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REVIEW

Aerosols and contact insecticides as alternatives to methyl bromide in flour mills, food production facilities, and food warehouses

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Abstract The fumigant methyl bromide (MB) is being phased out of production and usage to control stored-product insects in flour and rice mills, as well as feed and food production plants, in the United States and other developed countries throughout the world. A phase-out schedule has also been established for undeveloped counties under a delayed timeline compared to the one established for developed countries. Whole-plant alternatives to MB treatment, such as the fumigant sulfuryl fluoride and heat, can be used in place of MB, but they have some limitations as well, which will be briefly discussed in this review. Hence, residual surface treatments with contact insecticides and insect growth regulators and aerosol applications are receiving increased attention for incorporation into management programs that historically relied on MB fumigations. This review will focus on recent research with contact insecticides and aerosols for controlling stored-product insects in structures and how they can be viewed as options for control to alleviate concerns regarding the phase-out and reduced availability of MB for structural fumigations. A brief discussion of emerging pest species or groups, and how they can be controlled with surface treatments and aerosols, is also included in the review.

Keywords Methyl bromide · Alternatives · Aerosols · Contact insecticides

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Introduction

The fumigant methyl bromide (MB) has been identified as an ozone-depleting agent, and under the terms of the 1991 Clean Air Act passed by the United States (US) Congress, and the Montreal Protocol (Fields and White 2002; Schneider et al. 2003) an international agreement was signed by a number of countries. A schedule was established for the withdrawal of MB as a soil fumigant and as a structural fumigant for mills, processing plants, and warehouse facilities. This timeline specified that the use of MB was to be ceased in developed countries by 2005 and undeveloped countries by 2015. Exemptions were made for all quarantine uses and a process was established where groups could receive critical use exemptions (CUEs) (Fields and White 2002; Schneider et al. 2003). As a result of the phase-out of MB, there is an increased interest and research into alternatives to MB for structural treatments to control stored-product insects, including new fumigants (Cryer 2008; Chayaprasert et al. 2009), heat treatment of mills and processing plants (Yu et al. 2011; Subramanyam et al. 2011), and integrated pest management approaches (IPM), which can include monitoring for insects and the use of contact insecticides and aerosol treatments (Campbell et al. 2010a, b; Nansen and Meikle 2011). Whole-plant structural treatments will be briefly discussed below in terms of their limitations and the resulting need for research with contact insecticides and aerosols. Most of the cited research is concerned with insect pest management in milling and processing facilities.

Environmental considerations for structural management of stored-product insects

A number of recent studies have documented the presence of stored-product insects in and around wheat flour mills, feed mills, processing plants, and warehousing facilities (Doud and Phillips 2000; Campbell and Arbogast 2004; Campbell and Mullen 2004; Toews et al. 2005b; Arthur and Campbell 2008; Larson et al. 2008; Campbell et al. 2010a, b; Semeao et al. 2012). However, much of our current knowledge regarding stored-product insects as interior structural pests is based on studies in flour mills, feed mills, or food warehouses. Stored-product insects are also associated with retail grocery stores (Platt et al. 1998; Arbogast et al. 2000) and specialty stores containing pet food products (Roesli et al. 2003), but there is less published data regarding pest populations in those environments compared to those in flour mills and food warehouses.

Regardless of the specific storage environment, outside pest populations can exert an infestation pressure on the structure depending on the specific species and the overall climatic conditions at the site. In one flour mill, inside infestations of the red flour beetle, *Tribolium castaneum* (Herbst), cycled inside the site, while infestations of Indianmeal moth, *Plodia interpunctella* (Hübner), primarily originated from outside the facility (Campbell and Arbogast 2004). There were also specific areas within flour mills where *T. castaneum* can become concentrated (Semeao et al. 2011). A survey of feed mills in the Midwestern US also showed abundant populations of *T. castaneum* inside the facilities (Larson et al. 2008). Field studies have also documented abundant populations of the warehouse beetle, *Trogoderma variable* Ballion, outside of storage and milling facilities with variation in the associated inside populations (Campbell and Arbogast 2004; Campbell and Mullen 2004).

Whole-plant alternatives to methyl bromide—some limitations

Whole-plant treatments that are similar to MB in terms of their ability to disperse and penetrate throughout and within structures are modified atmospheres, alternative fumigants, and heat treatments. Modified atmospheres have been used to control insect pests in stored grains, but they have not been widely adopted by the milling industry in the US for various reasons including perceived cost, sealing required for effectiveness, and expertise required for commercial applications. Because of issues with corrosion of metals and electrical equipment, phosphine has not been extensively used as a structural fumigant (Bell 2000), but new formulations with reduced corrosive effects may alleviate some of these concerns (Fields and White 2002). The current alternative fumigant to MB is sulfuryl fluoride (SF), registered as Profume (Dow AgroSciences, Indianapoils, IN, USA) in the US for commodity and structural fumigations. There are several published field studies concerning physical characteristics or efficacy of SF (Small 2007; Cryer 2008; Chayaprasert et al. 2009; Campbell et al. 2010a, b; Tsai et al. 2011); however, documentation of specific differences between MB and SF are difficult because exact repetition of test conditions in field sites is difficult. The concerns regarding relative efficacy of SF for control of eggs and the cost compared to MB has impeded widespread adoption by the milling industry in the US, and a recent publication regarding the impact of SF emissions on global climate change has also fostered debate (Sulbaek Andersen et al. 2009).

The use of high temperature as a structural pest control tactic for flour mills has received increased attention by the milling industry (Boina et al. 2008; Yu et al. 2011; Opit et al. 2011; Subramanyam et al. 2011). The technology for conducting heat treatments has been improved and costs have decreased relative to those of fumigation with MB. Whole-plant treatments involving fumigations or heat are expensive because of application costs and the economic consequences associated with shut-down time and production loss (Adam et al. 2010). Milling and processing facilities also contain refugial areas where insect pest populations can persist and may even escape exposure to whole-plant treatments (Toews et al. 2009; Campbell et al. 2010a, b). While fumigants and heat treatment may penetrate into some of these hidden refugial areas within a milling facility where stored-product insects persist, they do not provide residual control.

Residual surface treatments and aerosols as fumigant alternatives

Residual surface treatments and aerosols can perhaps be best considered as control options that can be done to reduce reliance on whole-plant fumigations with MB. They can reduce the need for fumigation through improved insect pest management, but may not necessarily replace all fumigations or whole-plant treatments. For the purposes of this review, residual surface treatments will include those insecticides that can be applied to a large broad flooring area of a mill, warehouse, or processing facility. In the US, the labels for these insecticides will specify their use as a "general surface treatment." This is a different wording from the label language used for insecticides that can be applied on a more limited basis as spot or crack and crevice treatment. In that instance, the spots will be restricted to a defined area, for example 0.09 m^2 (2 ft^2) with a restriction on the total area that can be treated in this manner, or the wording will state that the spray must be directed inside the crack or crevice. Surface treatments can be residual insecticides that will control all life stages, or insect growth regulators (IGRs) that affect immature insects. These will be discussed in turn.

There are a number of factors that influence the toxicity of residual surface treatments, but perhaps one of the most important is the type of surface that will be treated. In general, residual efficacy is greatest on non-porous surfaces such as metal, tile or glass, less on concrete or similar material, and least on various types of wood (Arthur 2009). Bibliographic citations of older literature are given in a number of recent papers (Toews et al. 2003; Arthur 2008a; Arthur et al. 2009; Wijayaratne et al. 2012a, b; Boina and Subramanyam 2012). There are exceptions to these general listings, and as Toews et al. (2003) discuss in detail, there is considerable variation regarding the descriptions of concrete or wood used in bioassay tests with stored-product insects.

The type of insecticidal formulation may also be important, for example, studies with the emulsifiable concentrate (ECs) and wettable powder (WP) formulations showed less residual efficacy of the EC compared to the WP (Arthur 1994). Reviews of previous studies showed that ECs tend to penetrate into concrete more than WPs, thus reducing residual efficacy (Arthur 1994, 2008a; Wijayaratne et al. 2012b). Although a number of surfaces have been evaluated for residual efficacy, perhaps the most relevant flooring surfaces to segments of the stored-product industry considering alternatives to MB are concrete or some type of floor tile covering over the concrete. Sealing concrete before insecticide application may reduce absorption into the concrete, thereby increasing residual efficacy (Arthur 1994). Sealing or painting wood may have similar effects in retarding penetration of insecticidal sprays into concrete (Wijayaratne et al. 2012b). However, there has been little recent research of absorption characteristics of newer commercial classes of insecticides such as neo-nicotenoids and pyrolles compared to other classes of insecticides.

Temperature and relative humidity may also affect efficacy of insecticidal surface treatments. In general, efficacy of synergized pyrethrins and most pyrethroids is negatively correlated with temperature, including cyfluthrin, which is commonly used in the US as a residual contact insecticide (Arthur 1999). In contrast, efficacy of most organophosphates, diatomaceous earth (DE), and the insecticidal pyrolle chlorfenapyr is positively correlated with temperature (Kavallieratos et al. 2011). With conventional insecticides, relative humidity (RH) has mixed effects on efficacy, while efficacy of DE usually declines as RH increases (Golob 1997; Korunic 1998; Arthur 2000c).

The presence of food material, either during or after exposure to a contact insecticide, is also an important factor in that providing the adults with food can increase survival of exposed adults. Studies in which adult *Tribolium confusum* (Jacqueline DuVal) or *T. castaneum* were provided with food during or after exposure greatly reduced residual efficacy (Arthur 2000a, b, 2008a, b). Similar results occurred in studies with the above species exposed to different formulations of diatomaceous earth (DE) (Arthur 2000c). This factor is extremely important in the milling, processing, and feed production industries, as residual accumulations and spillage provide numerous harborage sites where infestations can persist (Toews et al. 2009; Campbell et al. 2010a, b). In controlled environment studies, perimeter banding treatments of cyfluthrin did not reduce populations of *T. castaneum* in residual refuges, and the presence of these refuges limited the effectiveness of the insecticide (Toews et al. 2005a, b, 2009).

The other broad general category of surface treatments used to control insect pests inside structures is IGRs. In the US, the three registered IGRs are hydroprene, methoprene, and pyriproxfen. Hydroprene is the most volatile of the three and generally provides less residual control than either methoprene or pyriproxyfen (Arthur et al. 2009). The characteristics of the treated surface and insecticidal formulations described above will also apply to the IGRs (Arthur and Fontenot 2012). However, because IGRs are directed toward the immature stages of insects, the presence of food material is necessary to evaluate the effectiveness of an IGR. Many earlier studies evaluated IGRs by incorporating them into the diet of the insect (Oberlander et al. 1997), which might not be a realistic method to simulate field exposure in relation to stored-product environments. In recent studies with late-instar *T. castaneum* exposed on different surfaces, when flour is placed on that treated surface, some of the insecticide is being absorbed from the treated surface by the flour, and hence the larvae come into contact with the IGR through feeding and/or movement (Athanassiou et al. 2011b). There is also evidence that exposure of late-instar *Tribolium* on concrete treated with flour, along with a food source, will produce sublethal effects in adults such as reduced fecundity (Wijayaratne et al. 2012a).

One final characteristic to consider regarding efficacy of surface treatment is variation in susceptibility of stored-product insects to various insecticides. Generally, *T. castaneum* and *T. confusum* tend to be more difficult to kill than other stored-product beetles that are commonly found in interior structures (Arthur 2008a). Regarding these two species, they tend to also vary in susceptibility and it is not consistent between classes of insecticides. For example, *T. confusum* is more susceptible to cyfluthrin and chlorfenapyr compared to *T. castaneum* (Arthur 2000a, b, 2008a), while the reverse is true for pyrethrins (Arthur 2008b), IGRs (Arthur and Hoernemann 2004; Arthur et al. 2009) and DE (Arthur 2000c).

Aerosols as fumigant alternatives

Aerosols are liquid insecticide formulations that are mechanically atomized and dispensed as small particle sizes (5 to 50 μ) (Peckman and Arthur 2005). They are also known as "mists" or "fogs," but for the purposes of this review the term "aerosols" is used. They can be dispensed from fixed or portable application equipment, and are generally applied on a volume basis within an interior structure. Newer application systems will incorporate formulations comprising an oil-based carrier and a propellant such as CO_2 to aid in aerosol dispersion. The insecticide is dispensed and the particles drift downward to the flooring surface. In the US, there are currently a number of commercial manufacturers that have their own proprietary aerosol dispensing systems and formulations (Arthur 2010). Aerosols are not fumigants, they do not penetrate through material, and should not be confused with fumigants. A more complete description regarding the characteristics of aerosols, how they are dispensed, and application equipment can be found in Peckman and Arthur (2005) and in Boina and Subramanyam (2012).

There was considerable research with laboratory and field evaluations of aerosols in the 1960s and 1970s with the organophosphate dichlorvos and other insecticides (Boina and Subramanyam 2012), and with the impending phase-out of MB there is renewed interest in aerosols for control of stored-product insects in flour mills and food production facilities. Tests with newer formulations and dispensing equipment show excellent dispersion of aerosols in field situations (Arthur and Campbell 2008; Arthur 2008b).

Some of the factors that affect efficacy of insecticidal surface treatments also affect aerosol efficacy. The presence of food material, either during or after exposure to pyrethrin aerosol, will greatly increase survival of exposed adult *T. castanteum* and *T. confusum*, and generally this effect is more pronounced in *T. confusum* because it appears to be the more tolerant of the two species (Arthur 2008b). Evaluations with aerosol formulations of the IGR methoprene show that larval *T. castaneum* are more susceptible than larval *T. confusum* to methoprene as well (Arthur and Fontenot 2012; Sutton et al. 2011). Applications of either pyrethrin or pyrethroids along with methoprene are becoming more common in the US. Immature *Tribolium* are easier to kill with aerosols compared to adults, and there is some evidence of an additive effect on *Tribolium* larvae when pyrethrins and methoprene are used in combination (Sutton et al. 2011). In the tests cited above, larvae of *T. confusum* were exposed to different packaging surfaces or to flour treated with 1 % active ingredient (AI) pyrethrin plus methoprene or 3 % AI pyrethrin plus methoprene. The percentage of adult emergence was lower with the increased AI pyrethrin even though the amount of methoprene remained the same.

The IGR component of the mixture, for example methoprene, is added to the insecticidal mixture to increase residual efficacy. Synergized pyrethrins dissipate rapidly and there is little control of adults beyond initial exposure (Arthur 2010). Methoprene has excellent residual efficacy as an aerosol, especially when the target species is *T. castaneum*. In field studies where different packaging surfaces were treated with methoprene, there was complete adult suppression of exposed larvae of *T. castaneum* for a 16-week residual testing period (Sutton et al. 2011). Suppression of adult emergence from exposed larvae of *T. confusum* depended on the AI rate of pyrethrin and the individual packaging surface (Sutton et al. 2011).

The structural components within a flour mill, and the presence of refugial areas containing food material, as discussed in detail in Campbell et al. (2010a, b), present barriers to aerosol dispersion and efficacy. The presence of food material led to reduced efficacy of pyrethrin and esfenvalerate aerosols in a controlled environment though there was evidence of dispersal of the aerosol into the areas containing food refuges (Toews et al. 2009, 2010). Refugial areas within a mill may be in a site that could be considered obstructed or hidden to aerosol penetration and allow populations to persist and develop. Aerosols primarily affect that portion of the population that is active or moving so that they are exposed; hence, populations in hidden areas might not be exposed to the aerosol, and in addition the presence of food may mitigate effects of exposure. This is an area where new field research could provide additional data to more properly assess aerosol efficacy.

Most of the more recent studies cited and discussed above have involved either *Tribolium castaneum* or *T. confusum*, but a series of recent studies has also evaluated aerosols for control of *P. interpunctella*, perhaps the most important pest of stored processed food in the US (Mohandass et al. 2007). Although most of the historical use of MB in the US, as well as the current CUE exemptions for the flour and rice milling industry, was and is focused on either *T. castaneum* or *T. confusum* as the primary pests. However, in some situations *P. interpunctella* may be the main pest of interest. When late-instars of *P. interpunctella* are exposed to the IGR methoprene applied at labeled rates, as either an aerosol or as a surface treatment, adult emergence is greatly reduced relative to untreated controls (Jenson et al. 2009, 2010a, b). In simulated field studies with either synergized pyrethrins or the pyrethroid esfenvalerate applied as an aerosol, the majority of late-instar *P. interpunctella* exposed directly to the aerosol was able to complete emergence to the adult stage (Jenson et al. 2010a, b). Economic analysis of the cost of aerosol application showed that the addition of the methoprene IGR to the insecticide and oil carrier formulation contributed little to the overall cost, yet greatly increased aerosol efficacy (Jenson et al. 2010a, b).

Emerging species in relation to contact insecticides and aerosols

Much of our research knowledge concerning stored-product insects is with the more common and economically important species from a historical perspective. However, there are certain groups of insects that may be considered as emerging pests in stored products. As these emerging pests become targets for management through surface treatments and aerosols, some of their inherent characteristics in relation to biology and response to environmental stimuli may be important in overall pest management.

The first group of insects to consider as emerging pests is psocids. There are a number of recent publications documenting the increasing incidence of psocids in stored products, their economic importance, response to environmental factors, economic effects, and even new species records (Opit and Throne 2009; Opit et al. 2012). They have a high reproductive potential, and a generation can be completed in 21 days at favorable conditions (Opit et al. 2010). There is ample evidence that psocids are much harder to kill with conventional neurotoxic insecticides compared to stored-product beetles (Collins et al. 2000; Guedes et al. 2008; Athanassiou et al. 2009); IGRs, DE, and the biological pesticide Spinosad as well have less efficacy toward psocids compared to beetles (Athanassiou et al. 2011a). Individual psocid species will also vary in their susceptibility to insecticides. *Liposcelis bostrychophila* (Badonnel) is considered to be a species susceptible to contact insecticides, while *Liposcelis paeta* Pearman was considered to be a comparatively tolerant species (Athanassiou et al. 2009). Results with aerosols have also shown that *L. bostrychophila* is generally more susceptible than *L. paeta* (Opit et al. 2012).

Another broad group of pests that can infest a variety of stored products are members of the family Dermestidae. Species, such as *T. variable*, are detected in trapping studies (Campbell and Mullen 2004; Arthur and Campbell 2008), but there are few studies directly comparing insecticidal susceptibility of *T. variable* to flour beetles. Similarly, the hide beetle, *Dermestes maculatus* (DeGeer), can also infest stored products, but there are no recent studies evaluating susceptibility of *D. maculatus* to insecticides. Lord (2011) conducted studies with three entomopathogenic fungi on concrete, plastic, leather, and wood surfaces, and found that persistence of conidia of all three fungi was lowest on the wood surface resulting in reduced efficacy of the fungi toward *D. maculatus*. There are no recent studies evaluating residual surface treatments or aerosols as controls for *D. maculatus*. Perhaps the most important Dermestid in relation to stored products is the Khapra beetle *Trogoderma granarium* (Everts), which is the only stored-product pest that is quarantined in the US. Many other countries also include this species in their quarantine regulations. Currently, MB for quarantine treatment will be continued under the terms of the Montreal Protocol (Schneider et al. 2003), but if even if this stipulation does not change there is a need to evaluate surface treatments and aerosols for control of *T. granarium*.

A final group to consider is stored-product mites, which are important arthropod pests of grains and interior structures in much of continental Europe (Collins 2006). Insecticides that will control other insect pests, including those of stored products, are often less effective against mite species (Collins 2006; Hubert et al. 2007). Chitin metabolic inhibitors incorporated into the diet of different mite species affected growth and development (Stara et al. 2011), but there are no studies evaluating contact insecticides as surface treatments for mite control, nor any studies on susceptibility to aerosols. Mites found in feed and flour mills have also been associated with allergens (Stejskal and Hubert 2008), hence the contamination issues caused by mites could warrant expanded studies regarding management and control in mills, processing facilities, and food storage warehouses.

Summary

Residual surface treatments and aerosols can be important inclusions into insect pest management plans as options to whole-plant fumigations with MB. As further restrictions on fumigants are expected to be forthcoming, research regarding the use of more targeted insecticidal treatments to limited areas could be expanded to meet current needs. A future without MB will present challenges for insect pest management in stored products, but could also open up new avenues for research as well. In conclusion, this review highlights recent research with surface treatments and aerosols, and the relevance to stored-product insect control and management. It is not meant to be a comprehensive historical review of research.

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