Pak. J. Agri. Sci., Vol. 58(X), xxx-xxx; 2021
ISSN (Print) 0552-9034, ISSN (Online) 2076-0906
DOI:10.21162/PAKJAS/21.746
http://www.pakjas.com.pk

ROLE OF ABIOTIC FACTORS ON THE EFFECTIVENESS OF INERT DUSTS FOR THE CONTROL OF *Trogoderma granarium* (COLEOPTERA: DERMESTIDAE)

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Diatomaceous earth (SilicoSec®) and zeolite (ZeoFeed) were evaluated as insecticides for the management of *Trogoderma granarium* on wheat, rice and maize. Both inert dusts were tested at three dose rates (250, 500 and 750 ppm), at three temperatures of 15°C, 25°C and 35°C and relative humidity of 55% and 75% were used to conduct bioassays. Third instar larvae were used in bioassays. After 1, 3, 7 and 14 days of treatments, mortality of the insects was recorded. As dose rate and exposure period increased, mortality of the insects was also increased. Increase in temperature and decrease in relative humidity (R.H.) increased the mortality of insects. In case of grain commodities, mortality on wheat was more comparative to rice and maize. Maximum mortality in *T. granarium* was observed on wheat @ dose rate of 750 ppm at 35°C and 55% R.H. after 14 days of treatment which was 49.62% for diatomaceous earth and 45.90% in case of zeolite. Results of current study suggested that both inert dusts (diatomaceous earth and zeolite) can be used in managing this insect species but it requires further investigations because complete mortality of the insects was not recorded in any case.
Keywords: Diatomaceous earth, dose rate, relative humidity, temperature, zeolite.

INTRODUCTION

Khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) is a key insect pest of stored grains across the world (Myers and Hagstrum, 2012). It is indigenous from India and like to live in dry and warm weather (Aitken,1975). Larval stage feeds on wide variety of stored as well as dried food products (Athanassiou *et al.*, 2016). *Trogoderma granarium* is listed among the top 100 most destructive pests (Lowe *et al.*, 2000) and is capable of moving easily from one region to another as it has wide host range (Aitken, 1975; Myers and Hagstrum, 2012). EPPO has categorized *T. granarium* as A2 quarantine insect pest, indicating its occurrence in geographical zone of European and Mediterranean Plant Protection Organization (EPPO, 2016). In order to impede the spread of *T. granarium,* importation of infested products is prohibited by the committee of World Trade Organization on Sanitary and Phytosanitary Measures.
Stored grain insects cause substantial losses to grains (Phillips and Throne, 2010). Ongoing control methods of storage insects are predominately comprised of using fumigants and insecticides (Boyer *et al.,* 2012). Alternative control methods are needed due to development of insect resistance to these chemicals (Tay *et al.,* 2016) and public demand of insecticide's residue free products. In recent researches, alternative methods of insect control have focused on the use of various inert dusts like diatomaceous earths (Athanassiou *et al.,* 2011). Comparative to the presently used nerve poisons, diatomaceous earths are quite promising substitute due to their effectiveness, ease in removal from the grains, low toxicity to mammals and akin procedure to grain application as that of contact insecticides (Subramanyam and Roesli, 2000). They have physical action on the insects and can be applied as dusts and in the form of slurries. These dusts act efficiently on vast range of insects and commodities of storage (Athanassiou *et al.*, 2011). Effectiveness of these dusts varies according to the insect species, grains types and abiotic factors (Subramanyam and Roesli, 2000).
Zeolites are alkaline based crystals of hydrated aluminum silicates (Christidis *et al.*, 2003). These are grouped as inert dusts among diatomaceous earths due to their silicon dioxide content. Impact of zeolites as insecticides is determined by their chemical and physical characteristics such as their molecular structure, silica content, particle size, pH, sorption capability and geographic origin (Eroglu *et al.*, 2017). Diatomaceous earths and zeolites are known to have high sportive capacities. Action of both inert dusts is through the cuticle of the insect. Diatomaceous earths are fossilized remaining of diatoms while zeolites are hydrated aluminum silicates and are comprised of amorphous silica (Andric *et al.*, 2012). Their use in agriculture has been increased after their approval from FDA of USA as safe for human beings (FDA GRAS Listings, 2006) and by WHO International Agency for Research on Cancer as non-toxins (IARC, 1997). Zeolites are listed as approved product by Codex Alimentarius

Commission (1999) to be used in Organic Food Production and Plant Protection.

Insecticidal impact of DEs regarding stored grain insects have been reported in many studies (Vardeman *et al.,* 2006; Kavallieratos *et al.,* 2007; Doumbia *et al.,* 2014), but very few studies are available on the use of zeolites in this field (Eroglu *et al.,* 2017). Effect of zeolites as insecticides has been examined against various insects of genus *Sitophilus* and *Tribolium* (Andric *et al.,* 2012; Perez *et al.,* 2012). These studies have reported the successful use of zeolites on different grain commodities and against many insect species. However, insecticidal potential of zeolites under different abiotic factors have not been studied so far. In case of other inert dusts, these factors have reported to play important role in effecting their efficacy against stored product insects (Vayias and Athanassiou, 2004; Athanassiou *et al.,* 2005b). Athanassiou *et al.* (2005b) noted the variable efficacy of DE at varying exposure period, dose and temperature against *S. oryzae* (L) and *T. confusum* du Val. Athanassiou *et al.* (2006) reported the lower efficacy of diatomaceous earth at lower temperature for the control of larval stage of *Ephestia kuehniella*. Additionally, efficacy of diatomaceous earth decreased with increasing relative humidity (Vayias and Athanassiou, 2004).

In present study, insecticidal impact of a DE and zeolite was evaluated on three types of grain commodities, i.e. wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*) for management of *T. granarium* using different levels of temperature and relative humidity.

MATERIALS AND METHODS

***Inert dusts*:** Diatomaceous earth formulation "SilicoSec®" (Biofa GmbH, Münsingen, Germany) was used which is a fresh water originated diatomaceous earth. Formulation of zeolite was "ZeoFeed" (Zeocem, Bystre, Slovakia) which is registered in its country of origin as a feed additive.

***Test insects and grain commodities*:** Insect used in the studies was *T. granarium*. Insects were obtained from different storages and grain market of Faisalabad and were reared in the incubator at 30±2°C and 60±10 % R.H. for increasing their number and obtaining homogenous population. For bioassays, larvae of *T. granarium* 3rd instar were used.

Tested grain commodities (clean and infestation free) were wheat (var. Galaxy 2013), rice (var. Basmati 515) and maize (var. Malka-2016). Moisture content of commodities was measured by moisture meter (Dickey-John Multigrain CAC II; Dickey-John Co., USA) which was 11.25% (wheat), 10.50% (rice) and 11.65% (maize).

***Bioassays*:** Seven lots of 1-kilogram (kg) of each grain type were prepared in plastic containers. From each grain type, three lots of 1 kg were taken and treated separately with diatomaceous earth at doses of 250, 500 and 750 mg/kg by admixing. Similarly, another 3 lots were taken and treated with zeolite at the concentration of 250, 500 and 750 mg/kg. Then they were manually shaken for 5 minutes to equally distribute inert dusts particles with grains. One untreated lot of each commodity served as control. From each grain lot 50 g samples were taken out to serve as experimental units and placed in small plastic jars (300 ml capacity). For aeration, small holes were made at top of each jar and jars were covered with muslin cloth. 50 larvae of *T. granarium* were placed in each jar. Experiment was conducted at three different levels of temperature (15, 25 and 35°C) and two levels of relative humidity (R.H. i.e. 55 and 75%) so there were 6 different combinations of temperature and R.H. Jars were placed in the incubator that were set at each tested level of temperature and R.H. Saturated salt solutions recommended by Greenspan (1977) were used for the maintenance of desired relative humidity levels during whole experimental period. Whole experiment was repeated three times. Mortality data was taken 1, 3, 7 and 14 days of post treatments.

***Data analysis*:** Control mortalities were adjusted by using Abbott's formula (Abbott, 1925). Factorial under Completely Randomized Design was used for assigning of treatments. Analysis of variance (ANOVA) was assessed and means of mortality were compared by applying Tukey-Kramer (HSD) test at α=0.05 (Sokal and Rohlf, 1995) by employing Statistix 8.1 (Analytical software, 2003).

RESULTS

Mortality of Trogoderma granarium: With diatomaceous earth, all main effects were significant while their associated interactions were non-significant except at 15°C + 55% R.H. after 1 day of treatment (Table 1). Maximum mortality was observed at 35°C + 55% R.H. with 750 ppm and its rates were 18.79% in wheat, 14.76% in rice and 11.42% in maize (Table 2). Three days after the exposure, all main effects were found significant and all their interactions were also significant except at 25°C + 75% R.H. (Table 1). With the 750 ppm dose, levels of highest mortality were 28.86% in wheat, 22.15% in rice and 18.14% in maize at 35°C + 55% R.H. (Table 2). After 7 days of exposure period, main effects were all significant and their interactions were also significant (Table 1). Mortality rates were highest at 750 ppm which was 40.54% in wheat, 35.58% in rice and 27.52% in maize at 35°C + 55% R.H. (Table 3). After 14 days of post exposure all main effects were significant and their interactions were also significant except at 35°C + 55% R.H. and 35°C + 75% R.H. (Table 1). At 35°C + 55% R.H. highest mortality of the larvae with the rates of 49.62% in wheat, 42.83% in rice and 35.63% in maize was obtained with the dose of 750 ppm (Table 3).

In case of zeolite, all main effects were significant while their interactions were significant only at 15°C + 55% R.H. and 15°C + 75% R.H. after 1 day of treatment (Table 4). Highest mortality levels were 16.78% in wheat, 14.08% in rice and 10.74% in maize with the highest dose at 35°C + 55% R.H.

(Table 5). Three days after the exposure, all main effects were significant but their interactions were significant only at 25°C + 55% R.H. and 35°C + 75% R.H. (Table 4). Mortality was highest at 35°C + 55% R.H. with 750 ppm and its values were 26.18% in wheat, 19.46% in rice and 16.79% in maize (Table 5). After 7 days of post treatment, all main effects were found significant and their related interactions were also significantly important except at 25°C + 55% R.H., 35°C + 55% R.H. and 35°C + 75% R.H. (Table 4). Maximum mortality was caused by highest dose of 750 ppm at 35°C + 55% R.H. which was 35.14% in wheat, 33.57% in rice and 25.51% in maize (Table 6). After the exposure interval of 14 days, all main effects were significantly important while their interactions were non-significant only at 35°C + 55% R.H. and 35°C + 75% R.H. (Table 4). With the dose of 750 ppm at 35°C + 55% R.H. highest mortality was 45.90% in wheat, 40.39% in rice and 32.89% in maize (Table 6).

Table 1. ANOVA for the mortality of *Trogoderma granarium* after exposure at three temperature and two R.H. levels on three grain commodities treated with DE.

Temperature	R.H.	Source	df	*F* (1 Day)	*P* (1 Day)	*F* (3 Days)	*P* (3 Days)	*F* (7 Days)	*P* (7 Days)	*F* (14 Days)	*P* (14 Days)
15°C	55%	Commodity	2	10.82	0.0011	19.36	0.0001	109.89	0.0000	118.90	0.0000
		Dose rate	2	82.30	0.0000	133.94	0.0000	176.68	0.0000	282.45	0.0000
		Commodity × Dose rate	4	5.21	0.0070	4.42	0.0135	9.27	0.0004	13.67	0.0000
	75%	Commodity	2	4.41	0.0299	242.34	0.0000	98.06	0.0000	155.95	0.0000
		Dose rate	2	34.66	0.0000	339.49	0.0000	227.40	0.0000	200.31	0.0000
		Commodity × Dose rate	4	0.35	0.8401	10.25	0.0003	32.51	0.0000	5.57	0.0053
25°C	55%	Commodity	2	19.37	0.0001	182.42	0.0000	77.90	0.0000	252.91	0.0000
		Dose rate	2	58.70	0.0000	178.35	0.0000	313.68	0.0000	827.45	0.0000
		Commodity × Dose rate	4	2.68	0.0695	5.63	0.0050	3.95	0.0203	15.97	0.0000
	75%	Commodity	2	21.15	0.0000	22.04	0.0000	43.55	0.0000	349.00	0.0000
		Dose rate	2	50.26	0.0000	39.91	0.0000	47.06	0.0000	356.08	0.0000
		Commodity × Dose rate	4	1.51	0.2458	0.51	0.7267	4.31	0.0148	26.67	0.0000
35°C	55%	Commodity	2	39.95	0.0000	114.74	0.0000	533.16	0.0000	72.25	0.0000
		Dose rate	2	105.37	0.0000	211.25	0.0000	650.35	0.0000	152.11	0.0000
		Commodity × Dose rate	4	1.34	0.2996	4.65	0.0111	7.00	0.0019	1.72	0.1952
	75%	Commodity	2	19.03	0.0001	36.44	0.0000	107.27	0.0000	102.85	0.0000
		Dose rate	2	55.45	0.0000	88.59	0.0000	174.11	0.0000	183.00	0.0000
		Commodity × Dose rate	4	1.07	0.4049	4.32	0.0147	6.94	0.0019	1.76	0.1855

Table 2. Percentage mean mortality (±SE) of *Trogoderma granarium* after 1- and 3-days exposure to three doses of DE at three temperature and two R.H. levels on three grain commodities.

Temperature	R.H.	Commodity	1 Day Dose rate 250 ppm	1 Day Dose rate 500 ppm	1 Day Dose rate 750 ppm	3 Days Dose rate 250 ppm	3 Days Dose rate 500 ppm	3 Days Dose rate 750 ppm
15°C	55%	Wheat	1.35±0.67d	3.36±0.68cd	10.07±0.07a	3.37±0.67d	8.11±0.05bc	14.18±1.09a
		Rice	2.68±0.66cd	4.03±0.03cd	7.39±0.70ab	5.37±0.69cd	6.04±0.04bcd	14.76±0.62a
		Maize	1.33±0.67d	2.01±0.01d	5.37±0.69bc	2.68±0.66d	4.69±0.65cd	9.40±0.70b
	75%	Wheat	2.01±0.01bc	4.03±0.03abc	6.72±0.72a	6.04±0.04c	10.74±0.64b	16.11±0.11a
		Rice	2.01±0.01bc	4.03±0.03abc	6.04±1.16a	2.68±0.66de	6.04±0.04c	10.74±0.64b
		Maize	1.33±0.67c	2.68±0.66bc	4.71±0.71ab	2.01±0.01e	4.03±0.03d	7.39±0.70c
25°C	55%	Wheat	6.03±1.13cd	6.04±0.04bcd	13.44±1.44a	13.52±0.76cd	18.23±1.06b	26.35±0.18a
		Rice	2.68±0.66de	6.04±0.04bcd	10.07±0.07ab	8.05±0.05fg	11.42±0.71de	15.44±0.73bc
		Maize	1.33±0.67e	4.67±0.67cde	7.33±0.67bc	6.04±0.04g	10.07±0.07ef	14.76±0.62c
	75%	Wheat	3.36±0.68cd	6.71±0.65ab	9.40±0.70a	8.05±0.05b	10.07±1.16ab	13.43±0.72a
		Rice	2.68±0.66d	4.03±0.03bcd	6.04±0.04bc	7.39±0.70b	10.74±0.64ab	13.40±1.70a
		Maize	1.35±0.67d	3.35±0.65cd	6.04±0.04bc	2.68±0.66c	6.71±0.65bc	10.07±0.07ab
35°C	55%	Wheat	8.04±1.12cd	13.40±1.70b	18.79±0.61a	14.76±0.62e	24.83±0.60b	28.86±0.59a
		Rice	5.37±0.69de	9.40±0.70c	14.76±0.62b	10.07±0.07f	19.46±1.28cd	22.15±0.15bc
		Maize	4.03±0.03e	8.05±0.05cd	11.42±0.71bc	9.40±0.70f	14.78±0.76e	18.14±1.27de
	75%	Wheat	7.39±0.70bcd	8.05±0.05bc	12.74±1.27a	11.40±1.30cd	14.11±1.25bc	26.16±1.92a
		Rice	4.03±0.03de	7.39±0.70bcd	10.07±0.07ab	8.05±0.05de	14.76±0.62bc	19.47±0.74b
		Maize	3.33±0.67e	5.33±0.67cde	9.33±0.67ab	4.69±0.65e	10.05±1.11cde	14.11±1.25bc

Means following same letters are non-significant; HSD test at p<0.05at each exposure interval, within each temperature and R.H. combination for all three grain types

Table 3. Percentage mean mortality (±SE) of *Trogoderma granarium* after 7- and 14-days exposure to three doses of DE at three temperature and two R.H. levels on three grain commodities.

Temperature	R.H.	Commodity	7 Days Dose rate			14 Days Dose rate		
			250 ppm	500 ppm	750 ppm	250 ppm	500 ppm	750 ppm
15°C	55%	Wheat	12.16±1.18c	14.87±0.73c	26.37±1.32a	13.71±0.73d	27.06±0.29b	35.63±1.50a
		Rice	7.43±0.65d	12.15±1.10c	20.95±0.76b	14.53±0.40d	20.29±1.29c	32.44±1.20a
		Maize	5.37±0.69d	8.05±0.05d	12.08±0.08c	10.14±0.07d	12.16±0.08d	21.63±0.82c
	75%	Wheat	7.43±0.65d	10.82±0.72c	21.62±0.62a	17.00±0.51d	22.46±0.26c	30.62±0.36a
		Rice	5.37±0.69d	8.05±0.05cd	17.46±0.74b	12.16±0.08e	16.22±0.11d	26.37±1.32b
		Maize	5.37±0.69d	6.71±0.65d	8.05±0.05cd	9.51±0.59e	10.19±1.13e	17.66±1.17d
25°C	55%	Wheat	16.22±0.11de	19.59±0.62cd	31.74±1.13a	20.27±0.14d	36.49±0.24b	43.25±0.86a
		Rice	11.42±0.71fg	16.79±1.40de	26.84±0.60b	15.64±0.54e	27.89±0.43c	37.43±0.80b
		Maize	10.14±0.07g	14.19±0.10ef	21.62±0.62c	14.39±0.10e	21.93±0.77d	30.15±0.81c
	75%	Wheat	12.75±0.63cd	15.44±0.73bc	21.48±0.75a	17.68±0.52c	26.54±0.31b	39.45±0.36a
		Rice	9.46±0.65de	15.54±1.78bc	18.93±0.75ab	13.52±0.76d	18.93±0.75c	25.67±0.61b
		Maize	8.04±1.12e	10.07±0.07de	11.42±0.71cde	9.50±1.25e	13.60±0.55d	18.37±0.22c
35°C	55%	Wheat	26.35±0.18de	31.76±0.60c	40.54±0.27a	30.62±0.36de	40.13±0.36bc	49.62±2.21a
		Rice	22.82±0.61f	24.83±0.60ef	35.58±0.82b	23.83±0.93f	35.38±0.79cd	42.83±1.64b
		Maize	13.43±0.72h	20.14±0.14g	27.52±0.78d	21.23±0.62f	27.40±0.61ef	35.63±1.50cd
	75%	Wheat	17.46±0.74cd	26.84±0.60b	33.58±1.58a	23.65±0.62de	31.77±1.47bc	39.86±0.59a
		Rice	15.44±0.73d	21.48±0.75c	26.84±0.60b	16.87±1.67fg	29.73±0.60c	35.80±1.61ab
		Maize	10.74±0.64e	18.80±0.80cd	19.47±0.74cd	11.50±1.40g	20.27±0.14ef	26.37±1.32cd

Means following same letters are non-significant; HSD test at $p<0.05$ at each exposure interval, within each temperature and R.H. combination for all three grain types

Table 4. ANOVA for the mortality of *Trogoderma granarium* after exposure at three temperature and two R.H. levels on three grain commodities treated with zeolite.

Temperature	R.H.	Source	df	*F* (1 Day)	*P* (1 Day)	*F* (3 Days)	*P* (3 Days)	*F* (7 Days)	*P* (7 Days)	*F* (14 Days)	*P* (14 Days)
15°C	55%	Commodity	2	7.47	0.0051	10.65	0.0011	81.67	0.0000	240.12	0.0000
		Dose rate	2	56.83	0.0000	105.92	0.0000	116.44	0.0000	505.75	0.0000
		Commodity × Dose rate	4	5.20	0.0071	1.89	0.1619	5.94	0.0040	27.36	0.0000
	75%	Commodity	2	10.85	0.0011	34.70	0.0000	29.52	0.0000	199.23	0.0000
		Dose rate	2	61.52	0.0000	97.26	0.0000	78.80	0.0000	192.32	0.0000
		Commodity × Dose rate	4	3.52	0.0304	2.70	0.0683	9.69	0.0004	3.48	0.0314
25°C	55%	Commodity	2	14.21	0.0003	96.03	0.0000	84.39	0.0000	99.61	0.0000
		Dose rate	2	56.02	0.0000	107.47	0.0000	246.14	0.0000	370.84	0.0000
		Commodity × Dose rate	4	1.10	0.3908	4.97	0.0085	1.14	0.3719	9.50	0.0004
	75%	Commodity	2	7.60	0.0048	26.60	0.0000	45.25	0.0000	304.09	0.0000
		Dose rate	2	13.13	0.0004	73.25	0.0000	95.92	0.0000	298.58	0.0000
		Commodity × Dose rate	4	0.78	0.5563	1.24	0.3345	9.35	0.0004	32.84	0.0000
35°C	55%	Commodity	2	22.92	0.0000	63.99	0.0000	79.89	0.0000	108.14	0.0000
		Dose rate	2	71.36	0.0000	116.07	0.0000	205.44	0.0000	229.23	0.0000
		Commodity × Dose rate	4	0.53	0.7162	1.51	0.2457	1.62	0.2183	2.64	0.0724
	75%	Commodity	2	10.97	0.0010	65.55	0.0000	75.37	0.0000	107.06	0.0000
		Dose rate	2	36.09	0.0000	104.37	0.0000	108.16	0.0000	228.20	0.0000
		Commodity × Dose rate	4	0.97	0.4533	3.94	0.0207	1.28	0.3192	2.74	0.0655

DISCUSSION

Diatomaceous earths (DEs) are diatoms that are fossilized over time, having low toxicity to mammals; kill the insect physically by removing lipid layers from body cuticle followed by desiccation and death (Subramanyam and Roesli, 2000). Zeolites (natural as well as synthetic) are crystals of aluminosilicates having microporous structure (de Smedt *et al.*, 2015). Results show that diatomaceous earth and zeolite can be used against tested insects but regarding their effectiveness on various important factors such as doses, exposure duration, grain type, temperature and relative humidity is questioned. Mortality of the insects increased with increasing exposure interval which is in accordance to the previous studies (Nwaubani *et al.*, 2014) that proved that increasing interval of exposure increased mortality rate.

Longer exposure period was required for diatomaceous earth in order to kill the insects (Athanassiou *et al.*, 2006, 2007, 2008) because as the result of longer exposure, more dust is attached to insect body leading to more water loss (Arthur, 2000a, b, 2001). Previous studies are also in the support of this fact that effectiveness of the inert dusts was increased by increasing the exposure duration (Athanassiou *et al.*, 2005a; Kljajić *et al.*, 2010a, b; Perisic *et al.*, 2018).

Table 5. Percentage mean mortality (±SE) of *Trogoderma granarium* after 1- and 3-days exposure to three doses of zeolite at three temperature and two R.H. levels on three grain commodities.

Temperature	R.H.	Commodity	1 Day			3 Days		
			Dose rate			Dose rate		
			250 ppm	500 ppm	750 ppm	250 ppm	500 ppm	750 ppm
15°C	55%	Wheat	1.35±0.67c	2.68±0.66c	8.74±0.73a	2.03±0.01de	6.76±0.70bc	12.15±1.10a
		Rice	2.01±0.01c	2.68±0.66c	6.04±1.16ab	4.03±0.03cde	5.37±0.69bcd	12.08±1.16a
		Maize	1.35±0.67c	2.01±0.01c	4.03±0.03bc	1.35±0.67e	4.03±0.03cde	8.72±0.64ab
	75%	Wheat	2.01±0.01bc	2.68±0.66bc	6.04±0.04a	4.03±0.03d	8.05±0.05b	13.43±0.72a
		Rice	1.35±0.67c	3.36±0.68b	5.37±0.69a	2.68±0.66d	4.69±0.65cd	9.39±1.31b
		Maize	1.35±0.67c	2.01±0.01bc	3.36±0.68b	2.01±0.01d	3.36±0.68d	7.39±0.70bc
25°C	55%	Wheat	4.71±0.71cde	5.37±0.69cd	11.42±0.71a	11.48±0.64cd	15.55±1.41b	23.65±0.62a
		Rice	2.01±0.01de	4.71±0.71cde	9.40±0.70ab	7.39±0.70ef	10.07±0.07cde	13.43±0.72bc
		Maize	1.35±0.67e	3.35±0.65cde	6.69±1.31bc	5.37±0.69f	8.74±0.73def	13.42±0.59bc
	75%	Wheat	2.69±0.69b	4.68±1.75ab	8.05±0.05a	4.69±0.65cd	9.39±0.64ab	11.40±0.60a
		Rice	2.01±0.01b	2.68±0.66b	4.69±0.65ab	6.03±1.13bc	8.72±0.64ab	12.07±1.10a
		Maize	1.35±0.67b	2.01±0.01b	4.04±1.19ab	2.01±0.01d	4.03±0.03cd	9.39±0.61ab
35°C	55%	Wheat	7.37±1.31def	12.07±1.10bc	16.78±0.62a	13.43±0.72cd	20.82±0.82b	26.18±1.17a
		Rice	4.71±0.71ef	8.72±0.64cde	14.08±1.08ab	10.05±1.11de	16.79±1.40bc	19.46±1.27b
		Maize	3.35±0.65f	7.39±0.70def	10.74±0.64bcd	7.39±0.70e	12.76±0.76cd	16.79±1.40bc
	75%	Wheat	6.72±0.72bcd	6.71±0.65bcd	12.75±0.63a	10.07±0.07cd	12.75±0.63bc	20.82±0.82a
		Rice	2.68±0.66d	6.05±1.20bcd	9.40±0.70ab	6.71±0.65de	14.08±1.08bc	16.79±0.79ab
		Maize	2.67±1.33d	4.68±1.32cd	8.72±0.64abc	3.36±0.68e	6.69±1.31de	11.42±0.71c

Means following same letters are non-significant; HSD test at p<0.05at each exposure interval, within each temperature and R.H. combination for all three grain types

Table 6. Percentage mean mortality (±SE) of *Trogoderma granarium* after 7- and 14-days exposure to three doses of zeolite at three temperature and two R.H. levels on three grain commodities.

Temperature	R.H.	Commodity	7 Days			14 Days		
			Dose rate			Dose rate		
			250 ppm	500 ppm	750 ppm	250 ppm	500 ppm	750 ppm
15°C	55%	Wheat	10.12±1.11cd	12.84±0.72bc	23.65±0.62a	12.50±1.20e	26.04±0.60c	34.72±0.69a
		Rice	5.40±0.66ef	8.10±1.12de	16.22±1.18b	11.57±0.68ef	17.69±0.68d	30.81±1.01b
		Maize	3.36±0.68f	6.71±0.65def	10.07±0.07cd	8.17±0.10f	10.21±0.12ef	19.05±0.71d
	75%	Wheat	5.39±1.31c	10.14±0.07b	17.58±1.42a	15.18±0.75c	20.00±0.64b	28.27±0.62a
		Rice	4.71±0.71c	6.71±0.65bc	14.76±0.62a	10.28±0.07de	11.65±0.73d	19.87±0.76b
		Maize	4.71±0.71c	5.37±0.69c	7.39±0.70bc	6.86±0.74e	7.54±0.71e	15.75±0.58c
25°C	55%	Wheat	14.87±0.73de	17.57±0.63cd	27.69±1.16a	17.12±0.63de	34.92±0.99b	39.73±0.59a
		Rice	10.07±0.07fg	14.78±0.78de	23.48±0.52b	13.01±0.64e	25.33±1.20c	33.56±0.60b
		Maize	6.75±0.63g	11.48±0.64ef	18.91±0.54c	13.01±0.64e	20.56±1.32d	28.09±0.80c
	75%	Wheat	10.07±0.07cd	11.42±0.71c	20.80±0.61a	15.86±0.65cd	23.46±0.78b	38.62±0.61a
		Rice	6.75±0.63de	12.16±0.08bc	15.55±1.41b	11.57±0.68e	16.33±0c	21.77±0.68b
		Maize	6.04±0.04e	8.72±0.64cde	10.75±0.75c	7.54±0.71f	12.33±0.09de	16.45±1.29c
35°C	55%	Wheat	20.95±0.76c	26.34±1.02b	35.14±0.82a	27.41±0.88e	37.68±0.95bc	45.90±1.01a
		Rice	19.47±0.74c	23.48±1.27bc	33.57±0.81a	22.61±0.31ef	32.86±0.83d	40.39±1.45b
		Maize	12.76±0.76d	19.47±0.74c	25.51±0.77b	19.18±0.63f	24.66±0.17e	32.89±1.39cd
	75%	Wheat	16.10±1.07def	22.83±0.83b	28.20±1.34a	19.87±0.76de	27.38±1.67bc	37.67±0.60a
		Rice	12.76±0.76f	19.47±0.74bcd	21.47±1.27bc	14.39±0.10f	27.40±0.61bc	32.20±0.82b
		Maize	8.05±0.05g	14.78±0.78ef	18.12±0.12cde	8.22±0.06g	17.13±0.81ef	24.63±1.90cd

Means following same letters are non-significant; HSD test at p<0.05at each exposure interval, within each temperature and R.H. combination for all three grain types

Dose is also important determinant for inert dusts. Mortality of the insects was more at the higher dose rates. Vayias and Athanassiou (2004) found that more larvae of *T. confusum* died at higher doses of diatomaceous earth. Trdan *et al.* (2015) found higher efficacy of zeolites and DE at higher dose rates for the control of *S. zeamais*. Athanassiou *et al.* (2003) determined that impact of DEs was dependent on the dose but very high dose rates affected the quality and grain's bulk density (Korunic *et al.,* 1996).

Mortality was more at increased temperature and decreased R.H. Bohinc and Trdan (2017) also described importance of these factors in the effectiveness of inert dusts against various stored grain insects. Increased mortality due to diatomaceous earths at elevated temperature and decreased relative humidity has also been reported against *T. confusum* (Vayias and Athanassiou, 2004) and against *S. oryzae* (Athanassiou *et al.*, 2014). Bohinc *et al.* (2018) also reported that zeolites were most effective against *S. zeamais* at higher temperature and lower R.H. At increased temperature, mobility of the insects is increased due to which more particles of the inert dusts are attached to their bodies. High level of temperature also caused increased water loss and more respiration in the insects (Arthur, 2000b; Subramanyam and Roesli, 2000). Mortality of *S. oryzae* increased with an increase in temperature by using the diatomaceous earth (Athanassiou *et al.*, 2005b). Zeolites caused high mortality at higher temperature (Kjajic *et al.*,2010a, b; Eroglu *et al.*, 2019). Regarding the relative humidity, more insects died at 55% R.H. This may be due to the fact that at lower levels of R.H. more water is lost from the insect body as reported in previous studies by using the diatomaceous earth (Vayias and Athanassiou, 2004). In present study, differences in the mortality at both relative humidity levels were less while it was reported against *T. confusum* (Vayias and Athanassiou, 2004). Similar effect was also reported by using natural zeolites against *S. oryzae* and *Oryzaephilus surinamensis* (L.) (Eroglu *et al.*, 2019). But according to the Vayias and Athanassiou (2004) mortality of the larvae of *T. confusum* decreased by increasing the relative humidity levels from 55 to 65% by using diatomaceous earth. Kljajic *et al.* (2010a, b, 2011) and Andric *et al.* (2012) reported that zeolites showed effect of R.H. on insect mortality but for other R.H. had no effect regarding mortality showing that formulation of the inert dust is also important.

In present study, less mortality of *T. granarium* due to DE and Zeolite was observed as compared with that in *R. dominica* which may be due to the fact that larval body of *T. granarium* is covered with the hair due to which dust particles are unable to attach the body of the insect (Carlson and Ball, 1962; Vayias and Athanassiou, 2004). Similarly, Kavallieratos *et al.* (2017) reported less efficiency of DE against larvae of *T. granarium* as compared to the other insecticides. Zeolite was also effective for managing various insects of stored products (Yao, 2014) but mortality was higher in case of diatomaceous earth as compared to the zeolite in most of the cases. These differences may be due to difference in the structure of the both type of tested inert dusts.

In present study, mortality was more in wheat as compared to rice or maize in most of the cases. Athanassiou *et al.* (2003, 2011) also found similar reports that more mortality occurred on wheat as compared to other tested grain commodities against *S. oryzae, R. dominica* and *T. confusum*. Similarly, Vayias *et al.* (2006) reported high mortality of the insects on wheat treated with diatomaceous earth as compared to the maize. Diatomaceous earth was more effective regarding mortality of *R. dominica* on wheat than on rice and maize (Wakil *et al.,* 2013). Less mortality in maize may be due to low adherence of particles of DE with maize as compared to the wheat, rice or barley (Athanassiou and Kavallieratos, 2005). In case of zeolite, Rumbos *et al.* (2016) noted less zeolite particles adhered to maize in comparison with barley and rice. Less efficacy of the inert dusts on the maize may be due to the fact that wide spaces between the seeds of maize allow insect to avoid the contact with the dust particles (Athanassiou *et al.,* 2003). Physio chemical characteristics of the maize kernels such as lipids and oils interaction with the diatomaceous earth that may affect its efficacy (Subramanyam and Roesli, 2000).

In summary, results of the current study show that DE (SilicoSec®) and zeolite (ZeoFeed) can be used for the management of *T. granarium* but several factors like temperature, R.H. and grain commodities are important in affecting the efficacy of these dusts. These factors should be taken into account while applying these dusts commercially.

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