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Particle size matters: Efficacy of aerosols for the control of stored product psocids

Christos G. Athanassiou [a, b, *], Frank H. Arthur [b], James F. Campbell [b], John E. Donaldson [c, 1]

[a] Laboratory of Entomology and Agricultural Zoology, Department of Agriculture, Crop Production and Rural Environment, University of Thessaly, Phytokou Str., 38446, Nea Ionia, Magnesia, Greece
[b] USDA-ARS, Center for Grain and Animal Health Research, 1515 College Avenue, Manhattan, KS, 66502, USA
[c] Formerly MRIGlobal, 425 Volker Boulevard, Kansas City, MO, 64110, USA

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ABSTRACT

The insecticidal effect of an aerosol formulation that contained a 100: 1 mixture of pyrethrin and methoprene (by volume), was evaluated for control of nymphs of four stored-product psocid species, *Liposcelis bostrychophila*, *L. decolor*, *L. entomophila* and *L. paeta*. The aerosol was applied at two particle sizes, 2 and 16 μm. The application time of the aerosols was 0 (untreated controls, no aerosol), 5, 10, 20 and 30 min. Nymphs were examined at 5 days post-treatment. The aerosol was effective on all species tested, with mortality of 100% after 5–20 min, depending on the species. There was a strong interaction between the application time and the particle size. In all cases, the application of the aerosol at 16 μm was more effective than 2 μm for all species. Moreover, the application at 16 μm required less time to reach 100% mortality, suggesting that this particle size may provide a more cost-effective application, as it requires less formulation and a considerably shorter application time. Our results provide the first series of data for the application of aerosols at different particle sizes against stored-product psocids and could be used as a guide for improved management of psocids.

1. Introduction

Psocids are important stored-product pests that cause serious infestations in a wide range of durable commodities worldwide (Nayak et al., 2014). Moreover, their presence is associated with health hazards, such as allergenic reactions, and as such they are listed in the list of the World Health Organization (WHO) as species that produce arthropod-related allergens (Hubert et al., 2018). They can infest sound grains, in a manner similar to primary colonizers, where they can build rapidly high population densities (Athanassiou et al., 2010a).

Given their importance, recent studies have been focused on evaluating various control methods for psocid control. Psocids are tolerant to many of the insecticides that have been tested so far, which might be innate and not due to previous exposure (Nayak et al., 2002, 2014; Athanassiou et al., 2009a). For example, pyrethrum and certain pyrethroids were not able to satisfactorily control many psocid species, in contrast with organophosphorus (OP) compounds, which were more effective (Nayak et al., 1998, 2002; 2003a; Collins et al., 2000; Daglish et al., 2003; Athanassiou et al., 2009a). Insect growth regulators (IGRs), such as S-methoprene and pyriproxifen were moderately effective when tested on grains and surfaces (Athanassiou et al., 2010b, 2011). Furthermore, certain psocid species were tolerant to diatomaceous earths (DEs) at dose rates that are usually lethal for stored-product beetles and moths (Athanassiou et al., 2009b). Several studies have also indicated that there are populations of psocids that are resistant to the fumigant phosphine (Nayak et al., 1998, 2003b; Nayak and Collins, 2008). Finally, a recent study revealed that the psocid *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae) was able to survive for 7 d at −15 °C, suggesting that cold treatment may have limited effectiveness for the control of stored-product psocids (Athanassiou et al., 2018).

Due to the global phase-out of the fumigant methyl bromide, the control of crawling stored-product arthropods inside mills and warehouses, including stored-product beetles, psocids and mites, has shifted to the use of contact insecticides, which can be applied

* Corresponding author. Laboratory of Entomology and Agricultural Zoology, Department of Agriculture, Crop Production and Rural Environment, University of Thessaly, Phytokou Str., 38446, Nea Ionia, Magnesia, Greece.
E-mail address: athanassiou@agr.uth.gr (C.G. Athanassiou).
[1] Current address: Honeywell FM&T, 14520 Botts Rd., Kansas City, MO, USA, s64147.

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to flooring surfaces or aerosol insecticides as space sprays (Arthur, 2012, 2018). In this context, there are some good paradigms of successful control of stored-product psocids with newer insecticides. For example, Athanassiou et al. (2013) found that the pyrrole chlorfenapyr was very effective on concrete for the control of the liposcelidids *L. bostrychophila*, *Liposcelis entomophila* (Enderlein) and *Liposcelis paeta* Pearman. However, most of these formulations are labelled and used as residual surface treatments, while there are very few data on the use of aerosols for the control of stored-product psocids.

The insecticidal efficacy of aerosols is influenced by numerous factors, such as the aerosol particle size. Arthur et al. (2017) found that smaller particle sizes of a mixture of pyrethrin with the IGR methoprene were not effective for the control of adults and larvae of several stored-product beetle species, such as the confused flour beetle, *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae), the warehouse beetle, *Trogoderma variabile* Ballion (Coleoptera: Dermestidae) and the cigarette (tobacco) beetle, *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae), while the presence of food, reduced further the efficacy of the pyrethrin component for control of adults. Moreover, in field applications, larger particles seem to be deposited first, and smaller particle sizes may not deposit on the flooring surface (Arthur et al., 2018). In this context, smaller particle sizes may provide a better distribution of the insecticide, but, at the same time, most of these particles do not land on the target surfaces. This phenomenon may be alleviated by the presence of fans or pressurized air, which may benefit distribution and increase insect exposure to the insecticide (Arthur, 2012, 2018, Arthur et al., 2017, 2018). Apparently, longer exposure increases the lethal effects of aerosols, through increased absorbance of the aerosol particles.

Despite the extensive research that has been done with aerosols and the factors that affect their efficacy for the control of stored-product beetles, the data for the efficacy of aerosols in the case of stored-product psocids are disproportionally lacking. In this study, we evaluated a combination of pyrethrin with methoprene, applied as aerosol at two different particle sizes, and at different exposure intervals, against nymphs of four stored-product psocid species.

2. Materials and methods

2.1. Insects

The species tested were the liposcelidids *Liposcelis decolor* (Pearman), *L. bostrychophila*, *L. entomophila* and *L. paeta*. All psocid species were reared on a mixture of 97% cracked wheat kernels, 2% crisped rice breakfast cereals and 1% brewer's yeast at 30 °C and 70% RH, as suggested by Opit and Throne (2008). Nymphs (N2–N3) were used in the tests. Cultures were maintained at the USDA-ARS-Center for Grain and Animal Health Research (CGAHR), Manhattan, KS, USA. To obtain the nymphs, female adults of each species were left to oviposit for 3 d, and then the females were removed. After an additional period of approx. 10 d, the emerged nymphs were removed with a fine brush (Opit and Throne, 2008).

2.2. Insecticides

The insecticides used contained 1% active ingredient (AI) pyrethrin with a kerosene carrier (Entech Fog 10, Entech Systems, Kenner, LA, USA) and 33% methoprene (Diacon IGR, Central Life Sciences, Schaumberg, IL, USA). These insecticides were mixed at a 100: 1 vol ratio (pyrethrin: methoprene), as specified on the product labels (Arthur et al., 2017).

2.3. Bioassays

All tests were conducted using disposable plastic Petri dishes (9-cm diameter by 1.5-cm high, hereby termed arenas), which had a total surface area of ca. 62 cm^2. The bottoms of the arenas were covered with patching material (Rockite, Hartline Products, Cleveland, OH, USA) to create a concrete surface, as described by Arthur et al. (2014). The internal sides of the arenas were coated with Fluon (polytetrafluoroethylene, Northern Products, Woonsocket, RI, USA) to prevent psocid escape. Before the insecticidal application, 10 individual psocids were placed within each arena, with different arenas for each species.

All arenas were transported to MRIGlobal (Kansas City, MO, USA) for the bioassays. The application of the insecticide was carried out in a vertical flow chamber, which is described in detail in previous experiments (Arthur et al., 2014, 2017). Two different systems were used to apply the aerosol at the particle sizes of 2 and 16 μm (microns), measured as previously described (Arthur et al., 2017). The application times for both particle sizes were 0 (no insecticide), 5, 10, 20 and 30 min. After the termination of the trials, all arenas were returned to the CGAHR and placed in incubators set at the conditions mentioned above. Five days later, the dishes were checked for psocid survival. Treatments were blocked 2 times for applications on different days, on each day there were 2 replicates of each particle size and exposure time, and 3 sub-replicates for each replicate. Thus, there were 12 arenas per species.

2.4. Data analysis

For the initial ANOVA, an analysis was done to determine if blocks were different, and they were not (for all species df = 1,58, F range = 0.01–1.01, P range 0.19–0.97); also, the corresponding Levene's tests were not significant (F range = 0.06–3.26, P range = 0.07–0.93). Replicates and sub-replicates were then combined separately for each psocid species, the data were submitted to a two-way ANOVA with survival as the response variable and particle size and exposure as main effects. Within each exposure, differences between the two particle sizes were tested by using the two-tailed *t*-test at n-2 df and at 0.05 level. Within each particle size, differences among application intervals were tested by using the Tukey-Kramer HSD test at $P < 0.05$.

3. Results

Application interval and its interaction with particle size were significant for all species, with the exception of *L. entomophila* (Table 1). In contrast, particle size was significant only in the case of two out of the four species tested. For L. *bostrychophila*, control mortality was low, and there were no differences in survival between the two particle size controls (Fig. 1). For the pyrethrin + methoprene insecticide treatments using 16 μm droplets there was no survival at any of the exposure times (5–30 min), but with the 2 μm treatment survival was reduced by about half with 5 and 10 min of exposure and complete psocid mortality was achieved only where spraying was performed for 20 or 30 min.

Similar to the previous species, for *L. decolor* there was low control mortality and survival did not differ between the two particle size controls (Fig. 2). Very low or no survival was observed for both particle sizes and for all application intervals in the insecticide treated arenas and there were no significant differences between particle sizes within an interval or among intervals within a particle size (Fig. 2). In the treated arenas, the only survival recorded was at the 2-μm particle size and 5 and 10-min application intervals.

For L. *entomophila*, nymph survival was low in the untreated

Table 1
ANOVA parameters for main effects and their interaction for the four psocid species tested (in all cases, total df = 59).

Source	*df*	*L. bostrychophila*		*L. decolor*		*L. entomophila*		*L. paeta*	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Particle Size	1	6.3	0.02	1.5	0.23	0.3	0.56	5.7	0.02
Application Interval	4	42.5	<0.01	301.9	<0.01	9.9	<0.01	139.7	<0.01
Size X Interval	4	4.5	<0.01	6.7	<0.01	0.5	0.75	6.7	<0.01

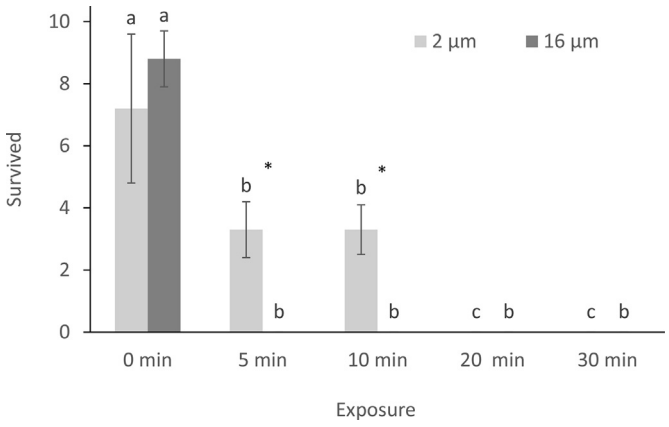

Fig. 1. *L. bostrychophila* survival (individuals out of 10 ± SE), 5 d after their exposure to pyrethrin + methoprene, for different application intervals, with two particle sizes (within each exposure, asterisks indicate significant differences between the two particle sizes; for 0 min: t ratio = −0.7, P = 0.49, for 5 min: t ratio = 3.6, P < 0.01, for 10 min: t ratio = 3.9, P < 0.01, for the other intervals analysis could not be performed as there was no survival, in all cases df = 10, two-tailed *t*-test at 0.05; within each particle size, means followed by the same letter do not differ significantly; for 2 µm: F = 19.1, P < 0.01, for 16 µm: F = 27.7, P < 0.01, and in all cases df = 4,25, HSD test at 0.05).

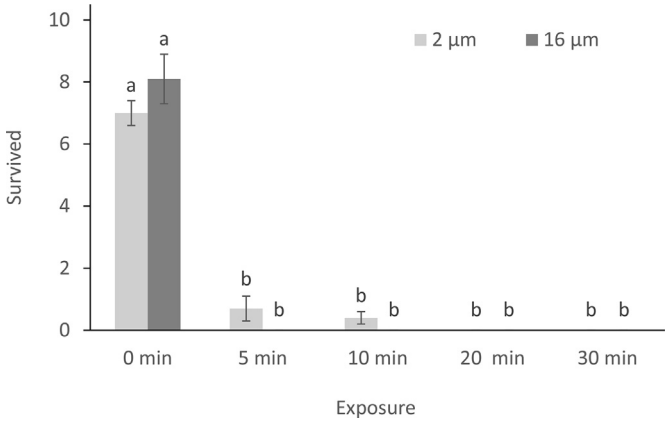

Fig. 2. *L. decolor* survival (individuals out of 10 ± SE), 5 d after their exposure to pyrethrin + methoprene, for different application intervals, with two particle sizes (no significant differences were noted for any of the particle sizes; for 0 min: t ratio = −0.3, P = 0.29, for 5 min: t ratio = 1.6, P = 0.14, for 10 min: t ratio = 1.0, P = 0.34, for the other intervals analysis could not be performed as there was no survival, in all cases df = 10, two-tailed *t*-test at 0.05; within each particle size, means followed by the same letter do not differ significantly; for 2 µm: F = 53.3, P < 0.01, for 16 µm: F = 413.9, P < 0.01, and in all cases df = 4,25, HSD test at 0.05).

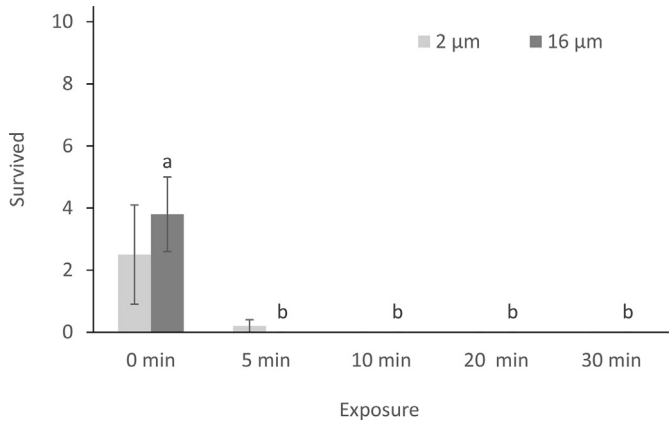

Fig. 3. *L. entomophila* survival (individuals out of 10 ± SE), 5 d after their exposure to pyrethrin + methoprene, for different application intervals, with two particle sizes (no significant differences were noted for any of the particle sizes; for 0 min: t ratio = −0.7, P = 0.52, for 5 min: t ratio = 1.58, P = 0.14, for the other intervals analysis could not be performed as there was no survival, in all cases df = 10, two-tailed *t*-test at 0.05; within each particle size, means followed by the same letter do not differ significantly, while where no letters exist, no significant differences were noted; for 2 µm: F = 2.4, P = 0.08, for 16 µm: F = 10.3, P < 0.01, and in all cases df = 4,25, HSD test at 0.05).

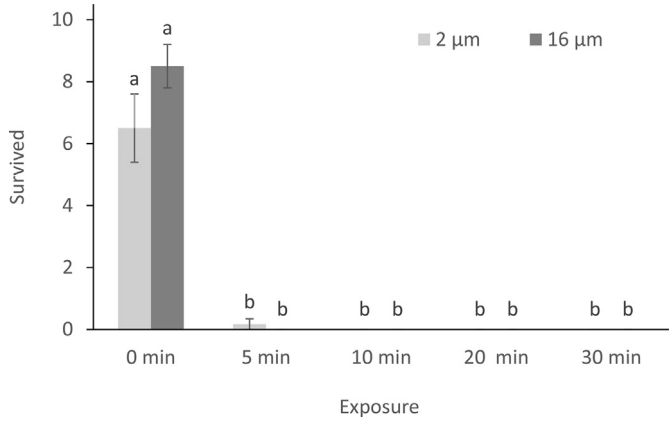

Fig. 4. *L. paeta* survival (individuals out or 10 ± SE), 5 d after their exposure to pyrethrin + methoprene, for different application intervals, with two particle sizes (no significant differences were noted for any of the particle sizes; for 0 min: t ratio = −1.5, P = 0.16, for 5 min: t ratio = 1.0, P = 0.34, for the other intervals analysis could not be performed as there was no survival, in all cases df = 10, two-tailed *t*-test at 0.05; within each particle size, means followed by the same letter do not differ significantly; for 2 µm: F = 76.6, P < 0.01, for 16 µm: F = 57.8, P < 0.01, and in all cases df = 4,25, HSD test at 0.05).

control dishes, and there was no survival in any of the insecticide treated dishes except for a low level at 2 µm and 5 min application interval treatment (Fig. 3).

For L. *paeta,* when no insecticide was used there was high survival and no differences in survival levels between the two particle sizes controls (Fig. 4). Furthermore, there was no survival for either particle size and any of the exposure times, except for negligible survival with 2 µm particles at the 5 min application (Fig. 4). There were no significant differences among insecticide exposure times, except in relation to the controls, or between droplet sizes within an exposure time.

4. Discussion

The combination of a neurotoxic insecticide, with a non-neurotoxic compound, such as an IGR, has been evaluated for stored-product insects under different scenarios. Given that IGRs do not kill the stored-product insect adults (Athanassiou et al., 2010b, 2011), the addition of pyrethrin or a pyrethroid to the mixture will control adults of stored-product beetles (Sutton et al., 2011). However, pyrethrin or pyrethroids will cause knockdown of adults or immobilization of larvae, which may decrease the overall efficacy of the IGR through reduced immature contact. In addition, the results differ from the previous deposition studies for direct and indirect control of adults and immature stored product beetles where smaller particle size did not cause any mortality (Arthur et al., 2014, 2017). Our data show that particle size is less important in the case of psocids, as compared to beetles. The differences between particle sizes occurred mainly at the shorter exposure intervals.

In the current study, the differences between particle sizes were most apparent for *L. bostrychophila*, where survival in the treated arenas was higher than that of the other species. Even 10 min of the application of the aerosol was not enough to cause complete mortality of the exposed individuals, at the particle size of 2 μm. Consequently, the 16-μm particle size was more effective for this species, but for all other species, there were significance differences between the two particle sizes only at the shorter exposure intervals.

This study provides further evidence that small aerosol particle sizes may result in reduced efficacy or no efficacy at all. For example, Arthur et al. (2017), by using the same spraying technique and the same insecticide as in here, found that 16 μm was much more effective than 2 μm for the control of *L. serricorne*, *T. variabile* and *T. confusum*. In fact, in that study, the authors found that apart from initial mortality, larger particle sizes provided higher residual effect on the treated surface, during an 8-wk bioassay period. Similarly, Arthur et al. (2014) noted that recovery of treated adult *T. confusum* was close to 100% when the insecticide was applied at the particle size of 2 μm.

As a continuance of the previous studies by Arthur et al. (2014, 2017), we used the same experimental set-up to examine the insecticidal effect of pyrethrin + methoprene against stored-product psocids, for which there are no data available. Hence, we selected nymphs to evaluate adult emergence and possible deformities that might have been caused by the application of the IGR. Nevertheless, the formulation tested here caused a high level of mortality to the exposed psocid nymphs for all four species tested, even at the shortest treatment interval, thus effects on adult emergence could not be assessed. Our results contrast somewhat with a previous study examining the pyrethroid esfenvalerate, applied alone and in combination with methoprene on different psocid species using adults and nymphs. In that study, nymphs of *L. decolor* and *L. paeta* were used, and the greatest mortality achieved was 76% (Opit et al., 2012). However, in that study, nymphs were exposed in arenas held inside a metal shed, and applications were made using a portable hand-held applicator, and there were no assessments of particle size. It is possible that the application system in the current study gave a higher overall concentration of aerosol in contrast to the Opit et al. (2012) study.

In the current study, there was little recovery from knockdown, as contrasted to the previous studies with adult *T. castaneum* (Arthur et al., 2014). Theoretically, quick immobilization means the termination of the exposure to the lethal agent through contact or digestion, which may allow insects to metabolize the insecticide, recover and move out of the treated area, or move to areas where a lethal concentration was not achieved (Georghiou, 1962; Agrafioti et al., 2015). Under the scenario that was tested here, longer application intervals apparently are beneficial for the insecticidal effect of the formulation tested, not only through the increase of the concentration of the insecticide, but also through the decrease of the size of the areas that do not receive insecticide or are under dosed. Still, larger particle sizes may help towards this direction. With L. *bostrychophila*, we found that when the insecticide was applied at 16 μm, 100% mortality could be achieved in 5 min of application, while, for the same mortality level, at 2 μm, the applications required 20 min. However, for the other more susceptible species, extending the application time had less effect. In general, for some insecticides that have been tested so far, *L. bostrychophila* is less susceptible than other species (Nayak et al., 2014). For example, for the IGR pyriproxifen which had been applied on concrete, Athanassiou et al. (2011) found that *L. bostrychophila* has increased survival than *L. decolor* and *L. paeta.*

To our knowledge, this is the first report on the efficacy of particle size of aerosols for the control of stored-product psocids. Our results show that large particle sizes were more effective primarily at short intervals for the control of the species tested here, in contrast to results reported for stored product beetles. It is difficult to draw conclusions for *L. entomophila* due to the high control mortality hence additional testing may be necessary to obtain more conclusive results for this species. Moreover, apart from the insecticidal efficacy *per se*, larger particles of aerosols may be considerably more cost-effective, as they could shorten the exposure times required for psocid mortality. We also found variations among the psocid species tested, but overall the pyrethrin-methoprene formulation was very effective for all four species.

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Appendix A. Supplementary data

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