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Insecticidal effect of three insecticides applied on different surfaces for the control of three stored-product beetle species

Evagelia Lampiri [*], Paraskevi Agrafioti, Christos G. Athanassiou

Laboratory of Entomology and Agricultural Zoology, Department of Agriculture, Crop Production and Rural Environment, University of Thessaly, Phytokou str., 38446, N. Ionia, Magnesia, Greece

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ABSTRACT

We evaluated the efficacy of alpha-cypermethrin, deltamethrin and spinosad on concrete, ceramic, plastic and metallic surfaces against found major stored-product beetle species, the confused flour beetle, *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae), the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), and the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae). For alpha-cypermethrin, deltamethrin and spinosad the dose rates applied to surfaces were 0.01, 0.05, and 0.1 mg (Al)/cm^{-2}, respectively. All three insecticides were applied at the label dose, while the bioassays were carried out against the adult stage of the three target species. Mortality was assessed after 3, 7 and 14 days of exposure. The results of the present study revealed that the active ingredient with the highest efficacy for all species was spinosad, while the most tolerant species for all the active ingredients evaluated was *T. confusum.* Surface type was significant for all species, except for *T. confusum*. Concrete reduced the efficacy of deltamethrin, while ceramic reduced the efficacy of spinosad. Regarding the overall data, spinosad and deltamethrin can effectively control the species tested here, but there are certain factors that affect their efficacy, such as the exposure interval and the type of the surface.

1. Introduction

One of the most common strategies for controlling storage insects in food processing and storage facilities, is the direct application of insecticidal formulations on the grain. There are numerous published papers highlighting the effectiveness of the particular method on a variety of insecticides, grains and stored product insects (Arthur 2019; Gourgouta et al., 2019; Scully et al., 2021; Baliota et al., 2022). For instance, Baliota et al. (2022) found that 1 ppm of deltamethrin and cypermethrin effectively controlled the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) and the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Laemophloeidae) on soft wheat, in a relatively short exposure interval. Nevertheless, the direct use of such substances on the grains can be responsible for increased chemical residues on the product, which in turn can lead to adverse effects on human health. Thus, one of the tactics that has been adopted in integrated insect management (IMP) programs in these facilities is spraying insecticides of low mammalian toxicity on surfaces, crevices and cracks of the storage facilities, avoiding the direct exposure of the insecticide with the commodity. Apart from reduction in the insecticide residues on the product, this method can provide long-term protection against insects, while it is generally considered as cheaper compared to other methods used, such as phosphine fumigation, in which control failures are commonly observed (Vassilakos et al., 2014; Athanassiou et al., 2016; Athanassiou and Arthur, 2018).

The type of surface to which different insecticides are applied plays an important role in their insecticidal activity. In this context, there is an extremely large variety of published studies on the so called “surface treatment”, which demonstrates that porous surfaces significantly decrease the effectiveness of insecticides compared to non-porous ones (Williams et al., 1982, 1983; Jain and Yadav 1989; Collins et al., 2000; Arthur et al., 2009). For example, Arthur et al. (2009) indicated that hydroprene reduce the adult emergence of the confused flour beetle, *Tribolium confusum* Jacqueline DuVal (Coleoptera: Tenebrionidae) on concrete compared to wood and metal surfaces. Furthermore, Giga and Canhao (1991) found that glass sprayed with deltamethrin and permethrin resulted in higher mortality rates of adults of the maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) and the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrychidae) relative to wood, mud and jute surfaces. Conversely, there are published studies in which insecticides that have been sprayed in porous surfaces are more effective in controlling storage insects than the

* Corresponding author.
E-mail address: elampiri@agr.uth.gr (E. Lampiri).

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non-porous surfaces (Arthur 2008; Vassilakos et al., 2014; Saglam et al., 2022). Vassilakos et al. (2014) recorded that spinetoram applied on concrete was more effective to control *T. confusum* adults compared to steel, ceramic tile and plywood. However, in the same work no differences were noted between the different surfaces for *R. dominica* and the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) (Vassilakos et al., 2014). Similarly, Saglam et al. (2022) reported spinetoram applied on concrete surfaces was more effective for the control of the bean weevil, *Acanthoscelides obtectus* (Say) (Coleoptera: Chrysomelidae) as compared to ceramic tile and laminate. Likewise, Arthur (2008) found that chlorfenapyr was more effective to control *T. confusum* and the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) on concrete compared to plywood and vinyl tile surfaces.

Considering the diversity of the data, it becomes evident that the efficacy of certain insecticides that are applied on surfaces in food processing and storage facilities, is highly determined by the insecticide *per se*, but also by the type of the surface and the target species. Hence, most of the knowledge is based upon different studies that focus on a small group of parameters only, e.g. one insecticide on different surfaces, one species on different surfaces etc., and thus, often data that appear in one study are not always transferable and comparable with those of other similar studies. In this context, and considering the contradictory data that are currently available, we carried out a large-scale series of bioassays, with different surfaces, different species and different insecticides, using the same experimental protocol in all combinations. For this purpose, we selected one primary colonizer, *S. oryzae*, as well as two secondary colonizers, *T. confusum* and the sawthothed grain beetle *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) and two pyrethroids, which are mediated through preventing the closure of Na^+ channels, as well as a microbial insecticide, which acts on both GABA and nicotine acetylcholine receptors, in order to cover a wide range of application scenarios and infestation patterns.

2. Materials and methods

2.1. Species tested

All insect species used in the bioassays were reared at the Laboratory of Entomology and Agricultural Zoology (LEAZ), Department of Agriculture Crop Production and Rural Environment, at the University of Thessaly. The rearings are kept in incubators set at 25 °C, 55% relative humidity (r.h.) and continuous darkness. From the species tested, *T. confusum* was reared on wheat flour, *O. surinamensis* on oat flakes, and *S. oryzae* on whole wheat kernels. For all species, adult beetles <1 month-old were used in the tests.

2.2. Insecticidal application

The formulations examined were the pyrethroid Fendona®Top (containing 1.5% of alpha-cypermethrin, BASF Hellas, Marousi, Athens, Greece), the pyrethroid Seguro 2.5 EC (containing 2.5% of deltamethrin, Agrotechnica, Sindos, Thessaloniki, Greece), and the bacterial metabolite-based Laser 480SC (containing 48% of spinosad, Elanco Hellas S.A., Chalandri, Athens, Greece). For alpha-cypermethrin, deltamethrin and spinosad the dose rates applied to surfaces were 0.01 mg (AI)/cm^{-2}, 0.05 mg (AI)/cm^{-2} and 0.1 mg (AI)/cm^{-2}, respectively. In case of alpha-cypermethrin and deltamethrin the label dose was applied. However, for spinosad we used the dose as suggested by Toews et al. (2003) and Vassilakos et al. (2014).

Plastic petri dishes (90 mm diameter, 15 mm high) with 63.61 cm^2 bottom surface (Greiner Bio-One, Carl Roth GmbH + Co. KG, Karlsruhe, Germany), as suggested by Doganay et al. (2018), were the experimental units for the tests. The preparation of the solution was done by dissolving the required amount of each formulation in distilled water. The total volume of solution sprayed into each petri dish was 1 ml. The solution was applied in all cases by spraying, using an airbrush (Kyoto BD – 183 K, Japan). In addition, petri dishes sprayed with 1 ml of distilled water per petri dish served as controls.

2.3. Bioassays

The effectiveness of insecticidal formulations was studied on four surfaces, plastic, metal, ceramic and concrete. For each treatment there were 3 replicates and the whole procedure was repeated 2 times by preparing new spray solutions each time (3 × 2 = 6 replicates for each insecticide, insect species and surface). For the preparation of the concrete-bottom petri dishes, cement (Grey cement 42.5, Isomat S.A., Thessaloniki, Greece) was mixed with tap water in a ratio of 1:3 until a uniform mass was created. A quantity of the mixture (about 15 g) was placed on each petri dish in order to create a concrete flat surface about 2 mm high. The petri dishes were then left for at least 24 h at room temperature to dry. For the experiments on metal (Lazarou, A′ Industrial Area, Magnesia, Volos) and ceramic (Valtsioti, Magnesia, Volos) surfaces, the petri dishes were covered with metal or ceramic sheets, respectively, which were cut to the dimensions of the petri dishes and glued using hot melt adhesive on the base of the petri dishes, while for the experiments on a plastic surface, the petri dishes remained as they were. Then, the “neck” of the petri dishes was covered with Fluon (polytetrafluoroethylene; Northern Products, Woonsocket, USA) to avoid insects from escaping. When the bottom-surfaces were ready, the spray solutions were applied as mentioned above, while a separate series of dishes was sprayed with distilled water to serve as a control. The petri dishes were allowed to dry (24 h), and then 20 mixed-sex adults for each insect species were placed in each petri, using different petri dishes for each insect species, with a small amount of food. For *T. confusum*, *O. surinamensis* and *S. oryzae* a small amount of wheat flour (1.0 ± 0.1 g/dish), oat flakes (1.0 ± 0.1 g/dish) and soft wheat (0.5 ± 0.1 g/dish) was added, respectively. Subsequently, all petri dishes were maintained in incubators set at controlled conditions, 26 °C and 55% r.h. with continuous darkness. Mortality of exposed insects was assessed after 3, 7 and 14 days of exposure.

2.4. Statistical analysis

The data were analyzed by using the MANOVA Fit Repeated Measures method with exposure time as a repeated variable and the type of surface (concrete, metal, ceramic and plastic) and the insecticide active ingredient (alpha-cypermethrin, deltamethrin, spinosad and control) as main effects. Subsequently, a two-way ANOVA was used to determine if there were differences between the mean of insect mortality for each active ingredient and surface type within each exposure time. Comparison of means was performed by using the Tukey-Kramer HSD test at the 5% level (Zar, 1999).

For the repeated measures MANOVA method, it emerged that the type of surface did not significantly affect the mortality of *T. confusum* and therefore, for this species, an one-way ANOVA analysis was carried out with the active ingredient as main effect.

3. Results

In general, all main effects and their interactions were significant for all insect species tested (Table 1), with the exception of the surface type for *T. confusum* and the interaction of surface type with exposure time for *T. confusum* and *O. surinamensis*.

3.1. Tribolium confusum

Spinosad presented the highest efficiency rates for *T. confusum* on all the surfaces examined, while for the metal and ceramic surfaces these rates did not differ significantly with the corresponding petri dishes that were sprayed with deltamethrin (Table 2). The lowest mortality rates for the majority of the surface types were obtained in petri dishes sprayed

Table 1
Repeated Measures MANOVA parameters for the mortality of the species tested, which were exposed to three active ingredients (alpha-cypermethrin, deltamethrin and spinosad) applied on four surfaces (plastic, metal, ceramic and concrete) [total degrees of freedom *(d. f.)* =*80*].

	d. f.	*Tribolium confusum*		*Sitophilus oryzae*		*Oryzaephilus surinamensis*	
		F	*P*	F	*P*	F	*P*
Between the variables	15	86.52	**<0.01**	13.99	**<0.01**	66.14	**<0.01**
Intercept	1	5.27	**0.02**	626.16	**<0.01**	298.92	**<0.01**
Active ingredient	3	225.62	**<0.01**	14.47	**<0.01**	81.88	**<0.01**
Surface type	3	0.99	0.39	3.27	**0.02**	17.05	**<0.01**
Active ingredient[a] Surface type	9	23.44	**<0.01**	6.34	**<0.01**	24.93	**<0.01**
Within the variables	30	37.87[a]	**<0.01**	12.57[a]	**<0.01**	4.72[a]	**<0.01**
Exposure time	2	6.72	**<0.01**	77.42	**<0.01**	6.87	**<0.01**
Exposure time[a] Active ingredient	6	30.93[a]	**<0.01**	19.11[a]	**<0.01**	2.38[a]	**0.03**
Exposure time[a] Surface type	6	1.24[a]	0.28	9.45[a]	**<0.01**	1.80[a]	0.10
Exposure time[a] Active ingredient[a] Surface type	18	15.01[a]	**<0.01**	8.69[a]	**<0.01**	5.22[a]	**<0.01**

[a] Wilks' Lamda approximate F value.

Table 2
Mean mortality of *Tribolium confusum* (% ± SE) after exposure to three active ingredients (alpha-cypermethrin, deltamethrin and spinosad) applied on four surfaces (plastic, metal, ceramic and concrete) for 3, 7 and 14 days [in all cases total degrees of freedom *(d. f.)* = *3.23*].

Surface type	Exposure time	Alpha-cypermethrin	Deltamethrin	Spinosad	Control	F	*P*
Plastic	Day 3	0.0 ± 0.0	0.83 ± 0.83	0.83 ± 0.83	0.83 ± 0.83	0.33	0.80
	Day 7	0.0 ± 0.0A	0.83 ± 0.83A	43.33 ± 8.62B	0.83 ± 0.83A	24.13	<0.01
	Day14	3.33 ± 1.66A	13.33 ± 5.42A	86.66 ± 6.28B	1.66 ± 1.05A	90.62	<0.01
Metal	Day 3	0.83 ± 0.83AB	0.0 ± 0.0A	5.83 ± 2.38B	0.0 ± 0.0A	4.92	<0.01
	Day 7	0.83 ± 0.83A	8.33 ± 1.05A	25.83 ± 5.54B	0.0 ± 0.0A	17.69	<0.01
	Day14	3.33 ± 1.66A	73.33 ± 5.42B	86.66 ± 4.94B	6.66 ± 2.47A	121.47	<0.01
Ceramic	Day 3	0.0 ± 0.0A	0.0 ± 0.0A	5.00 ± 2.23B	0.0 ± 0.0A	5.00	<0.01
	Day 7	5.83 ± 2.38A	4.16 ± 2.38A	40.00 ± 7.85B	0.0 ± 0.0A	18.73	<0.01
	Day14	10.83 ± 2.38A	70.00 ± 8.85B	84.16 ± 6.24B	3.33 ± 3.33A	49.97	<0.01
Concrete	Day 3	0.0 ± 0.0A	0.0 ± 0.0A	32.50 ± 4.78B	0.83 ± 0.83A	44.00	<0.01
	Day 7	1.66 ± 1.05A	0.0 ± 0.0A	97.50 ± 1.70B	1.66 ± 1.05A	1808.42	<0.01
	Day14	15.00 ± 4.28A	8.33 ± 3.33A	99.16 ± 0.83B	6.66 ± 1.66A	243.11	<0.01

Within each surface type and exposure day, means followed by the same uppercase letter are not significantly different, according to Tukey-Kramer HSD test at 0.05; where no letters exist, no significant differences were noted.

with alpha-cypermethrin, which did not differ from the corresponding rates observed in the controls. Similarly, deltamethrin showed a reduced effect in concrete-bottom petri dishes (Table 2).

3.2. *Sitophilus oryzae*

As in the case of *T. confusum*, the highest mortality of *S. oryzae* adults was recorded in petri dishes sprayed with spinosad, showing up to 100% mortality from the Day 3 of exposure for plastic, metal and concrete-bottom petri dishes (Table 3). The lowest mortality rates were noted at the petri dishes sprayed with alpha-cypermethrin for all surfaces tested, with the exception of concrete on Day 3 of exposure, where this was achieved at the dishes sprayed with deltamethrin. However, on Day 3 of exposure in the concrete surface, no significant differences were observed between mortality rates of alpha-cypermethrin, deltamethrin and control (Table 3). The lowest effectiveness rates were noted for alpha-cypermethrin on plastic and concrete, for deltamethrin on concrete and for spinosad on the ceramic surfaces (Table 3).

Table 3
Mean mortality of *Sitophilus oryzae* (% ± SE) after exposure to three active ingredients (alpha-cypermethrin, deltamethrin and spinosad) applied on four surfaces (plastic, metal, ceramic and concrete) for 3, 7 and 14 days [in all cases total degrees of freedom *(d. f.)* = *3.23*].

Surface type	Exposure time	Alpha - cypermethrin	Deltamethrin	Spinosad	Control	F	*P*
Plastic	Day 3	35.00 ± 5.16Aa	84.16 ± 3.51Ba	100.00 ± 0.00Ca	10.00 ± 3.16Da	143.58	<0.01
	Day 7	96.66 ± 1.66AB	100.00 ± 0.00B	100.00 ± 0.00B	90.00 ± 3.65Aa	5.51	<0.01
	Day14	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	–	–
Metal	Day 3	66.66 ± 4.77Ab	92.50 ± 1.70Ca	100.00 ± 0.00Ca	16.66 ± 3.33Ba	154.23	<0.01
	Day 7	100.00 ± 0.00A	100.00 ± 0.00A	100.00 ± 0.00A	97.50 ± 1.11Bab	5.00	<0.01
	Day14	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	–	–
Ceramic	Day 3	65.83 ± 16.40ABb	97.50 ± 1.70Ba	76.66 ± 6.14ABb	44.16 ± 2.38Ab	6.26	<0.01
	Day 7	83.33 ± 13.88	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00b	1.44	0.26
	Day14	94.16 ± 3.74	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	2.42	0.09
Concrete	Day 3	36.66 ± 5.57Aa	24.16 ± 6.75Ab	100.00 ± 0.00Ba	37.50 ± 8.03Ab	33.01	<0.01
	Day 7	94.16 ± 2.38A	100.00 ± 0.00B	100.00 ± 0.00B	99.16 ± 0.83ABb	4.92	<0.01
	Day14	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	–	–

Within each surface type and exposure day, means followed by the same uppercase letter are not significantly different, according to Tukey-Kramer HSD test at 0.05, where no letters exist, no significant differences were noted. Within each active ingredient and exposure day, means followed by the same lowercase are not significantly different, according to Tukey-Kramer HSD test at 0.05; where no letters exist, no significant differences were noted.

3.3. *Oryzaephilus surinamensis*

In all surfaces tested, the highest mortality rates of *O. surinamensis* were presented in the surfaces treated with deltamethrin and spinosad. In the case of concrete, it was observed that deltamethrin was the least effective even on the last day of exposure (14th day) causing only 17% mortality in *O. surinamensis* adults and did not differ from the control for any of the exposure days tested (Table 4). In general, the efficacy of alpha-cypermethrin was reducedon plastic, causing 23 and 36% mortality on the 3rd and the 7th day of exposure, respectively. Mortality caused by deltamethrin on concrete ranged from 4 to 12% on days 3 and 7 of exposure, respectively, and did not differ from the corresponding control rates, while spinosad on ceramic tile resulted in 50 and 78% mortality of *O. surinamensis*, respectively for the aforementioned exposure days (Table 4).

4. Discussion

The type of surface from which the various storage areas that host durable commodities are made greatly affects the effectiveness of a wide variety of insecticides (Giga and Canhao 1991; Arthur 1997; Wijayaratne et al., 2012; Rumbos et al., 2014). For instance, in the study of Wijayaratne et al. (2012), methoprene efficacy decreased with time on concrete, but not on varnished wood. Similarly, Vassilakos and Athanassiou (2015) found that dissipation of spinetoram through time was faster on concrete than on steel, but this was not always related with changes in the insecticidal efficacy against *S. oryzae*. For the treatment combinations tested here, we have found that spinosad resulted in greater efficacy compared to other insecticidal formulations examined. Fang et al. (2002a) found that spinosad effectively controlled *R. dominica* adults and the indianmeal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) larvae on four classes of wheat. Moreover, *T. confusum* was the most tolerant insect species tested for all the insecticidal formulations tested. Indeed, Toews et al. (2003) tested the efficacy of spinosad on eight stored product insects and found that among them, *T. confusum* was the least susceptible. In our study, it was found that for deltamethrin, the lowest mortality rates were observed on concrete. Reduced activity of various insecticides on concrete has been reported in many similar bioassay-based papers (Arthur 1997, 2012; Arthur et al., 2009; Wijayaratne et al., 2012; Jankov et al., 2013; Agrafioti et al., 2015). For example, Agrafioti et al. (2015) reported that metal surfaces, which had been sprayed with alpha-cypermethrin, pirimiphos-methyl and fipronil caused higher mortality rates of both *T. confusum* and *O. surinamensis* compared to the corresponding concrete surfaces. According to Chadwick (1985) a possible reason for the reduction in the effectiveness of insecticides after the application to porous surfaces, such as concrete, may be the fact that this material retains a part of the active substance making it non available to insects that will encounter the surface. Furthermore, apart from being porous, concrete is also an alkaline material, which contributes greatly to the breakdown and degradation of the insecticides (Arthur 2012; Vassilakos et al., 2014; Agrafioti et al., 2015).

In contrast with deltamethrin, spinosad showed the lowest mortality rates on ceramic compared to plastic, metal and concrete surfaces. This phenomenon was also highlighted in the research of Toews et al. (2003), who tested the efficacy of spinosad, on cement, ceramic and metal, and noted that 13–20% of the exposed *T. confusum* adults recovered after exposure to ceramic and metal surface, while the recovery was lower in the case of concrete. In addition, Saglam et al. (2022) reported that ceramic tile was the least effective surface treated with spinetoram against *A. obtectus* adults relative to concrete and plywood surfaces after 3 days of exposure for the majority of the concentrations tested. This could be attributed to certain characteristics of these bacterial-based insecticides, i.e. spinosad and the relative spinetoram, which might be different than those of the pyrethroids, such as the way that these insecticides are attached to the treated surface.

Regarding alpha-cypermethrin, reduced efficacy was recorded on different surfaces depending on the insect species exposed, suggesting that the efficacy of this insecticide is more species-than surface-mediated. Hence, the application of this insecticide on the plastic and concrete surfaces caused the lowest mortality rates for *S. oryzae*, which was also noted in the case of *O. surinamensis*, but only for the plastic surfaces. In contrast, for *T. confusum* adults, it was found that the type of the surface did not significantly affect the effectiveness of alpha-cypermethrin. In a previous study, Arthur (1998) found that both *R. dominica* and *T. castaneum* were effectively controlled by 0.05% deltamethrin dust and there were no significant differences among plywood, concrete and tile surfaces, while the survival rate of *T. confusum* was higher in tile, followed by concrete and plywood surfaces. In this context, despite the "general belief" that the influence of surface is similar to most of the currently used insecticides that are applied on surfaces, it seems that the interaction of some active

Table 4
Mean mortality of *Oryzaephilus surinamensis* (% ± SE) after exposure to three active ingredients (alpha-cypermethrin, deltamethrin and spinosad) applied on four surfaces (plastic, metal, ceramic and concrete) for 3, 7 and 14 days [in all cases total degrees of freedom *(d. f.) = 3.23*].

Surface type	Exposure time	Alpha - cypermethrin	Deltamethrin	Spinosad	Control	F	*P*
Plastic	Day 3	23.33 ± 6.66Aa	56.66 ± 10.05Ba	98.33 ± 1.66Ca	2.50 ± 1.70B	46.33	<0.01
	Day 7	35.83 ± 8.50Aa	96.66 ± 1.66Ca	100.00 ± 0.00Ca	2.50 ± 1.70B	116.64	<0.01
	Day14	42.50 ± 9.72A	97.50 ± 1.11Ca	100.00 ± 0.00C	3.33 ± 1.66B	88.16	<0.01
Metal	Day 3	55.83 ± 8.00Ab	90.83 ± 2.00Bb	73.33 ± 7.03ABb	3.33 ± 1.66C	47.52	<0.01
	Day 7	72.50 ± 9.01Ab	100.00 ± 0.00Ba	92.50 ± 3.81Bab	3.33 ± 1.66C	78.73	<0.01
	Day14	73.33 ± 8.91A	100.00 ± 0.00Ba	95.00 ± 2.23B	8.33 ± 2.47C	78.56	<0.01
Ceramic	Day 3	52.50 ± 10.06Aab	85.83 ± 6.37Bb	50.00 ± 9.39Ab	2.50 ± 1.11C	20.30	<0.01
	Day 7	65.83 ± 8.50Aab	100.00 ± 0.00Ba	78.33 ± 8.23ABb	2.50 ± 1.11C	49.65	<0.01
	Day14	66.66 ± 8.02A	100.00 ± 0.00Ba	92.50 ± 4.03B	5.83 ± 3.27C	79.92	<0.01
Concrete	Day 3	32.50 ± 4.95Aab	4.16 ± 3.27Ac	100.00 ± 0.00Ba	6.66 ± 3.07A	178.34	<0.01
	Day 7	50.83 ± 7.46Bab	11.66 ± 3.80Ab	100.00 ± 0.00Ca	7.50 ± 3.09A	92.84	<0.01
	Day14	54.16 ± 8.70B	16.66 ± 4.59Ab	100.00 ± 0.00C	8.33 ± 3.07A	65.95	<0.01

Within each surface type and exposure day, means followed by the same uppercase letter are not significantly different, according to Tukey-Kramer HSD test at 0.05, where no letters exist, no significant differences were noted. Within each active ingredient and exposure day, means followed by the same lowercase are not significantly different, according to Tukey-Kramer HSD test at 0.05; where no letters exist, no significant differences were noted.

ingredients with certain surfaces is different, and cannot be comparable with that of other insecticides.

The active substance with the highest efficacy for all the stored product insect species examined here was spinosad, with *T. confusum* being the least susceptible for all three insecticides tested. These results are consistent with those of several published works on the efficacy of spinosad on a wide range of storage insects (Fang et al. 2002a, 2002b; Nayak et al., 2005; Vayias et al., 2009), but also for the efficacy of pyrethroids that are used for surface treatments (Arthur, 1998; Athanassiou et al., 2004; Agrafioti et al., 2015). This has been also noted not only for neurotoxic insecticides, just like the ones tested here, but also to non-neurotoxic compounds, such as diatomaceous earths (Korunic 1998; Arthur 2000; Fields and Korunic 2000; Subramanyam and Roesli 2000; Athanassiou et al., 2003; Vayias and Athanassiou, 2004). For instance, Baliota et al. (2022) found that *T. confusum* adults were much less susceptible to those of *O. surinamensis* and *C. ferrugineous*, on wheat treated with diatomaceous earths. Vayias and Athanassiou (2004) indicated that diatomaceous earth formulation SilicoSec effectively control adults and larvae of T. *confusum*. Many contact insecticides have been found ineffective against this insect species (Arthur 1998; Toews et al., 2003; Athanassiou et al., 2008, 2013; Agrafioti et al., 2015; Tsaganou et al., 2021). Indicatively, Tsaganou et al. (2021) illustrated that *T. confusum* adults had reduced susceptibility to grains treated with thiamethoxam. Also, Athanassiou et al. (2013) indicated that *T. confusum* was the least affected insect species among seven stored product insects species tested, which had been exposed to concrete surfaces treated with a formulation contained beta-cyßuthrin and imidacloprid, as active ingredients. Nevertheless, larvae of *T. confusum* are considered more susceptible than adults of this species to many contact insecticides, so it is estimated that this species can be controlled through increased immature mortality (Vayias and Athanassiou, 2004; Hertlein et al., 2011; Saglam et al., 2013; Tsaganou et al., 2021; Boukouvala et al., 2022).

In conclusion, the results indicated that concrete and ceramic surface contribute to a reduced effectiveness of deltamethrin and spinosad, respectively, while regarding alpha-cypermethrin the results differed depending on the insect species. Among the insecticidal formulations tested, the most effective was spinosad, followed by deltamethrin and alpha-cypermethrin, while *T. confusum* was the least susceptible insect species for all insecticides examined. Finally, the current results illustrated that spinosad and deltamethrin can be used successfully against stored product insects, but several parameters, such as surface area of exposure and target insect species, should be considered in a comprehensive insect management program, which will be applied on production, processing and storage facilities of agricultural products. To the best of our knowledge, from these two insecticides, only deltamethrin is registered as a surface treatment, while spinosad is registered solely as a grain protectant. Our results underline the need to further evaluate spinosad for surface treatments as well, as it can be incorporated into IPM programs as a valuable and effective tool for the control of stored product insects.

Author statement

Evagelia Lampiri: conceptualization, methodology, formal analysis, draft preparation, investigation, writing. Paraskevi Agrafioti: draft preparation, methodology, writing, reviewing. Christos G. Athanassiou: writing, reviewing, editing, supervision, project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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