efficacy of DEs can be increased by combining them with natural substances. These include botanicals (Kavallieratos et al., 2015), baits (Kavallieratos et al., 2015), low-risk insecticides (Wakil et al., 2024), and biocontrol agents (Zeni et al., 2021).

On the other hand, spinetoram is an advanced spinosyn derived from the actinomycete *Saccharopolyspora spinosa* Mertz & Yao, 1990 (Actinomycetales: Pseudonocardiaceae) (Sparks et al., 2021). It targets the insect's nervous system by affecting the nicotinic acetylcholine (nACh) and gamma-aminobutyric acid (GABA) receptors (Sparks et al., 2012, Vassilakos & Athanassiou, 2023). It has been effectively used against different kinds of storage insect pests. It has broad-spectrum activity against primary and secondary storage pests such as *R. dominica* Fabricius, 1792 (Coleoptera: Bostrichidae), *T. castaneum* Herbst 1797 (Coleoptera: Tenebrionidae), and *Lasioderma serricorne* Fabricius 1792 (Coleoptera: Anobiidae) and has been validated under various environmental conditions (Vassilakos & Athanassiou, 2023). Moreover, spinetoram exhibits relatively low mammalian toxicity and high selectivity toward insect pests, with minimal risks to non-target organisms (Bacci et al., 2016). Similarly, diatomaceous earth, particularly food-grade formulations, are generally considered safe for mammals, including humans (Korunic, 1998). Inclusion of such agents in stored grain IPM programs thus offers both efficacy and safety under well-regulated conditions. Hence, it is evident that further studies should be conducted to investigate the novel insecticidal compound spinetoram and diatomaceous earth (DE) against stored grain insect pests.

Cereal grains are economically important, and there is increasing pressure to reduce pesticide residues. Therefore, the study aims to evaluate the bio-efficacy of diatomaceous earth (DE) and spinetoram (SPM) against Lesser grain borer (*R. dominica*), Khapra beetle (*Trogoderma granarium*), Red flour beetle (*T. castaneum*) in stored wheat, as well as Rice weevil (*S. oryzae*), Lesser grain borer (*R. dominica*), Red flour beetle (*T. castaneum*) collected from stored rice. The research was conducted to contribute toward safer, sustainable pest management practices aligned with global food safety standards.

MATERIALS AND METHODS

Tested Insects

Insects were collected from samples of wheat and rice grains exhibiting signs of insect infestation, such as grain holes, frass, and live insects, sourced from various grain storage facilities and local markets of Punjab, Pakistan. Samples weighing 1 to 2 kg were sealed and transported to the Insect Biodiversity and Biosystematics laboratory, Department of Entomology, University of Agriculture, Faisalabad (Pakistan) under ambient conditions for further processing and insect identification. Upon arrival, the samples were screened to isolate insect species and later stored under controlled temperature and humidity conditions (25 ± 2 °C and 65 ± 5% R.H.) until use in bioassays. *Rhyzopertha dominica* and *T. granarium* were reared on wheat, *T. castaneum* was reared on wheat flour composed of cracked wheat grains (Opit & Throne, 2014), while *S. oryzae* was reared on wheat and rice.

Diatomaceous Earth and Spinetoram formulations

The DE formulation used in the experiment was Diatoms Dust (99% food-grade diatomaceous earth; Detia Degesch, Germany). Similarly, spinetoram was applied in the form of Radiant 120SC, a soluble concentrate containing 80 ml/l of active ingredient (Arysta Life Sciences, Pakistan).

Bioassays

Wheat and rice were used in all bioassays. The experimental arena consisted of plastic cylindrical jars (200 ml), each containing 100 g of grain. Thirty insects (15 males and 15 females) were used per replicate in each treatment jar, with three independent replications of each treatment. The treatments consisted of DE at 0, 100, 200, and 300 ppm, and spinetoram at 0, 0.5, 1, and 2 ppm. The DE formulation was dusted on wheat and rice grains placed inside the plastic jars, manually agitated for 3-4 minutes to ensure uniform coating on all grains. In a separate treatment, 2ml of an aqueous spinetoram solution, at different concentrations, was sprayed onto the wheat and rice grains, forming a thin layer of pesticide on the grains. Subsequently, the treated grains were manually agitated for 3-4 min to achieve uniform insecticide spread throughout the grain mass. Three lots of wheat and three lots of rice were treated along with an untreated control. Later, 100 grams of grains were taken from each treated or untreated (control) lots. The 100 grams of treated or untreated grains were weighed with the G&G Elektronische Waage Model: JJ224BC digital balance (Kaarst Deutschland). The plastic jars were kept in a growth chamber at 25±2°C, 65±5% R.H. The openings of the plastic jars were closed with muslin cloth secured with rubber bands to allow adequate aeration. Adult mortality were recorded 1, 2, 7, 14, and 21 days after the application of treatments. Adults (dead or alive) were left under the same conditions, for further progeny emergence during 65 days. Bioassays corresponding to all tested insects in treated wheat and rice were conducted as mentioned above.

Statistical analysis

The mortality data were adjusted using Abbott's formula (Abbott, 1925):

Corrected mortality (%) = [1 - No. of insects in treated sample / No. of insects in the control sample] × 100

Later, the mortality data were subjected to one-way Analysis of Variance (ANOVA) to check the significance of the treatments as primary factors while considering mortality intervals as the response variable. Progeny production data were also subjected to one-way Analysis of Variance (ANOVA), considering treatments as the main effects while the number of progenies were the response variable. All the analyses were performed with R Studio (R 4.3.2 version) (R Core Team, 2025). Tukey Honest Significant Difference (HSD) test at the 5% significance level was used for the comparison of experimental treatments (Sokal & Rohlf, 1981).

RESULTS

The tables summarize the impact of diatomaceous earth (DE) at 100, 200, and 300 ppm (T2-T4) and spinetoram (SPM) at 0.5, 1.0, and 2.0 ppm (T5-T7), on adult mortality and progeny production of four key stored grain pests, *R. dominica*, *T. granarium, T. castaneum*, and *S. oryzae* in treated wheat and rice grains over different time intervals. The untreated control group (T1) exhibited 0% mortality at all time intervals (1, 2, 7, 14, and 21 days), and produced the highest progeny count for *R. dominica*, with 78.33±1.67 (f= 539.20, p< 0.001) individuals after 65 days (Table I, Figure 1), indicating ideal conditions for insect survival and reproduction. In the DE-treated groups, mortality increased progressively with both dosage and exposure duration. After 21 days, the mortality rate reached 81.75±4.16%, 87.38±2.61%, and 85.08±4.34% in T2 (100 ppm), T3 (200 ppm), and T4 (300 ppm), respectively (f= 164.53, p< 0.001). Correspondingly, progeny production declined with rising DE concentrations, with 13.00±1.00, 8.33±0.88, and 8.00±2.08 individuals recorded in the same treatments (f= 539.20, p< 0.001). The results indicated that DE has a moderate insecticidal effect, which was improved by both concentration and duration.

Table I

Mortality percentage and progeny of *Rhyzopertha dominica* reared on wheat grains treated with diatomaceous earth and spinetoram during different time intervals

Notes *%= percentage, SE= standard error, DE= diatomaceous earth, SPM= spinetoram, ppm= parts per million, f-value= F-ratio, p-value= probability value, *Significant (p ≤ 0.05), ns Non-Significant, means within the same column followed by different lowercase letters are significantly different at p< 0.05, according to Tukey's HSD (Honestly Significant Difference) test.*

Figure 1

Mortality percentage and progeny of *Rhyzoperthadominica* reared on wheat grains treated with diatomaceous earth and spinetoram during different times

Error bars represent the standard error of the mean (SEM). Different letters above the bars indicate statistically significant differences (p< 0.05) as determined by post hoc analysis (within time intervals)

In contrast, spinetoram treatments were noticeably more effective. At the lowest concentration (T5, 0.5 ppm), mortality reached 95.48±2.92% after 21 days (f= 164.53, p< 0.001), with progeny reduced to 2.00±1.15 individuals (f= 539.20, p< 0.001). Higher concentrations T6 (1.0 ppm) and T7 (2.0 ppm) reached

98.89±1.11% and 100±0.00% mortality, respectively, after 21 days ($f= 164.53$, $p< 0.001$), and both completely suppressed progeny production. These findings demonstrate that even at lower concentrations, spinetoram was highly effective against *R. dominica* and prevented adult survival and reproduction. Treatments with higher concentrations of both DE and spinetoram led to substantial reductions in *R. dominica* mortality and progeny production, with spinetoram exhibiting the most pronounced impact across all parameters.

Similarly, the DE and SPM treatments induced mortality and reduced progeny production of *T. granarium* on treated wheat grains across different time points (Table II, Figure 2). The untreated control (T1) exhibited no mortality across all time intervals, and a high progeny count (78.33±1.67 individuals) after 65 days ($f= 539.20$, $p< 0.001$), confirming optimal conditions for insect survival and reproduction. DE treatments demonstrated a dose and time-dependent increase in mortality. In T2, mortality reached 72.22±2.22% after 21 days ($f= 485.20$, $p< 0.001$), while higher doses, T3 and T4, reached 83.33±1.92 % and 86.67±1.92% mortality, respectively, after 21 days ($f= 485.20$, $p< 0.001$). This upward trend in mortality correlated with a decrease in progeny numbers, which dropped to 13.00±1.00, 8.33±0.88, and 8.00±2.08 individuals in T2, T3, and T4, respectively ($f= 539.20$, $p< 0.001$). The SPM treatments exhibited a stronger insecticidal effect even at lower doses. In T5, mortality reached 91.11±0.11 % after 21 days ($f= 485.20$, $p< 0.001$), with a significant reduction in progeny to 2.00±1.15 ($f= 539.20$, $p< 0.001$). Higher doses, T6 and T7, were more effective, achieved 96.67±1.92 % and 100±0.00% mortality after 21 days ($f= 485.20$, $p< 0.001$) and completely inhibited progeny production. These results confirm that spinetoram was highly lethal to *T. granarium* and prevented population growth when applied even at low concentrations. Overall, while DE showed a moderate but an increasing effect with dosage and time, spinetoram offers rapid and complete control of *T. granarium*, both in terms of adult mortality and reproduction suppression.

Table II

Mortality percentage and progeny of *Trogoderma granarium* reared on wheat grains treated with diatomaceous earth and spinetoram during different time intervals

Notes *%= percentage, SE= standard error, DE= diatomaceous earth, SPM= spinetoram, ppm= parts per million, f-value= F-ratio, p-value= probability value, *Significant (p ≤ 0.05), ^{ns} Non-Significant, means within the same column followed by different lowercase letters are significantly different at p< 0.05, according to Tukey's HSD (Honestly Significant Difference) test*

Figure 2

Mortality percentage and progeny of *Trogoderma granarium* reared on wheat grains treated with diatomaceous earth and spinetoram during different times

Error bars represent the standard error of the mean (SEM). Different letters above the bars indicate statistically significant differences ($p < 0.05$) as determined by post hoc analysis (within time intervals)

The progressive impact of DE and SPM on the mortality percentage and reproductive capacity of *T. castaneum* was also observed in the treated wheat grains (Table III, Figure 3). The untreated control group (T1) consistently showed no mortality across all time intervals ($f = 436.25$, $p < 0.001$) and produced the highest progeny count (69.00±4.58 individuals) after 65 days ($f = 181.20$, $p < 0.001$), indicating an ideal environment for the pest's survival and reproduction. DE treatments exhibited a consistent dose-dependent effect. At the lowest concentration T2, mortality gradually increased to 77.78±2.93% after 21 days ($f = 436.25$, $p < 0.001$), while progeny production dropped significantly to 14.00±1.00 individuals ($f = 181.20$, $p < 0.001$). Increasing the DE concentration T3 and T4 improved mortality percentage (up to 84.45±2.22% and 86.67±1.92%, respectively after 21) ($f = 436.25$, $p < 0.001$), with corresponding reductions in progeny to 9.00±0.58 and 6.00±1.00 ($f = 181.20$, $p < 0.001$). Spinetoram, even at very low concentrations, showed superior efficacy compared to DE. In T5, mortality reached 94.44±1.11% after 21 days ($f = 436.25$, $p < 0.001$), and progeny were almost completely suppressed at just 2.33±0.33 ($f = 181.20$, $p < 0.001$). The higher concentrations of spinetoram (T6 and T7) increased the mortality percentage. T6 produced 98.89±1.11% mortality, and T7 produced 100±0.00% mortality after 21 days ($f = 436.25$, $p < 0.001$), both completely inhibited progeny emergence. These results underline spinetoram's high potency against *T. castaneum* in both adult and reproductive stages.

Table III

Mortality percentage and progeny of *Tribolium castaneum* reared on treated wheat grains treated with diatomaceous earth and spinetoram during different time intervals

Notes *%= percentage, SE= standard error, DE= diatomaceous earth, SPM= spinetoram, ppm= parts per million, f-value= F-ratio, p-value= probability value, *Significant (p ≤ 0.05), ^{ns} Non-Significant, means within the same column followed by different lowercase letters are significantly different at p< 0.05, according to Tukey's HSD (Honestly Significant Difference) test*

Figure 3

Mortality percentage and progeny of *Tribolium castaneum* reared on wheat grains treated with diatomaceous earth and spinetoram during different times

Error bars represent the standard error of the mean (SEM). Different letters above the bars indicate statistically significant differences ($p < 0.05$) as determined by post hoc analysis (within time intervals)

The effectiveness of DE and spinetoram (SPM) was also checked for *S. oryzae* individuals in treated rice samples over 21 days and progeny counted over 65 days (Table IV, Figure 4). The untreated control (T1) recorded 0±0.00% mortality across all time intervals (f= 586.87, p< 0.001) and produced the highest number of progeny (84.00±2.60) (f= 398.93, p< 0.001), reflecting optimal conditions for rice weevil survival and reproduction. Among the DE treatments, increased concentrations consistently led to improved *S. oryzae* control. The lowest DE concentration (T2) showed a gradual increase in mortality, reaching 60% after 21 days of treatment application (f= 586.87, p< 0.001) and reducing the progeny count to 25.00±1.15 (f= 398.93, p< 0.001). In T3, mortality increased slightly to 65.56±1.11% (f= 586.87, p< 0.001) with a marginally better reduction in offspring (22.00±2.31). DE in T4 proved more effective, killing over 73.33±1.92% of adults after 21 days (f= 586.87, p< 0.001) and reducing progeny to 12.33±1.45 (f= 398.93, p< 0.001). Spinetoram treatments, however, delivered far superior results, even at much lower concentrations. T5 caused significant mortality (84.44±1.11%) after 21 days (f= 586.87, p< 0.001) and reduced progeny emergence to 6.33±1.02 (f= 398.93, p< 0.001). When the dose was doubled to 1.0 ppm (T6), mortality reached 96.67±1.92 % (f= 586.87, p< 0.001) with a near-complete block in reproduction (0.67±0.67) (f= 398.93, p< 0.001). The highest spinetoram dose (T7) achieved 100±0.00% mortality after 21 days (f= 586.87, p< 0.001) and completely prevented progeny emergence.

Table IV

Mortality percentage and progeny of *Sitophilus oryzae* reared on rice grains treated with diatomaceous earth and spinetoram during different time intervals

Notes *%= percentage, SE= standard error, DE= diatomaceous earth, SPM= spinetoram, ppm= parts per million, f-value= F-ratio, p-value= probability value, *Significant (p ≤ 0.05), ns Non-Significant, means within the same column followed by different lowercase letters are significantly different at p< 0.05, according to Tukey's HSD (Honestly Significant Difference) test*

Figure 4

Mortality percentage and progeny of *Sitophilus oryzae* reared on rice grains treated with diatomaceous earth and spinetoram during different times

Error bars represent the standard error of the mean (SEM). Different letters above the bars indicate statistically significant differences (p< 0.05) as determined by post hoc analysis (within time intervals)

The effectiveness and progeny production of DE and SPM-treated rice against *R. dominica* were also measured (Table V, Figure 5). The untreated control (T1) displayed no mortality across all time intervals (f= 258.76, p< 0.001), leading to the highest progeny emergence, with 73.00±4.93 individuals (f= 105.12, p< 0.001), underscoring the pest's uninhibited reproductive potential in the absence of a treatment. Among DE treatments, a dose-dependent effect was evident. The lowest dose (T2) resulted in 57.77±4.00% mortality after 21 days (f= 258.76, p< 0.001) and brought down progeny numbers to 26.67±3.76 (f= 105.12, p< 0.001). With increasing concentrations, T3 led to nearly 67.78±1.11% mortality (f= 258.76, p< 0.001) and fewer progeny (15.67±1.86) (f= 105.12, p< 0.001), while T4 resulted in 76.67±0.00% mortality after 21 days (f= 258.76, p< 0.001) and further reduced the progeny count to 8.33±1.76 (f= 105.12, p< 0.001). Spinetoram, in contrast, demonstrated far stronger and quicker insecticidal action. The lowest SPM dose (T5) caused over 92.22±4.00% mortality by day 21 (f= 258.76, p< 0.001) and nearly eliminated progeny production (1.33±0.88) (f= 105.12, p< 0.001). In T6, spinetoram resulted in 100±0.00% mortality within 21 days (f= 258.76, p< 0.001) and completely prevented reproduction (0.00±0.00 progeny) (f= 105.12, p< 0.001). The highest dose (T7) showed equally rapid results, with 100±0.00% mortality by day 21 (f= 258.76, p< 0.001) with no offspring observed, confirming its superior potency.

Table V

Mortality percentage and progeny of *Rhyzopertha dominica* reared on rice grains treated with diatomaceous earth and spinetoram during different time intervals

Notes *%= percentage, SE= standard error, DE= diatomaceous earth, SPM= spinetoram, ppm= parts per million, f-value= F-ratio, p-value= probability value, *Significant (p ≤ 0.05), [ns] Non-Significant, means within the same column followed by different lowercase letters are significantly different at p< 0.05, according to Tukey's HSD (Honestly Significant Difference) test*

Figure 5

Mortality percentage and progeny of *Rhyzopertha dominica* reared on rice grains treated with diatomaceous earth and spinetoram during different times

Error bars represent the standard error of the mean (SEM). Different letters above the bars indicate statistically significant differences (p< 0.05) as determined by post hoc analysis (within time intervals)

The mortality rates and progeny suppression of *T. castaneum* in rice-treated samples exposed to DE and SPM were observed over 21 days, while the reproductive output was assessed after 65 days (Table VI, Figure 6). The untreated control (T1) exhibited zero mortality throughout the study period (f= 586.67, p< 0.001) and resulted in the highest progeny count (45.33±7.75) (f= 26.50, p< 0.001), highlighting the pest's population growth in the absence of treatments. The lowest DE concentration (T2) achieved just under 57.78±1.11% mortality after 21 days of treatment application (f= 586.67, p< 0.001) and limited progeny to 16.00±2.08 (f= 26.50, p< 0.001). Increasing the concentration to 200 ppm (T3) resulted in about 62.22±2.93% mortality (f= 586.67, p< 0.001) and a slightly lower progeny count (10.67±1.45) (f= 26.50, p< 0.001). The highest

DE dose (T4) was more effective, reaching nearly 67.78±1.11% mortality (*f*= 586.67, *p*< 0.001) and reducing offspring production substantially to 5.00±1.53 (*f*= 26.50, *p*< 0.001). However, even at the maximum DE concentration, complete control was not reached. On the other hand, spinetoram proved substantially more potent and fast-acting. In T5, it caused over 93.33±1.92% mortality after 21 days (*f*= 586.67, *p*< 0.001) and reduced progeny numbers to 1.33±0.67 (*f*= 26.50, *p*< 0.001). Increasing the dose to 1.0 ppm (T6) and 2.0 ppm (T7) delivered near-complete or full mortality after 21 days (*f*= 586.67, *p*< 0.001), with both treatments entirely suppressing reproduction (0.00±0.00 progeny) (*f*= 26.50, *p*< 0.001). These results confirm spinetoram's high efficacy at even low doses.

Table VI

Mortality percentage and progeny of *Tribolium castaneum* reared on rice grains treated with diatomaceous earth and spinetoram during different time intervals

Notes *%= percentage, SE= standard error, DE= diatomaceous earth, SPM= spinetoram, ppm= parts per million, f-value= F-ratio, p-value= probability value, *Significant (p ≤ 0.05), ^{ns} Non-Significant, means within the same column followed by different lowercase letters are significantly different at p< 0.05, according to Tukey's HSD (Honestly Significant Difference) test*

Figure 6

Mortality percentage and progeny of *Tribolium castaneum* reared on rice grains treated with diatomaceous earth and spinetoram during different times

Error bars represent the standard error of the mean (SEM). Different letters above the bars indicate statistically significant differences (*p*< 0.05) as determined by post hoc analysis (within time intervals)

DISCUSION

In this study, the efficacy of different doses of diatomaceous earth (DE) or spinetoram (SPM) were evaluated in the major insect pests infesting stored wheat and rice grains. The results demonstrated significant variations in the mortality percentage of insects after the DE and SPM-treated wheat and rice grains over different time points (1, 2, 7, 14, and 21 days). The progeny production was also noted after 65 days of treatment application. The results indicated that the DE formulations exhibited prolonged effects, and spinetoram displayed rapid mortality. Diatomaceous earth is usually known for its mechanical mode of action, causing desiccation and death of insect pests by damaging their exoskeletons (Zeni et al., 2021). The study demonstrated that low insect mortalities were recorded in DE formulations across all test species in wheat and rice-treated samples. Although mortalities increased with the increase in dose and exposure time, it was also observed by Korunić (2013), who reported that none of DEs treatments achieved 100% mortality after different time intervals, even at the highest concentration of 300 ppm.

Similarly, these trends have been observed by different researchers previously (Mutambuki, 2013; Kavallieratos et al., 2015), who tested DE against different stored wheat and maize pests, such as *T. granarium*, *S. oryzae*, *S. zeamais*, *R. dominica*, and *T. castaneum*; the mortality for all formulations of DE were below 90%. The lower efficacy of DE formulations can be attributed to its mode of action, which requires extended contact and is influenced by multiple factors, including insect species and developmental stage (Vayias et al., 2009), temperature (Athanassiou et al., 2005), relative humidity (Stathers et al., 2004), source of DE (Nwaubani et al., 2014) and DE quality (Korunić, 2013). Additionally, prolonged exposure to DE may contribute to tolerance or behavioral avoidance, although this aspect warrants further investigation.

Furthermore, DE exhibited more persistent effects, which is consistent previous studies indicating that DE can provide long-term protection against stored product pests (Lupu et al., 2018). The mortality rates continued to rise with time, suggesting that DE's effectiveness may be attributed to its accumulation on the insect's body and the progressive drying out process, which ultimately leads to death (Hariprasad, 2020). However, the progeny insect count after 65 days was low, highlighting that the sublethal effects have a significant impact on the reproductive potential of the pests, reducing future generations. The slower mortality and reproductive inhibition observed in this study are in line with previous work by Paponja et al. (2020), who found that DE formulations were slow-acting and less effective in controlling stored grain pests developing inside the grains. Subsequently, the efficacy can be different due to the insect species (Shah & Khan, 2014; Liška et al., 2015; Liška et al., 2017) and different development stages (Vayias et al., 2009). This extended efficacy supports the idea that DE could be a sustainable and non-chemical alternative for managing insect pests in stored grains (Zhanda et al., 2020). Spinetoram, a spinosyn-based insecticide, showed rapid insect mortality of insect pests, especially under controlled environments. Spinetoram interferes with the nervous system of insects (Sparks et al., 2012) by acting on the nicotinic acetylcholine receptors (Nauen et al., 2019), leading to paralysis and death (Nauen et al., 2019). Spinetoram is a potent insecticide, and its quick knockdown action is particularly beneficial for fast control of stored grain pests in the initial stages of infestation. The effectiveness of spinetoram in causing quick mortality increased with the increase in time of exposure. A 100% mortality rate of *R. dominica, T. granarium, T. castaneum in treated wheat samples* and *S. oryzae, R. dominica, T. castaneum* in treated rice samples after 21 days of treatment application, suggested that spinetoram's effectiveness may be short-lived compared to DE.

Previous studies also showed that spinetoram is effective for the control of both stored grain insect pests, such as *S. oryzae* and *R.*

dominica (Vassilakos et al., 2015; Rumbos et al., 2018). The mortality rate of *R. dominica* was high compared with *S. oryzae* in rice treated samples in treatments T5 (0.5 ppm), T6 (1 ppm), and T7 (2 ppm). This is in line with studies that show that the mortality levels of *R. dominica* were high compared with *S. oryzae* (Vassilakos et al., 2015). Furthermore, the mortality level of *S. oryzae* increased with the increase in time of exposure and dose 0.5-2 ppm resulting in 100%. Our results are also in line with the studies of Vassilakos et al. (2015) and Rumbos et al. (2018), who also reported that *S. oryzae* mortality increased with both exposure time and dose, reaching nearly complete mortality at higher concentrations. Moreover, the progeny after 65 days indicated that spinetoram may not completely prevent reproductive success in the long term, as it did not achieve full control over future generations of the insects, which is a common limitation of insecticides that do not have a residual effect (Andrić et al., 2019).

The comparison of DE and spinetoram reveals that while spinetoram provides rapid pest knockdown, DE has a more gradual but persistent impact. The choice of formulation largely depends on the specific requirements for pest control. For situations where immediate elimination is critical, spinetoram may be preferred, but DE offers a more durable solution for long-term management where sustained control is necessary. The observed differences in mortality and progeny production also underscore the importance of combining different pest control strategies. Integrated pest management (IPM), which incorporates both chemical and non-chemical methods like DE, may help enhance the overall effectiveness of control measures while reducing the reliance on chemical insecticides (Kavallieratos et al., 2015). Diatomaceous earth, particularly food-grade formulations, is generally considered safe for mammals, including humans (Korunić, 1998). Spinetoram exhibits relatively low mammalian toxicity and high selectivity toward insect pests, with minimal risks to non-target organisms (Bacci et al., 2016). Including such agents in stored grain IPM programs thus offers both efficacy and safety under well-regulated conditions. Although this study provides valuable insights into the effectiveness of DE and spinetoram for managing stored wheat and rice insect pests, further research is needed to explore the interaction between these two treatments and their combination for enhanced control. Additionally, understanding the environmental factors (e.g., temperature, humidity) that influence the efficacy of DE and spinetoram could provide further guidance on optimizing their use under different storage conditions.

CONCLUSION

In conclusion, SPM exhibits rapid and comprehensive control over major stored wheat and rice grain insect pests, making it a valuable tool in integrated pest management strategies. The study design also allowed for the assessment of SPM residual effects, as demonstrated by continued insect mortality and reduced progeny production over time. This demonstrates its potential for long-term protection of stored grains. However, DE is less potent in the long-term trials which makes SPM a promising, sustainable substitute with its prolonged efficacy. The integration of both agents, considering their respective strengths, could enhance the overall effectiveness of pest control programs in stored grain systems.

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DATA STATEMENT

All the data is within the manuscript file. Further inquiries can be directed to the corresponding authors.

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Estrategias de protección poscosecha: Comparación de la tierra de diatomeas y el espinetoram contra las principales plagas del almacenamiento

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