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The Effect of Diatomaceous Earth, Sodium Chloride, and Temperature on the Control of the Red Flour Beetle *Tribolium Castaneum* (Herbst, 1797) (Coleoptera; Tenebrionidae)

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ABSTRACT

The red flour beetle [*Tribolium castaneum* (Herbst, 1797)] is a major secondary pest of stored wheat and flour, posing significant threats to both quantity and quality. In this study, we evaluated the effects of natural physical control methods, specifically temperature and humidity, on the larvae and adults of *T. castaneum*. A range of low temperatures (9, 11, 13, 15, and 17 °C) was tested in comparison to a warm control (31 °C), along with the use of Diatomaceous Earth (DE) and coarse salt (NaCl) to reduce ambient humidity in storage environments over five days. Results showed that DE and NaCl were particularly effective under cool conditions, with up to 80% mortality observed at 9 °C on the first day and complete mortality (100%) by day five. This preliminary study represents the first of its kind on Iraqi populations of *T. castaneum*, and offers promising insight for developing low-cost, sustainable and eco-friendly strategies for stored-product pest control.

تأثير تراب الدياتومي، وكلوريد الصوديوم، ودرجة الحرارة على مكافحة خنفساء الدقيق الحمراء
TRIBOLIUM CASTANEUM (HERBST, 1797) (COLEOPTERA; TENEBRIONIDAE)

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الخلاصة

الخنفساء الحمراء للطحين تُعدّ من الآفات الثانوية الرئيسية التي تصيب القمح والدقيق المخزن، وتشكل تهديداً كبيراً لكل من الكمية والنوعية. في هذه الدراسة، قمنا بتقييم تأثير الوسائل الفيزيائية الطبيعية وبشكل خاص درجة الحرارة والرطوبة،للسيطرة على يرقات وحشرات البالغة من الخنفساء الحمراء للطحين .تم اختبار مجموعة من درجات الحرارة المنخفضة(٩، ١١، ١٣، ١٥، و ١٧ درجة مئوية)مقارنة بدرجة حرارة دافئة(٣١ درجة مئوية)، بالإضافة إلى استخدام التراب الدياتومي(أو الدياتوميت)و الملح الخشن لتقليل الرطوبة النسبية في بيئة التخزين لمدة خمسة أيام .أظهرت النتائج أن التراب الدياتومي والملح الخشن كانا فعالين بشكل خاص في الظروف الباردة، حيث تم تسجيل معدل نفوق وصل إلى ٨٠٪ عند 9 درجات مئوية في اليوم الأول، ووصل إلى ١٠٠٪ بعد خمسة أيام .تُعدّ هذه الدراسة التمهيدية الأولى من نوعها على مجتمعات الخنفساء الحمراء للطحين في العراق، وتُقدم رؤى واعدة لتطوير استراتيجيات منخفضة التكلفة، مستدامة وصديقة للبيئة للسيطرة على آفات المنتجات المخزنة.

الكلمات المفتاحية: استراتيجية المكافحة، المنتجات المخزنة، درجة الحرارة، الرطوبة

INTRODUCTION

Stored product insects pose significant challenges to global food storage and safety (Rivers & Dahlem, 2014). The Food and Drug Administration (FDA) sets defect action levels for insect contamination in stored products, underscoring the need for constant monitoring, particularly by regulatory bodies. Wheat, a globally vital staple (Arregui & Quemada, 2008), is especially vulnerable to post-harvest insect damage during storage (Benhalima *et al*., 2004; Jeyasankar *et al*., 2014; Rajashekar, 2016).

Tribolium castaneum (Herbst, 1797), commonly known as the red flour beetle, is a notorious secondary pest of stored seeds (and their products) like wheat, rice, and sometimes corn (Arthur, 2000a; Gerken & Campbell, 2020). It exhibits high reproductive rates on wheat flour (Abdel-Hady *et al*., 2021) and significantly reduces product quality through contamination, biomass loss, and secretion of carcinogenic compounds (Naseri *et al*., 2017; Hodges *et al*., 1996). Prolonged infestation alters flour's color and taste, rendering it unfit for consumption (Atwal & Dhaliwal, 1997). Larvae, considered more destructive than adults, bore into grains and promote mold and mildew development (Athanassiou *et al*., 2016).

Conventional control relies heavily on fumigants like phosphine and methyl bromide. However, rising resistance, particularly to phosphine (Rajendran & Sriranjini, 2008; Taylor, 1989), has spurred interest in safer alternatives such as physical and natural substances. Among these, Diatomaceous Earth (DE) or diatomite, a chemically inert natural powder, damages insects by disrupting their protective wax layer, leading to dehydration and death (Subramanyam & Roesli, 2000). DE's efficacy depends on dose, exposure time, temperature, humidity, grain type, and insect life stage, with larvae generally more vulnerable (Arthur, 2004; Vayias *et al*., 2009).

Salt (NaCl) is another none-toxic substance known for reducing water activity in food and causing osmotic stress to microorganisms (Fennema, 1996; Davidson *et al*., 2012). By binding water molecules, salt preserves stored food and may impact insect survival.

This study aims to evaluate the effects of DE and NaCl on the mortality and development of the adults and larvae of *T. castaneum* under relatively low temperatures (9, 11, 13, 15, and 17 °C), hypothesizing that both agents, combined with cooler conditions, will suppress the beetle's development compared to higher temperatures (e.g., 31 °C).

MATERIALS AND METHODS

This study was conducted to support pest management strategies at the Iraqi Ministry of Trade by evaluating the effects of natural substances (Diatomaceous Earth [DE] and sodium chloride [NaCl]) and low temperature on the development of *Tribolium castaneum*.

Insect source and rearing conditions:

Adult *T. castaneum* specimens were obtained from the Genetic Control Department, Integrated Pest Control Center, Ministry of Science and Technology, Baghdad, Iraq. The studied insects were pre-determined at specific level then the identification of the species was confirmed by the authors. The insects were reared in the Insect Laboratory, University of Baghdad, in transparent plastic containers (3 kg capacity) containing wheat and flour. Containers were covered with a soft, breathable cloth to allow ventilation. Rearing was conducted at 28 ± 2 °C and 70 ± 5% relative humidity (RH), conditions optimal for *T. castaneum* reproduction.

Experimental setup:

Petri dishes (10 cm diameter) were used for all bioassays, with four replicates per treatment. Each dish contained 10 g of either wheat or flour. Treatments included the addition of 2 g (2000 ppm) of either DE or coarse NaCl to the substrate. Separate experimental sets were conducted at each of the following temperatures: 9, 11, 13, 15, and 17 °C. Control experiments were conducted at 25 °C and 31 °C for comparative analysis. Temperature conditions were maintained in precision incubators with relative humidity (RH) held constant at 20%, monitored directly inside the Petri dishes.

Insect developmental stages and exposure:

Each life stage of *T. castaneum* (eggs, larvae, pupae, and adults) was tested independently. For each stage, 25 individuals were placed in Petri dishes, with four replicates per treatment. Larvae of mixed instars were used to reflect natural heterogeneity. Inspections were performed daily over the full developmental period of the beetles

Statistical analysis:

Data were analyzed using a Randomized Complete Block Design (RCBD) to account for variability among developmental stages and environmental conditions. We used this statistical method since the experimental units or the insects are not homogeneous they are of different developmental instars. However we grouped them into relatively homogeneous blocks or stages. Duncan's Multiple Range Test at a 5% significance level was used for mean comparisons. Statistical analyses were conducted using the Statistical Analysis System (SAS, 2018). A factorial Completely Randomized Design (CRD) was applied to examine the effects of insect type, treatment, exposure time, and developmental stage. Analysis of variance (ANOVA) and the Least Significant Difference (LSD) test were used to determine significant differences among treatment means.

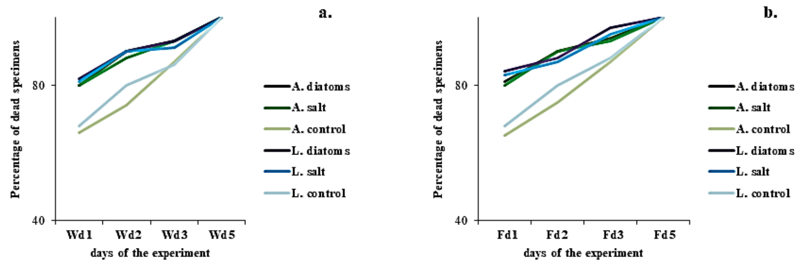
RESULTS AND DISCUSSION

The mortality rates of *Tribolium castaneum* at temperatures of 9, 11, 13, 15, and 17 °C, along with internal relative humidity values for each treatment, DE (8%), NaCl (10%), and control (18%), are presented in Tables 1–5. Significant differences ($P \leq 0.05$) in adult mortality were observed among the treatments (DE, NaCl, and control) on days 1 and 2, for both wheat and flour diets at all tested temperatures (Figs 1–5). Diatomaceous Earth is the most efficient to decrease the rate of humidity and consistently showed the highest adult mortality rates during the first three days, while the control group exhibited the lowest. By day 5, 100% mortality was recorded across all treatments and both diets.

Table 1: The mortality percentages of *Tribolium castaneum* adults and immatures during experiment at 9 °C

Insect phases	Materials	one day		two days		three days		five days		LSD value
		Wheat	Flour	Wheat	Flour	Wheat	Flour	Wheat	Flour	
Adults	Diatoms	80	81	90	90	93	94	100	100	7.64 *
	Salt	80	80	88	90	93	93	100	100	7.95 *
	Control	66	65	74	75	87	87	100	100	9.13 *
LSD value	---	7.37 *	7.85 *	6.71 *	6.93 8	6.02 NS	6.43 *	0.00 NS	0.00 NS	---
Pupae	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
Larvae	Diatoms	82	84	90	88	93	97	100	100	7.69 *
	Salt	81	83	90	87	94	95	100	100	8.02 *
	Control	68	68	80	80	86	88	100	100	8.52 *
LSD value	---	7.61 *	7.08 *	6.42 *	6.17 *	6.20 *	6.92 *	0.00 NS	0.00 NS	---
Eggs	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* ($P \leq 0.05$).



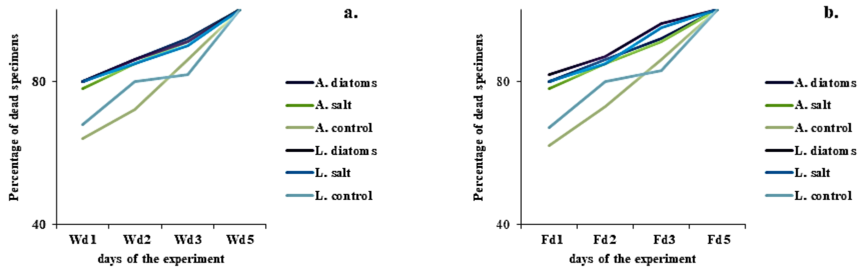
Temperature 9°C

Figure 1: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 9 °C during the first 5 days of the experiment.

Table 2: The mortality percentages of *Tribolium castaneum* adults and immatures during the experiment at 11 °C

Insect phases	**Materials**	**one day**		**two days**		**three days**		**five days**		**LSD value**
		Wheat	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	
	Diatoms	80	80	86	86	92	92	100	100	9.53 *
Adults	Salt	78	78	85	85	91	91	100	100	9.86 *
	Control	64	62	72	73	86	86	100	100	11.25 *
LSD value	---	7.86 *	8.70 *	7.14 *	7.65 *	6.08 NS	6.08 NS	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Pupae	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
	Diatoms	80	82	86	87	91	96	100	100	8.94 *
Larvae	Salt	80	80	85	85	90	95	100	100	8.57 *
	Control	68	67	80	80	82	83	100	100	10.42 *
LSD value	---	7.91 *	8.35 *	6.10 NS	6.57 *	6.83 *	6.92 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Eggs	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* ($P \leq 0.05$).



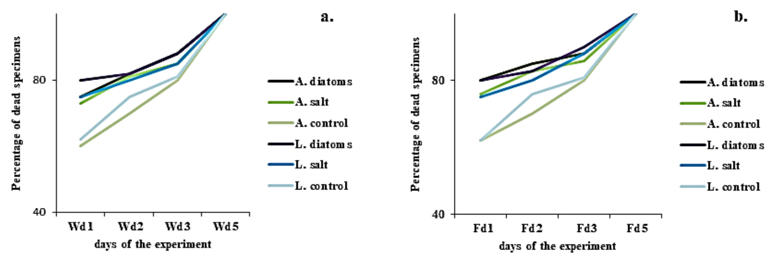
Temperature 11°C

Figure 2: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 11 °C during the first 5 days of the experiment.

Table 3: The mortality percentages of *Tribolium castaneum* adults and immatures during the experiment at 13 °C

Insect phases	**Materials**	**one day**		**two days**		**three days**		**five days**		**LSD value**
		Wheat	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	
	Diatoms	75	80	82	85	88	88	100	100	9.84 *
Adults	Salt	73	76	81	83	85	86	100	100	9.56 *
	Control	60	60	70	70	80	80	100	100	11.42 *
LSD value	---	7.02 *	7.88 *	7.96 *	7.35 *	6.97 *	6.82 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Pupae	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
	Diatoms	82	80	86	83	88	90	100	100	9.05 *
Larvae	Salt	80	75	80	80	85	88	100	100	8.93 *
	Control	61	62	75	76	81	81	100	100	11.36 *
LSD value	---	7.69 *	8.94 *	6.79 *	6.83 *	6.97 *	6.92 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Eggs	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* ($P \leq 0.05$).



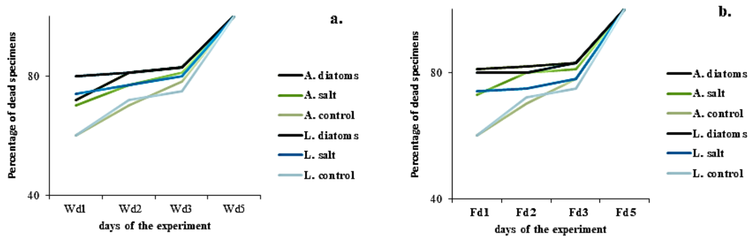
Temperature 13°C

Figure 3: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 13 °C during the first 5 days of the experiment.

Table 4: The mortality percentages of *Tribolium castaneum* adults and immatures during the experiment at 15 °C

Insect phases	**Materials**	**one day**		**two days**		**three days**		**five days**		**LSD value**
		Wheat	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	
	Diatoms	72	81	81	82	83	83	100	100	8.95 *
Adults	Salt	70	73	77	80	81	81	100	100	8.72 *
	Control	60	60	70	70	78	78	100	100	10.57 *
LSD value	---	7.95 *	8.44 *	7.05 *	7.32 *	6.01 NS	6.01 NS	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Pupae	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
	Diatoms	80	80	81	81	83	83	100	100	8.77 *
Larvae	Salt	74	74	77	75	80	80	100	100	9.26 *
	Control	60	60	72	72	75	75	100	100	11.04 *
LSD value	---	9.04 *	9.04 *	7.46 *	7.61 *	7.56 *	7.56 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Eggs	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* ($P \leq 0.05$).



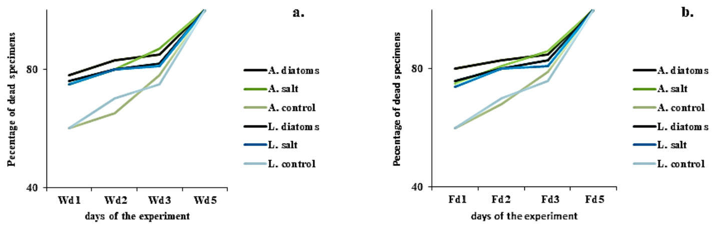
Temperature 15°C

Figure 4: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 15 °C during the first 5 days of the experiment.

Table 5: The mortality percentages of *Tribolium castaneum* adults and immatures during the experiment at 17 °C

Insect phases	**Materials**	**one day**		**two days**		**three days**		**five days**		**LSD value**
		Wheat	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	
	Diatoms	78	80	83	83	85	85	100	100	8.94 *
Adults	Salt	75	75	80	81	87	86	100	100	9.62 *
	Control	60	60	65	66	78	79	100	100	11.07 *
LSD value	---	6.52 *	7.84 *	7.09 *	7.22 *	6.14 NS	6.14 NS	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Pupae	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
	Diatoms	76	76	80	80	82	83	100	100	8.75 *
Larvae	Salt	75	74	80	80	81	81	100	100	9.36 *
	Control	60	60	70	70	75	76	100	100	11.29 *
LSD value	---	8.77 *	8.56 *	6.08 NS	6.11 NS	7.52 *	7.20 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Eggs	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* ($P \leq 0.05$).



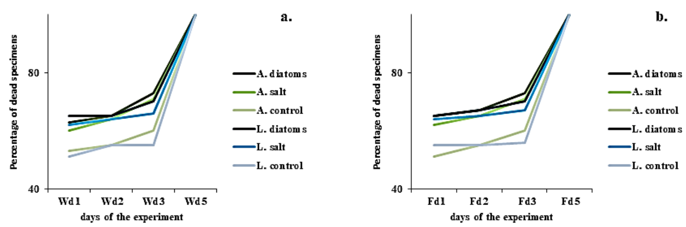
Temperature 17°C

Figure 5: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 17 °C during the first 5 days of the experiment.

Table 6: The mortality percentages of *Tribolium castaneum* adults and immatures during the experiment at 25 °C

Insect phases	**Materials**	**one day**		**two days**		**three days**		**five days**		**LSD value**
		Wheat	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	**Wheat**	**Flour**	
	Diatoms	63	65	65	67	73	73	100	100	8.94 *
Adults	Salt	60	62	64	65	71	71	100	100	9.62 *
	Control	53	51	55	55	60	60	100	100	11.07 *
LSD value	---	6.52 *	7.84 *	7.09 *	7.22 *	6.14 NS	6.14 NS	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Pu;ae	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
	Diatoms	65	65	65	67	70	70	100	100	8.75 *
Larvae	Salt	62	64	64	65	66	67	100	100	9.36 *
	Control	51	55	55	55	55	56	100	100	11.29 *
LSD value	---	8.77 *	8.56 *	6.08 NS	6.11 NS	7.52 *	7.20 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Eggs	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* (P≤0.05).



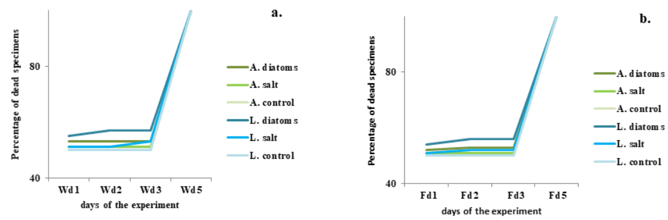
Temperature 25°C

Figure 6: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 25 °C during the first 5 days of the experiment.

Table 7: The mortality percentages of *Tribolium castaneum* adults and immatures during the experiment at 31 °C

Insect phases	Materials	one day		two days		three days		five days		LSD value
		Wheat	Flour	Wheat	Flour	Wheat	Flour	Wheat	Flour	
	Diatoms	53	52	53	53	53	53	100	100	8.94 *
Adults	Salt	51	51	51	51	51	51	100	100	9.62 *
	Control	50	50	50	50	50	50	100	100	11.07 *
LSD value	---	6.52 *	7.84 *	7.09 *	7.22 *	6.14 NS	6.14 NS	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Pupae	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---
	Diatoms	55	54	57	56	57	56	100	100	8.75 *
Larvae	Salt	51	51	51	52	53	52	100	100	9.36 *
	Control	50	50	50	50	50	50	100	100	11.29 *
LSD value	---	8.77 *	8.56 *	6.08 NS	6.11 NS	7.52 *	7.20 *	0.00 NS	0.00 NS	---
	Diatoms	100	100	100	100	100	100	100	100	0.00 NS
Eggs	Salt	100	100	100	100	100	100	100	100	0.00 NS
	Control	100	100	100	100	100	100	100	100	0.00 NS
LSD value	---	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	0.00 NS	---

* (P≤0.05).



Temperature 31°C

Figure 7: The percentage of mortality of *Tribolium castaneum* adults and larvae feeding on wheat (W) (a.) and flour (F) (b.) at 31 °C during the first 5 days of the experiment.

In the larval stage, mortality rates also differed significantly ($P \leq 0.05$) across treatments at all time points and for both wheat and flour. DE and NaCl treatments demonstrated superior effectiveness compared to the control on days 1, 2, and 3. As with adults, 100% mortality was reached in all groups by day 5. In contrast, mortality in the pupal and egg stages reached 100% for all treatments, diets, and exposure durations, as detailed in Tables 1–7. Temperature had a marked effect on mortality. At 9 °C, adult mortality reached 90% by day 2, decreasing to 83% at 17 °C. At 25 °C, adult and larval mortality rates were 73% and 70% respectively by day 3, while both reached 93% at 9 °C. At 31 °C, the mortality rates for adults and larvae feeding on wheat treated with DE dropped to 53% and 57%, respectively. These results indicate that lower temperatures, in combination with DE or NaCl, significantly hinder the development and survival of *T. castaneum* across its life stages (Figs 6–7).

This study demonstrates that both *Tribolium castaneum* adults and larvae are highly susceptible to Diatomaceous Earth (DE) and sodium chloride (NaCl), with 100% mortality achieved within five days of exposure in both wheat and flour, under relatively low temperatures. These findings are consistent with Agrafioti *et al*. (2023), who reported complete control of stored-product pests using DE (Figs. 1-6) (Tables 1-6).

The use of low temperatures (9–11 °C) in our experiments was critical in enhancing the efficacy of DE and NaCl. For example, at 9 °C, 66% of control adults died within one day, compared to 80% in the DE treatment, indicating a synergistic effect. This impact was even more pronounced in the egg and pupal stages, which showed 100% mortality across all treatments after five days, likely due to developmental arrest under suboptimal thermal conditions (Figs. 1-2)(Tables 1-2).

The larval stage appeared particularly vulnerable to both treatments. In our trials, larval mortality was consistently higher in DE and NaCl treatments than in the control. This may be attributed to desiccation caused by the hygroscopic and abrasive properties of DE, which disrupts the insect's cuticle, leading to dehydration and death (Korunić, 1998). Similarly, NaCl induces osmotic stress by lowering water activity, causing cellular dehydration (Davidson *et al*., 2012).

Our results align with previous studies that highlight the time-dependent effectiveness of DE. Parsaeyan *et al*. (2012) reported that two days of exposure were sufficient to achieve significant insect mortality, while Ciniviz & Mutlu (2020) confirmed that three days of DE exposure controlled common storage pests. In our study, mortality reached 90% by day 2 in wheat treated with DE at 9 °C, compared to 74% in the control, emphasizing the combined impact of physical control agents and environmental conditions.

Insect survival is strongly influenced by environmental temperature. According to Abdel-Hady *et al*. (2021), insects function optimally within a narrow thermal range. Temperatures below this range are sublethal or lethal, impairing metabolic functions and reproductive capacity. This was reflected in our control groups, where low temperatures alone caused considerable mortality. In contrast, at 31 °C, mortality did not exceed ~55% after three days, confirming that lower temperatures are more effective in reducing survival, especially when combined with DE or NaCl (Fig. 7)(Table 7).

Humidity also played a key role. Reduced ambient moisture, particularly in DE-treated conditions (8% RH), accelerated dehydration and increased mortality. Moisture imbalance can lead to protein denaturation, enzyme dysfunction, and disruption of vital metabolic processes in insects (Divagar *et al*., 2019).

In conclusion, the combination of DE, NaCl, and relatively low temperatures proved highly effective in suppressing *T. castaneum* populations. These findings support the implementation of integrated pest management strategies using natural, non-chemical agents in grain storage environments, particularly under conditions prevalent in Iraq. Such approaches not only improve food security and product quality but also support compliance with international trade standards.

CONCLUSION

This study demonstrated that both diatomaceous earth (DE) and coarse salt (NaCl) effectively increased mortality across all life stages of *Tribolium castaneum* when applied to wheat and flour at low temperatures. No significant differences were observed between DE and NaCl in their effectiveness on insect mortality. Mortality rates reached 100% within five days at temperatures ranging from 9 °C to 17 °C, underscoring the combined impact of desiccating agents and suboptimal thermal conditions.

Based on these findings, we recommend incorporating DE and NaCl as part of integrated pest management strategies in wheat and flour storage facilities. Their use not only suppresses beetle populations by reducing humidity, which is critical for the pest's development, but also limits fungal and microbial growth. Applying these physical control methods at moderately low temperatures may offer a sustainable and chemical-free approach to improving grain preservation and food safety during storage and trade.

CONFLICT OF INTEREST

The authors declare no conflicts of interest associated with this manuscript.

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