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Efficacy of four insecticides on different types of storage bags for the management of *Trogoderma granarium* Everts (Coleoptera: Dermestidae) adults and larvae

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A B S T R A C T

The khapra beetle, *Trogoderma granarium* Everts (Coloeptera: Dermestidae), is a globally serious pest of several agricultural stored-commodities. Among new methods that target to control this species is the insecticidal treatment of storage bags. In the present study, we tested the efficiency of alpha-cypermethrin (= α-cypermethrin), chlorfenapyr, deltamethrin and pirimiphos-methyl applied on woven polypropylene, biaxially oriented polypropylene and kraft paper storage bags against adults and larvae of *T. granarium* under three treatment scenarios: one surface of the storage bag was treated and individuals were exposed on treated or untreated surface or both surfaces were treated. We estimated the immediate mortality after 1, 3 and 5 days (d) of exposure. Then, we placed adults and larvae that were alive unto untreated surfaces of the same type of storage bags and evaluated the delayed mortality after 7 d of exposure. Regarding immediate mortality, the most effective insecticides were chlorfenapyr and pirimiphos-methyl against both life stages. All insecticidal combinations resulted in very high delayed mortality values that finally killed ≥91.1% of the initially exposed adult population of *T. granarium* while in several combinations all adults died due to the delayed mortality. The initial population of *T. granarium* larvae was further reduced through delayed mortality, but there were still alive individuals on the storage bags. In the majority of combinations with α-cypermethrin, deltamethrin and pirimiphos-methyl, there were no significant differences in the mortality levels of adults and larvae when they were exposed onto the treated surface of the storage bags having one or both surfaces treated. All insecticides performed equally on the three tested types of storage bags. The present study illustrates that the application of chlorfenapyr and pirimiphos-methyl on different types of storage bags could be considered as additional tools for the management and regulation of expansion of *T. granarium*.

1. Introduction

The invasive khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) is a calamitous stored-product insect species whose identification is followed by certain phytosanitary regulations (Banks, 1977; Lowe et al., 2000; Hill, 2002; Myers and Hagstrum, 2012; EPPO, 2013). Although *T. granarium* has Indian origin (Rahman et al., 1945), it is now present in Palaearctic and Afrotropical realms (Athanassiou et al., 2015; EPPO, 2018). *T. granarium* phytosanitary classification is A1 (absent from the EPPO region) or A2 (present in the EPPO region) (EPPO, 1981, 2013, 2018) while it is a quarantine organism in several countries worldwide (EPPO, 2018). Nearly 84% of all *Trogoderma* spp. intercepted at the US ports from 1985 to 2010, were identified as *T. granarium*. At the beginning of 2011 and thence, there was a rapid increase of *T. granarium* interceptions (162 from January–September) (Myers and Hagstrum, 2012). This is also evident in Europe since *T. granarium* has been recently intercepted in several European countries (EPPO, 2018), indicating potential global population outbreak of this species. The reasons for this extensive distribution are that *T. granarium* can easily locomote by the international trade, it is able to develop between 21 and 40 °C with an optimum at 35 °C, it feeds on 96 commodities, it infests very dry food with 2% moisture content in very dry environment with 2% relative

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humidity (r.h.). Moreover, its larvae fall into long diapause (i.e., 8 years) below 30 °C and can easily penetrate package material and contaminate food with cast skins and hairs that are dangerous for the public health (Morison, 1925; Pruthi and Singh, 1950; Lindgren et al., 1955; Hadaway, 1956; Burges, 1957, 1959, 1962; Aitken, 1975; Peacock, 1993; Hagstrum and Subramanyam, 2009; Athanassiou et al., 2011, 2016).

Under favorable conditions of temperature and rearing media, *T. granarium* can easily build high population densities in short period of time (Munro, 1966; Aitken, 1975; Athanassiou et al., 2016; Kavallieratos et al., 2017c). Although *T. granarium* develops on great variety of stored-food of plant and animal origin its population growth depends on type and status of commodity that is used as a substratum (Bhattacharya and Pant, 1969; Rao et al., 2005; Borzoui et al., 2015; Rajput et al., 2015; Athanassiou et al., 2016). *T. granarium* is a primary colonizer, but its larvae can feed on damaged and whole kernels depending on their instar (Lindgren et al., 1955). Athanassiou et al. (2016) reported that *T. granarium* develops better on wheat, triticale or whole barley flour rather than barley, maize, oats or pasta. Also, the increase of the percentage of cracked wheat mixed with intact kernels provided higher population growth of *T. granarium* than intact wheat kernels only. This is a realistic scenario given that grain commodities contain a percentage of damaged kernels. Therefore, cargoes which contain small number of *T. granarium* individuals in conjunction with cracked kernels can produce large numbers of *T. granarium* by the time they reach entry points of their destinations (Athanassiou et al., 2016; Kavallieratos et al., 2017c).

One possible way to protect stored-products during their transportation from the place of manufacture till they reach consumers is to place them in packages (Campbell et al., 2004). The ongoing exhaustive research has developed numerous types of packaging material that can offer different levels of protection to stored-products and exhibit a cost that can be afforded either by individuals or companies (Stejskal et al., 2017). However, even packaged products can be infested by insect pests by penetrating the packaging material or invading through already existing openings (i.e., holes/vents made by insects, mechanical handling, improper sealing) (Mullen et al., 2012; Navaro, 2012; Costa, 2014; Stejskal et al., 2017). Particularly, concerning bagged grains, a novel concept that further decreases the risk of insect infestations has started being developed the recent years. For this reason, insecticides can be impregnated into the fabrics of the storage bags [e.g., ZeroFly® polypropylene polymer storage bags (Vestergaard S.A., Lausanne, Switzerland)] or treated directly on the packaging material (e.g., paper, polyethylene, polypropylene) (Highland et al., 1977, 1984a,b; Highland and Cline, 1986; Scheff et al., 2016; Kavallieratos et al., 2017a,b; Paudyal et al., 2017a,b; Scheff et al., 2017, Scheff and Arthur, 2018). Therefore, the treated package blocks insect infestations either originating from the storage environment into the packaged grain commodities or vice versa (Kavallieratos et al., 2017a, b; Paudyal et al., 2017a). It should be noted that this management strategy requires a pre-fumigation treatment of the grains that are going to be bagged so as to avoid/delay damages by insects during the storage period (Kavallieratos et al., 2017a; Paudyal et al., 2017b).

Previous studies have shown that the management of *T. granarium* with contact insecticides is not always effective especially when it is attempted to control with chemicals, either applied as surface treatments or as grain protectants, larvae of this species (Athanassiou et al., 2015; Kavallieratos et al., 2016, 2017d; Ghimire et al., 2017; Arthur et al., 2018). However, there are no published data to show whether treatments with different insecticides on different types of storage bags can offer satisfactory levels of protection against *T. granarium*. Even when the grains are fumigated before being placed into insecticide-treated storage bags, a certain portion of the pests' population could survive the treatment and also avoid adequate contact of the insecticide-treaded storage bag (Paudyal et al., 2017b). Consequently, pests' populations will be multiplied inside the treated storage bags before they reach port cities. It has been clearly documented that *T. granarium* larvae can rapidly establish high populations on grain commodities while some grains favor the development of this insect more than others (Athanassiou et al., 2016; Kavallieratos et al., 2017c). Therefore, the objectives of this study were to evaluate the immediate and delayed mortality of *T. granarium* adults and larvae exposed to three types of storage bags made of plastic and paper treated with four insecticides: two pyrethroids (α-cypermethrin, deltamethrin), one pyrrole derivative (chlorfenapyr) and one organophosphate (pirimiphos-methyl), under three treatment scenarios. The selection of these insecticides has been based on the fact that they are registered for surface treatments against stored-product insect pest species.

2. Materials and methods

2.1. Insects

Adults <24 hours (h) old and 2–4 mm size larvae (Athanassiou et al., 2015; Kavallieratos et al., 2016) were used in the tests. The colony of *T. granarium* was established in 2014 from individuals collected in Greek storage facilities and since then it has been maintained in the Laboratory of Agricultural Zoology and Entomology, Agricultural University of Athens at 30 °C, 65% r. h. and continuous darkness.

2.2. Formulations

The following four insecticidal formulations were tested: Power SC with 62.4 g/l α-cypermethrin active ingredient (a.i.) (provided by Hybrid Hellas, Metamorphossis, Greece), Phantom EC with 21.45% chlorfenapyr (a.i.) (provided by BASF Hellas, Amaroussion, Greece), K-Othrine WG with 25% deltamethrin (a.i.) (provided by Bayer Hellas, Amaroussion Greece) and Actellic EC with 50% pirimiphos-methyl (a.i.) (provided by Syngenta, Anthousa, Greece).

2.3. Bag material

Three different types of bags were used in the experiments: woven polypropylene (WPP) bags (Hatzigeorgiou - Fakaros G.P., Aigaleo, Greece), that are suitable for storage of olives, cotton, charcoal, wood and grains; biaxially oriented polypropylene (BOPP) bags (Alpha Beta Roto S.A., Aigaleo, Greece), that are suitable for storage of human- or animal-food and grains; and kraft paper (KP) bags (Mondi, Vienna, Austria), that are suitable for storage of grains and fresh vegetables, fruits, fish or meat.

The WPP bags have 100 μm of thickness (measured with a No 208M Starret micrometer, Athol, MA, USA), strength of warp minimum 44.3 kgf, strength of weft minimum 40.2 kgf, weaving 10 × 9 threads per inch, density of warp 10 threads per inch and density of weft 9 threads per inch. The BOPP bags have 70 μm of thickness (measured with a No 208M Starret micrometer, Athol, MA, USA), weight 27.3 g/m^2 and water vapour transition rate <2.5 g/m^2/24 h.

The KP bags are consisted of two layers of paper: a) an outside white calendered KP that has 100 μm of thickness (measured with a No 208M Starret micrometer, Athol, MA, USA), weight 70 g/m^2, water absorptiveness, Cob 60'' (absorbed g of water by 1 m^2 of the paper in 60 s) 27 g/m^2, tensile strength (maximum force that paper will withstand before breaking) 5.6 kN/m [machine direction (MD)] or 4.1 kN/m [cross direction (CD)] and tensile energy absorption