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Alternatives to chemical control of stored-product insects in temperate regions

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Abstract

Since the 1950 s, chemical insecticides have been used extensively in grain storage facilities to control stored-product insect pests. Before the invention of these synthetic insecticides, there were several of non-chemical methods used in grain stores and food processing facilities. Today, there is an increased interest in these methods, because of the development of resistance to synthetic insecticides, the concerns about worker safety and the demands by consumers for finished products free of insecticide residues. The goal of non-chemical control is to render the habitat unsuitable for the growth and reproduction of stored-product insects. In this review, I will cover the following approaches: low temperature, high temperature, low moisture grain, diatomaceous earth, exclusion, hermetic storage, impact and varietal resistance.

Key words: review, temperature, hermetic, impact, DE.

Introduction

Since the 1950 s, chemical insecticides have been used extensively in grain storage facilities to control stored-product insect pests. Fumigants, such as methyl bromide, phosphine or sulfuryl fluoride, rapidly kill all life stages of stored-product insects in a commodity or in a structure (Bond, 1984). Contact insecticides, such as malathion, chlorpyriphos-methyl or deltamethrin, are sprayed directly on grain or structures, and provide protection from infestation for several months (Snelson, 1987). The latest developments in these methods of control will be covered by other researchers, in this proceedings.

There are a number of reasons people are looking for alternatives to chemical insecticides. Some of the contact insecticides have become ineffective because of wide-spread resistance in insect populations. Resistance to malathion is widespread in Canada, USA and Australia (Subramanyam and Hagstrum, 1995). Resistant to phosphine is so great in Australia and India, it may cause control failures (Collins et al., 2000). Although, chemical insecticides are usually very effective, there are risks for a company using them. In 1994, General Mills lost over 60 million US$ when a contractor sprayed oats General Mills were using for the production of a popular breakfast food, Cheerios, with pirimiphos-methyl instead of the approved chlorpyrifos-methyl (Feder, 1994). Worker safety is a growing concern for many companies, and insuring the workers are not exposed to chemical insecticides can make the use of these products expensive and disruptive to the operation of the grain handling or processing facility. For, example fumigation with methyl bromide requires the shut down of the entire complex, even parts that are not being fumigated. Consumers are demanding finished products that are free of synthetic

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insecticides. The consumption of organic products increases each year. Some insecticides, such as methyl bromide, are being de-registered because they damage the environment (Fields and White, 2002).

Before the invention of synthetic insecticides, there were several of non-chemical methods used in grain stores and food processing facilities. The goal of non-chemical control is to render the habitat unsuitable for the growth and reproduction of stored-product insects. In this review, I will cover the following approaches: low temperature, high temperature, low moisture grain, diatomaceous earth, hermetic storage, impact and varietal resistance.

Low temperature

Underground grain storage has been used for over 4,000 years (Dunkel, 1985). The main advantage is that soil temperatures are below that of the development of insects. Ideal temperatures for growth, reproduction and movement for most stored-stored product insects are between 25 and 35 °C (Howe, 1965). Temperatures between 25 and 15 °C results in fewer eggs laid, slower development, less movement and longer life spans. For most insects, 20 °C is the limit at which they can complete development (Table 1, Fields, 1992). *Sitophilus granarius* (L.) is an exception to this general rule, as it can complete its development at 15 °C. Mites, such as *Acarus siro* L. can develop at 7 °C. It is well known that lower temperature lowers the rate of development. For example, at 18.2 °C *Sitophilus oryzae* (L.) takes 15 wk to complete a generation, a female will lay 4 eggs/wk and will give rise to 4 females in 10 wk. Where as at 29 °C, it will take 4 wks to go from egg to adult and a female will lay 344 eggs and will give rise to 2,110 females in 10 wk. Even if the temperature is lowered only a few degrees to 23 °C, one female with only give rise to 75 females (Birch, 1953). Therefore, there is a great advantage to lowering the grain temperature below the optimal temperature for growth as soon as possible after harvest.

There are a number of ways to lower the temperature of the grain mass, either through turning grain over, ambient air aeration or chilled aeration. Turing grain from one silo to another silo will break up localized hot spots. In some cases if the movement is done during the winter and grain is moved slowly through chilled equipment, there can be small overall reduction in grain temperature.

Table 1. Response of stored-product insect pests to temperature (adapted from Fields, 1992).

Zone	Temperature (°C)	Effects
Lethal	Above 62	Death in <1 min
	50 to 62	death in <1 h
	45 to 50	death in <1 day
	35 to 42	Populations die out, mobile insects seek cooler environment
	35	Maximum temperature for reproduction
Suboptimum	32 to 35	Slow population increase
Optimum	25 to 32	Maximum rate of population increase
Suboptimum	13 to 25	Slow population increase
	13-20	Development stops
Lethal	5 to 13	Slowly lethal
	1-5	Movement ceases
	-10 to -5	Death in weeks, or months if acclimated
	-25 to -15	Death in <1 h

However, to dramatically lower grain temperature the most effective way is to force cool air through the grain bulk. There are several good reviews on the use of ambient aeration to cool grain (Fields and Muir, 1995; Reed and Arthur, 2000; Jayas and White, 2003). Storage systems have many features; fan type, fan power, duct type, height and width of silo, method of loading, dockage and commodity stored, that impact the effectiveness of the aeration. For example, silos often have ducts rather that fully perforated floors causing uneven cooling of grain and longer times to cool the entire grain bulk. Air flows of only 1-2 (L/s)/m^3 cool grain to ambient in 1-2 wks, whereas air flows of 12 (L/s)/m^3 are required to reduce moisture content. The height of the silo dramatically affects the power needed ventilate the grain. Doubling the height requires five times the fan power to get the same air flow rates. In the USA and Canada, aeration is used mainly to prevent spoilage due to high moisture, whereas in Europe and Australia, aeration is used mainly to reduce insect damage (Reed and Arthur, 2000). In the USA, aerated grain is fumigated with phosphine half as much as non-aerated grain (Cuperus et al., 1986). We often forget that insects are mobile and will seek out the habits that are the best for growth. For example, *C. ferrugineus* can detect differences of 1 ^{o}C, and it will move to the warmer grain (Flinn and Hagstrum, 1998). This underlines the importance of cooling the entire grain mass.

Chilled aeration has been used in a limited way for many years in Australia, Europe and more recently the USA (Fields, 1992; Maier, 1994; Rulon et al., 1999). There are several manufacturers of grain chillers, with the average capacity of the grain chillers being approximately 350 t/day. The cost of chilling grain (12.8 US$/t) was estimated to be about twice the cost of fumigation with phosphine and aeration (6.5 US$/t) (Rulon et al., 1999).

At temperatures below the development threshold, insects will eventually die. The length of time this takes depends on many factors; temperature, insect species, life stage, moisture content of the grain and acclimation to cold. There are several good reviews covering the effects of temperature on stored-product insects (Fields, 1992; Strang, 1992; Fields and Muir, 1995; Mason and Strail, 1998; Burks et al., 2000).

Obviously the lower the temperature, the faster the insects die. The shape of the curve is usually a “J” shaped (Figure 1). There have been a number of models developed to predict mortality at low temperature (Hagstrum and Flinn, 1994; Burks et al., 2000, Jian et al., 2006). These models have not rigorously verified with studies of insect survival in grain silos. The supercooling point, the temperature at which the water in the insect begins freezing, is the lowest temperature stored-product insects can survive, as all stored-product insects are freeze-intolerant. The supercooling of stored-product insects varies between -22 ^{o}C for the larvae of *Ephestia kuehniella* (Zeller) or a high of -8 ^{o}C for the larvae of *Tenbrio molitor* (L.) (Fields, 1992). However, stored-product insects are not as cold-hardy as most insects found in temperate habitats, and they often die at temperatures well above their supercooling points in a matter of days.

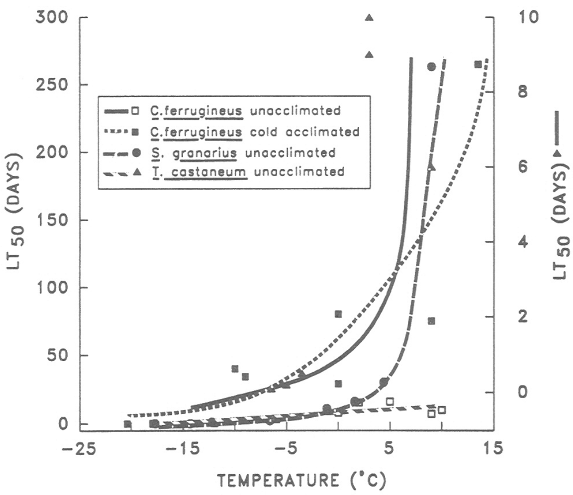

Figure 1. The lethal time for 50 % of the population for some stored-product insects at temperature below their development threshold (from Fields, 1992).

In general, *Tribolium castaneum* Herbst, *Tribolium confusum* Jacquelin du Val and *Oryzaephilus mercator* (F.) are the most cold susceptible species, whereas *Trogoderma granarium* Everts, *S. granarius, Ephestia elutella* (Hübner), *E. kuehniella* and *Plodia* (Hübner), are the most cold tolerant species, with the rest of the stored-product insects falling between these two extremes (Fields, 1992; Fields and Muir, 1995). Although the moths are some of the most cold tolerant stored-product insects, their inability to penetrate deeply into the grain mass makes them more vulnerable to cold temperatures. The life stage that is the most cold-hardy varies with the species. For the few insects with a diapause, such as *P. interpunctella*, the diapausing stage is the most cold-hardy. For other insect species, it can be any stage.

One factor that is often neglected when considering insect survival at low temperatures is the ability of insects to acclimate to cold. At temperatures between 20 and 0 °C insects increase their tolerance to low temperatures. There are a number of physiological changes, such as, higher concentrations of cryoprotectants, clearing of ice nucleators, changes in the cell membrane, within the insect responsible for this increase in cold hardiness. Depending upon the insect's ability to acclimate and the manner in that it is acclimated insects can be four to ten times more cold-hardy than unacclimated insects (Fields, 1992; Burks et al., 2000)

Low temperature has been used occasionally to control insects in warehouses and flour mills in Canada (Fields 1992). However, it has fallen out of use because of the need to empty water and the unpredictability of low outside temperatures, -17 °C, needed to control insect populations.

High temperature

Sensitivity of stored-product insects to heat has been known for thousands of years. The first recorded use of high temperature to disinfest grain was in China, 1,500 years ago (Liu et al., 1983). There are records from the late 16th century in France to control *Sitotroga cerealella* (Olivier) and in US flour mills in the early 20th century (Fields, 1992). Heat continues to be used as a method of control insects in structures and equipment of food processing facilities today. There are two general areas that heat is used with stored products, either to disinfest commodities such wheat seed or to disinfest structures and equipment. There are several good reviews of the use of heat treatment to control stored-product insects (Evans, 1986; Fields, 1992; Mason and Strait, 1998; Burks et al., 2000, Dosland et al., 2005; Beckett et al., 2006).

At temperatures slightly above those that promote the fastest rate of development, the fitness of insects rapidly fall with increasing temperature (Birch, 1953; Fields, 1992, Table 1). At temperature above 45 °C most stored product insects die within 24 h. As with low temperature, there are a number of factors that affect the mortality of insects when exposed to high temperature; duration of exposure, temperature, species, stage and acclimation. It is difficult to compare results between studies, because there a number of different methods to heat the grain, durations at the high temperatures are short and the media the insects are placed effect the rate of heating. There are a few studies that have compared several species using the same methods (Fields, 1992) and they found that *Ephesita* spp, *Oryzaephilus* spp, *P. interpunctella* and *Sitophilus* spp, are the least tolerant of heat, followed *Tribolium* spp, and the group that is the most tolerant of heat are *Lasioderma serricorne* (F.), *Rhyzopertha dominica* (F.) and *Trogoderma* spp. As with low temperature, there is no general rule which stage is most heat tolerant, and there can be an 8-fold difference in sensitivity to heat between least and most tolerant stage. When exposed to high temperatures, insects produce heat shock proteins, which help mitigate the harmfully effects of the heat (Dosland et al., 2005). However, acclimation does not affect heat tolerance or has only a minor effect on the amount of time (three-fold increase) required to kill insects, whereas acclimation to cold is common and can increase the durations required to control insects by a factor of 10. There have been a several models developed to predict the mortality at high temperatures (Beckett et al., 2006; Jian et al., 2006).

One difference between low temperature treatment and high temperature treatment is that high temperature can damage the product, whereas low temperature rarely causes damage. In addition to the efficacy of heat treatment, the effects on the target commodity must also be evaluated to verify that there is no loss in quality in the commodity. Sometimes there is only a very narrow window of temperature-time that kills the insects, yet does not damage the commodity. The narrower this window, the better the control of heating and cooling must be. This is one of the reasons that fluidized-bed heating was been developed for heat treatment of grain (Evans et al., 1983; Beckett et al., 2006).

Methyl bromide is a structural fumigant that is used widely in flour mills, cereal processing facilities and warehouses. However, it is being phased out because it depletes stratospheric ozone (Fields and White, 2002). This has meant there is a renewed interest in heat to control insects in these facilities. A common approach to heat treatments is to heat the structure to 50 ^{o}C air temperature for 24-36 hours, with a rate of heating or cooling of not more than 5 ^{o}C/hour (Imholte and Imholte-Tauscher, 1999; Fields and White, 2002, Dosland et al., 2006). Although, insects die in a few minutes at 50 ^{o}C, at least 24 hours is needed to insure that all locations in the facility receive adequate heat. Good air circulation is important to distribute the heat within the structure, and additional fans are often used to distribute the heat.

Monitoring of the temperatures is often done by handheld electronic thermometers. This should be done at hourly intervals throughout the building to insure that heat is well distributed, heaters, fans are functioning and sprinklers are not activated. Some basic precautions should be taken to avoid heat stress of workers (Anonymous, 1992).

Some modifications may be required before a structure is heat treated. Sprinkler heads should be rated for at least 85 ^{o}C. Some electronic equipment may have to be removed or enclosed and provided with cool air. Some plastics (e.g. brooms and water lines) may warp with the heat. Fire extinguishers should be removed before the heat treatment. Certain food additives are heat sensitive, and should be removed before the heat treatment. As with a methyl bromide fumigation, the structure and the equipment should be cleaned of food residues to allow good penetration of the heat (Fields and White, 2002, Dosland et al., 2006).

Low moisture grain

The main source of water for stored-product insects is their food. A few insects, such as *L. sericorne*, larvae can absorb water directly from the atmosphere at r.h. of 55 % and higher. As with temperature, there is an ideal range of moisture which is ideal for growth and development. Moisture content of the food affects the number of offspring, rate of development, longevity and survivorship to adults. For *S. oryzae* at 14 % m.c. there is only 10 % mortality of immatures and females lay on average 344 eggs, whereas at 10.5 % m.c. there is 75 % mortality of immatures and females lay only a total of 10 eggs.

Moisture content of crops at harvest varies enormously between years, regions and crops. For example in Australia, wheat is almost never dried and goes into storage between 9-12 %. Whereas, maize in the US Midwest is harvested at 18 % m.c., and it must always be dried to approximately 15 % m.c. before being placed in storage. There are several types of grain drying; solar aided, ambient air or heated air (Jayas and White, 2003; Parde et al., 2003). There seems to be good evidence that heated grain dryers can be used to disinfest grain (Banks, 1998; Qaisrani and Beckett, 2003). However, the grain dryers are used at the beginning of storage, rather than a few months after storage when the insects become a problem.

In all countries, there are maximum levels of moisture content that are allowed in grain. In Canada for wheat this it can be no more than 14.5 % m.c., in France no more than 15.5 % m.c. in Australia it is 12.5 % mc. As grain is sold throughout the world on a wet-basis, there is an economic disincentive to store cereals lower than straight grade, despite the advantages in insect growth and lower mould growth at the lower m.c.

Inert dusts

Inert dusts are powders that render the insects more sensitive to desiccation. Inert dusts can be divided into four groups; clays and ashes, minerals, diatomaceous earth (DE) and synthetic silica aerogels. There are a number of reviews on inert dusts (Ebeling, 1971; Banks and Fields, 1995; Fields and Muir, 1995; Korunic, 1998; Subramanyam and Roesli, 2000; Fields and Korunic, 2002). There has been extensive speculation about how inert dusts kill insects (Subramanyam and Roesli, 2000), but the most accepted explanation is that the inert dusts damage the waxy layer of the cuticle of the insect causing the insects to lose so much water that it eventually dies from desiccation.

Of the many inert dusts, only DE and silica aerogels are used extensively. DE are the skeletal remains of single celled algae, diatoms. DE is mined from chalky deposits found around the world, from diatoms that lived millions years ago. The DE used in stored-products has a high concentration of silica dioxide and less than 1 % crystalline silica dioxide, a form of silica that is carcinogenic. DE is registered for the control of stored-product insects in many countries: Australia, Brazil, Canada, Croatia, Denmark, Germany, Indonesia, Japan, Saudi Arabia, United Kingdom and USA. In Australia, USA and Canada DE is used mainly in empty silos and in empty structures in wall voids. Grain can also be treated directly with DE, but there are some factors which limits it use as a grain protectant.

The main advantages of DE are; it has a very low mammalian toxicity and as long as the grain or structure remains dry it will be effective. The main limitations that hinder its widespread use are: grain must be below 14 % m.c. or lower depending upon target species and type of DE applies, it is dusty for workers to apply, it reduces the bulk density of grain (4-10 %, Korunic et al., 1998) and it reduces the flowablity of grain. Unlike synthetic insecticides, DE deposits have a considerable variation in efficacy, over a ten-fold difference in efficacy has been seen (Korunic, 1998). Korunic (1997) has developed a rapid method of assessing the potential efficacy of natural DE.

Hermetic storage

Most grain storage structures have many avenues of entry for insects into the grain mass; cracks in the concrete, openings metal sections of bolted steel silos or ventilation ducts. With care, silos can be made to prevent the entry of insects, but also to be so welled sealed, even gas can not enter. Hermetic storage is widely used in Australia, China and Israel (Andrews et al., 1994; Banks and Fields, 1995; Alder et al., 2000).

The oxygen in hermetic storage drops to zero preventing the development of insect infestation and mold. In Australia, they have developed hermetic bins that have seals at the grain load-in and load-out and an oil-filled air-lock that allows for changes in air volume in the storage caused by diurnal or seasonal changes in temperature (Andrews et al., 1994). Researchers in Israel have developed a portable system that has been commercialized by a US company, GrainPro and can be used for bagged products with a total capacity ranging from 5 to 1,000 t.

Impact

Insects can die when grain or flour is moved. Grain and processed cereal products are constantly being moved, as the place that the grain is grown, is often thousands of kilometres from where it is finally consumed. Certain types of movement, such as a screw auger or a bucket elevation will cause very little mortality (Fields and Muir, 1995), or considerable mortality (Joffe, 1963) whereas pneumatic conveyance is very effective at controlling insects at the farm (White et al., 1997) or unloading ships (Bahr, 1991).

Impact machines or Entoleters have been used in flour mills since the 1940 s to control insects either within the grain or in flour (Fields and Muir, 1995; Plarre and Reichmuth, 2000). The grain or flour drops on to a rapidly spinning disk studded with pins. Insects or grain with internal infestations hit the pins and the insects are killed on impact. The speed of the product throughput, velocity of pegs, and the number of pegs determine the efficacy.

Varietal resistance

Breeding resistance to plant diseases and Hessian fly and wheat midge has been done successfully in the USA and Canada with wheat. However, I know of no program to breed resistance to stored-product insects in wheat. There is a program to breed resistance for both field insects and storage insects with maize (Bergvinson, 2001). Throne et al. (2000) reviewed the work that has been done on varietal resistance in cereals and legumes. There have been several assessments of differences in susceptibility of wheat to stored product infestation. Sinha et al. (1988) and McGaughey et al. (1990) found that although there were some small differences between classes of wheat, there were no differences within a class. Amos et al. (1986), working with some experimental varieties found a four-fold difference in number of offspring produced by *R. dominica* and a two-fold difference with *S. oryzae* between varieties, so there are resistance characteristics that could possibly be incorporated into a commercial variety of wheat that would have better storage capacity.

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