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ORIGINAL RESEARCH ARTICLE

Factors influencing the combined efficacy of microbial insecticides and inert dusts for the control of *Trogoderma granarium*

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Abstract

Combined action of various inert dusts (diatomaceous earth DE and zeolite) and microbial insecticides (abamectin and spinetoram) was evaluated against *Trogoderma granarium* Everts at Grain Research Training and Storage Management Cell, department of Entomology, University of Agriculture, Faisalabad, Pakistan during the year 2018–19. Doses were 750 ppm in case of inert dusts and 1 ppm in case of insecticides. Efficacy was checked on wheat, rice and maize at three different temperatures (15, 25 and 35 °C) and two relative humidity levels (55 and 75%). Mortality data was taken 1, 3, 5 and 7 days after treatments. Factorial under Completely Randomized Design was used for analysis. In all combinations tested, complete mortality (100%) of the insects was achieved at 35 °C + 55% R.H. after 14 days of exposure. But in general, mortality was higher at increased temperature and decreased R.H. With an increase in exposure period, mortality was also increased. Wheat was most susceptible as compared to rice and maize regarding the mortality of insects except in cases of 100% mortality. Results suggested that both DEs and zeolites can be combined with insecticides in order to achieve complete control of this specie but certain factors like dose, temperature, R.H., commodity and exposure time are important in affecting their efficacies which should be kept in mind for the integrated control of this insect. This is first report in which zeolite is used in combination with insecticides against *Trogoderma granarium.*

Keywords Abamectin · Diatomaceous earth · Relative humidity · Spinetoram · Temperature · Zeolite

Introduction

Chemicals and fumigants that are currently being used in stored grains have uncertain future because they cause environmental issues, are not safe and many stored grain insects have developed resistance against many of these grain protectants specially to organophosphates (Daglish 2008). So, for the successful effectiveness of these chemicals higher doses are required. Nowadays, people are demanding products that are free from pesticides residues which have led to evaluating alternative controls like use of pyrethroids (Athanassiou et al. 2004). The use of inert dusts, microbial insecticides, bio-control agents and botanical based insecticides have been evaluated in this regard.

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Spinetoram is based on spinosyn L and J derived synthetically from the metabolism of soil actinomycete *Saccharopolyspora spinosa* Mertz and Yao. It has been studied against many stored product species and has been found effective for their control (Vassilakos and Athanassiou 2012). It is a nerve poison that attacks on receptors of nicotine acetylcholine and it acts via contact and ingestion (Dripps et al. 2011) and is more active than spinosad (Sparks et al. 2008). Abamectin, belonging to the avermectin family is another bacterial insecticide derived from a soil bacterium, *Streptomyces avermitilis* (Pozo et al. 2003). This insecticide has a vast range which leads to its effective use for managing various insect pests (Kavallieratos et al. 2009).

Use of inert dusts is another alternative control tactic in stored grain insect management. Diatomaceous earths (DEs) are inert dusts that are natural in origin and are made up from the fossil remains of diatoms (Subramanyam and Roesli 2000). Zeolites, among other naturally occurring silica dusts are known and classified in the same group as the diatomaceous earths because of their silica content (Eroglu et al. 2017). Both diatomaceous earths and zeolites have a physical mode of action, i.e., act via cuticle of insect causing desiccation and death (Andric et al. 2012). The difference between zeolites and DEs are of the structure. DEs are fossilised remaining of diatoms but zeolites are crystalised alumina silicates having amorphous silica (Golob 1997; Andric et al. 2012).

Certain abiotic factors of the environment are of great significance for the development of insects in the storage ecosystem such as temperature, R.H. and composition of gases (Muir 2000). In case of insecticides various studies with contradictory results have been done depicting the role of temperature on action of various insecticides (Nayak and Collins 2008; Golic et al. 2016). In case of inert dusts, their efficacy has been found to be affected by insect species (Fields & Korunic 2000), physical properties (Vayias et al. 2009b), type of dust, temperature, R.H. and exposure time (Athanassiou et al. 2005; Vardeman et al. 2006).

These inert dusts adhere to the grains that may cause negative impact on the physical characteristics of the grains reducing their value commercially (Korunic et al. 1996). A possible solution of this problem is to apply these dusts (at low doses) in combination with other control methods. This combination could be useful in applying inert dusts widely as a grain protectant (Arthur 2003). Combined use of inert dust, especially of DEs, with other control methods have been tested previously like the combination of DEs with entomopathogenic fungi (Athanassiou and Steenberg 2007), with plant extracts (Athanassiou et al. 2008a), with pyrethroids (Vayias et al. 2006), or with insecticidal dusts like spinosad (Chintzoglou et al. 2008a).

In the present study combined efficacy of inert dusts with bacterial based insecticides was evaluated and the effect of other factors like temperature and grain commodities was also studied against *Trogoderma granarium*.

Materials and methods

Test products

Inert dusts used were diatomaceous earth "SilicoSec" (Biofa GmbH, Münsingen, Germany) which is a fresh water originated diatomaceous earth and zeolite "ZeoFeed" (Zeocem, Bystre, Slovakia) which is registered in its country of origin as a feed additive.

Insecticides used in the bioassay were spinetoram (Radiant) and abamectin (Vertimec) that were obtained from Dow Agro Chemical Company and Syngenta Pakistan Ltd., respectively.

Test insects and grain commodities

Experiment was conducted at Grain Research Training and Storage Management Cell, department of Entomology, University of Agriculture, Faisalabad, Pakistan during the year 2018–19. The insect used in studies was *T. granarium*. Insects were obtained from different storages and grain market of Faisalabad and were reared in laboratory at 30 ± 2 °C and 60 ± 10% R.H. For bioassays, *T. granarium* larvae of third instar were used.

Tested grain commodities were wheat, rice and maize which were clean and free of infestation. Moisture content of commodities was measured by moisture meter (Dickey-John Multigrain CAC II; Dickey-John Co., U.S.A) which was 11.25% (wheat), 10.50% (rice) and 11.65% (maize).

Bioassays

Five lots of 1-kg of each grain type were prepared in plastic containers. From each grain type, four lots were taken and two lots of each type of grains were separately treated with diatomaceous earth (DE), other two lots with zeolite at the rate 750 mg/kg by admixing. Then these were shaken for 5 min by hand to equally distribute inert dusts particles with grains. Two DE-treated lots of each commodity were treated with spinetoram and abamectin at the rate of 1 ppm separately. Two zeolites treated lots of each grain commodity were also treated separately with abamectin and spinetoram at 1 ppm. Grains were spread in the trays for the uniform application of the insecticides. Using a hand sprayer, 5 ml of each of insecticide or water (in control) was sprayed on each grain type and then grains were placed in the incubator at 25 °C and 65% R.H. for two days so that moisture could equilibrate (Kavallieratos et al. 2009). These doses were selected from the previous experiments on the basis of mortality of insects. 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 jars (11 cm × 6.5 cm). Jars were covered with muslin cloth for aeration. Fifty 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 R.H. (55% and 75%) so there were six different combinations of temperature and relative humidity. Jars were placed in the incubator that was set at each tested level of temperature and relative humidity. Saturated salt solutions recommended by Greenspan (1977) were used for the maintenance of desired relative humidity levels during the whole experimental period. Whole experiment was repeated three times. Data of mortality was taken at 1, 3, 7 and 14 days of post treatments.

Data analysis

Control mortalities were adjusted by using Abbott's formula (Abbot 1925). Factorial analysis under Completely

Randomized Design was used. Means for mortality were compared by using Tukey–Kramer (HSD) test at α = 0.05 (Sokal and Rohlf 1995). The Statistix 8.1 program was used for statistical analyses.

Results

Mortality

In combined treatment of DE + abamectin, for all exposure intervals all main effects were significant but their associated interactions were non-significant with the exception of Temperature × R.H. after 1 day, Commodity × R.H. and Temperature × R.H. after 7 days and Commodity × Temperature and Temperature × R.H. after 14 days (Table 1). As temperature and exposure interval increased mortality increased but it was opposite in case of R.H. (Table 2). Generally, mortality was more in wheat than in rice or maize (Table 2). After the 14 days of exposure period at 35 °C + 55% R.H. 100% of mortality was found in all three tested grain commodities (Table 2).

In case of DE + spinetoram, at each exposure interval all main effects were significant but their interactions were non-significant except Commodity × Temperature, Commodity × R.H. and Temperature × R.H. after 7 days and Commodity × Temperature and Temperature × R.H. after 14 days of exposure (Table 3). In most of the cases, mortality was higher as compare to combined treatment of DE + abamectin. More insects were died on wheat than on rice or maize in most of the cases (Table 4). Increased R.H. decreased the mortality while increased temperature and exposure period increased the mortality (Table 4). On all grain commodities 100% mortality was achieved at 35 °C + 55% R.H. at 14 days of post treatment (Table 4).

In combined application on zeolite + abamectin, all main effects were found significant at all exposure periods while their associated interactions were significant only for Temperature × R.H. after 1 day, Commodity × Temperature after 3 days and Commodity × Temperature and Temperature × R.H. after 14 days of exposure (Table 5). Effect of temperature was positive on the mortality of the insects but in case of R.H. mortality decreased with increase in R.H. (Table 6). As exposure period increased mortality was also increased (Table 6). Generally, wheat found to be more susceptible as compared to the other grain types (Table 6). Complete mortality was obtained after 14 days of treatment at 35 °C + 55% R.H. in all tested grain types (Table 6).

For combination of zeolite + spinetoram, at all exposure durations main effects were found to be significant while their associated interactions were non-significant with the exception of Commodity × R.H. after 3 days, Commodity × Temperature and Temperature × R.H. after 7 days and Commodity × Temperature and Temperature × R.H. after 14 days of exposure (Table 7). Overall, in this combination mortality was more as compared to the combination of zeolite + abamectin. High temperature and low R.H. caused more mortality (Table 8). Mortality was tended to increase at increased exposure (Table 8). Among grain types, wheat was generally most susceptible as compared to rice or maize (Table 8). 100% mortality of insects in all grain commodities occurred at 35 °C + 55% R.H. after 14 days of exposure (Table 8).

Table 1 ANOVA for the mortality of *T. granarium* at different exposure intervals after the combined treatment of DE + abamectin at different temperature and relative humidity (R.H.) levels on three grain commodities

Exposure interval	Source	df	*F*	*P*
1 day	Commodity	2	119.94	0.0000
	Temperature	2	149.41	0.0000
	R.H	1	85.75	0.0000
	Commodity × Temperature	4	1.43	0.2449
	Commodity × R.H	2	0.64	0.5316
	Temperature × R.H	2	7.69	0.0018
	Commodity × Temperature × R.H	4	0.49	0.7425
3 days	Commodity	2	75.34	0.0000
	Temperature	2	514.65	0.0000
	R.H	1	185.29	0.0000
	Commodity × Temperature	4	2.22	0.0876
	Commodity × R.H	2	0.15	0.8602
	Temperature × R.H	2	1.80	0.1808
	Commodity × Temperature × R.H	4	0.98	0.4294
7 days	Commodity	2	90.14	0.0000
	Temperature	2	524.86	0.0000
	R.H	1	178.47	0.0000
	Commodity × Temperature	4	1.89	0.1340
	Commodity × R.H	2	4.65	0.0163
	Temperature × R.H	2	5.01	0.0123
	Commodity × Temperature × R.H	4	0.63	0.6411
14 days	Commodity	2	47.25	0.0000
	Temperature	2	678.73	0.0000
	R.H	1	236.23	0.0000
	Commodity × Temperature	4	9.71	0.0000
	Commodity × R.H	2	1.53	0.2311
	Temperature × R.H	2	9.85	0.0004
	Commodity × Temperature × R.H	4	0.08	0.9868

Table 2 Percentage mean mortality (± SE) of *T. granarium* at different exposure intervals after the combined treatment of DE + abamectin at different temperature and relative humidity (R.H.) levels on three grain commodities. Within each exposure interval, means following same letters are non-significant; HSD test at $P < 0.05$

Temperature	R.H	Commodity	Exposure interval			
			1 day	3 days	7 days	14 days
15 °C	55%	Wheat	21.48 ± 0.75cde	27.02 ± 1.28f	46.26 ± 1.80efgh	64.63 ± 1.80efg
		Rice	13.40 ± 1.70fgh	23.48 ± 1.27fgh	43.24 ± 1.24fghi	61.50 ± 0.95fgh
		Maize	9.39 ± 1.31hi	19.33 ± 0.67gh	34.25 ± 1.37ij	55.43 ± 2.91ghi
	75%	Wheat	16.00 ± 1.15efgh	20.15 ± 1.29gh	39.62 ± 1.99ghi	52.68 ± 2.04hi
		Rice	10.67 ± 0.67ghi	17.44 ± 1.28 h	37.14 ± 1.55hij	48.98 ± 1.18ij
		Maize	6.04 ± 0.04i	10.08 ± 1.23i	22.26 ± 2.93 k	41.24 ± 2.86j
25 °C	55%	Wheat	29.55 ± 0.79ab	39.61 ± 0.84 cd	55.37 ± 2.60de	74.83 ± 1.80bcd
		Rice	21.47 ± 1.27cde	36.23 ± 1.89 cd	50.35 ± 1.47ef	72.30 ± 1.77cde
		Maize	14.08 ± 1.96fgh	27.03 ± 0.78f	44.97 ± 1.73fgh	60.11 ± 2.03fgh
	75%	Wheat	24.84 ± 1.43bcd	29.06 ± 0.79ef	48.64 ± 0.90efg	68.93 ± 0.46def
		Rice	16.00 ± 1.15efgh	25.48 ± 1.62 fg	40.14 ± 1.80ghi	63.27 ± 2.36efg
		Maize	10.67 ± 1.33ghi	19.46 ± 1.28gh	29.25 ± 1.80jk	49.66 ± 1.80ij
35 °C	55%	Wheat	36.67 ± 1.76a	49.01 ± 1.53a	81.09 ± 2.42a	100.00 ± 0.00a
		Rice	31.54 ± 1.24ab	47.31 ± 0.88ab	77.20 ± 1.66ab	100.00 ± 0.00a
		Maize	25.48 ± 1.62bcd	42.56 ± 1.91abc	71.61 ± 1.33ab	100.00 ± 0.00a
	75%	Wheat	27.54 ± 1.92bc	40.97 ± 2.05bcd	69.39 ± 1.18bc	84.35 ± 1.80b
		Rice	20.15 ± 1.29def	40.97 ± 2.05bcd	60.83 ± 2.26 cd	82.41 ± 1.89b
		Maize	17.44 ± 1.28efg	35.57 ± 1.23de	55.39 ± 1.43de	80.27 ± 1.80bc

Table 3 ANOVA for the mortality of *T. granarium* at different exposure intervals after the combined treatment of DE + spinetoram at different temperature and relative humidity (R.H.) levels on three grain commodities

Exposure interval	Source	df	*F*	*P*
1 day	Commodity	2	25.22	0.0000
	Temperature	2	122.98	0.0000
	R.H	1	63.37	0.0000
	Commodity × Temperature	4	1.28	0.2984
	Commodity × R.H	2	0.13	0.8751
	Temperature × R.H	2	1.43	0.2544
	Commodity × Temperature × R.H	4	0.48	0.7531
3 days	Commodity	2	26.32	0.0000
	Temperature	2	364.48	0.0000
	R.H	1	133.49	0.0000
	Commodity × Temperature	4	0.69	0.6068
	Commodity × R.H	2	0.19	0.8317
	Temperature × R.H	2	0.42	0.6603
	Commodity × Temperature × R.H	4	0.06	0.9938
7 days	Commodity	2	148.67	0.0000
	Temperature	2	679.94	0.0000
	R.H	1	255.06	0.0000
	Commodity × Temperature	4	5.08	0.0026
	Commodity × R.H	2	4.68	0.0160
	Temperature × R.H	2	9.80	0.0004
	Commodity × Temperature × R.H	4	0.36	0.8335
14 days	Commodity	2	40.91	0.0000
	Temperature	2	396.77	0.0000
	R.H	1	264.58	0.0000
	Commodity × Temperature	4	4.41	0.0056
	Commodity × R.H	2	2.53	0.0948
	Temperature × R.H	2	8.72	0.0009
	Commodity × Temperature × R.H	4	0.61	0.6577

Discussion

Results of current study suggest that inert dusts can be used in combination with microbial insecticides against *T. granarium* but many factors influence their efficacy like temperature, R.H. and exposure periods. In present study increased exposure caused more mortality of the insects. Nwaubani et al. (2014) also reported increased mortality by increasing interval of exposure. Longer exposure period is required for diatomaceous earth in order to kill the insects (Athanassiou et al. 2006, 2007, 2008a, b) because at longer exposure more dust is attached to the body of insect 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 is increased by increasing the exposure duration (Kljajić et al. 2010a, b; Perisic et al. 2018). Regarding the insecticides, Kavallieratos et al. (2009) noted more mortality of *T. confusum* with increasing exposure interval from 7 to 14 days by using abamectin.

It was obvious that temperature was positively co related with the mortality of insects while the effect of R.H. was negative. These results are in the light of pervious reports depicting that mortality of stored grain insects was more at higher temperature and lower relative humidity using various inert dusts (Vayias and Athanassiou 2004; Kjajic et al. 2010a, b, Vassilakos and Athanassiou 2013; Athanassiou et al. 2014; Bohinc et al. 2018 and Eroglu et al. (2019). At increased temperature food uptake and 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

Table 4 Percentage mean mortality (±SE) of *T. granarium* at different exposure intervals after the combined treatment of DE + spinetoram at different temperature and relative humidity (R.H.) levels on three grain commodities. Within each exposure interval, means following same letters are non-significant; HSD test at $P<0.05$

Temperature	R.H	Commodity	Exposure interval			
			1 day	3 days	7 days	14 days
15 °C	55%	Wheat	24.83 ± 2.89def	34.49 ± 3.25hijk	55.10 ± 2.36def	72.79 ± 1.80de
		Rice	22.14 ± 1.94defg	31.54 ± 1.24ijk	52.00 ± 2.08efgh	65.51 ± 2.54ef
		Maize	20.12 ± 1.05efg	28.00 ± 1.15jkl	44.97 ± 1.73hi	61.51 ± 2.11 fg
	75%	Wheat	18.67 ± 1.76efg	25.47 ± 2.78kl	49.66 ± 1.20fgh	63.51 ± 2.37efg
		Rice	15.33 ± 1.76 fg	20.80 ± 1.74 l	45.29 ± 2.02ghi	55.10 ± 1.18gh
		Maize	13.40 ± 1.70 g	19.47 ± 0.74 l	33.08 ± 1.57j	49.29 ± 2.63 h
25 °C	55%	Wheat	36.93 ± 0.93abc	48.29 ± 2.78fdef	68.90 ± 1.95c	86.39 ± 2.45b
		Rice	28.86 ± 1.74cde	43.63 ± 0.86efgh	55.69 ± 1.43def	81.77 ± 1.06bcd
		Maize	26.15 ± 2.18de	38.52 ± 0.26fghi	53.05 ± 2.13defg	76.37 ± 1.67 cd
	75%	Wheat	28.18 ± 1.92cde	37.81 ± 2.18ghij	59.44 ± 1.41de	77.71 ± 1.04bcd
		Rice	23.33 ± 2.40defg	32.88 ± 1.74ijk	46.94 ± 1.18ghi	66.67 ± 3.79ef
		Maize	22.67 ± 1.76defg	27.52 ± 0.78jkl	40.82 ± 1.18ij	63.95 ± 2.45efg
35 °C	55%	Wheat	46.67 ± 2.40a	66.48 ± 2.73a	89.86 ± 1.18a	100.00 ± 0.00a
		Rice	40.94 ± 0.58ab	61.48 ± 1.21ab	85.21 ± 2.49ab	100.00 ± 0.00a
		Maize	36.87 ± 3.34abc	58.78 ± 1.87abc	79.08 ± 1.65b	100.00 ± 0.00a
	75%	Wheat	37.59 ± 0.83abc	55.73 ± 2.88bcd	77.55 ± 1.18b	84.35 ± 2.97bc
		Rice	32.23 ± 1.36bcd	49.01 ± 1.53cde	69.61 ± 1.00c	81.76 ± 1.18bcd
		Maize	26.19 ± 1.32de	47.66 ± 1.85defg	60.83 ± 2.26d	77.55 ± 1.18bcd

Table 5 ANOVA for the mortality of *T. granarium* at different exposure intervals after the combined treatment of zeolite + abamectin at different temperature and relative humidity (R.H.) levels on three grain commodities

Exposure interval	Source	df	*F*	*P*
1 day	Commodity	2	51.89	0.0000
	Temperature	2	144.80	0.0000
	R.H	1	61.41	0.0000
	Commodity × Temperature	4	2.07	0.1067
	Commodity × R.H	2	0.71	0.4979
	Temperature × R.H	2	7.75	0.0017
	Commodity × Temperature × R.H	4	1.09	0.3777
3 days	Commodity	2	54.27	0.0000
	Temperature	2	325.35	0.0000
	R.H	1	102.94	0.0000
	Commodity × Temperature	4	2.82	0.0404
	Commodity × R.H	2	0.28	0.7571
	Temperature × R.H	2	0.20	0.8236
	Commodity × Temperature × R.H	4	0.71	0.5878
7 days	Commodity	2	75.46	0.0000
	Temperature	2	555.44	0.0000
	R.H	1	138.64	0.0000
	Commodity × Temperature	4	1.62	0.1911
	Commodity × R.H	2	3.07	0.0596
	Temperature × R.H	2	1.03	0.3685
	Commodity × Temperature × R.H	4	0.44	0.7753
14 days	Commodity	2	75.33	0.0000
	Temperature	2	892.44	0.0000
	R.H	1	255.72	0.0000
	Commodity × Temperature	4	18.19	0.0000
	Commodity × R.H	2	0.68	0.5150
	Temperature × R.H	2	18.13	0.0000
	Commodity × Temperature × R.H	4	0.93	0.4595

the insects (Arthur 2000b; Subramanyam and Roesli 2000). Vayias et al. (2009b) noted high mortality of *T. confusum* with increased temperature by the combined treatment of DE + spinosad which is similar to this study. In this study 55% R.H. caused more insect mortality. 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). Similar effect of these factors in case of various insecticides has been previously reported by Athanassiou et al. (2007), Kavallieratos, et al. (2009, 2010) and Vassilakos et al. (2012).

More insects died on wheat than on rice and maize in all combinations but difference between the mortalities on commodities was not so strong. Kavallieratos et al. (2017) and Perisic et al. (2018) have also reported that effectiveness of DEs was more on wheat as compared to other grain commodities against various stored grain insects. Perisic et al. (2018) reported less adherence of zeolite particles to maize grains was less than rice or barley. In case of insecticides, effect of commodity has been studied by many authors. Similarly, Vayias et al. (2009a) found less mortality of S. oryzae on maize. Chintzoglou et al. (2008b) noted less action of dust of spinosad on maize than on wheat. Vassilakos et al. (2015) also showed similar results depicting that efficacy of spinetoram was lower in the maize while it was highest in the hard wheat regarding the mortality of stored grain insects but effect of commodity on the efficacy of insecticide was not so strong similar to the present study. Vayias et al. (2009b) reported that combined treatment of DE + spinosad was

Table 6 Percentage mean mortality (±SE) of *T. granarium* at different exposure intervals after the combined treatment of zeolite + abamectin at different temperature and relative humidity (R.H.) levels on three grain commodities. Within each exposure interval, means following same letters are non-significant; HSD test at $P < 0.05$

Temperature	R.H	Commodity	Exposure interval			
			1 day	3 days	7 days	14 days
15 °C	55%	Wheat	18.78 ± 1.22defg	25.02 ± 1.92ef	43.54 ± 1.80 fg	64.63 ± 1.80ef
		Rice	15.44 ± 0.73fghi	23.50 ± 0.76efg	39.17 ± 1.53ghi	58.12 ± 1.06fgh
		Maize	8.71 ± 1.29hi	19.33 ± 1.76fgh	33.57 ± 0.81hi	51.33 ± 1.46hij
	75%	Wheat	15.33 ± 1.76ghi	19.47 ± 0.74fgh	36.93 ± 1.48ghi	57.44 ± 0.93fgh
		Rice	10.67 ± 1.33hi	16.80 ± 1.89gh	33.76 ± 2.76hi	45.58 ± 1.80jk
		Maize	7.37 ± 1.31i	11.40 ± 1.30 h	21.63 ± 1.43j	41.22 ± 0.85 k
25 °C	55%	Wheat	26.16 ± 1.92bcd	39.61 ± 0.84bc	50.67 ± 1.89def	73.47 ± 3.12 cd
		Rice	21.47 ± 1.27cdefg	34.87 ± 2.74 cd	44.97 ± 2.89efg	68.93 ± 2.40de
		Maize	16.11 ± 1.11efgh	24.98 ± 1.62ef	42.98 ± 2.06 fg	55.39 ± 1.43ghi
	75%	Wheat	24.18 ± 2.09cde	31.09 ± 0.80de	41.89 ± 1.77fgh	64.22 ± 2.19ef
		Rice	16.67 ± 2.40efgh	26.84 ± 2.89def	38.78 ± 1.18ghi	62.59 ± 1.80efg
		Maize	10.67 ± 0.67hi	19.46 ± 1.28fgh	30.61 ± 1.18i	46.94 ± 2.04ijk
35 °C	55%	Wheat	36.00 ± 2.31a	49.67 ± 0.89a	77.70 ± 1.19a	100.00 ± 0.00a
		Rice	33.58 ± 1.96ab	45.97 ± 2.07ab	69.78 ± 1.35ab	100.00 ± 0.00a
		Maize	27.51 ± 1.25bc	41.21 ± 1.24bc	64.88 ± 1.56bc	100.00 ± 0.00a
	75%	Wheat	24.14 ± 2.19cde	39.58 ± 1.53bc	67.35 ± 1.18bc	83.67 ± 1.18b
		Rice	23.47 ± 1.64cdef	39.61 ± 0.84bc	59.44 ± 1.41 cd	80.38 ± 1.90bc
		Maize	20.82 ± 1.41cdefg	34.20 ± 2.14 cd	53.36 ± 1.45de	80.27 ± 1.80bc

Table 7 ANOVA for the mortality of *T. granarium* at different exposure intervals after the combined treatment of zeolite + spinetoram at different temperature and relative humidity (R.H.) levels on three grain commodities

Exposure interval	Source	df	*F*	*P*
1 day	Commodity	2	45.79	0.0000
	Temperature	2	173.42	0.0000
	R.H	1	89.92	0.0000
	Commodity × Temperature	4	2.73	0.0452
	Commodity × R.H	2	0.18	0.8385
	Temperature × R.H	2	1.94	0.1589
	Commodity × Temperature × R.H	4	1.16	0.3463
3 days	Commodity	2	48.20	0.0000
	Temperature	2	424.21	0.0000
	R.H	1	192.93	0.0000
	Commodity × Temperature	4	1.21	0.3227
	Commodity × R.H	2	3.64	0.0370
	Temperature × R.H	2	1.17	0.3228
	Commodity × Temperature × R.H	4	0.89	0.4815
7 days	Commodity	2	102.62	0.0000
	Temperature	2	635.15	0.0000
	R.H	1	205.16	0.0000
	Commodity × Temperature	4	5.08	0.0025
	Commodity × R.H	2	1.18	0.3206
	Temperature × R.H	2	7.03	0.0028
	Commodity × Temperature × R.H	4	0.97	0.4391
14 days	Commodity	2	46.97	0.0000
	Temperature	2	779.15	0.0000
	R.H	1	410.46	0.0000
	Commodity × Temperature	4	8.64	0.0001
	Commodity × R.H	2	0.16	0.8539
	Temperature × R.H	2	17.11	0.0000
	Commodity × Temperature × R.H	4	2.47	0.0632

more effective against *T. confusum* on wheat. Similarly, Wakil et al. (2013) examined that more *R. dominica* died on wheat than on rice and maize with combined treatment of diatomaceous earth + thiamethoxam. Difference in the efficacy of dusts or insecticides to various grains may be due to physiochemical characters of grains.

Combination of inert dusts (DEs) with other control methods as an integrated control has been suggested by Arthur (2003). Combination of DE with betacyfluthrin (Athanassiou 2006), with spinosad (Vayias et al. 2009b), with plant extract (Athanassiou et al. 2008a), with thiamethoxam (Wakil et al. 2013) has been studied by many researchers indicating that these dusts can be combined with other control methods. In summary, results of present study suggested that it is possible to obtain complete mortality of *T. granarium* by combined treatment of inert dusts and bacterial based insecticides but their efficacy is dependent on various factors like temperature, R.H., doses and grain commodities. These factors should be kept in mind while planning IPM strategy.

Table 8 Percentage mean mortality (±SE) of *T. granarium* at different exposure intervals after the combined treatment of zeolite + spinetoram at different temperature and relative humidity (R.H.) levels on three grain commodities. Within each exposure interval, means following same letters are non-significant; HSD test at $P < 0.05$

Temperature	R.H	Commodity	Exposure interval			
			1 day	3 days	7 days	14 days
15 °C	55%	Wheat	18.79 ± 0.61def	29.74 ± 1.47de	50.34 ± 1.80efgh	72.11 ± 1.80de
		Rice	15.43 ± 1.29defgh	26.86 ± 1.44def	45.27 ± 1.23fghi	61.50 ± 0.95fgh
		Maize	13.40 ± 1.70efgh	22.67 ± 1.76efg	37.58 ± 1.23ij	55.40 ± 1.22hi
	75%	Wheat	12.00 ± 1.15fgh	20.79 ± 1.67fgh	40.97 ± 2.62i	57.44 ± 0.93ghi
		Rice	9.33 ± 1.33gh	17.43 ± 1.67gh	37.17 ± 0.83ij	53.06 ± 1.18ij
		Maize	8.05 ± 1.16 h	13.42 ± 1.29 h	30.40 ± 1.94j	47.28 ± 1.48j
25 °C	55%	Wheat	30.19 ± 0.99bc	43.61 ± 1.51b	61.47 ± 1.40 cd	82.31 ± 1.80b
		Rice	21.47 ± 1.27cde	39.61 ± 0.84bc	52.37 ± 1.48efg	79.07 ± 1.65bcd
		Maize	18.10 ± 2.23defg	31.08 ± 1.27cde	44.33 ± 2.60ghi	73.63 ± 1.32 cd
	75%	Wheat	21.48 ± 0.75cde	31.76 ± 1.77 cd	53.37 ± 1.22def	72.30 ± 1.77de
		Rice	17.33 ± 2.40defg	24.14 ± 2.19defg	42.18 ± 1.80hi	65.31 ± 2.36ef
		Maize	11.33 ± 2.40fgh	23.47 ± 1.64defg	31.97 ± 2.45j	63.27 ± 1.18 fg
35 °C	55%	Wheat	40.67 ± 1.76a	60.38 ± 1.99a	83.10 ± 1.82a	100.00 ± 0.00a
		Rice	35.57 ± 2.35ab	58.75 ± 2.69a	81.88 ± 1.16a	100.00 ± 0.00a
		Maize	29.54 ± 0.79bc	47.29 ± 1.23b	76.35 ± 1.78ab	100.00 ± 0.00a
	75%	Wheat	32.90 ± 1.46ab	47.63 ± 1.48b	70.75 ± 1.80b	82.31 ± 1.80b
		Rice	22.80 ± 2.60 cd	43.61 ± 1.51b	67.57 ± 1.20bc	81.09 ± 0.54bc
		Maize	21.46 ± 1.65cde	39.61 ± 0.84bc	57.43 ± 1.21de	78.91 ± 2.45bcd

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