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ORIGINAL RESEARCH ARTICLE

Efficacy of surface applications of Diaterra® against *Sitophilus granarius* (Linnaeus, 1758) (Coleoptera: Dryophthoridae) and *Tribolium castaneum* (Herbst, 1797) (Coleoptera: Tenebrionidae)

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Abstract
The present study investigated the insecticidal efficacy of Diaterra®, a native diatomaceous earth, against two significant stored grain pests, the grain weevil, *Sitophilus granarius* (Linnaeus, 1758), (Coleoptera: Dryophthoridae) and the red flour beetle, *Tribolium castaneum* (Herbst, 1797) (Coleoptera: Tenebrionidae). To control of insect pests in stores or warehouses, grain industry relies on synthetic insecticides, but they have significant environmental and health risks. Diatomaceous earth offers a natural and environmentally friendly alternative. In addition, it is safe for wildlife, leaves no residues, and effectively controls pests. In the study, different doses (0.25, 0.5, 1, 2, and 4 g/m^2) of diatomaceous earth were applied on concrete and wooden surface. A mortality of 100.0% was achieved for *S. granarius* on the wooden surface at a dose of 4 g/m^2 during the 96-hour and subsequent application periods, whereas for *T. castaneum*, this rate was recorded as 88.9% under the same dose and a 192-hour application period. On the concrete surface, a mortality rate of 100.0% was achieved for *S. granarius* at a dose of 4 g/m^2 after 120 h of exposure. In contrast, for *T. castaneum*, this rate did not exceed 59.5% even with the same dose and a 192-hour application period. Under controlled laboratory conditions, a dose of 4 g/m^2 of Diaterra® showed efficacy in managing *S. granarius* populations on wooden and concrete surfaces. The desired level of efficacy was not achieved for *T. castaneum* on either surface type. Based on the data obtained from this study, it can be concluded that prolonged exposure to diatomaceous earth leads to enhanced insecticidal efficacy against both *S. granarius* and *T. castaneum* on different surface types. This study emphasizes the importance of considering application duration and surface type as critical factors in maximizing the effectiveness of diatomaceous earth applications.

Keywords Diatomaceous earth · Surface application · Mortality · *Sitophilus granarius* · *Tribolium castaneum*

Introduction

Sitophilus granarius (Linnaeus, 1758) (Coleoptera: Dryophthoridae) is a primary pest that causes direct damage to all kinds of cereals such as wheat, barley, oats, rice, sorghum, and maize (Schwartz and Burkholder 1991; Lemić et al. 2021; Alpkent et al. 2023). *Tribolium castaneum* (Herbst, 1797) (Coleoptera: Tenebrionidae), a secondary insect pest known to cause significant losses in previously damaged grain or processed products such as flour, bran, pasta, rice, millet, dried fruit, biscuits, nuts, sorghum, and maize, has been a high priority and ongoing research topic for researchers to improve pest management in stored products (Ajayi and Rahman 2006; Banga et al. 2020; Campbell et al. 2022; Johnson 2020; Sokoloff et al. 1966; Sinha and Watters 1985; Mills and Pedersen 1990; Karunakaran et al. 2004). Much of the damage can be attributed to the rust-red flour beetle *T. castaneum*, which can cause a significant reduction in grain weight of up to 40% (Ajayi and Rahman 2006; Rees 2007). This species feeds predominantly on the endosperm of seeds, resulting in a coagulated texture and an unpleasant, musty odor. The presence of stored insect pests results in direct or indirect feeding damage, leading to compromised

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seed quality, weight loss, detrimental alterations in quality and nutritional composition, ultimately diminishing the commercial value of the product (Boxall 2001). On a global scale, stored grain insect pests are responsible for significant qualitative and quantitative losses in stored commodities, with reported ranges of 10–60% (Lorini and Filho 2004; Fields 2006; Mihale et al. 2009). It is important to develop an effective control strategy to reduce such grain spoilage and keep these products healthy with minimal losses. Given this situation, cereals are staples of the global human and animal diet, serving as long-lasting food sources that are stored to meet daily subsistence, reserve feed resources, and ensure seed availability throughout the year (Norambuena et al. 2016).

The adoption of effective control measures is of paramount importance in order to protect raw, semi-finished, or finished products from the harmful effects of insect pests, thus reducing spoilage and minimizing economic losses associated with insect activities. As a result of these efforts, producers, consumers, and researchers are looking for various control methods to manage stored insect pests. The stored grain industry currently relies on synthetic insecticides to control insects because of their rapid action, low cost, ease of application, and no special knowledge required for use (Subramanyam 1995). However, the environmental impacts of these chemicals and the health risks they pose to consumers are significant (Salem et al. 2007). Moreover, their widespread and indiscriminate use against stored grain pests has led to the emergence of strong resistance in these insects against synthetic active substances. Consequently, there is a compelling need to assess natural compounds that are both effective in controlling these pests and pose minimal threats to human health and grain quality, thereby addressing the detrimental impacts associated with chemical insect control methods (Emekci and Ferizli 2000; Mahdi and Rahman 2009; Salem et al. 2007; Fields 2006).

The growing concerns regarding biodiversity, animal and human welfare, and food security are propelling the agricultural industry towards a more sustainable approach, prompting research efforts to explore eco-friendly alternatives for adoption within Integrated Pest Management (IPM) protocols. In this context, inert dusts particularly diatomaceous earth (DEs), hold significant promise in preventing and controlling a wide variety of arthropod pests. DEs are a type of naturally occurring soft siliceous sedimentary rock composed of the fossilized exoskeleton of single-celled algae called diatoms (Korunić 1998). Diatomaceous earth is considered an environmentally friendly insecticide due to its organic and natural composition. Exhibiting negligible toxicity towards fish, aquatic organisms, birds, and other wildlife, diatomaceous earths (DEs) can be applied without leaving any residue in the surrounding environment or food products, making them a suitable candidate for utilization as an insecticidal agent. (Anonymous 1991; Korunić 1998; Losic and Korunic 2018). Adopted primarily for the control of stored product pests, DEs have also found use against some household insects that live in a dry environment, for example bed bugs or agriculturally important insects. It is possible to use DEs against different arthropod pest taxa such as Acarina, Blattodea, Coleoptera, Diptera, Hemiptera, Hymenoptera, Ixodida, Lepidoptera alone or when applied with other techniques (Zeni et al. 2021; Ertürk 2021). The death of insects caused by DE is primarily attributed to abrasion of the chitin layer, absorption of chitin wax from the epicuticular surface, damage to the digestive system, blockage of spiracles and tracheae, and dehydration based on surface area. Recent studies have concluded that the effective absorption of epicuticular lipids and fatty acids by DE is a fundamental mechanism leading to desiccation in arthropods (Korunić 1998; Subramanyam and Roesli 2000; Prasantha 2003; Vayias et al. 2009). The configuration of DEs might be a crucial aspect in this regard, as circular diatoms could result in faster water absorption, whereas angular DEs function more as an abrasive factor (Korunić 1997, 1998; Subramanyam and Roesli 2000; Vayias et al. 2009). However, the morphology of the diatom and its function, whether it involves sorption or abrasion, can be altered by employing various processing techniques (Baliota and Athanassiou 2020).

Many studies have been conducted to demonstrate the effectiveness of diatomaceous earth against stored product pests. These studies revealed that the effect of diatomaceous earth varies according to the insect species (Maceljski and Korunic 1972; Athanassiou et al. 2005; Fields and Korunic 2000; Gad et al. 2020; Perišić et al. 2021; Ogreten et al. 2023), the origin of the diatomaceous earth (Salim et al. 2020), the type of treated food (Doğanay and Işıkber 2020) and surface applied (Cook et al. 2004; Ertürk et al. 2020), and the temperature at which it is applied (Field and Korunić 2000; Athanassiou et al. 2005; Athanassiou et al. 2011; Batistič et al. 2023). Among these studies, there are very few studies to determine the effectiveness of novel diatomaceous earth against storage pests on different surfaces (Cook et al. 2004; Ertürk et al. 2020).

The study aims to assess the insecticidal potential of natural diatomaceous earth on *S. granarius* and *T. castaneu*m, evaluate the impact of different surface type (concrete and wood), and determine the effects of exposure duration and dosage on adult mortality. This study also addresses data gaps not comprehensively covered in previous research, such as DE efficacy, surface type effects, and exposure condition impacts. Furthermore, it focuses on exploring new diatomaceous earth variations that haven't been extensively studied in prior research. Ultimately, to contribute

to sustainable agriculture by providing more effective and environmentally friendly pest control methods in the long term within Integrated Pest Management (IPM) protocols.

Materials and methods

Insect rearing

Sitophilus granarius and *T. castaneum* used in the experiments were grown in one liter glass jars under dark room conditions (25 ± 1 °C, 65 ± 5% relative humidity). The glass jars were filled with 250 g whole wheat for *S. granarius* and 250 g wheat flour for *T. castaneum*. The mouth of the glass jars were covered with cheesecloth and secured with rubber bands to ensure ventilation and prevent insect escape. In order to obtain sufficient numbers of adult beetles for the experiments, 300–500 adults of both sexes of *S. granarius* and *T. castaneum* individuals were transferred to each jar and allowed to lay eggs for 48 h. After oviposition, all adult insects of *S. granarius* and *T. castaneum* were removed from the diet, thus obtaining eggs of the same age. After weekly and daily monitoring, newly hatched 7–21 days old adults were used in the experiments.

Diatomaceous earth

The diatomaceous earth, Diaterra® (Organo Mineral Tarim Maden. Sn. Tic. Iht. Ith. Ltd. Şti., Ankara, Türkiye) was used in the study. Diaterra® consists of 72.80% SiO_2, 9.00% Al_2O_3, 2.40% Fe_2O_3, 1.70% CaO, 2.40% MgO, 0.10% MnO, 0.20% P_2O_5, 0.20% Na_2O, 0.90% K_2O and 0.40% TiO_2. The particle size of Diaterra® between 2.594 and 39.745 µm, and the average was 9.492 µm.

Application of the diatomaceous earth

The insecticidal activity of the native diatomaceous earth Diaterra® was tested against adult individuals of *S. granarius* and *T. castaneum*. The experiments were carried out on two different surfaces, wooden and concrete (15 × 15 cm), at 25 ± 2°C and 60 ± 5% relative humidity, at five different doses (0.25, 0.50, 1, 2 and 4 g/m^2). Using drigalski spatulas, determined doses of Diaterra® were spread onto both surfaces. To provide food for *S. granarius* adults, 0.5 g of whole wheat and 0.5 g of wheat flour for *T. castaneum* adults were left. After the adults were released on the surfaces, the treatment area was covered with inverted petri dishes (9 cm diameter) to prevent insects from escaping. To determine the efficacy of Diaterra®, insects were counted 24, 48, 72, 96, 120, 144, 168, and 192 h after application, and recorded dead and alive. In the negative control groups of the experiments, insects were exposed to non-diatomaceous earth surfaces. The positive control group was treated with K-Obiol® EC 25 (Bayer AG, Germany) containing 25 g/l deltamethrin and 250 g/l piperonyl butoxide at a dose of 0.4 ml/m^2. Each treatment was repeated four times and 20 adult insects were used in each replicate. The whole experiment was repeated twice.

Statistical analysis

Initially, the raw data was transformed into mortality percentages and subsequently underwent an Arcsine transformation to normalize proportional data, as suggested by Zar (1999) and Warton et al. (2011). The mortality data obtained from the transformation was subjected to variance analysis (ANOVA), and the differences among treatments were assessed using Tukey's multiple comparison test at a significant level of 5%. The statistical analysis was conducted using the "General Linear Model" in the software package MINITAB Release 18, as described by McKenzie and Goldman (2005). In addition, analysis of mean (ANOM), a type of ANOVA test frequently used in quality improvement programs, was used to compare the means of different groups (Pallmann and Hothorn 2016).

Results

The data obtained from the study were evaluated according to ANOVA ($P < 0.05$). Complete mortality for *S. granarius* was achieved at a dose of 4 g/m^2 after 96 h on wooden surfaces ($F = 125.23$; $df = 6.48$; $P < 0.05$), and at 2 g/m^2 after 120 h. In trials on wooden surfaces with *S. granarius*, no significant mortality was observed after the first 24 h of treatment. Table 1 shows that when applied at a dose of 0.25 g/m^2, the lowest effect was observed in *S. granarius* individuals on wooden surfaces, which was 0.08% ($F = 260.09$; $df = 6.48$; $P < 0.05$) after 24 h. Although mortality increased with increasing dose and exposure time, complete mortality was not achieved for *S. granarius* at all doses and exposure durations except for doses of 2 and 4 g/m^2. K-Obiol® EC 25 treatment, which served as a positive control group, caused 100.00% mortality at all-time intervals. In addition, the Diaterra® application at a dose of 4 g/m^2 on the wooden surface for *S. garanarius* was in the same statistical group as K-Obiol® EC 25 at 72 h and subsequent applications (Table 1).

For *T. castaneum*, the highest mortality on the wooden surface was recorded as 88.88% in individuals exposed to 4 g/m^2 dose of Diaterra® after 192 h ($F = 32.4$; $df = 6.49$; $P < 0.05$). No mortality of *T. castaneum* was obtained in the first 24 h at Diaterra® doses of 0.25, 0.50, and 1 g/m^2

on the wooden surface. Following the 192-hour application, the maximum mortality of *T. castaneum* was observed as 28.90% at the dose of 2g/m^2 of Diaterra® (F = 32.4; df = 6.49; $P < 0.05$). The application of Diaterra® at a rate of 4 g/m^2 on the wooden surface for *T. castaneum* exhibited similar statistical group as K-Obiol® EC 25 after 168 h and subsequent applications (Table 1).

Diaterra® treatment of the concrete surface was highly effective against *S. granarius* at a dose of 4 g/m^2 and complete mortality occurred after 120 h of exposure (F = 104.02; df = 6, 49; $P < 0.05$), whereas 100.00% mortality occurred at a dose of 2 g/m^2 after 168 h (F = 132.62; df = 6, 49; $P < 0.05$). For concrete surface application, no significant mortality was obtained for *S. granarius* in the first 24 h and all responses were in the same statistical group with the negative control group. When applied to the concrete surface at a dose of 4 g m/^{2}, Diaterra® for *S. garanarius* was in the same statistical group as K-Obiol® EC 25 at 120 h and beyond (Table 2).

Similar to the wooden surface studies for *T. castaneum*, the highest mortality was achieved after 192 h of exposure when Diaterra® was applied to concrete surface at a dose of 4 g/m^2 with 59.47% mortality (F = 73.60; df = 6, 49; $P < 0.05$). Except for the 4 g/m^2 dose of Diaterra®, and the positive control group, no deaths occurred in the first 24 h at all other doses for *T. castaneum*. All doses of Diaterra® for surface application on concrete were in different statistical groups for *T. castaneum*, in contrast to the synthetic insecticide K-Obiol® EC 25 (Table 2).

*Means followed by the same lowercase letter within each column are not significantly different using Tukey test at $P < 0.05$.

The ANOVA analysis of the parameters (insect × dose × time × surface) identified significant interactions among the tested factors for diatomaceous earth. Specifically, the results indicated that the interactions of dose-surface-time and insect-surface-time were not significant, whereas the interactions of dose-insect, dose-surface, dose-time, insect-surface, insect-time, and surface-time were found to be significant. The analysis revealed that the quadruple interaction (insect × dose × time × surface) was found to be significant (Table 3).

According to the ANOM (Analysis of Means) analysis, it was revealed that the effects were intensified in the range of 22.86–31.18% ($P < 0.05$) when different doses were applied, with the maximum effect being detected at a dose of 4 g/m^2. Furthermore, it was determined that the average of all applications was 27.02% (Fig. 1). In addition, the results of ANOM analysis, which can be considered as a graphical alternative to ANOVA, show that the decision limits vary between 22.86% and 31.18% as mentioned above. However, the results show us that the

Table 1 Mean mortality percentage (±SE) of *Sitophilus granarius* and *Tribolium castaneum* adults exposed on wooden surface treated with different Diaterra® diatomaceous earth dosages and time

	Treatment g/m^2	24 h	48 h	72 h	96 h	120 h	144 h	168 h	192 h
Sitophilus granarius	**Control**	0.10 ± 0.27b*	0.41 ± 0.46ef	0.61 ± 0.70e	1.22 ± 0.75e	1.22 ± 0.75d	1.22 ± 0.75d	1.81 ± 1.15d	2.77 ± 1.05d
	0.25	0.08 ± 0.22b	0.32 ± 0.38f	10.72 ± 0.85d	22.83 ± 1.63d	38.06 ± 3.86c	40.80 ± 2.65c	44.53 ± 2.17c	46.79 ± 1.77c
	0.5	0.32 ± 0.38b	5.31 ± 0.99e	30.53 ± 0.10c	68.24 ± 0.72c	86.51 ± 1.97b	88.35 ± 1.86b	88.35 ± 1.86b	90.10 ± 2.34b
	1	0.71 ± 0.48b	19.13 ± 0.15d	76.39 ± 0.67b	94.24 ± 1.08b	99.53 ± 0.59a	99.53 ± 0.59a	99.53 ± 0.59a	99.53 ± 0.59a
	2	0.47 ± 0.59b	40.94 ± 0.62c	85.01 ± 0.35b	99.35 ± 0.78ab	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a
	4	1.27 ± 0.51b	71.65 ± 0.43b	97.68 ± 0.60a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a
	K-Obiol®	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a
Tribolium castaneum	**Control**	0.00 ± 0.00b	0.08 ± 0.22b	0.08 ± 0.22b	0.47 ± 0.59c	1.55 ± 0.66c	1.79 ± 0.83c	1.79 ± 0.83b	2.91 ± 1.49bc
	0.25	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00c	0.08 ± 0.22c	0.32 ± 0.38c	0.32 ± 0.38b	0.32 ± 0.38c
	0.5	0.00 ± 0.00b	0.08 ± 0.22b	0.47 ± 0.59b	0.93 ± 0.66bc	1.86 ± 0.80c	1.86 ± 0.80c	2.70 ± 0.71b	3.69 ± 0.56bc
	1	0.00 ± 0.00b	0.43 ± 1.20b	2.75 ± 5.06b	4.55 ± 5.54bc	4.55 ± 5.54c	4.96 ± 6.22c	6.25 ± 5.96b	9.96 ± 5.25bc
	2	0.47 ± 0.59b	4.55 ± 5.54b	7.81 ± 7.48b	14.77 ± 8.95bc	17.86 ± 8.47bc	21.05 ± 7.66bc	25.47 ± 7.75b	28.90 ± 7.64b
	4	0.32 ± 0.38b	5.14 ± 6.96b	17.82 ± 7.89b	32.41 ± 10.04b	44.43 ± 9.16b	67.43 ± 9.22b	79.84 ± 7.56a	88.88 ± 4.76a
	K-Obiol®	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a

Table 2 Mean mortality percentage (±SE) of *Sitophilus granarius* and *Tribolium castaneum* adults exposed on concrete surface treated with different Diaterra® diatomaceous earth dosages and time

	Treatment g/m^2	24 h	48 h	72 h	96 h	120 h	144 h	168 h	192 h
Sitophilus granarius	**Control**	0.00 ± 0.00b*	0.08 ± 0.22e	0.32 ± 0.38d	0.71 ± 0.48e	1.27 ± 0.51d	1.98 ± 0.48d	2.70 ± 0.71d	2.70 ± 0.71d
	0.25	0.00 ± 0.00b	0.71 ± 0.48de	4.15 ± 0.63d	5.35 ± 0.39e	8.32 ± 0.21d	8.78 ± 0.30d	11.24 ± 0.34d	12.55 ± 0.32d
	0.50	0.08 ± 0.22b	2.49 ± 1.08de	15.18 ± 0.28c	27.67 ± 1.26d	39.08 ± 2.39c	41.92 ± 2.57c	45.45 ± 2.90c	46.76 ± 2.99c
	1	0.00 ± 0.00b	6.17 ± 1.75 cd	22.07 ± 0.75c	58.17 ± 2.09c	71.82 ± 3.03b	76.92 ± 2.06b	81.96 ± 1.39b	85.44 ± 1.19b
	2	0.32 ± 0.38b	26.19 ± 0.65b	70.14 ± 0.71b	92.86 ± 1.32b	98.83 ± 0.82a	99.92 ± 0.22a	100.00 ± 0.00a	100.00 ± 0.00a
	4	0.71 ± 0.48b	16.84 ± 0.38bc	77.92 ± 0.29b	95.46 ± 0.75ab	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a
	K-Obiol®	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a
Tribolium castaneum	**Control**	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00d	0.00 ± 0.00d	0.32 ± 0.38d	0.71 ± 0.48 cd
	0.25	0.00 ± 0.00c	0.00 ± 0.00c	0.08 ± 0.22c	0.08 ± 0.22c	0.08 ± 0.22 cd	0.08 ± 0.22d	0.08 ± 0.22d	0.08 ± 0.22d
	0.50	0.00 ± 0.00c	0.00 ± 0.00c	0.08 ± 0.22c	0.08 ± 0.22c	0.93 ± 0.66 cd	1.12 ± 0.85 cd	1.12 ± 0.85 cd	1.12 ± 0.85 cd
	1	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.47 ± 0.59 cd	1.55 ± 0.66 cd	2.89 ± 0.93 cd	3.14 ± 1.12 cd
	2	0.00 ± 0.00c	0.08 ± 0.22c	0.47 ± 0.59c	0.93 ± 0.66c	3.30 ± 1.02c	6.05 ± 1.83c	11.90 ± 4.29c	12.36 ± 4.39c
	4	8.09 ± 1.88b	13.48 ± 2.02b	17.38 ± 1.38b	21.68 ± 1.09b	30.48 ± 0.81b	39.52 ± 1.36b	49.25 ± 1.71b	59.47 ± 1.45b
	K-Obiol®	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a

*Means followed by the same lowercase letter within each column are not significantly different using Tukey test ($P < 0.05$)

Table 3 ANOVA parameters for different applications of Diaterra® diatomaceous earth against *Sitophilus granarius* and *Tribolium castaneum*

Source	df	F-Value	P-Value
Dose	5	563.55	$P < 0.05$
Insect	1	2603.66	$P < 0.05$
Surface	1	193.93	$P < 0.05$
Time	7	243.33	$P < 0.05$
Dose × Insect	5	129.62	$P < 0.05$
Dose × Surface	5	4.57	$P < 0.05$
Dose × Time	35	13.40	$P < 0.05$
Insect × Surface	1	31.45	$P < 0.05$
Insect × Time	7	81.83	$P < 0.05$
Surface × Time	7	4.84	$P < 0.05$
Dose × Insect × Surface	5	9.59	$P < 0.05$
Dose × Insect × Time	35	5.25	$P < 0.05$
Dose × Surface × Time	35	0.83	$P > 0.05$
Insect × Surface × Time	7	0.37	$P > 0.05$
Dose × Insect × Surface × Time	35	1.98	$P < 0.05$
Error	1344		
Total	1535		

interaction effects are not within the decision limits and there is evidence of interaction. When the Fig. 1 is examined, it shows that except for the 1 g/m^2 application dose, the other treatments including the control treatment are outside the decision limits and the interaction is caused by these treatments.

Discussion

Diatomaceous earth products have been the subject of various research studies investigating their efficacy against *S. granarius* and *T. castaneum* management (Keszthelyi and Pál-Fám 2012; Doğanay and Işıkber 2020; Mortazavi et al. 2020; Salim et al. 2020; Ertürk 2021). Different DEs derived from different geological sources, or even from the same area, have different physical characteristics that are connected to their efficacy as an insecticide against stored-product pests (Korunić 2013). Diaterra® is a local diatomaceous earth originating from Central Anatolia. Another ACN-1 coded diatomaceous earth, obtained from Ankara, Türkiye, was highly effective against *Blattella germanica* (L.) (Blattodea: Ectobiidae) adults at a dose of 2.5 g/m^2 and achieved 100.0% mortality (Özcan and Tunaz 2022). Kavallieratos et al. (2007), conducted laboratory experiments to assess the effectiveness of PyriSec, Insecto, and Protect-It, three modified diatomaceous earth formulations commercially available, against adult *Tribolium confusum* Jacquelin du Val, 1868 (Coleoptera: Tenebrionidae) individuals originating from various geographical locations in Europe. The study reported mortality rates ranging from 13 to 36% for

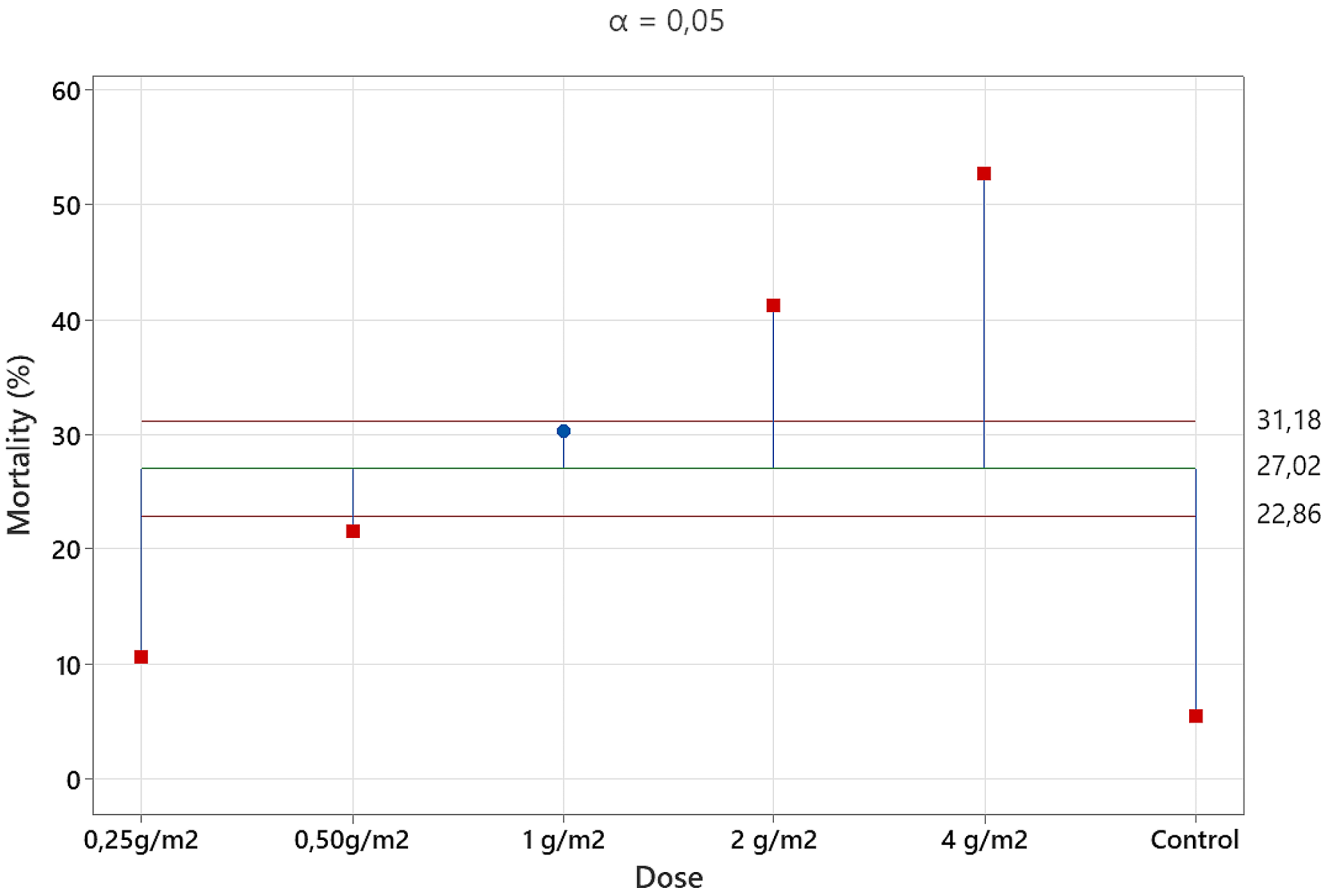


Fig. 1 Decision chart for different doses on the *Sitophilus granarius* and *Tribolium castaneum*

PyriSec, 5 to 25% for Insecto, and 18 to 39% for Protect-It at a concentration of 500 ppm after a 7-day exposure, depending on the specific population of *T. confusum* being tested. Similarly, Ogreten et al. (2023), revealed that DEs treatments resulted in increasing mortality rates over time, with the highest overall mortality observed at 21 days after treatment (DAT) and the lowest at 7 DAT. The mortality caused by AnkaraDE, AydinDE, and SilicoSec varied under different temperatures (27.79–54.76%, 34.60–67.21%, 33.06–64.68%, respectively) and relative humidity levels (26.90–55.41%, 33.35–68.15%, 31.86–65.62%, respectively). Specifically, the lowest mortality occurred at 25 °C at 7 DAT, while the highest was noted at 30 °C at 21 DAT. The study indicates that high temperature (30 °C) and low humidity (40%) conditions are more effective in initiating the insecticidal action of DEs. Salim et al. (2020), reported that local diatomaceous earth applied to wheat grain at a dose of 2000 mg/kg caused 89.75% mortality in *S. granarius* adults after 7 days. Similarly, Mortazavi et al. (2020) reported a death rate of 76% in *S. granarius* adults at the same dose and same exposure time. However, in a study conducted by Arnaud et al. (2005), considerable variations in the susceptibility of adult *T. castaneum* individuals to diatomaceous earth formulations were observed. One could say that these variations were attributed to the geographical origins of the tested beetle populations, indicating significant differences in their response to DE treatment.

The DEs susceptibility of stored-product insects varies greatly (Fields and Korunić 2000). The present study revealed that local diatomaceous earth was more effective on *S. granarius* on both surfaces. On the other hand, complete mortality on both surfaces was not observed at any dose for *T. castaneum* (Tables 1 and 2). It can be said that *T. castaneum* is more tolerant than *S. granarius.* Previous scientific studies have established that the species belonging to the genus *Tribolium* exhibit a notably high level of tolerance towards inert dusts, making them the most resilient among stored product beetle species in this regard (Athanassiou et al. 2003; Carlson and Ball 1962; Rumbos et al. 2016; Zeni et al. 2021). The mortality findings derived from the investigations conducted with *T. castaneum*, which exhibited species-specific variations, were found to be in accordance with the findings observed in the current study. When evaluating the influence of various characteristics of DEs on its insecticidal effectiveness, Korunić (1997), indicated that DEs particles ranging from 1 to 30 µm could be

positively associated with a high efficacy of DEs. Vayias et al. (2009), conducted a study with 14 different diatom soils on C*ryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujiidae), *Sitophilus oryzae* (L.) (Coleoptera: Dryophthoridae) and *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) and found that diatom soils with particles smaller than <45 µm had stronger insecticidal activity. Furthermore, it was stated by Alkan et al. (2019), that a positive interaction was observed between particle size and biological activity. In the present study, the average particle size of Diaterra® was 9.492 µm, which was similar to the studies cited above and resulted in a high insecticidal efficacy especially to *S. granarius*. According to Korunić (1998), species with a rough or hairy body surface will collect more particles per unit area, leading to more cuticle damage and therefore more susceptible to diatomaceous earth. The findings in the present study suggest that these differences in sensitivity to Diaterra® may be partially explained by the fact that *T. castaneum* is more tolerant to DEs.

Various pesticides exhibit distinct efficacy against stored pests based on the type, shape, and composition of the treated surface. Nevertheless, there exists a limited number of research specifically investigating the effectiveness of DEs products on different surfaces (Vayias and Athanassiou 2004; Athanassiou et al. 2007; Baliota and Athanassiou 2023). Laboratory experiments were undertaken to assess the insecticidal efficacy of diverse diatomaceous earth formulations when directly applied to a range of surfaces, encompassing concrete, ceramic, plywood, plastic, metal, and other materials (Collins and Cook 2006; Schöller and Reichmuth 2010; Ertürk et al. 2020). In addition, insect mortality also occurs as a result of prolonged exposure to DE surfaces because more DE particles are in contact with insects (Athanassiou et al. 2003, 2005). In the current study, in the applications against *S. granarius* on wooden surfaces, all insects were killed at the doses of 2 and 4 g/m^2 after 120 h and 96 h, respectively. However, Cook et al. (2004), observed that diatomaceous earth was more effective against *S. granarius* when applied to glass and plastic surfaces compared to wooden surfaces. In addition, Ertürk et al. (2020), found that the mortality of *S. oryzae* on the concrete surface was higher than that on the wooden surface. However, 100% mortality for *S. granarius* was obtained at a dose of 2 g/m^2 after 168 h and at a dose of 4 g/m^2 after 120 h on concrete surfaces. It was observed that the application on the wooden surface was more effective against *T. castaneum* at all doses than on the concrete surface. Besides the body size, shape, and characteristics of the insects exposed to DEs, insect mobility is also a critical parameter for insecticidal efficacy, as slow-moving insects may have lower DEs particle uptake. This can be considered an important characteristic of the reduced susceptibility of *T. castaneum* to DE. In general, the efficacy of DE against insects is thought to decrease as the moisture content of the grain and the relative humidity of the environment increase. It is generally accepted that a high relative humidity content or increase in humidity leads to a reduction in water loss from the insect body through the abrasive effect of DE particles on the cuticle, and hence to a reduction in desiccation and hence to a slowing of insect mortality (Subramanyam and Roesli 2000; Fields and Korunic 2000; Mewis and Ulrichs 2001; Athanassiou et al. 2011). Kabir and Lawan (2016), conducted laboratory bioassays to evaluate the insecticidal effect of DE (SilicoSec) against *T. castaneum* at different relative humidity levels, shedding light on the potential controversies related to the impact of humidity on DE efficacy. Additionally, Mohale et al. (2010), evaluated the toxicity of DE (Protect-It™) on *T. castaneum* under varying temperature and relative humidity conditions, reporting delayed toxic effects from exposure to DE. Arthur (2000), investigated the toxicity of DE *T. castaneum* and *T. confusum*, highlighting delayed toxic effects at different temperature-humidity combinations. These studies collectively demonstrate the controversies surrounding the effect of relative humidity on the insecticidal activity of DE when applied in *T. castaneum*, emphasizing the need for further research to elucidate the complex interactions between DE efficacy and relative humidity. Since the way in which insects come into contact with inert dust particles applied to surfaces may be different, the mortality rates determined on concrete and wood surfaces may be due to this difference.

In conclusion, the current study elucidated that effective protection of residual treatment of Diaterra® at dosages of 2 and 4 mg/m^2 on wooden and concrete surfaces against *S. granarius* can be achieved through the application but not *T. castaneum*. These findings contribute to our understanding of the effectiveness of diatomaceous earth products for the management of stored-product pests and highlight the importance of considering surface characteristics in optimizing their efficacy. Further research is warranted to explore the underlying mechanisms and to evaluate the long-term effectiveness and practical applicability of Diaterra® in integrated pest management strategies.

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Credit authorship contribution statement **MA**: Investigation, Formal analysis, Writing - original draft, Writing -review & editing; **TA**: Investigation, Conceptualization, Validation, Writing - original draft, Writing -review & editing. **BT**: Investigation, Methodology, Validation, Writing- original draft; **SE**: Conceptualization, Methodology, Investigation, Writing -review & editing.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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