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Chemical control of stored product insects with fumigants and residual treatments

J. Larry Zettler[a,]*, Frank H. Arthur[b]

[a]USDA, ARS, Horticultural Crops Research Laboratory, 2021 S Peach Avenue, Fresno, CA 93727 USA

[b]USDA, ARS, US Grain Marketing Research and Production Center, Manhattan, KS 66502 USA

Abstract

Integrated pest management (IPM) programs that eliminate infestations and prevent economic damage in raw commodities, food storage facilities, and milling and processing plants typically involve chemicals. They are preferred because they are often the cheapest and most efficient strategies available. When evaluating pesticides, it is important to recognize the biological and environmental factors that can affect pesticide efficacy so the insecticide can be effectively used in control programs. We illustrate these concepts with data from research studies with cyfluthrin, a pyrethroid insecticide used as a residual surface treatment, and with data from developmental research with new fumigants. These chemical pesticides and others like them could have specific applications and strategies in an IPM program for post harvest pests well into the 21st Century. Published by Elsevier Science Ltd.

Keywords: Fumigation; Insecticides; Surface treatments; Environment; Pest control; IPM

1. Introduction

Chemical control strategies have evolved through the years, resulting in fewer but safer, more specific, and environmentally friendly chemicals. As specific pesticides are lost, new ones providing protection at lower doses are being registered. There is renewed emphasis on chemicals with little or no mammalian toxicity (i.e. IGRs, insect pathogens, natural products, inert dusts). Advances in application methods allow precise targeting, reducing active ingredients and frequency of applications. Health, environmental, legislative and pest resistance concerns are the selective mechanisms driving this evolutionary change (Arthur, 1996).

A developmental program for chemical pesticides should involve a through examination of the physical, biological and environmental factors that can affect pesticide toxicity. These factors include, but are not limited to, the actual application rate, specific insecticide and formulation, the time interval insects are exposed to the pesticide, surface substrate, target insect species, and environmental conditions when insects are exposed. For example, cyfluthrin is a residual pyrethroid insecticide that is used as a general surface treatment in milling and processing plants. Several studies have been conducted whereby toxicity has been evaluated in relation to formulation, species specificity, application rate and exposure interval. Similarly, efficacies of carbonyl sulfide, methyl iodide, and sulfuryl fluoride (Vikane®), new fumigants that have been targeted as potential replacements for methyl bromide, can vary depending on specific parameters. Specific results from our research programs are reviewed and discussed in relation to practical applicability for control programs.

2. Development of residual insecticides — studies with cyfluthrin

Cyfluthrin (Tempo®) is labeled in the United States as a residual surface treatment for interior surfaces. It is available as an emulsifiable concentrate (EC) and wettable powder (WP), and can be applied at 2 label rates; 8 or 16 ml of 23% [AI] EC or 9.5 and 19.0 g of 20% [AI] WP/94 m^2. There are several biological and physical factors that influence the residual effectiveness of cyfluthrin (Arthur, 1999). These factors should be considered when planning research projects with residual insecticides or developing insect management plans for flour mills, processing plants, and food warehouses. Some may be

* Corresponding author. Tel.: 1-559-453-3023; fax: 1-559-453-3088.
E-mail address: lzetter@qnis.net (J.L. Zettler).

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unique to cyfluthrin, but all are applicable for practical IPM in storage facilities.

2.1. Formulation

Ready-mix concrete was treated with the maximum label rates of the EC (16 ml/94 m^2) and WP (19.0 g/94 m^2) formulations of cyfluthrin (Arthur, 1994a). Bioassays were conducted at weekly intervals for 14 weeks by confining adults of red flour beetle, *Tribolium castaneum* Herbst, and confused flour beetle, *T. confusum* Jacquelin du Val, on the treated concrete at regular post-treatment intervals. As the residues aged, survival of both *T. castaneum* and *T. confusum* steadily increased on concrete treated with the EC, in contrast to survival on concrete treated with the WP. Survival of *T. castaneum* and *T. confusum* was 75.0 and 57.5%, respectively, for bioassays conducted 6 weeks after the concrete had been treated with the EC. In contrast, less than 3% survived when they were exposed to the 6 week old WP residue on concrete. At the end of the 14 week test, survival was 100% for both species exposed to the EC, while survival on the concrete treated with the WP was 25% for *T. castaneum* and 20% for *T. confusum*. The results clearly indicate that the residual efficacy of the WP formulation is superior to that of the EC formulation on concrete surfaces.

2.2. Species variability

Concrete was treated with the WP at both label rates, and *T. castaneum* and *T. confusum* were exposed for 1 and 2 h at regular post-treatment intervals (Arthur, 1998a,b). Survival of *T. castaneum* was greater than survival of *T. confusum* at both the 1- and 2-h exposure intervals for all residual bioassays except at 6 weeks, indicating that *T. confusum* was more susceptible than *T. castaneum* to cyfluthrin WP. If both species are present in the same environment, residual applications should be directed to control *T. castaneum*, the least susceptible of the two species. However, it is important to note that these results showing the relative susceptibilities of *T. castaneum* and *T. confusum* to cyfluthrin WP may not be applicable for other insecticides. Some research reports state that *T. castaneum* was more susceptible to a particular insecticide (Ardley, 1976; LaHue, 1977; Bengston et al., 1980; Arthur, 1997), while in other trials either the reverse was stated (Arthur and Gillenwater, 1990; Arthur and Zettler, 1991, 1992; Arthur, 1998b), or there was no difference in susceptibility (Arthur, 1994a,b)

2.3. Application rate

As residues from a contact insecticide age on a treated surface they break down and become less effective. One of the important considerations in evaluating the residual control of a contact insecticide is the application rate, because increasing the application rate will normally increase the residual effectiveness of that insecticide. This is demonstrated by comparing survival when *T. castaneum* was exposed for 1 and 2 h on concrete treated with both label rates of cyfluthrin WP (Arthur, 1998a). In those tests, survival of *T. castaneum* exposed for 1 h at 18 weeks post treatment was 90 and 10%, respectively, on concrete treated with 9.5 and 19.0 g per m^2. No beetles survived when exposed for 2 h at 18 weeks post treatment on concrete treated with 19.0 g per m^2. These results indicate that when cyfluthrin WP is used to control *T. castaneum*, several applications of the low label rate will be necessary to achieve the same degree of residual control as one application of the high label rate.

2.4. Exposure interval

It is often difficult to eradicate infestations inside mills and storage facilities because insects spend much of their time in protected refuges, and will have limited contact with insecticides applied as residual surface treatments (Pinniger, 1974; Barson, 1991). This is especially important when insecticides are specifically targeted to selected sites within the facility instead of being broadcast over a large area. Insects such as *T. castaneum* may encounter a treated surface, then leave that surface before it is knocked down by the residues. The actual time that *T. castaneum* individuals are exposed on a treated surface before they can be knocked down is an important mortality factor that should be considered in addition to the application rate. The concept of exposure interval as a dosage factor is illustrated using data from Arthur (1998c). *T. castaneum* were exposed for different time periods at selected post treatment intervals on concrete treated with 9.5 g/m^2 cyfluthrin WP, removed from the treated surface, and held for one week. Survival decreased as exposure interval increased, and as the residues aged, survival increased for a given exposure interval.

3. Development of fumigants

While new residual pesticides continue to become available, new fumigants have not been forthcoming. At least 16 chemicals have been labeled as fumigants for postharvest IPM programs and quarantine treatments; of these, only methyl bromide and phosphine remain in use today. Because of regulatory (Anon, 1997) environmental (EPA, 1993), human health (Garry et al., 1989, 1990) and pest resistance (Zettler et al., 1989; Zettler and Cuperus, 1990; Zettler, 1991) concerns, both of these fumigants are threatened. Because of this, there is a renewed interest in developing new, alternative fumigants that will be effective in IPM programs. Three fumigants were identified for evaluation against various postharvest and quarantine insect pests.

3.1. Carbonyl sulfide

This chemical was recently patented as a fumigant for control of insects and mites in post harvest commodities (Banks et al., 1993) and registration as a grain protectant is pending in Australia. It has good penetrating action and is toxic to a variety of insect pests (Desmarchelier, 1994; Weller, 1999; Xianchang et al., 1999). In our tests (Zettler et al., 1997), carbonyl sulfide was toxic at fairly low doses in 24 h fumigations to a variety of post harvest pests: 5th instars of *Amyelois transitella* walker (navel orangeworm) and adults of *T. confusum*, *Lasioderma serricorne* (F.) (cigarette beetle), *Carpophilus hemipterus* (L.) (driedfruit beetle) and *Oryzaephilus surinamensis* (L) (sawtooth grain beetle). Adult beetles were more tolerant than were 5th instars of *A. transitella*. Of the 4 species of beetles, *T. confusum* was the most tolerant with an LC_{50} of 11.38 mg/L and LC_{95} of 16.74 mg/L.

Because *T. confusum* was the most tolerant species tested, carbonyl sulfide toxicity to all its life stages was evaluated. Of these, the eggs were most tolerant ($LC_{50} = 29.67$ mg/L), followed by the pupae ($LC_{50} = 16.08$ mg/L), and the adults were the least tolerant. There appears to be a wide species variability in the susceptibility of various pest populations to carbonyl sulfide (Desmarchelier, 1994; Plarre and Reichmuth, 1997) such that toxicity must be empirically tested rather than extrapolating data to other species or populations.

Walnuts infested with diapausing larvae of codling moth, *Cydia pomonella* (L), were fumigated for 24 h with carbonyl sulfide (Leesch and Zettler, 2000) under a standard methyl bromide fumigation protocol (Anon, 1976). By measuring carbonyl sulfide concentrations at different times during the fumigation, it was determined that about half of the fumigant was sorbed by the walnuts compared with about 80% for methyl bromide. Bioassays from these disinfestation trials showed that the minimum effective dose for control of diapausing larvae of *C. pomonella* is 40 mg/L during 24 h exposure at 15.6°C under normal atmospheric pressure (NAP) ($C \times T = 738$ mg/L).

Exposure times shorter than 12 h for carbonyl sulfide fumigation may not be sufficient to control some insects. For example, 8 h laboratory fumigations of the Mediterranean fruit fly (medfly), *Ceratitis capitata* Wiedemann, were insufficient in quarantine treatments for control of medfly in lemons (Obenland et al., 1998). It was only at 12 h that we obtained complete control at reasonable doses of carbonyl sulfide. Indeed, 48 h appears to be the minimum threshold exposure time for maximizing effects of carbonyl sulfide dosage (L. Zettler, unpublished data; Weller, 1999).

During these quarantine fumigations of fresh fruit (lemons) to control *C. capitata*, we determined that a 12 h fumigation was sufficient to control this pest but the high dose ($C \times T = 430$ mgh/L) produced slight peel injury. Longer exposures led to increasing rind injury and persisting off-odors in juice (Obenland et al., 1998). Even in our disinfestation tests with walnuts, there was a distinct off-odor in the walnuts immediately following fumigation. After 24 h aeration, the off-odor had dissipated from both the fresh fruit and the nuts. Permanent off-odors have been reported from both bread and rice made from fumigated wheat and paddy when these grains had been milled and baked 6 months following fumigation (Xianchang et al., 1999). Thus, carbonyl sulfide probably will not be a viable quarantine treatment where short exposures of several hours are required. On the other hand. commodity disinfestation treatments are indeed potential, viable uses of carbonyl sulfide, particularly if 2 or more days of exposure time are acceptable. Additional laboratory tests are needed to evaluate its influence on organoleptic properties and potential residues on commodities.

3.2. Methyl iodide

This chemical has recently been patented as a preplant soil fumigant for control of a broad range of organisms including nematodes, fungi, and weeds (Grech et al., 1996) and the patent has subsequently been expanded to include structural fumigation against termites and wood rotting fungi (Ohr et al., 1998). Methyl iodide's potential as a fumigant for postharvest pest control has been known for more than 60 yr (Lindgren, 1938). However, economic considerations at that time precluded its development in favor of the less-expensive methyl bromide.

Methyl iodide was toxic in 3 h fumigations to diapausing larvae of *C. pomonella* and to all life stages of *T. confusum* (Zettler et al., 1999). Unlike carbonyl sulfide, methyl iodide was most toxic to eggs and least toxic to adults of *T. confusum*. Indeed, eggs were about 38 times more susceptible than adults at the LC_{50}. In comparison with methyl bromide, methyl iodide was only slightly less toxic to adults (Tebbets et al., 1986). In addition, it was more toxic to eggs than was methyl bromide.

Disinfestation fumigations of *C. pomonella*-infested walnuts with the methyl bromide fumigation protocol (Leesch and Zettler, 2000) showed that walnuts were much more sorptive of methyl iodide (90%) than carbonyl sulfide (50%) or methyl bromide (80%). Bioassays showed that the minimum effective dose for control of diapausing larvae of *C. pomonella* is 32 mg/L during 24 h exposure at 15.6°C under NAP ($C \times T = 146$ mgh/L). Methyl iodide could prove valuable as a quarantine treatment for *C. pomonella* in fresh fruits (Yokoyama et al., 1987) and as a rapid commodity disinfestation treatment of 24 h or less. Its high degree of sorption may preclude longer exposure times, however. The fact that the US Environmental Protection Agency has listed methyl iodide as a possible human carcinogen (EPA, 1998) could preclude registration in the US, particularly in California where it is listed as a compound known to cause cancer (CalEPA, 1996).

3.3. Sulfuryl fluoride

Sulfuryl fluoride has been registered in the US for structural fumigations against termites, wood boring beetles and pantry pests for nearly 40 yr (Stewart, 1956; Schneider, 1993) and has been used to fumigate buildings, construction materials, furnishings, nonedible commodities, and vehicles including rail cars for a variety of destructive pests. It has not been used in food premises because of the lack of food tolerances. Sulfuryl fluoride has the lowest boiling point of any fumigant (-55.2°C) and is thus a gas under all practical fumigation conditions. Sulfuryl fluoride is quite toxic to the active life stages of insects whereas the egg stage is substantially more tolerant (Thoms and Scheffrahn, 1994; Bell and Savvidou, 1999; Bell et al., 1999; Schneider and Hartsell, 1999).

Tests (Zettler et al., 1999) have shown similar results for *C. pomonella*. The diapausing larvae of *C. pomonella*, a life stage relatively tolerant to some fumigants, is considerably more susceptible than the egg stage and sulfuryl fluoride is toxic to the diapausing larvae at relatively low dosages. In 2 h exposures, diapausing larvae fumigated under NAP showed an LC_{95} of 51.51 mg/l, but vacuum (VAC) fumigation (100 mm Hg) reduced the LC values by about half to 28.03 mg/L. Earlier studies had shown similar reductions in tolerance to methyl bromide when *C. pomonella* was fumigated under VAC (Tebbets et al., 1986). The $LC_{99.9}$ for sulfuryl fluoride in VAC fumigation of the diapausing larvae was 36 mg/L, well below the standard methyl bromide quarantine treatment dose of 56 mg/L. As expected, eggs of *C. pomonella* were more tolerant to sulfuryl fluoride when compared with larvae. However, there was only about a seven-fold difference in tolerance between larvae and eggs at the LC_{95}. Two- and three-day-old eggs were about equally susceptible but were about two-fold more tolerant than one-day-old eggs. Bell and Savvidou (1999) also demonstrated that eggs of *Ephestia kuehniella* (Mediterranean flour moth) showed a range of susceptibility to sulfuryl fluoride, and concluded that the most tolerant ages were one- to two-day-old eggs followed by two- to three-day-old eggs.

VAC fumigation had no effect on reducing *C. pomonella* egg tolerance to sulfuryl fluoride. The $LC_{99.9}$ for the 2-day-old eggs, the most tolerant stage under VAC fumigation, was more than 880 mg/L, an impractical quarantine dose. Though VAC fumigation had no effect, temperature can have a dramatic effect on egg susceptibility to sulfuryl fluoride. Eggs of *E. kuehniella* fumigated at 25°C were killed by less than one-third the dose required at 15°C (Bell and Savvidou, 1999). In addition, extending the fumigation time from 24 to 48 h greatly improves sulfuryl fluoride toxicity to postharvest pests (Reichmuth et al., 1999; Schneider and Hartsell, 1999; Williams and Schneider, 1999).

Disinfestation fumigations of *C. pomonella*-infested walnuts with the methyl bromide fumigation protocol showed that sulfuryl fluoride was highly toxic to the diapausing larvae; the minimum effective dose was 8 mg/L ($C \times T = 217$ mgh/L) compared with the methyl bromide quarantine dose of 56 mg/L (Leesch and Zettler, 2000). Also, sorption was very low (30%) compared with that of methyl bromide (80%), methyl iodide (90%), or carbonyl sulfide (50%). In addition, it has been shown that sorption of sulfuryl fluoride by wheat, corn and soybean was 30% (Goughan et al., 1999). Thus, sulfuryl fluoride demonstrates good penetrating action and any residues following fumigation are likely to be minimal.

In addition to a general commodity disinfestation treatment, sulfuryl fluoride has potential as a quarantine treatment for dried fruits and nuts where control of the tolerant egg stage is not a consideration, i.e., *C. pomonella* on walnuts and *A. transitella* on almonds (Curtis et al., 1984). The fact that sulfuryl fluoride has registrations or is licensed for use in several countries is an important consideration in expanding the use of sulfuryl fluoride in postharvest control technology.

4. Summary

When residual insecticides such as cyfluthrin are applied as residual surface treatments, efficacy will be dependent on a variety of physical and biological factors. Specific results from one pesticide may not be applicable to others, especially when insecticides vary in class or mode of action, and these same factors should be considered when evaluating insecticides for residual control on treated surfaces. The concept of exposure interval as dosage factor should be given special consideration, because in actual field situations insects may have the opportunity to escape treated surfaces. Most stored-product beetles are mobile and will rarely be continuously exposed to insecticidal surface treatments.

Several fumigants have potential to replace or supplement some methyl bromide and phosphine treatments presently in use. Carbonyl sulfide is toxic to a variety of postharvest insect species and life stages and would be effective as a disinfestation treatment of 2 or more days exposure. Presently, registration of carbonyl sulfide as a grain fumigant is being sought in Australia. Methyl iodide is comparable to methyl bromide in toxicity at very short exposure times (i.e., hours). It is patented as a structural and soil fumigant and shows potential for quarantine treatments against *C. pomonella* and as a rapid disinfestation treatment of 24 h or less. High sorption rates could lead to unacceptable residues, however. The fact that it is listed by the US EPA as a possible human carcinogen may be problematic for registration as a commodity or quarantine treatment. Sulfuryl fluoride is very toxic to active life stages of postharvest pests, but higher doses or longer exposure periods are required to kill eggs compared with other life stages. Dosages for active life stages compare with those of methyl bromide at very short exposure times. It is presently registered as a structural fumigant and could be effective as a general commodity disinfestation treatment and as a quarantine treatment.

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