New trends in the use of diatomaceous earth against stored-grain insects

C.G. Athanassiou¹*, Z. Korunic², N.G. Kavallieratos³, G.G. Peteinatos¹, M.C. Boukouvala⁴, N.H. Mikeli⁵

Abstract

In order to mitigate the effect of diatomaceous earth (DE) on bulk density and grain flowability, during the recent years, two new enhanced DEs with synergistic mode of physical and chemical actions have been developed; one with the addition of the soil bacteria metabolite abamectin (DEA) and the other with the addition of the plant extract bitterbarkomycin (DEBBM). Both formulations have very low mammalian toxicity with the oral LD₅₀ for rat higher than 4,500 mg/kg. The insecticidal effects of both formulations have been extensively evaluated under laboratory conditions. Against the larger grain borer, Prostephanus truncatus (Horn) (Coleoptera: Bostrychidae) and the lesser grain borer, Rhyzopertha dominica (F.) (Coleoptera: Bostrychidae) 75 ppm of DEA on maize and wheat, respectively, provided 100 % parental mortality after 14 days of exposure. In the case of R. dominica, 75 ppm of DEA provided complete progeny suppression. Similar results were produced in the case of the rice weevil, Sitophilus oryzae (L.) (Coleoptera: Curculionidae); however but 125 ppm were required to provide complete progeny suppression. In the case of P. truncatus, it was found that DEA performance remained unaffected in all combinations of the temperature 20, 25 and 30 °C and of the relative humidity (r.h.) levels 55 and 75 %, while mortality was 100 % after only 7 days. For DEBBM, 75 ppm provided 100 % mortality of R. dominica and of the rusty grain beetle, Cryptolestes ferrugineus (Stephens) (Coleoptera: Cucujidae) after 14 d, and complete suppression of progeny production. For a 100 % mortality of S. oryzae and of the red flour beetle, Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae) 100-125 ppm was required, but progeny production was extremely low. Based on these results, it becomes evident that these two formulations could be used with success against stored-grain beetle species, at very low application rates.

Key words: enhanced diatomaceous earths, abamectin, bitterbarkomycin, physical control, natural insecticides

Introduction

In an effective Integrated Stored Grain Pest Management (ISGPM) program, methods of
prevention and control are integrated to give the maximum protection of grain at the lowest possible cost. Diatomaceous earths (DEs) may be successfully incorporated into ISGPM program since they are natural insecticides of low mammalian toxicity, and have proved very effective against a wide range of species (Subramanyam and Roesli, 2000). DEs are composed by the fossils of phytoplanktons (diatoms) which absorb the epicuticular lipids of the insect cuticle, causing death through desiccation (Ebeling, 1971). It is generally thought that DE should be used as a preventive measure for grain protection and not as a curative measure or means of disinfestation. However, DE is an effective and safe insecticide to protect a private farmer’s grain supply and feed grain (FDA, 1995). The main drawback in the use of DEs with grains is their high application rates which negatively affect the physical properties of the grain, chiefly bulk density and grain flowability (Fields, 1999). Several DEs are now commercially available, but, for a satisfactory level of protection, they should be applied at dose rates between 400 -1,000 ppm (Subramanyam and Roesli, 2000). One of the possible solutions to this implication is the combined use of DEs with other reduced-risk natural compounds (Arthur, 2004a, b). During the last decade there has been an increased interest from several researchers from various parts of the world in the use of diatomaceous earths (DEs) as insecticides in stored-products, particularly cereals (Korunic, 1998; Subramanyam and Roesli, 2000; Fields and Korunic, 2000; Arthur, 2003; Mewis and Ulrichs, 2001; Athanassiou et al., 2003)

Several DE formulations have been registered for use as grain protectants in many countries. However, the main disadvantage in the use of DEs is their negative effect in the physical properties of grains, particularly bulk density (Jackson and Webley, 1994; Korunic et al., 1996, 1998; Korunic, 1998). DEs should be applied at application rates which are considered extremely high and cause a considerable bulk density reduction (Korunic et al., 1998; Subramanyam and Roesli, 2000). Hence, it is essential to evaluate newer DE formulations that can be effective at lower dose rates.

The possible solutions to these implications is the combination of DEs with other application methods and substances, such as grain cooling (Nickson et al., 1994), heat treatment (Fields et al., 1997; Dowdy, 1999), fumigation (Winks et al., 1994), low doses of insecticides (Subramanyan and Roesli, 2000; Arthur, 2004a, b; Athanassiou et al., 2004; Athanassiou and Kavallieratos, 2005; Athanassiou, 2006) and fungal pathogens (Lord, 2001; Kavallieratos et al., 2006; Michalaki et al., 2006; Vassilakos et al., 2006). However, the simultaneous use of DEs with insecticides is not compatible with organic production, which is a serious advantage for the use of DEs alone.

To mitigate the adverse effect of DE on grain quality and grain handling, and also to make the insecticide formulations compatible with organic production, during the last years, two new enhanced DE formulations have been developed by Diatom Research and Consulting Inc., Canada. The first is DEA, which is a combination of DE with abamectin, a soil bacteria metabolite, and the second is DEBBM, which is a combination of DE with bitterbarkomycin, a plant extract. Both formulations have very low mammalian toxicity with an oral LD50 for rat higher than 4,500 mg/kg.

Abamectin is a natural fermentation product of the soil bacterium Streptomyces avermitilis (Burg et al.) Kim and Goodfellow (Actinobacteria: Actinobacteridae). Abamectin is a mixture of avermectins containing > 80 % avermectin B1a and < 20 % avermectin B1b. It acts as an insecticide by affecting the nervous system and paralyzing the insects (Extoxnet, 1996).

The powdered root bark of Celastrus angulata Maxim. (Celastrales: Celastraceae) has been used for a long period of time in China to protect plants from insects damage (Jacobson and Crosby, 1971). Wang et al. (1991) isolated an insecticidal sesquiterpene polyl ester, angulatin A, from the root bark of the same plant species. The results of preliminary insecticidal tests showed that sesquiterpene polyl ester mixture (25 to 50 ppm) containing angulatin A, named as
bitterbarkomycin (BBM), had strong insecticidal and antifeedant effects against *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), *Aphis gossypii* Glover (Hemiptera: Aphidoidea), *Pieris rapae* (L.) (Lepidoptera: Pieridae) and *Brevicoryne brassicae* L. (Hemiptera: Aphidoidea).

Initial tests with these two new DE-based formulations indicated that they are highly effective at extremely low doses, suggesting that these formulations could be used in grain commodities without the significant negative effects in bulk density and grain flowability. In the present work, the results from a series of laboratory experiments with these enhanced DEs are presented.

**Materials and methods**

**Formulations**

DEA-P/WP is a mixture of DE and abamectin containing 83% of DE and 0.25% of abamectin active ingredient dissolved in a solvent and emulsifier.

The DE belongs to a group of fresh water DEs containing 89% amorphous silicon dioxide, 4.0% Al₂O₃, 1.7% Fe₂O₃, 1.4% CaO, less than 1% of MgO and K₂O and 3% moisture (as shipped by the producer). The median particle size is 10 microns, specific gravity is 2.2, surface area is 35.7 m²/g, pH is 8 and crystalline silica is > 0.1% (Celite Corporation Technical Data; 14 December 2001).

DEBBM-P/WP is a mixture of DE and the Chinese plant extract bitterbarkomycin (BBM) containing 90% of DE and 0.05% of BBM active ingredient dissolved in solvent and emulsifier.

The DE is the same as the one used in DEA-P formulation. Both formulations can be used as powders (P) or wettable powders (WP).

**Insects**

Adults of *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae) and *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) were used in the tests. *S. oryzae* and *R. dominica* were reared on whole hard wheat, *T. castaneum* on wheat flour plus 5% brewers yeast, *C. ferrugineus* on whole hard wheat with 10% cracked kernels and 10% wheat flour, and *P. truncatus* on whole maize. All species were kept at 27 ± 1°C and 65 ± 5% r.h.

**Commodities**

Untreated, clean, hard wheat with approx. 12% moisture content (mc) was used in the tests for all species, with the exception of *P. truncatus* for which untreated, clean maize with 12% mc was used.

**Bioassays series 1**

Exposure studies were carried out at 27 ± 1°C and 65 ± 5% r.h. Samples of 50 g of treated wheat were placed in vials and treated with application rates of 75, 100 and 125 ppm of DEA, used as powder (4 samples for each case, plus a series with untreated wheat which served as control). Then, 50 adults of *S. oryzae* were introduced into each vial, and the same procedure was followed with *R. dominica*. In the case of *P. truncatus*, the same protocol was applied, but maize was used. Mortality was measured after 7 and 14 d of exposure. After this interval all adults (dead or alive) were removed and the samples were left for an additional period of 65 d (in the cases of *S. oryzae* and *R. dominica*), after which the vials were opened and the number of adult progeny was measured.

**Bioassay series 2**

The same experimental procedure was followed as above, at the same conditions, for *P. truncatus* adults on treated and untreated maize. The samples were treated with 75 and 150 ppm of DEA as powder, and with 500 and 1,500 ppm
of the enhanced DEs PyriSec (Biofa GmbH, Germany), that contains 1.2 % natural pyrethrum (25 %) and 3.1 % piperonyl butoxide and Protect-It (Hedley Technologies Inc., Canada) that contains 10 % silica aerogel. Mortality was assessed after 7 d of exposure. The bioassays were carried out at all combinations of three temperature levels, 20, 25 and 30 °C, and two r.h. levels, 55 and 75 %.

**Bioassays series 3**

The testing protocol and conditions were the same as in Bioassay series 1, but in this case mortality was assessed only after 14 d of exposure. In these tests, adults of *C. ferrugineus*, *R. dominica*, *S. oryzae* and *T. castaneum* were exposed on wheat treated with DEBBM as powder or as wettable powder, at four doses: 75, 100, 125 and 150 ppm. Mortality was measured after 14 d of exposure, and progeny production was assessed 65 d later.

For slurry application, the application rates were mixed with water and the grain was sprayed with 0.2 ml of the corresponding suspension per kg of grain (2 liters per 1,000 kg of grain). For the application of 75 ppm, 100 ppm, 125 ppm and 150 ppm the quantity of the formulation of 0.75 g, 1 gram, 1.25 g and 1.5 g, respectively, was mixed with 20 ml of water and with 0.2 g of the suspension 100 grams was sprayed.

**Data analysis**

Control mortality was corrected by using Abbott’s (1925) formula. Before the analysis, all data were arcsine transformed to standardize means and normalize variances. For each species, exposure interval, mortality and progeny data were submitted to a one-way ANOVA for DE dose. Progeny production in the control vials were not included in the analysis, since a preliminary ANOVA indicated that significantly more progeny were found in the control vials than in the treated ones (*P* < 0.01). For the comparison of the means the Tukey-Kramer (HSD) test was used, at 5 % (Sokal and Rohlf, 1995).

**Results**

**Bioassay series 1**

For *P. truncatus* and *R. dominica*, all adults were dead after 7 d of exposure, even on commodities treated with the lowest dose of DEA (75 ppm) (Table 1). For *S. oryzae*, after 7 d of exposure, significantly fewer adults were dead at 75 ppm than at the other two doses, but even then mortality reached 95 %. Seven days later, all adults were dead. As far as progeny production in the treated substrate is concerned, low progeny numbers were found only for *S. oryzae*, while progeny was decreased with the increase of dose (Table 2).

**Bioassay series 2**

In all temperature and r.h. combinations, all *P. truncatus* adults were dead on maize treated with DEA (Table 3). In contrast, mortality was significantly lower on maize treated with PyriSec or Protect-It, at both doses tested. For these two DEs, in most cases, the increase of dose from 500 to 1,500 ppm did not increase adult mortality significantly. Moreover, in PyriSec and Protect-It-treated maize, the increase of temperature and decrease of r.h. increased mortality, but even then, mortality did not reach 60 %.

**Bioassay series 3**

On wheat treated with powder, for the four species tested, all adults were dead, with the exception of *S. oryzae* and *T. castaneum* at 75 ppm, where mortalities were 98 and 95 %, respectively (Table 4). On wheat treated with wettable powder, mortality was lower than previously, but significant differences were noted only for *T. castaneum*. Thus, at 75 ppm, for *C. ferrugineus* and *R. dominica*, all adults were dead at doses =100 ppm, while mortalities were 98 and 96 %, respectively. For *S. oryzae*, a complete (100 %) mortality was noted only at =125 ppm of DEBBM-WP, but at the two lowest doses > 94 % of the exposed adults were dead. Finally, in the case of *T. castaneum*, morality was low on
wheat treated with 75 and 100 ppm, and reached 100% only at 150 ppm. No progeny was found in the treated vials for *C. ferrugineus* and *R. dominica*. For *S. oryzae* and *T. castaneum*, progeny was recorded at 75 and 100 ppm and at 75 ppm, respectively (Table 5).

**Table 1.** Mortality (% ± SE) of adults of *P. truncatus*, *R. dominica* and *S. oryzae* exposed for 7 or 14 d on maize (for *P. truncatus*) or wheat (for *R. dominica* and *S. oryzae*) treated with DEA-P at three dose rates (within each column, means followed by different letters are significantly different; Tukey-Kramer-HSD test at *P* = 0.05; where no letters exist no significant differences were noted; in all cases df = 2, 9).

<table>
<thead>
<tr>
<th>Dose/species</th>
<th>7 d of exposure</th>
<th>14 d of exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P. truncatus</strong></td>
<td><strong>R. dominica</strong></td>
<td><strong>S. oryzae</strong></td>
</tr>
<tr>
<td>75 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
</tr>
<tr>
<td>100 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
</tr>
<tr>
<td>125 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 2.** Progeny production (adults/vial ± SE) of *P. truncatus*, *R. dominica* and *S. oryzae* 65 d after the removal of the parental adults on maize (for *P. truncatus*) or wheat (for *R. dominica* and *S. oryzae*) treated with DEA-P at three dose rates (df = 2, 9).

<table>
<thead>
<tr>
<th>Dose/species</th>
<th>R. dominica</th>
<th>S. oryzae</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ppm</td>
<td>-</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>100 ppm</td>
<td>-</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>125 ppm</td>
<td>-</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>1.28</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Table 3.** Mortality (% ± SE) of *P. truncatus* adults exposed for 7 d on maize treated with DEA-P, PyriSec or Protect-It at two dose rates, at combinations of three temperature levels and two r.h. (within each column, means followed by different letters are significantly different; Tukey-Kramer-HSD test at *P* = 0.05; df = 5, 18).

<table>
<thead>
<tr>
<th>DE formul.</th>
<th>55%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DE formul.</strong></td>
<td><strong>20 °C</strong></td>
<td><strong>25 °C</strong></td>
</tr>
<tr>
<td>DEA</td>
<td>75 ppm</td>
<td>100 ± 0.0a</td>
</tr>
<tr>
<td></td>
<td>150 ppm</td>
<td>100 ± 0.0a</td>
</tr>
<tr>
<td>PyriSec</td>
<td>500 ppm</td>
<td>14.9 ± 3.6b</td>
</tr>
<tr>
<td></td>
<td>1,500 ppm</td>
<td>32.2 ± 9.7c</td>
</tr>
<tr>
<td>Protect-It</td>
<td>500 ppm</td>
<td>14.8 ± 2.5b</td>
</tr>
<tr>
<td></td>
<td>1,500 ppm</td>
<td>27.2 ± 4.2c</td>
</tr>
<tr>
<td>F</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

734
Table 4. Mortality (% ± SE) of adults of four beetle species exposed for 14 d on wheat treated with DEBBM at four dose rates, applied as powder (P) or wettable powder (WP) (within each column, means followed by different letters are significantly different; Tukey-Kramer-HSD test at $P = 0.05$; where no letters exist, no significant differences were noted; in all cases df = 3, 12).

<table>
<thead>
<tr>
<th>Dose (P)/species</th>
<th>C. ferrugineus</th>
<th>R. dominica</th>
<th>S. oryzae</th>
<th>T. castaneum</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>98.5 ± 1.3</td>
<td>95.1 ± 4.4</td>
</tr>
<tr>
<td>100 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
</tr>
<tr>
<td>125 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
</tr>
<tr>
<td>150 ppm</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
<td>100 ± 0.0</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>-</td>
<td>2.45</td>
<td>2.54</td>
</tr>
<tr>
<td>$P$</td>
<td>-</td>
<td>-</td>
<td>0.11</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 5. Progeny production (adults/vial ± SE) of four beetle species on wheat treated with DEBBM at four dose rates, applied as powder (P) or wettable powder (WP) (within each column, means followed by different letters are significantly different; Tukey-Kramer-HSD test at $P = 0.05$; where no letters exist, no significant differences were noted; in all cases df = 3, 12).

<table>
<thead>
<tr>
<th>Dose (P)/species</th>
<th>C. ferrugineus</th>
<th>R. dominica</th>
<th>S. oryzae</th>
<th>T. castaneum</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ppm</td>
<td>0.5 ± 0.3</td>
<td>31.8 ± 7.4a</td>
<td>10.5 ± 4.5a</td>
<td></td>
</tr>
<tr>
<td>100 ppm</td>
<td>0.3 ± 0.3</td>
<td>7.3 ± 3.3b</td>
<td>0.5 ± 0.5b</td>
<td></td>
</tr>
<tr>
<td>125 ppm</td>
<td>0.0 ± 0.0</td>
<td>1.2 ± 0.7c</td>
<td>0.0 ± 0.0b</td>
<td></td>
</tr>
<tr>
<td>150 ppm</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0d</td>
<td>0.0 ± 0.0b</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1.57</td>
<td>10.45</td>
<td>4.05</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>0.24</td>
<td>&lt;0.01</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>
Discussion

Based on the results of the present work, DEA and DEBBM were highly effective against the species tested here, at very low dose rates, in comparison with the doses suggested for most commercially available DE and enhanced DE formulations (Subramanyam and Roesli, 2000). For instance, Athanassiou et al. (2004) and Athanassiou and Kavallieratos (2005) by using PyriSec against adults of *S. oryzae*, *R. dominica* and the confused flour beetle, *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae) found that, for a satisfactory level of mortality, the dose rates should be > 500 ppm.

Among the species tested in the present tests, *C. ferrugineus*, *R. dominica* and *P. truncatus* were the most susceptible, followed by *S. oryzae* and *T. castaneum*. Previous studies with other DEs indicated that adults of *Tribolium* spp. are among the most DE-tolerant species (Arthur, 2000; Fields and Korunic; 2000; Athanassiou et al., 2004, 2005). On the other hand, *S. oryzae* and *R. dominica* are considered more susceptible than *Tribolium* spp. (Arthur, 2000; Fields and Korunic, 2000; Athanassiou et al., 2003, 2004, 2005, Kavallieratos et al., 2005). For instance, Athanassiou et al. (2005), by using the DE SilicoSec, found that *T. confusum* adults could survive at doses that were lethal to *S. oryzae* adults.

Previously published data clearly suggest that *P. truncatus* is also among the most tolerant stored-grain insect species to DEs. Stathers et al. (2002) and Stathers (2003) using Protect-It found that parental survival and progeny production of *P. truncatus* were high, even at doses > 1,000 ppm. Our study indicates that DEA powder is highly effective against this species; in fact, 75 ppm caused 100% mortality and complete progeny production. Since mortality occurred within 7 d of exposure, we can assume that this progeny suppression is a direct consequence of rapid parental mortality. According to preliminary observations in the treated vials, exposed adults were immobilised during the first 1-2 d of exposure; hence we assume that a sufficient proportion of the individuals might had died long before the 7-d count. Consequently, DEA-P can be considered as a very powerful tool for the control of this species, and this finding is of a practical value, since *P. truncatus* is resistant to many traditional grain protectants.

The effect of temperature and relative humidity on the efficacy of DEs has been extensively evaluated in the past (Aldryhim, 1990; Arthur, 2000; Fields and Korunic, 2000; Subramanyam and Roesli, 2000; Vayias and Athanassiou, 2004; Athanassiou et al., 2005). Although data are not always consistent through relative studies, most DEs are more effective at higher temperatures and lower relative humidities. However, this was not clear from the results obtained from the Bioassay series 2 for PyriSec and Protect-It, although some general trends for the effect of temperature and humidity can be drawn. In contrast, the high mortality caused by DEA-P concealed any possible variations at different temperature/humidity combinations. In other words, the insecticidal effect of DEA-P was not affected by temperature and humidity. Also, the mortality levels reported here suggest that doses lower than 75 ppm should be evaluated.

Despite the fact that both formulations (DEA and DEBBM) were effective, there were variations among the species tested. Thus, for *S. oryzae*, DEA-P/ WP was more effective than DEBBM-P/ WP, while for *R. dominica* both formulations were equally effective. Also, the slurry application of these formulations was less effective than the dust application. This trend was more evident at the lowest dose (75 ppm). The use of a slurry formulation may have some advantages during application than dusts. Thus, if liquid applications are planned, the dose rates should be increased in comparison with dusts. Also, the knowledge of the species that is to be controlled should be seriously taken into consideration. For instance, for the control of *T. castaneum*, lower doses of up to 125 ppm of slurry application of DEBBM may not be effective enough, and the highest dose of 150 ppm should be applied.
In summary, the results of this study clearly indicate that combinations of DEs with other natural substances, used at very low concentrations, could make them more acceptable by grain industry and farmers for the protection stored grains. However, prior to the introduction of these formulations into an effective ISGPM, regulatory approval must be obtained for each constituent substance in the formulation, as well as for the mixture.

Acknowledgments

We would like to thank Lisa Redmond and Maike Erb-Brinkmann for providing the Protect-It and PyriSec quantities for experimentation, respectively. We also thank Lise Stengaard Hansen for providing the *P. truncatus* individuals. This work was partially supported by the Hellenic Ministry of Rural Development and Food, Directorate of Plant Protection and by the 34.0108 project (ELKE/Agricultural University of Athens).

References


Athanassiou, C.G., 2006. Toxicity of beta cyfluthrin applied alone or in combination with diatomaceous earth against adults of *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) and *Tribolium confusum* du Val (Coleoptera: Tenebrionidae) on stored wheat. Crop Protection 25, 788-794.


SilicoSec against *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae). Crop Protection 22: 1141-1147.


FDA (Food and Drug Administration, USA), 1995. Specifications for diatomaceous earth as a maximum 2% animal feed additive. 21 CFR Section 573.340.


Mewis, I., Ulrichs, Ch., 2001. Action of amorphous diatomaceous earth against different stages of the stored product pests Tribolium confusum (Coleoptera: Tenebrionidae), Tenebrio molitor (Coleoptera: Tenebrionidae), Sitophilus granarius (Coleoptera: Curculionidae) and Plodia interpunctella (Lepidoptera: Pyralidae). Journal of Stored Products Research 37, 153-164.


Insecticidal sesquiterpene polyol ester from
*Celastrus angulatus*. Phytochemistry 30,
3931-3933.

Winks, R.G., Deschmarchelier, J.M., Russell,

Phosphine and its application to stored
products. Annual Report 1993-1994,
SGRL Stored Grain Research Laboratory,
CSIRO Division of Entomology,
Canberra, Australia.