9

Insect Management with Aerosols in Food-Processing Facilities

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1. Introduction

Stored-product insects infest raw grain, processed cereal grains, warehouses, and food-processing facilities such as flour and feed mills. The presence of insects in commodities or structures leads to quantitative and qualitative losses of grain and processed food. The presence of insects and insect-related materials (insect fragments) in processed products is regulated by federal food and drug laws. Management of insects in food-processing facilities is important to prevent adulteration of finished products. Several tactics that are recommended for management of insects associated with food-processing facilities include stock rotation, inspection of inbound and outbound materials, sanitation, exclusion practices, fumigation with sulfuryl fluoride or methyl bromide, use of heat treatments (Mahroof et al. 2003, Boina et al. 2008), crack and crevice treatments with residual insecticides (Toews et al. 2005, 2009), and the use of aerosols or fogs. A lot of research has been done documenting the effectiveness of whole structure treatments with fumigants and heat treatments, and limited information is available on efficacy of the other chemical and non-chemical (sanitation) insect management tactics. Among these, application of insecticides as aerosols (fogging) is one tool with great potential for effective management of insects in food-processing facilities based on pilot-scale and a few commercial-scale tests. In this chapter, we provide a detailed account on the history of aerosol technology and suitability of this technology for insect management in food-storage and food-processing facilities with supporting information from studies conducted in laboratory and field settings with notes on advantages and limitations of this technology.

2. Brief history of aerosols and stored product insect management

In a typical aerosol application for food-processing facilities, the pressurized insecticide formulation is dispensed through a specialized hand-held, portable or preinstalled applicator's nozzles with fine openings to deliver spray particles of 5-50 µm in size as a mist or fog into a confined space (Peckman and Arthur 2006). These applications are also known as fogging, ultra-low volume (ULV) or space treatments depending on the type of formulation used and particle sizes dispersed. The concept is to have the aerosol particles settle on exposed flying or crawling insects and poison them with little or significant residual activity to insects coming into contact with settled particles. The application of insecticides as aerosols for controlling stored-product insects is an old technique and was initially used for controlling tobacco pests such as the cigarette beetle, *Lasioderma serricorne* (F.), in tobacco warehouses (Tenhet et al. 1957, 1958). The first and the most widely used insecticide for such application was an organophosphate, dichlorvos (DDVP) (Tenhet et al. 1957, 1958; Gillenwater and Harein 1964, Jay et al. 1964, Press and Childs 1966, Childs et al. 1966, Childs 1967, Harein et al. 1970, 1971). In the initial experiments, in contrast to our perception of aerosol treatment where insect control is achieved by deposition of aerosol particles on exposed insects, the efficacy of dichlorvos against *L. serricorne* life stages was measured by exposing them to the dichlorvos vapor (which permeated 30 meters of air space from the point of release) by introducing life stages of insects into the treated warehouse 2 h after the aerosol particles had settled down to the floor (Tenhet et al 1958). Based on the findings from this and other studies, the commercial application of dichlorvos aerosol at a daily application rate of 0.5 g AI/28.3 m^3 headspace was begun in tobacco warehouses for controlling *L. serricorne* and the tobacco moth, *Ephestia elutella* (Hübner).

In 1960s and 1970s, another group of researchers started working on the use of dichlorvos aerosol for controlling insects other than those associated with stored tobacco (Gillenwater and Harein 1964, Jay et al. 1964, Harein et al. 1970, 1971; Gillenwater et al. 1971; Cogburn and Simonaitis 1975). In the late 1970s, some researchers evaluated various synthetic pyrethroids and organophosphates as aerosols for controlling stored-product insects in transport vehicles such as tractor trailers and transport trailer vans (Kirkpatrick and Gillenwater 1979, 1981; Halliday et al. 1987). Then in late 1980s and early 1990s, some studies focused on evaluating synergized pyrethroids as alternatives to dichlorvos for controlling stored-product insects in laboratory settings in artificially constructed air-tight chambers (Arthur 1988, 1993; Arthur and Gillenwater 1990). The current trend in aerosol applications is to evaluate efficacy of neurotoxic aerosols such as dichlorvos, synergized pyrethrins, and pyrethroids alone or combined with insect growth regulators (IGRs) such as methoprene, hydroprene, and pyriproxyfen under laboratory and field conditions (air-tight chambers or flour mills, warehouses and other food-processing facilities) applied via portable application devices or permanently installed systems within the facilities (Jenson et al. 2010a; Phillips and Throne 2010).

From the beginning of this technology in late 1950s until now, several types of application devices have been used for delivering aerosol insecticides for controlling stored-product insects. These include pressurized cylinder-based automatic aerosol dispensing systems (Childs et al. 1966) and pressurized cans which are held in hand and a person, with proper personal protective apparel, walks through the middle (aisle) of a storage facility or a transport vehicle releasing the aerosol (Kirkpatrick and Gillenwater 1979, 1981). Alternatively, a person stands outside the facility and releases the aerosol by directing the aerosol can inside the facility through a window or door (Arthur 1988, 1993; Arthur and Gillenwater 1990). Some researchers used resin pellets impregnated with an insecticide, mainly dichlorvos, for releasing insecticide in vapor form either by a dispenser for providing large quantities of vapor (Gillenwater and Harein 1964, Harein et al. 1971) or by placing pellets in a wire mesh tray to release the vapor into a confined space of a facility (Gillenwater et al. 1971). In some studies, researchers have used portable devices or equipment to release the insecticide aerosols into the facilities such as a DeVilbiss sprayer equipped with an air-atomizing nozzle (Jay et al. 1964), a 'Tifa'generating thermal aerosol machine (Childs 1967), a Dyna-Fog 70 thermal aerosol machine, a 6-nozzle McGill Fog-Trol pneumatic aerosol machine, a rotary-whip ULV applicator (Cogburn and Simonaitis 1975), a Micro-Gen S1W-5E unit dispenser (Bernhard and Bennett 1981), and a hand-held ULV applicator (Jenson et al. 2010b). Some of the devices mentioned above such as rotary-whip ULV applicator or vapor dispenser have a built-in fan or blower for dispersing the aerosol particles more efficiently within a facility (Gillenwater and Harein 1964, Harein et al. 1971, Cogburn and Simonaitis 1975).

All the aerosol application devices described above are either hand-held or portable and can be moved within and between facilities. Nevertheless, the growing need for repeated applications of aerosols for controlling insects in food-processing facilities necessitated the installation of a permanent overhead automatic dispensing system (Childs 1967) or aerosol/ULV compressed air application systems either to the roof or some other permanent structures in the middle of a warehouse/facility (Arthur 2008, Arthur and Campbell 2008, Arthur 2010, Jenson et al. 2010a). The installation of such permanent aerosol dispensing systems reduces the aerosol treatment costs in the long run. Freon 11/12 in 50:50 ratio and carbon dioxide (CO_2) are the two most common propellants used in aerosol formulations of insecticides available as pressurized cans or cylinders for use with permanently installed dispensing systems, because these propellants aid in aerosol dispersion when released.

Although use of a non-synergized insecticide such as dichlorvos was very common when aerosol technology was introduced, pyrethrins and pyrethroids, used as aerosols later, contained a synergist, piperonyl butoxide, for improving the efficacy of aerosols against stored-product insects (Bernhard and Bennett 1981, Arthur 1988, 1993, Arthur and Gillenwater 1990). The latest strategy in aerosol technology is to use a combination of insecticides. The most widely evaluated treatment in both laboratory and field settings is combining a synergized pyrethrin or pyrethroid with an IGR (Arthur 2008, 2010; Jenson et al. 2010a,b; Sutton et al. 2011), because the synergized pyrethrins or pyrethroids are effective against all life stages of insect pest species and provide quick knockdown but fail to provide longer periods of insect control due to poor residual activity. The IGRs are effective against immature life stages of pest species and provide longer periods of protection due to their slow degradation on deposited surfaces compared to synergized pyrethrins or pyrethorids (Jenson et al. 2010a, Phillips and Throne 2010). Table 1 presents the list of insecticides used and/or available for application as aerosols for controlling insects in food-storage and food-processing facilities.

3. Distribution and efficacy of aerosol insecticides in laboratory settings

Several food-storage and food-processing facilities do not permit researchers or scientists to bring live insects into the facilities for conducting experiments. Therefore, it is common practice to conduct these experiments under laboratory conditions in artificially constructed cardboard boxes, wooden chambers, or sheet metal chambers to simulate field conditions (Harein et al. 1971, Arthur 1988, 1993; Arthur and Gillenwater 1990, Jenson et al. 2010a). Several studies were conducted under laboratory settings to determine the distribution/dispersion pattern of aerosol insecticides in the facility by assessing the mortality of important stored-product insects placed in the experimental chamber.

For successful management of stored-product insects in facilities, uniform distribution of applied aerosol throughout the facility, including underneath the wooden pallets used for storage of raw or finished food products and inside pieces of equipment, where the insects take refuge is of utmost importance. Jenson et al. (2010a) studied the effect of a synthetic pyrethroid, esfenvalerate, and an IGR methoprene, applied as aerosols either alone at the label rate or combined at full or reduced label rates and distributed uniformly throughout an artificially constructed small wooden sheds on the mortality of eggs and larvae of the Indianmeal moth, *Plodia interpunctella* (Hübner). The insect stages were exposed in Petri dishes placed at various locations in the sheds. Some locations were open (aerosol particle deposition was not obstructed in anyway) and some were concealed (aerosol deposition was obstructed in a greater way as Petri dishes were placed inside equipment or under a wooden pallet). The application rate (full or reduced label rates), application type (alone or combined), and location of dishes with insects influenced the efficacy of aerosol treatment against the target insect life stages (Jenson et al. 2010a). Therefore, it may be a good idea to evaluate the efficacy of candidate aerosols against insect pests under laboratory settings first to determine and understand factors influencing efficacy under field conditions.

Application of aerosols at regular intervals not only controls the insects in warehouses and storage facilities that are flying but also prevents the movement of insects from infested to clean product packages either within a same stack or between stacks stored in a room. For instance, Harein et al. (1971) demonstrated that weekly application of dichlorvos as a vapor at a concentration of 3-4 µg/L volume of air effectively prevented the spread of adults of the confused flour beetle, *Tribolium confusum* (Jacquelin du Val), lesser grain borer, *Rhyzopertha dominica* (L.), and *L. serricorne* from infested to uninfested stacked flour for 5 months in air-tight chambers. Dichlorvos is a fast degrading insecticide with poor residual activity because chemical analysis of packaged flour collected in the treated chamber showed negligible amounts of dichlorvos residues (<0.1 ppm) indicating that dichlorvos is a safer insecticide to use as an aerosol for controlling insects in warehouses with finished packaged foods as it leaves minimal residues (Harein et al. 1971).

The success of an aerosol treatment in controlling insects in food-storage and food-processing facilities depends on the level of harborage available to the insect and duration of exposure of insects to aerosol particles. In a laboratory study, Bernhard and Bennett (1981) showed that the harborage level and exposure time to aerosol play a role in degree of insect control achieved in facilities. Simulating various levels of insect harborage by completely opening to completely closing the cabinet doors containing insects in an air-tight chamber, they showed that adults of the rice weevil, *Sitophilus oryzae* (L.), were more susceptible than adults of *T. confusum* to a synergized pyrethrin applied as an ULV with particle sizes ranging from 5.7-28.6 µm. The adult mortality was none to negligible at maximum harborage level and it increased as the harborage level decreased giving a maximum mortality at no harborage level. Similarly, the adult mortality increased with increase in exposure time from 15 to 120 minutes. Bernhard and Bennett (1981) concluded that aerosols applied at ULV with 5.7-28.6 µm particle size ranges would be most effective only during application and the first 15 minutes after application, because larger droplets carrying the most of active ingredient settle down in the initial 15 minutes and the effectiveness of treatment decreases drastically thereafter. The above conclusion was supported by less than 10% mortality of adults of *T. confusum* and *S. oryzae* obtained when they were introduced in the treatment room 15 or 60 minutes after the application of synergized pyrethrins (Bernhard and Bennett 1981).

In an effort to find safer alternative aerosols to dichlorvos for managing insects in food-storage and food-processing facilities, Arthur (1988, 1993) and Arthur and Gillenwater (1990) conducted several experiments in artificially constructed air-tight chambers (42.5 m^3). These studies evaluated the distribution and efficacy of three pyrethroids, prallethrin, esfenvalerate, and cyfluthrin with or without a synergist at various rates and exposure times against three moth and six beetle species. The results from these studies showed that three moth species [*P. interpunctella*, the almond moth, *Cadra cautella* (Walker), and *E. elutella*] were highly susceptible to pyrethroids tested compared to the beetle species. This conclusion was based on the fact that irrespective of the formulation, exposure time and presence or absence of synergist, near complete to complete knockdown and subsequent mortality of moths was obtained even at the lowest rates tested (Arthur 1988, 1993; Arthur and Gillenwater 1990). Although a near complete to complete knockdown of adults of all beetle species was noticed for all the treatments, most of them recovered and the final mortality ranged from 10-90% depending on the type of pyrethroid (synergized or non-synergized), formulation, rate, and exposure time (Arthur 1988, 1993; Arthur and Gillenwater 1990). The inherent higher susceptibility of moths to pyrethroids than beetles combined with release of moths in the chamber freely, which improved the chances of moths coming into contact with descending aerosol particles than that of beetles (confined to Petri dishes), resulted in greater mortality of moth species than beetle species. Furthermore, within beetle species, the susceptibility to an aerosol insecticide was species-specific because the relative susceptibility of two closely related insect species varied with the aerosol treatment. For instance, *T. confusum* was more sensitive to synergized esfenvalerate than *T. castaneum*, while *T. castaneum* was more sensitive to synergized prallethrin than *T. confusum* (Arthur and Gillenwater 1990, Arthur 1993).

In a few laboratory studies, it was observed that insects that survived the first application of aerosol were completely killed when the second application of the same aerosol was made within the next 1, 2, or 3 days or a week. This can be attributed to the stress from the previous exposure (Arthur and Gillenwater 1990; Arthur 1993). For example, adults of *T. confusum* and *T. castaneum* that survived the first application of prallethrin and esfenvalerate aerosols, respectively, were killed after exposure to a second application made at same the rate after 1, 2, or 3 days (Arthur and Gillenwater 1990; Arthur 1993). A similar cumulative effect of an aerosol insecticide (dichlorvos) against stored-product insects was also reported by Attfield and Webster (1966). Additionally, the post-exposure time between knockdown and complete adult mortality was reduced as the interval between the first and second application increased. In other words, adults died quickly when second application was made 3 days after the first versus 1 day after the first application (Arthur 1993). This finding with prallethrin and esfenvalerate suggests that a second application of these aerosols at least within 7-10 days following the first application will lead to complete control of *T. confusum* and *T. castaneum* adults (Arthur and Gillenwater 1990; Arthur 1993). However, these findings need to be confirmed with tests conducted under field conditions. Also, retaining the insects in the same exposed dishes instead of transferring them to new dishes may have resulted in increased mortality of exposed insects (Arthur and Gillenwater 1990).

4. Distribution and efficacy of aerosol insecticides in field settings

In practical commercial facilities, when the space treatments with aerosol insecticides are made, the deposition of the dispersed aerosol particles on the floor may be obstructed by the presence of several barriers such as walls, equipment, as well as processed or raw food material that are either shelved or stacked on wooden pallets. Therefore, the influence of barriers within a facility or structure on distribution pattern of dispersed aerosol particles and the consequent effect on insect lethality needs to be evaluated. Gauging the effectiveness of an aerosol treatment based on mortality/survival of resident insect populations in a facility is difficult because of our inability to determine total number of insect species, insect life stages, and numbers present. Commercial food-baited and sticky traps with pheromone lures have been used to gauge effectiveness of treatment intervention (Roesli et al. 2003), but these commercial traps capture only the adult stages, and it is difficult from trap captures to determine whether the insects in traps are resident populations or those that immigrated into the facility from outside.

In the initial experiments conducted using dichlorvos as the aerosol, the life stages of *L. serricorne* were exposed to the vapors but not to the dispersed aerosol particles. The exposure of insect life stages to vapors was achieved by introducing the insects 2 h after aerosol application in wire-mesh cages suspended above the floor surface by which the aerosol particles might have settled down on the floor (Tenhet et al. 1958). In this way, exposure of older eggs, young larvae, and adults of *L. serricorne* in wire-mesh cages to dichlorvos vapors for 1 h in tobacco warehouses resulted in complete mortality. Based on these findings, application of dichlorvos formulation weekly twice at 2 g/28.3 m^3 headspace was recommended for controlling *L. serricorne* in tobacco warehouses (Tenhet et al. 1958). On the other hand, the tobacco moth *E. elutella* control required less dosage because weekly applications of dichlorvos aerosol at 1 g AI/28.3 m^3 headspace reduced populations of this species in tobacco storage warehouses in Virginia, North Carolina, and South Carolina by 99% in 1960 over 1959 and 90% in 1961 over 1960 based on trap catches (Press and Childs 1966). However, Childs et al. (1966) reported that a higher dose than that recommended previously was required for controlling *L. serricorne* adults in tobacco warehouses as daily application of dichlorvos at 0.5 g/28.3 m^3 headspace via an automatic dispensing system in a tobacco warehouse effectively controlled adults based on reduced trap captures.

In late 1970s, efforts made to control *L. serricorne* adults in tobacco warehouses by combining dichlorvos aerosol with hydrogen cyanide (HCN) fumigation yielded good results. Of the various combinations tested, annual fumigation with HCN at 1360.8 g/28.3 m^3 headspace and dichlorvos applied daily at 0.5 g/28.3 m^3 headspace 10 days after fumigation completely controlled *L. serricorne* adults in tobacco warehouses in Virginia, North Carolina, and South Carolina containing flue-cured tobacco solely based on adult trap catch data. Furthermore, it was noticed that warehouses with flue-cured tobacco treated with this combination did not need a second fumigation with HCN for controlling *L. serricorne* for at least two years (Childs 1967).

In all the field studies mentioned above, the effectiveness of an aerosol treatment was gauged based on trap catch data. Although the effectiveness of an aerosol treatment can be gauged to some extent with the number of insects caught in sticky, pheromone or pitfall traps over time, this method is not completely reliable as traps can collect insects that may have immigrated into the facility after the treatment (Arbogast et al. 2000, 2002, 2005, Campbell et al. 2002, 2003, 2004; Roesli et al. 2003, Toews et al. 2006). Therefore, it is a common practice to confine the laboratory-reared insects in wire-mesh cages or Petri dishes and place them across the treatment room or facility at open, obstructed and concealed locations such as underneath equipment and stacked raw or processed material as well as within equipment. In addition to exposing insects alone, some studies included flour as a food source in the Petri dishes either during or after the exposure to aerosol. Therefore, the findings reported below from various field studies conducted in mills, warehouses and other facilities were based on the exposure of Petri dishes with or without insects and/or flour during an aerosol application.

Findings from a field study conducted in three port warehouses using three different aerosol application devices indicated that the level of insect control obtained in warehouses is influenced by the type of device used and circulation of air inside the food-processing facility during and after the application (Cogburn and Simonaitis 1975). The application of dichlorvos aerosol through pneumatic application device (still air) resulted in the lowest mortality of all three test species (adults of *T. confusum* and *L. serricorne* and larvae of *C. cautella*); moderate mortality was obtained when applied with a thermal aerosol (still air) and the highest mortality [*T. castaneum* (98-99%), *L. serricorne* (97-99%) and *C. cautella* (86-94%)] was obtained when the treatment was supplemented with air circulation via external fans (thermal aerosol) or built-in fan (rotary-whip ULV application device). The uniform mortality of all three test species obtained in wire-mesh cages placed across each warehouse including at concealed locations with air circulation versus uneven mortality (0 to 100%) at various locations without air circulation is a clear indication that circulation of air during aerosol treatment may improve the overall treatment effectiveness. This is mainly attributed to efficient distribution and deposition of aerosol particles into inaccessible areas such as equipment and wooden pallets and shelves via air circulation which in turn helped in killing the insects harbored in these areas. Application of aerosols in commercial facilities is done after the air handling system is shut down and any vents sealed, in order to maintain lethal concentration of particles suspended in air. The presence of air currents results in an exponential decay of the particles in air.

During aerosol applications, the deposition of aerosol particles on open surfaces is achieved primarily by their vertical downward movement, the speed of which is based on particle diameter. However, in obstructed and concealed places such as inside equipment and underneath wooden pallets the deposition is primarily achieved by the tendency of particles to move horizontally (drift) but at a lesser magnitude. Because of this, several studies reported more or less uniform distribution of aerosol particles throughout the facility measured by mortality of test insects placed at various locations across the facility (Arthur 2008, 2010; Jenson et al. 2010a,b). The uniform distribution of aerosol particles of esfenvalerate + methoprene under laboratory settings (Jenson et al. 2010a) and synergized pyrethrin alone and in combination with methoprene or pyriproxyfen under field conditions in a flour mill or warehouse (Arthur 2008, 2010; Jenson et al. 2010b) can be attributed to the above phenomenon. In these studies, irrespective of the location of the aerosol deposit collected such as open and obstructed/concealed in the mill, similar level of mortality of target insect life stages was achieved either due to direct exposure to aerosol particles or deposited residues. This could be due to the deposit being well above that required to cause complete mortality of insects.

Field studies conducted in a flour mill or warehouse suggested that use of synergized pyrethrins (1 or 3%), in combination with methoprene, is more effective (synergistic effect) than using either one alone for controlling eggs of *P. interpunctella* (Jenson et al. 2010b) or larvae of *T. castaneum* and *T. confusum* (Sutton et al. 2011). The findings also suggested that a higher suppression of adult emergence from eggs can be obtained when unexposed eggs were added to the diets exposed to the above aerosol combination than direct exposure of eggs without diet, perhaps due to consumption of or contact with aerosol-treated diet. Similarly, greater reduction in emergence of adults from 4-wk-old larvae of *T. castaneum* and *T. confusum* was obtained when larvae were added to the flour or various food-packaging materials exposed to the above aerosol combination in concrete poured Petri dishes (Sutton et al. 2011). Combining synergized pyrethrins with methoprene or pyriproxyfen (juvenile hormone mimic) resulted in longer residual activity against immatures of *T. castaneum* and *T. confusum* (Arthur 2010, Sutton et al. 2011). For instance, the 0- to 16-wk-old residues of the synergized pyrethrin + methoprene collected in concrete poured Petri dishes with flour or various food packaging materials during an aerosol application in a mill environment effectively controlled the immature life stages of *T. castaneum* and *T. confusum* that were added later to the Petri dishes. The residual activity of synergized pyrethrin + pyriproxyfen was shorter than the above combination as only few adults emerged from eggs and larvae of *T. castaneum* and larvae of *T. confusum* exposed to the residues that were 0- to 10-wk-old. Increasing the concentration of pyrethrin only (from 1 to 3%) in the combination treatment has proportionately increased the residual activity against eggs and larvae but not pupae of *T. castaneum.* The combined application of synergized pyrethrin and methoprene not only resulted in increased residual activity but also caused various morphological deformities in larvae of *T. castaneum* and *T. confusum* (Sutton et al. 2011). The longer residual activity of above aerosol combinations could be the result of quick knockdown and mortality effects imparted by synergized pyrethrins in the early days and slow and prolonged toxic effect imparted by the IGR in subsequent days (Mondal and Parween 2000, Phillips and Throne 2010, Sutton et al. 2011).

Although synergized pyrethrins when combined with IGRs did not show any effect on adults of *T. confusum* and *T. castaneum* (Arthur 2010), synergized pyrethrins applied alone as an aerosol at the label rate in a large storage room of a commercial food bank effectively controlled the larvae, pupae, and adults of *T. confusum* and *T. castaneum* exposed in Petri dishes even in the presence of flour as a food source at open locations, and the mortality increased with an increase in the post-exposure time (Arthur 2008). Similarly, methoprene applied alone at the label rate was highly toxic to larvae of *T. confusum* (open locations) and *T. castaneum* (open and concealed locations) but moderately toxic to eggs of *P. interpunctella* exposed in media (Arthur 2008, Jenson et al. 2010b).

Gillenwater et al. (1971), Arthur and Campbell (2008), and Toews et al. (2010) showed that both exposure location and presence of flour as the food source in a facility influenced insect control. Synergized pyrethrins applied at the label rate in an empty warehouse resulted in a wide variation in mortality (20-94%) of *T. confusum* adults exposed in Petri dishes without flour in the rear part of the warehouse whereas more than 80% mortality occurred in Petri dishes that were placed in the front part of the warehouse (Arthur and Campbell 2008). This discrepancy was partly explained by the fact that the nozzles delivering aerosol particles were directed to the front of the experimental room (Arthur and Campbell 2008), suggesting non-uniform distribution throughout the empty warehouse. Toews et al. (2010) observed that exposure to synergized pyrethrin and esfenvalerate applied separately as aerosols at label rates resulted in higher mortality of all life stages of *T. castaneum* in open locations than in concealed locations (under wooden pallets).

The exposure of *T. confusum* adults to synergized pyrethrins in Petri dishes with flour in open locations caused complete adult knockdown. However, the knocked down adults recovered later. The recovery and survival were positively correlated with post-exposure time and the amount of flour present in dishes (Arthur and Campbell 2008). Similar observations of knockdown and recovery of *T. castaneum* life stages exposed to synergized pyrethrins and esfenvalerate applied separately at label rates in pilot scale warehouses were made in the presence of flour as food, both in open and concealed locations (under wooden pallets) (Toews et al. 2010). Arthur and Campbell (2008) noticed that *T. confusum* adults exposed to the synergized pyrithrins in Petri dishes with flour during application and later transferred to new Petri dishes along with the same flour showed increased survival. This finding is similar to that observed in laboratory studies with esfenvalerate against *T. castaneum* adults exposed in Petri dishes without flour (Arthur and Gillenwater 1990). The plausible reasons may be related to absorption of aerosol by the flour, resulting in sub-lethal exposures.

The recovery and survival of *T. confusum* and *T. castaneum* life stages observed in the presence of flour as food in the above studies and with contact residual insecticides such as diatomaceous earth and cyfluthrin (Arthur 2000a,b) emphasizes the need for sanitation of facilities before aerosol applications. Furthermore, the fact that a 10% insect survival (90 percent control or 1-log reduction in pest numbers) in a food-processing facility after an insect control operation is sufficient to reach the population to its original density within a month (equivalent to one generation cycle at optimum temperatures) (Hagstrum and Flinn 1992), mainly due to increased oviposition rate by surviving females with abundant food and less competition (Campbell and Runnion 2003). This finding also stresses the need for sanitation of a facility prior to aerosol treatment. With proper sanitation the proportion of insects directly exposed to aerosol during application is considerably increased either by preventing them from taking refuge in the flour patches or forcing them to come out of their refugia. On the other hand, sanitation reduces the chances of insects coming into contact with food either during or after an aerosol application. As no or poor sanitation undermines the actual efficacy of aerosol insecticides, proper sanitation is important for realizing the maximum effectiveness of aerosol treatments in controlling insects in food-processing facilities.

Kirkpatrick and Gillenwater (1979) and Halliday et al. (1987) conducted experiments to control stored-product insects in tractor trailers with several synthetic pyrethroid insecticides. The exposure of adults of *T. confusum* and larvae of the black carpet beetle, *Attagenus megatoma* Lateille (*A. unicolor* Brahm) and larger cabinet beetle, *Trogoderma inclusum* LeConte, to various formulations of *cis*-Permethrin, permethrin and *d*-Phenothrin applied at 5 g of formulation /28.3 m^3 headspace occurred for 30 minutes in Petri dishes (without food). After exposure, insects were transferred to clean Petri dishes. Varying levels of knockdown of insects were observed but most of the *T. confusum* adults recovered and a wide variation in the recovery was observed with other two species depending upon the exposure location and formulation type. Based on these results Kirkpatrick and Gillenwater (1979) and Halliday et al. (1987) concluded that higher rates of aerosol formulations per unit volume of space and longer exposure times are required for controlling insects in cargo vehicles to meet quarantine treatment standards. Despite the increase in application rate (5 to 10 g) and exposure time (30 minutes to 10 h), there was no significant difference in terms of percent knockdown and percent mortality of the test species (Kirkpatrick and Gillenwater 1979, 1981). This showed that control of insects in transport vehicles is different from warehouses and food-processing facilities and requires an entirely different set of aerosol formulations and treatment protocols.

5. Suitability and adoption of aerosol technology for present pest problem situations in food-processing facilities

The ban on use of ozone-depleting fumigant, methyl bromide, for insect control in food-processing facilities (Fields and White 2002, Anonymous 2004) and problems associated with other fumigants such as development of resistance in insects, corrosion of exposed electrical and metal surfaces, development of fumigation management plans (phosphine) and need for higher doses to kill some insect life stages and reduced effectiveness against embryonic stages of insects (sulfuryl fluoride) (Bond et al. 1984, Arthur et al. 1988, Halliday et al. 1988, Zettler 1990) make aerosols a promising and viable tool for management of insect pests in food-storage and food-processing facilities. This technology is gaining popularity because of its low cost and the ability to do tactical treatments. The feasibility of treating only a portion of a facility makes aerosol application a desirable option for facility managers.

The insecticides applied as aerosols mainly belong to three classes with different modes of action namely organophosphates, pyrethrins/pyrethroids and IGRs (Table 1). Aerosol insecticides belonging to organophosphate and pyrethrins/pyrethroid classes such as dichlorvos, synergized pyrethrins, esfenvalerate, and cyfluthrin are toxic to all life stages of stored-product insects with short residual activity, while IGRs such as methoprene, pyriproxyfen, and hydroprene are toxic to immatures of all stored-product insects (as they cause morphologic and gonadotropic effects) with long residual activity, with some exceptions.

Except for a few earlier studies, a majority of the studies conducted in warehouses and mills proved that insecticides applied as aerosols using portable application devices or permanently installed aerosol application systems distributed the particles uniformly throughout the facility including underneath the wooden pallets (with stacked finished food) and inside equipment based on the similar level of insect control obtained in Petri dishes or wire-mesh cages placed at various locations. Our ongoing studies also proved that dichlorvos aerosol particles distributed uniformly throughout the facility and were able to penetrate into inaccessible areas through horizontal movement and killed insects that were placed in concealed locations. However, the rapid dissipation of residues significantly reduced the overall residual activity of applied dichlorvos. For instance, in a recent unpublished study conducted in a pilot flour mill at Kansas State University, dichlorvos applied at labeled rate killed most of the adults of *T. confusum* (as only few adults survived in concealed locations) exposed in concrete poured Petri dishes placed at various locations classified as open, obstructed and concealed in the first floor of the mill after 24 h exposure to the aerosol (Table 2). The results did not significantly change with additional 24 h holding of exposed insects to the residues on concrete disks in the same Petri dishes because complete mortality in open and obstructed locations and near complete mortality in concealed locations was already achieved during the first 24 h (Table 2). Petri dishes with aerosol deposits after 24 h were brought to the laboratory and exposed to adults of *T.*

Class	Insecticide	Mode of action	Reference
Organophosphate	Dichlorvos (DDVP)	Acetylcholinesterase inhibitor	Childs (1967)
			Cogburn and Simonaitis (1975)
			Gillenwater et al. (1971)
			Harein et al. (1971)
Natural pyrethrins	Synergized pyrethrins	Sodium ion channel modulator	Bernhard and Bennett (1981)
			Jenson et al. (2010b)
			Arthur and Campbell (2008)
			Toews et al. (2010)
Synthetic pyrethroids	*cis*-Permethrin	Sodium ion channel modulator	Kirkpatrick and Gillenwater (1979)
			Halliday et al. (1987)
	Permethrin	Sodium ion channel modulator	Kirkpatrick and Gillenwater (1979)
			Halliday et al. (1987)
	d-Phenothrin	Sodium ion channel modulator	Kirkpatrick and Gillenwater (1979)
	Phenothrin	Sodium ion channel modulator	Halliday et al. (1987)
	Synergized prallethrin	Sodium ion channel modulator	Arthur 1993, 2008
	Esfenvalerate	Sodium ion channel modulator	Jenson et al. (2010a)
			Toews et al. (2010)
	Fenvalerate	Sodium ion channel modulator	Halliday et al. (1987)
	Cypermethrin	Sodium ion channel modulator	Halliday et al. (1987)
	Fluvalinate	Sodium ion channel modulator	Halliday et al. (1987)
	Cyfluthrin	Sodium ion channel modulator	Halliday et al. (1987)
	Fenpropathrin	Sodium ion channel modulator	Halliday et al. (1987)
	Cyphenothrin	Sodium ion channel modulator	Halliday et al. (1987)
	Synergized resmethrin	Sodium ion channel modulator	Halliday et al. (1987)
	Synergized esfenvalerate	Sodium ion channel modulator	Arthur and Gillenwater (1990)
	Synergized cyfluthrin	Sodium ion channel modulator	Arthur (1988)
Insect growth regulator	Methoprene	Juvenile hormone analog	Arthur (2008)
			Jenson et al. (2010a)
	Pyriproxyfen	Juvenile hormone mimic	Arthur (2010)
Combinations	Dichlorvos	Acetylcholinesterase inhibitor	Toews et al. (2006)
	+		
	Pyrethrins	Sodium ion channel modulator	
	Synergized pyrethrins	Sodium ion channel modulator	Arthur (2010)
	+		Jenson et al. (2010b)
	Methoprene	Juvenile hormone analog	Sutton et al. (2011)
	Esfenvalerate	Sodium ion channel modulator	Jenson et al. (2010a)
	+		
	Methoprene	Juvenile hormone analog	
	Synergized pyrethrin	Sodium ion channel modulator	Arthur (2010)
	+		
	Pyriproxyfen	Juvenile hormone mimic	

Table 1. Insecticides used and/or available for aerosol application for managing stored-product insects.

Treatment	Mean (±SE) percent survival			
	Control[a]	Open	Obstructed[b]	Concealed[c]
Exposure during application (24 h)	100.0 ± 0.0a	0.0 ± 0.0b	0.0 ± 0.0b	6.7 ± 6.7b
Exposure during application (24 h) + 24 h on residues	97.2 ± 2.8a	0.0 ± 0.0b	0.0 ± 0.0b	10.0 ± 10.0b
Exposure to 0 h old residues	97.2 ± 2.8a	66.7 ± 8.8a	53.3 ± 26.7a	86.7 ± 8.8a
Exposure to 24 h old residues	97.2 ± 2.8a	96.7 ± 3.3a	100.0 ± 0.0a	96.7 ± 3.3a

[a]Petri dishes were placed in a laboratory growth chamber at 28°C and 65% RH.
[b]Petri dishes were placed below pieces of equipment or other barriers.
[c]Petri dishes were placed inside pieces of equipment.
Means (n = 3) among treatments for each row (control, open, obstructed, or concealed) followed by different letters are significantly different from one another (least significant difference test; $P < 0.05$).

Table 2. Survival of *T. confusum* adults exposed in concrete poured Petri dishes that were placed in different locations to dichlorvos aerosol applied in a flour mill.

confusum. A majority of these adults survived suggesting rapid dissipation of residues after 24 h. Holding the dishes for an additional 24 h resulted in greater survival of the exposed adults (Table 2).

6. Advantages and limitations of using aerosols for insect management in food-storage and food-processing facilities

There are several advantages of using aerosol technology for insect control in food-storage and food-processing facilities. The cost of using aerosol insecticides is less compared to fumigation with methyl bromide and sulfuryl fluoride or to heat treatment. For example, the costs based on volume treated in Kansas State University pilot flour mill of 9628 m^3 volume during 2009-2010 for methyl bromide, sulfuryl fluoride, heat treatment based on an average of three separate treatments was US$ 1.76, 3.77, and 3.14/m^3, respectively. In contrast, treatment with the aerosol formulations of esfenvalerate and methoprene each applied alone was US$ 0.0025/m^3 and applied together was US $0.0061/$m^3$ (Jensen, 2010a). Relatively air-tight sealing and documentation to comply with federal regulations are essential when using fumigants, but such requirements are little less stringent when using aerosols. However, air-tight sealing of the facility during aerosol treatments may be necessary if the facility is located in a residential area. Aerosol treatments can be conducted in a portion or the whole facility, and the treatment times are very short (2-4 hours) depending on the product. In the United States, aerosol treatments of food-storage and food-processing facilities are generally made during major holidays or on weekends when the facility is not in operation. Treatments with the fumigants, methyl bromide and sulfuryl fluoride, require a minimum exposure time of 24 hours. For heat treatments, the time may be as short as 24 hours or as long as 34 hours. Like fumigants, aerosol treatments require a period of clearing, which with certain aerosols, could range from 2 to 12 hours (overnight). After an aerosol treatment is conducted, concentrations of certain aerosols need to be monitored to make sure that it is safe for workers to reenter facilities. Nevertheless, the duration for which the facility should be out of operation (shutdown) for an aerosol treatment is much shorter (≤12 h) than that required for fumigation or heat treatments (24-34 h).

The presence of flour as a food source seems to influence effectiveness of aerosol treatments. Some studies showed mortality of *T. confusum* and *T. castaneum* life stages to be unaffected by the presence of flour (Arthur 2008), whereas other studies showed presence of flour either during or after aerosol exposure to increase insect survival (Arthur and Campbell 2008, Toews et al. 2010). Irrespective of these findings, it is always recommended that sanitation of the facility be conducted before an aerosol treatment. This measure forces the insects hiding or taking shelter in flour refugia to come out and increases their chances of exposure to aerosol particles. Aerosol applications can be integrated with other management tactics for controlling insects in food-storage and food-processing facilities such as fumigation, application of residual contact insecticides, and sanitation (Toews et al. 2006).

The main limitation is insecticides applied as aerosols lack the ability to penetrate packaged food. Therefore, insects, mostly in the egg stage, inside packaged food escape the exposure and need to be controlled by fumigation. This limitation can be offset to some extent by doing aerosol treatments in empty warehouses and bringing clean raw or finished or packaged products into the facilities so it reduces the chance of cross contamination and infestation. Alternatively, aerosols may complement control achieved by insect-resistant packaging.

7. Conclusions

The use of aerosol technology for insect control in food-storage and food-processing facilities is gaining popularity as a viable alternative to expensive methods of insect disinfestation such as fumigation and heat treatment. It has several advantages over other methods of insect disinfestation. Although the aerosol technology has been used by the food-storage and food-processing industry for many decades, only recently has there been a renewed interest in generating data on aerosol distribution, efficacy, and residual activity for various existing and new aerosol formulations of insecticides in both laboratory and field settings. The reason for the renewed interest can be attributed to the phase out of methyl bromide, because of its adverse effects on stratospheric ozone, and companies embracing cost-effective and reduced-risk technologies. There is room for additional information on several areas related to insect management with aerosol applications, such as the effect of temperature on aerosol efficacy. Other areas include the effect of sanitation and pretreatment of cracks and crevices with piperonyl butoxide on improving the effectiveness of aerosol applications for insect management in food-storage and food-processing facilities. Also, there is limited information on the effects of exposure to sublethal doses of aerosols during application on stored-product insect biology and reproduction and its influence on population rebounds. Similarly, the effects of exposure to sublethal doses of aerosols during application on stored-product insects physiology (levels of detoxifying enzymes) warrants further study. The information on the waiting period required between two subsequent aerosol treatments is necessary to exploit the advantage of insects being under physiological stress from the previous aerosol exposure for effective management of insect in food-processing facilities. In conclusion, aerosols will continue to play an important role in the management of stored-product insects in food-storage and food-processing industry for the foreseeable future.

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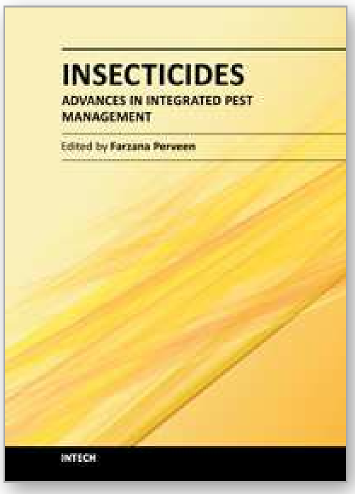

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