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Efficacy of diatomaceous earths and their low-dose combinations with spinosad or deltamethrin against three beetle pests of stored-maize

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ABSTRACT

A key element in postharvest IPM is the reduction of chemical residues in food through the use of reduced dosages of less toxic grain protectants. Two laboratory experiments were conducted: Experiment I determined the efficacies of straight diatomaceous earths (DEs) – “Chemutsi” (African raw DE), MN51 (new formulation) and Protect-It® (enhanced DE), and two new food grade DE-based formulations (A2 and A3) against adult *Prostephanus truncatus* (Horn), *Sitophilus zeamais* (Motschulsky) and *Tribolium castaneum* (Herbst) admixed with shelled maize. In Experiment II, Chemutsi and Protect-It® were further tested in varying combinations with low-dose deltamethrin and spinosad. At 21 days post-exposure, MN51 800 ppm and 1000 ppm, Chemutsi 1000 ppm, Protect-It® 600 ppm and food grade A3 150 ppm caused *S. zeamais* mortalities that were not significantly different from the positive control (Protect-It® 1000 ppm). However, after the same exposure period, all the straight DEs (applied at $\leq$ 1000 ppm) and the DE-based food grade formulations were not effective on *P. truncatus* and *T. castaneum*. In low dose combinations, 7 day mortalities showed high *S. zeamais* susceptibility to both DE-spinosad and DE-deltamethrin while *P. truncatus* was more susceptible only to DE-spinosad and *T. castaneum* to Protect-It®-deltamethrin only. At 21 days, all DE-spinosad and DE-deltamethrin treatments were effective and not significantly different from the commercial grain protectant (fenitrothion 1.0% w/w (10000 ppm) + deltamethrin 0.13% w/w (130 ppm)) on all test species. DE-spinosad and DE-deltamethrin combinations significantly suppressed ($P < 0.001$) F_1 progeny for the three test species whereas straight DEs and DE-based food grade formulations did not. Our results showed that at half the label rates or lower, DE-spinosad and DE-deltamethrin combinations were effective alternative grain protectants that are safer and possibly cheaper. We also give the first report on the effectiveness of Chemutsi in combination with spinosad or deltamethrin on maize grain.

1. Introduction

Maize (*Zea mays*) is a staple crop in sub-Saharan Africa (SSA); with dietary, economic, social and political importance. The persistent shortage of the staple grain in the region has greatly increased the necessity for effective methods of storage and preservation (Mvumi et al., 1995; Mvumi and Stathers, 2003; Chigoverah and Mvumi, 2016) of the little that is harvested considering expected poor harvests due to the already unfavourable climate (Stathers et al., 2013) and degraded environment (Hodges et al., 2011; Tefera, 2012). Maize storage losses in SSA are mainly due to the major primary pests of stored maize including the maize weevil, *Sitophilus zeamais* (Motschulsky) (Coleoptera: Curculionidae), the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae) (Mvumi et al., 2002; Nyagwaya et al., 2010; Tefera, 2012). Further damage later in stores is mainly due to the rust red flour beetle, *Tribolium castaneum* (Herbst)

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(Coleoptera: Tenebrionidae) which is the major secondary pest of maize in SSA (FAO, 1999).

Commercial grain protectants used in SSA are mainly organophosphate-pyrethroid-based combinations which are neurotoxic synthetic pesticides with label rates of up to 10000 ppm (Organophosphates) and up to 130 ppm Deltamethrin/Permethrin (Anecdotal evidence). Organophosphates fall into the 'highly hazardous' Class 1B of WHO insecticide toxicity classification (WHO, 2009). On the other hand, pyrethroids have variable toxicity. For example, deltamethrin is a Type 11 α-cyano synthetic pyrethroid (see details in Casida and Durkin, 2013), falling into 'acute hazard' Class 2 of WHO insecticide toxicity classification (WHO, 2009) and is three times more toxic than other synthetic pyrethroids (Gilbert, 2014).

The adoption of deltamethrin in stored grain protection was mainly based on its high stability in physical state, effectiveness at low dosages and most importantly its low residue levels (about 10%) at consumption in grain products due to high losses at various processing stages (Jermannaud and Pochon, 1994). Based on these facts, replacement of neurotoxic organophosphates with alternative inert materials like diatomaceous earths (DEs) and further reduction of deltamethrin dosages through combining it with inert materials in grain protectants might further reduce its health risks contributing to food safety (Mvumi and Stathers, 2003; Vassilakos et al., 2015).

The use of these organophosphate-pyrethroid-based neurotoxic synthetic pesticides in stored grain is a concern due to residues in food (Chintzoglou et al., 2008; FAO, undated) and short-lived effectiveness resulting in the need to constantly re-treat the grain (Eissa et al., 2014; Vassilakos et al., 2015). Synthetic pesticides have also been observed to have high mammalian toxicity, ecological side effects, prone to insecticide resistance and general consumer aversion from chemicals (Chintzoglou et al., 2008). Therefore, postharvest research efforts should be geared towards the reduction and possible elimination of the synthetic pesticides which smallholder farmers currently rely on (Vassilakos et al., 2015) due to lack of effective alternatives.

Diatomaceous earths (DEs) are a natural inert material derived from fossilised geological deposits of siliceous fresh water or marine unicellular algae called diatoms (Quarles and Winn, 1996; Korunic, 1997). They are mainly made up of silicon dioxide (Korunic, 1997). The effectiveness of different DEs on different grain types stored by small scale farmers in Africa under their typical storage conditions has been demonstrated by many researchers (Stathers et al., 2004, 2008; Mvumi et al., 2006; Nwaubani et al., 2014). Success of DEs has been demonstrated by its registration as a grain protectant in various countries (Korunic, 2013) mainly due to its unique physical mode of action, low insect resistance development, high persistence on grain, high level of adherence on grain, easy removal from the grain and low mammalian toxicity (Subramanyam and Roesli, 2000; Stathers et al., 2004; Korunic, 2013). However, previous studies by Fields and Korunic (2000), Athanassiou et al. (2005), Athanassiou and Korunic (2007, 2013) showed that the required DE dosage of at least 1 kg/tonne (1000 ppm) to effectively control insect pests in grain stores, is too high for worker safety and sustainable stored product pest management. Such high dosages were also observed to affect grain end use quality, bulk density and worker safety (Mvumi et al., 2006; Vayias et al., 2009; Korunic, 2013).

Due to these and other DE shortcomings (Stathers et al., 2004; Korunic, 2013), many researchers have recommended the potential use of DEs at reduced dosages (Subramanyam and Roesli, 2000; Korunic and Rozman, 2010; Almasi et al., 2013). The effectiveness of such dosages has mainly been enhanced by efficacious combinations of DEs with different additives (see Athanassiou and Korunic, 2007; Korunic and Rozman, 2010; Iatrou et al., 2010; Almasi et al., 2013). Varying degrees of success have been achieved, attributable to factors such as temperature, humidity, insect sources; insect species and the inherent chemical characteristics of the particular DE (Athanassiou et al., 2005, 2008). Effectiveness of DE combinations with fungal metabolites (Kavallieratos et al., 2006; Athanassiou and Korunic, 2007; Michalaki et al., 2007), bacterial metabolites (Chintzoglou et al., 2008; Vayias et al., 2009), insect growth regulators (Chanbang et al., 2007), pesticidal plants (Nukenine et al., 2010), plant extracts (Athanassiou et al., 2009; Vayias and Stephou, 2009), pyrethrins (Stathers, 2002; Korunic and Rozman, 2010; Almasi et al., 2013) and thiamethoxam (Wakil et al., 2013) on various stored product pests and different grain types have been reported.

Another possible alternative component for DE-combination is spinosad, which is derived from fermentation products of a naturally-occurring soil bacterium *Saccharopolyspora spinosa* Mertz and Yao (Bacteria: Actinobacteridae). It is a broad-spectrum insecticide registered in organic agriculture as it has low mammalian toxicity, is environmentally benign and is generally regarded as safe by international standards (Subramanyam et al., 2007; Hertlein et al., 2011). Though straight spinosad was observed to be very effective on *P. truncatus*, *S. zeamais* and *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), on its own, it was not as effective on *T. castaneum* (Mutambuki et al., 2012) hence the need to combine it with DEs. Spinosad is registered in Kenya as a commercial grain protectant.

To mitigate the shortcomings of pure DEs (reviewed in Korunic, 2016), reduce deltamethrin residues in stored grain and minimize chances of resistance development, the present work sought to evaluate: (1) the potential of straight local and enhanced food-grade DEs as grain protectants and (2) the efficacy of these DEs in combination with low-dose deltamethrin or spinosad, as a contribution towards postharvest IPM and food safety. Furthermore, the study assessed the grain protection potential of these combinations through evaluating the F_1 progeny emergence. Although the combination of DEs with deltamethrin and spinosad has been reported in separate previous studies, to our knowledge this is the first report to focus on maize grain, the most economically important starch staple in East and Southern Africa. The efficacy of enhanced DE-spinosad, enhanced DE-deltamethrin, raw DE-spinosad and raw DE-deltamethrin was evaluated on major maize storage pests. The study focused on the efficacy of these products on the most abundant primary maize beetle, *S. zeamais*; the most damaging bostrichid, *P. truncatus*; and the major secondary cosmopolitan cereal pest, *T. castaneum*. The objective of the study was to identify efficacious combinations that could later be commercially improved for marketing and thus reduce over-reliance on synthetic grain protectants that pose health risks to smallholder farmers, grain handlers and consumers.

2. Materials and methods

2.1. Test insects

Founder populations of *S. zeamais*, *P. truncatus* and *T. castaneum* were obtained from laboratory colonies kept at both the Departments of Crop Science and Biological Sciences, University of Zimbabwe. The insects were reared on maize grain which had been previously disinfected and disinfested by deep-freezing at −15 °C for 14 days followed by 7 days of preconditioning at experimental conditions of 27 ± 1 °C and 60± 5% RH experimental jars. The adult insects (parent colony) were sieved off every 14 days to retain only eggs that would give rise to emergency of same-age adults. Sieved off adults were introduced into fresh maize grain to lay eggs for a