Physical Control Methods in Plant Protection

With 102 Figures and 34 Tables
Control of Insects in Post-Harvest: Inert Dusts and Mechanical Means

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1 Introduction

Residual chemicals are currently used to control stored-product insects pests that are found in granaries and food-processing facilities. Long-term use of these chemicals has resulted in the development of insect populations that are resistant to the common insecticides (e.g. malathion, chlorpyrifos-methyl, pirimiphos-methyl, fenitrothion or deltamethrin) (White and Leesch 1995). Inert dusts are used in a fashion similar to the residual chemicals, and hence offer a convenient alternative for the control of insect pests in grain-and food-processing industry installations such as flour mills, food warehouses and retail outlets.

Inert dusts have been used for thousands of years (Ebeling 1971). Today, diatomaceous earth and silica gel are the predominant inert dusts used commercially, both of which are composed of silicon dioxide. Over the past 15 years, research has been directed at new dust formulations based on silicon dioxide. Formulations that are effective at 1000 ppm (or a lower rate) have been developed, and are now used around the world (Fields and Muir 1995; Banks and Fields 1995; Golob 1997; Korunic 1997; 1998). A recent workshop dealt with all aspects of diatomaceous earth as a protectant for stored grain (Fields 1998).

Mechanical control is another ancient method of controlling stored-product insects and it is still in use today (Fields and Muir 1995; Banks and Fields, 1995). This approach is used extensively in flour mills, and may become more widespread due to the impending ban of methyl bromide, a fumigant that is widely used in flour mills. Methyl bromide is slated to be banned in most parts of North America and Europe by 2005 because it is an ozone-depleting substance. Wheat that is destined to be milled into flour, or durum and corn that is to be milled into semolina, can also be disinfested by impact machines that hit grain hard enough to kill insects within the kernel. In some cases, pneumatic conveying of grain is sufficient to control certain insects in certain life stages. Some mites and lepidopteran larvae can be controlled simply by moving the grain.
2 Inert Duffs

2.1 As Traditional Grain Protectant

Ashes have been used as an insecticide for thousands of years by aboriginal peoples in North America and Africa (Ebeling 1971). Modern research on inert dusts to protect stored grain began in the 1920s (Ebeling 1971; Fields and Muir 1995; Golob 1997; Korunic 1997, 1998). The main advantage of inert dusts is their low toxicity to mammals. In Canada and the USA, diatomaceous earth is registered as an animal feed additive, and silicon dioxide is registered as a human food additive. Silica gel has an acute rat LD₅₀ of 3160 mg kg⁻¹ (Ebeling 1971). Other advantages of inert dusts are that they are effective for long periods and do not affect end use quality of the product (Desmarchelier and Dines 1987; Korunic et al. 1996).

There are four types of inert dusts: (1) powdered clay, sand and earth, (2) diatomaceous earth, (3) silica gel, and (4) non-silica dusts such as rock phosphate and lime. Powdered clay, sand and earth have been used as thick layers of dust on the top surface of a grain bulk. Diatomaceous earth is made up of the fossilized skeletal remains of diatoms, single-celled algae that are found in fresh and salt water. Diatoms are microscopic and have a fine skeleton made up of amorphous silica (SiO₂ + n H₂O). The accumulation of diatom skeletons over thousands of years produces the sedimentary rock, diatomaceous earth. The diatomaceous earth deposits currently mined are millions of years old, and certain deposits are hundreds of meters thick. The major constituent of diatomaceous earth is amorphous silicon dioxide (SiO₂) with minor amounts other minerals (aluminum, iron oxide, calcium hydroxide, magnesium and sodium). Its insecticidal properties depend upon the geological origin of the diatomaceous earth, some types being 20 times more effective than others (Korunic 1997). The diatomaceous earths that are the most effective in insect control have SiO₂ content above 80%, a pH below 8.5, and a tapped density below 300 g l⁻¹ (Korunic 1997). Silica gels, which are produced by drying aqueous solutions of sodium silicate, are very light hydrophobic powders (Quarles 1992). Non-silica dusts, such as rock phosphate, have been used in Egypt. Tests have shown that lime (calcium oxide) has some insecticidal activity (Fields and Muir 1995).

2.2 Mode of Action of Inert Duffs

Insects die when they have lost approximately 60% of their water or about 30% of their body weight (Ebeling 1971). Since stored-product insects are small and have a high surface to volume ratio, it is particularly difficult for them to maintain their water balance in very dry habitats such as granaries of dry grain. Insects have sever-
eral mechanisms to deal with desiccation, but the cuticle is one of the more important ones; however, it is sensitive to damage by inert dusts.

When insects move through the grain, inert dusts adsorb their cuticular waxes (Le Patourel et al. 1989). The mode of action of silicon dioxide-based inert dusts is generally accepted to be desiccation rather than abrasion. Two observations support this conclusion. First, inert dusts are more effective when the grain moisture content or the relative humidity is lower. Second, insects treated with inert dusts usually have higher rates of water loss (Fields and Muir 1995). The following species have been ranked as most to least sensitive to diatomaceous earth: Cryptolestes spp., Oryzaephilus spp., Sitophilus spp., Rhyzopertha dominica (F) and Tribolium spp. (Carlson and Ball 1962; Fields and Muir 1995).

Tolerance to desiccation is usually, but not always, positively correlated with tolerance to inert dusts. There are several possible reasons for these differences. Insects that can use metabolic water would be less sensitive to inert dusts. Species that have a better reabsorption of intestinal water also would have an advantage, as well as those that have a more waterproof cuticle. Thus, the composition of the cuticular waxes can be an important factor. The role of the cuticle depends on how much diatomaceous earth it can pick up. A sensitive species such as Cryptolestes ferrugineus (Stephens) picks up much more than Tribolium castaneum (Herbst) (Fields and Kornic 1999).

Behaviour may also play a role. Insects that move extensively through the grain, such as C. ferrugineus, may be more damaged than insects that are more sedentary, such as R. dominica. Insects are repelled by diatomaceous earth, which is an important consideration when only part of the grain bulk is treated, such as in top dressing. Finally, the type of grain also determines the effectiveness. Of the following grains, milled rice requires the greatest amount of diatomaceous earth for control of its insect pest, followed by sunflower, maize, paddy rice, oats, barley, wheat and durum, in that order.

Despite the numerous advantages of inert dusts, they have seen limited use. However, there has been an increase in use in the past decade due to concerns over the effects of chemical insecticides on worker safety, food safety and development of resistance by insect populations. Diatomaceous earth is registered as a grain protectant or for treating storage structures in Australia, Canada, USA, Croatia, Germany, China and some other Asian countries. In Australia, diatomaceous earth is used principally as a treatment for empty silos. However, it can also be used to treat the entire mass of feed grain. In all other countries, diatomaceous earth can also be used to treat grain aimed for human consumption. In India, during the 1960s, 70% of the grain was treated with activated kaolin clay. Egypt used rock phosphate and sulphur (Ebeling 1971).

The main problem with the use of diatomaceous earth is that it reduces grain bulk density and grain fluidity (Kornic et al. 1996; Fields 1998). Adding diatomaceous earth at 2 kg t⁻¹ reduces grain bulk density by approximately 4 kg hl⁻¹ for maize and by 6 kg hl⁻¹ for wheat. Another limitation is that grain must be dry for the diatomaceous earth to cause enough desiccation to control insect populations.
Application of inert dusts can be undesirable because of the dust generated. Diatomaceous earth can be used as a mild abrasive, and there is concern over increased wear on grain-handling machinery. However, diatomaceous earth is relatively soft, its Moh's hardness index being 2, which is softer than that of gold (2.5-3), copper (2.5-3), nickel iron (5), quartz (7) and diamond (10) (Glover 1997). It is necessary to determine to what extent diatomaceous earth increases wear on grain-handling and milling equipment.

Depending upon the source and processing method, diatomaceous earth can contain from 0.1 to 60% crystalline silica. Diatomaceous earths registered as insecticides generally have less than 7% crystalline silica. For other uses, diatomaceous earth is heated or burned and the crystalline silica content can increase up to 60%. Crystalline silica has been shown to be carcinogenic if inhaled (IARC 1997). Proper masks should therefore be used when handling diatomaceous earth of high crystalline silica content.

One solution to the airborne dust problem is to apply the diatomaceous earth in a water suspension. This method of application is widely used in Australia to treat empty structures (Bridgeman 1998). However, slurry application does somewhat reduce their effectiveness (Maceljski and Korunic 1971). On the farm, diatomaceous earth can be blown into empty granaries through the aeration ducts.

Another way to reduce the problems associated with diatomaceous earth is to lower the concentration needed to achieve control. A mixture of diatomaceous earth (90%) and silica gel (10%) is twice as effective as diatomaceous earth used alone (Korunic and Fields 1995). Silica gels are very effective, but they greatly reduce grain bulk density and are so light that they are difficult to apply to grain. This is another reason why it is better to use them in a mix with diatomaceous earth.

Insect resistance to residual insecticides has been one of the factors motivating the search for alternatives to chemical insecticides. Laboratory experiments have shown that the susceptibility of T. castaneum, C. ferrugineus and R. dominica can drop significantly when exposed to diatomaceous earth for five to seven generations (Korunic and Ormesher 1998). Although there are no reported cases of insects developing resistance to diatomaceous earth under field conditions, these results suggest that it will be necessary to use resistance management strategies to prevent widespread resistance to diatomaceous earth products.

Diatomaceous earth can be combined with other treatments to increase the effectiveness (Bridgeman 1998). In Australia, diatomaceous earth is used as a top dressing in conjunction with long duration, low dose phosphine fumigation (SiroFlo). The major limitation of SiroFlo used alone is that phosphine concentrations are too low to obtain control at the surface of the grain bulk. Diatomaceous earth serves a dual function: it controls insects directly, and provides a physical barrier to retain the phosphine. Diatomaceous earth is also used as a top dressing, in conjunction with cooling of the grain mass by ambient air or refrigerated air aeration. Low temperatures slow or stop the development of insects, but it is difficult to maintain the grain surfaces at low temperature. Diatomaceous earth can also be used in conjunction with heat. One method to control insects in food-processing facilities is to
raise the air temperature of the building to 50 °C for 24 h. In one experiment, it was found that control of Tribolium confusum J. du Val was obtained at 41°C when diatomaceous earth was also used, whereas a temperature of 47 °C was needed in the absence of the dust (Doudy and Fields, in press). Diatomaceous earth could make heat sterilization more acceptable to the industry because it would require lower temperatures to obtain control. As the use of methyl bromide as fumigant declines, new methods such as diatomaceous earth and heat will become more widely used.

3 Mechanical Means

Stored-product insects are very sensitive to mechanical shock. Even the effect of the movement of grain during conveying can reduce the fecundity of the insect and prevent a normal population increase (Banks 1986). However, the only mode of grain transportation that destroys significant numbers of individuals, including internal stages, are pneumatic conveyers (Fleurat-Lessard 1985, White et al. 1997, Paliwal et al. 1999).

3.1 Traditional Uses in Stored Grain

In 19th century France, mechanical mixing of grains was seen as a replacement for the traditional hand shoveling of grain that was usually stored on a wooden plat-

![Diagram](image)

**Fig. 1.** Cross-sectional view of a mobile granary invented in the first half of the 19th century to prevent insect infestation in grain stored for long durations. It was made up of a rotating cylinder with internal baffles (Vallery 1839).
form in layers of thickness 30 to 50 cm (Sigaut 1978). The first real attempt at mechanical mixing was a rotating granary (Vallery 1839). It consisted of a large horizontal drum with internal baffles and an axle running through the centre (Fig. 1). The concept of keeping the grain in motion, one which was used later for the design of certain grain dryers, offered the advantage of reducing the number of seeds infested by pests that must bore holes into the seed to lay their eggs or to begin their development (e.g. Sitophilus spp., R. dominica, and bruchids). This also reduced feeding and mating. More recent studies have shown that disturbing the grain, either continuously or periodically, reduces the reproductive potential of insects significantly (Joffe 1963; Bahr 1990). Joffe (1963) showed that turning maize every 2 weeks reduced Sitophilus spp., Tribolium spp. and Cryptolestes spp. by 87.75 and 89%, respectively. Pneumatic conveyors can reduce internal stages of S. oryzae by up to 85% (Fleurat-Lessard 1985), and external insects, such as Oryzaephilus surinamensis (L.) and C. ferrugineus and T. castaneum by over 90% (Bahr 1990; Paliwal et al. 1999). Bruchid larvae, such as Acanthoscelides obtectus (Say), can be effectively controlled by moving the beans every 8 h. Eggs are laid outside the bean, and first instar larvae take about 24 h to bore through the seed.

Fig. 2. Impact device (entoleter) used to destroy insects in whole grain or flour by the centrifugal forces.
coat. Moving the beans causes the larvae to lose the pit that they have started to bore in the seed coat, and they eventually die from starvation or crushing during movement (Quentin et al. 1991).

An indirect method of mechanical control that is widely used in mills is the exclusion of insects by sieving. Most cleaning sieves have a mesh size of 2 mm that separate the adult insects and other impurities from the flour. High-volume centrifugal separators can eliminate over 80% of external stages with a single pass. It is recommended that flour be passed through sieves with an opening of 0.6 to 0.8 mm, just before bulk storage or bagging of the finished product. This eliminates adult insects, but does allow the passage of insect fragments.

Another common physical control is obtained by impact, using devices called entoletes. Flour is projected onto a spinning disk equipped with pins. All insect stages are killed as they hit the pins or the walls of the entoletor (Fig. 2). The use of the entoletes is one of the final processing steps before packaging or bulk storage.

3.2 Integration into the Preventive Control Strategies for the Cereal Industry

Originally, the impact desinfestor were only used to destroy insects in flour (Stratil et al. 1987). They are now used to disinfect grain just before it enters the first grinding mill. It was noted that grain with internal feeders, such as Sitophilus spp., would break apart more easily than uninsected grain. Impact experiments showed that over 90% of the internal stages of S. granarius were destroyed when the kernels reached a speed of 33 m s⁻¹. However, under these conditions, 4-12% of uninsected kernels is also broken (Bailey 1962). These studies served as a starting point for using flour entoletes as a method of breaking infested kernels so that sound kernels can be separated from infested ones before milling (Fleurat-Lessard 1989), thus reducing insect fragment counts in the flour. The entoletes should be running at 1500 rpm⁻¹ to maximize the control of internal insects stages in grain, whereas a speed of 3000 rpm⁻¹ is needed to control insects in flour. If the entoletes are used at an appropriate stage of processing, one can ensure that flour or milled products are free of live insects or insect fragments (Fleurat-Lessard 1989). French mills that export a large percentage of their product must have entoletes to ensure that the flour will meet export standards (Fusillier 1986; Lagarde 1986) (Fig. 3).

Another inconvenience of impact desinfestor is that they can change the end use quality. For example, couscous semolina will be broken into smaller particles. Flour is not altered significantly by impact devices, but flour that becomes filled with air during treatment can have rheological properties slightly different from untreated flour.

Pneumatic conveyers can also reduce stored-grain insect populations. High throughput (38 t h⁻¹) pneumatic conveyers used at ports to unload ships, effectively control the adults of Sitophilus oryzae (L.), R. dominica and Cryptolestes spp. Insect mortalities of 48 to 95% have been observed immediately after pneumatic
Fig. 3. Flow chart of a cleaning processes of wheat and flour in a flour mill used to reduce insects and insect parts in the final product using separators and impact devices (After a Buhler-Miqag diagram).

conveying, whereas the mortality was 99% 1 week later (Bahr 1990). There are pneumatic conveyers designed for farm use that convey grain at a rate of 3 to 5 t h⁻¹. Moving wheat with a small pneumatic conveyer gave 100% control of C. ferrugineus and T. castaneum larvae and adults. Moving grain with the conventional auger caused 89% mortality of T. castaneum and 94% mortality of C. ferrugineus (White et al. 1997; Paliwal et al. 1999). Pneumatic samplers used in large grain-handling facilities can themselves cause mortality and give a false impression of live insect populatons. Insect-infested grain fed into a pneumatic sampling system at a terminal elevator that carried grain at 11 m s⁻¹, caused 73, 65, 65 and 22% mortality of C. ferrugineus, O. surinamensis, T. castaneum and Sitophilus granarius (L.), respectively (Bryan and Elvidge 1977).

Stored-product mite populations are greatly reduced when grain is moved pneumatically or by more conventional methods. However, mites can rapidly reestablish themselves if the moisture and temperature conditions are favourable. Survival of mites was 2 to 3% following movement of the grain by an auger, whereas there was no survival when pneumatic unloading was used (White et al. 1997). Moving grain within a terminal elevator using belt conveyers, bucket elevators and a free fall from 2 to 32 m reduced psocids (Liposcelis spp.) by 0 to 70% and Cryptoleses spp. by 0 to 96% (Rees et al. 1994). Hence, the turning over of grain stocks within an elevator should reduce populations, but it does not eliminate them.
4 Conclusion

Mechanical methods were probably one of the first means of protecting stored grain from insects. These are undergoing a renaissance now that the dangers of chemical fumigants are better known. Their integration into modern grain storage techniques will be aided by the applying these techniques (e.g., entoleters, pneumatic conveyers) as a regular step of grain handling, and in some cases the level of control is similar to chemical methods. The disadvantage of most physical control methods, with the exception of inert dusts, is that similar to fumigants, they offer no residual protection, which contact insecticides can provide. This is balanced by the low probability that insect populations could develop resistance to physical methods, as they have to contact insecticides. Another advantage is that they leave no residues on the grain and can be used by organic growers and distributors.

References


