Section: Engineering

Protecting and disinfesting stored products by drying and cooling, and disinfesting stored products during handling by mechanical treatments

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Abstract

Drying and cooling nonperishable products sufficiently to achieve effective protection or disinfestation has been considered difficult in the case of the former and mostly impractical in the case of the latter. Physical methods of disinfestation that could be incorporated into the handling process, such as cleaning and mechanical impact have either not given complete pest control or have caused unacceptable grain damage. Thus chemical options, particularly phosphine fumigation, have remained the main method of pest control. However, minimal use of chemical treatments is becoming increasingly necessary. Apart from market forces and stricter food safety standards, insect resistance to phosphine is growing and chemical alternatives are limited. In light of these circumstances, this paper reviews the effectiveness of grain drying and cooling not only as a means of protecting against insects and mites during storage, but also as a means of disinfesting during the drying and cooling process. Opportunities are identified that might capitalize on a specific pest's response to such conditions. The level of pest control that can be achieved when manipulation of grain temperature and moisture is used in conjunction with mechanical disinfestation is also considered. Recent studies of grain cleaning are reviewed and fresh data from mechanical impact research are presented on the mortality of *Sitophilus oryzae*, *Rhyzopertha dominica* and *Tribolium castaneum*. These data show real promise that mortality of insect development stages within grain kernels can be obtained at levels above 99% without damage to commodities such as wheat, which would overcome a major limitation to the technology. The results of the mechanical disinfestation research are discussed as part of a pest control strategy that includes the combined effects of grain drying, cooling and handling, to help deliver pesticide-free grain and extend the life of phosphine by restricting the development of resistance.

Keywords: Drying, Cooling, Handling, Aeration, Mechanical impact, Disinfestation

1. Introduction

Storing nonperishable products under dry, cool conditions is essential to maintain the quality of the product and minimize contamination by insects, mites and microbes (Hall, 1970). Drying grain with either ambient or heated air allows the product to be harvested at relatively high moisture content and, then with the active removal of moisture, stored at conditions that protect against fungal growth and infestation of mites and stored product insects. Aeration with ambient or chilled air cools the product to temperatures that maintain the quality required for its subsequent purpose, and reduces or stops the population growth of pest species or the development of fungal contamination. However, achieving the conditions required for effective protection and disinfestation has been considered limited by drying and, apart from limited circumstances, impractical by aeration or chilling.

Mechanical techniques that can be incorporated into handling processes, such as cleaning, can achieve substantial levels of disinfestation. Physical impact has generally been more effective against immature stages of primary pests developing inside grain kernels, but the trade off has been unacceptable levels of grain damage (Banks and Fields, 1995). These technologies have, therefore, been considered either insufficiently effective or having inherent limitations. Another physical method which can kill all stored-product pests without grain damage is heat treatment, but it is costly by comparison (Sutherland et al., 1987). Thus, chemical methods, primarily phosphine fumigation, have remained the mainstay of pest control.

The need for a minimal use of pesticides is becoming increasingly important. This is not only in response to market forces and stricter food safety standards, but also as a means of limiting the development of insect resistance, which is becoming increasingly critical. It is essential in the case with phosphine, where no alternatives are as versatile and effective. In light of these circumstances, it is timely to review not only the limiting effect that grain drying and cooling have on the population growth of stored product insects and mites during storage, but also the disinfesting effect that occurs during the drying and cooling process. This is done with a view to identifying opportunities that might capitalize on a specific pest's response to such conditions.

These opportunities may be enhanced in combination with mechanical disinfestation, either before or after storage. Data from recent research on mechanical impact will be presented that show real promise that mortality of insect development stages within grain kernels can be obtained at levels above 99% without damage to commodities such as wheat. This would overcome a major limitation to the technology and may allow mechanical treatments to play a substantial role in grain disinfestation, especially in a pesticide-free environment where the advantages of drying and cooling can be maximized. This paper will explore these possibilities.

2. Protection and disinfestation from grain drying and cooling

2.1. Drying

Storing a dry product has particular advantages for insect and mite control. The effect of aridity can be demonstrated by the mortality of *Oryzaephilus surinamensis* (L.) (Coleoptera: Cucujidae) during immature development (Beckett and Evans, 1994) (Fig. 1). At 30°C the level of mortality is 14.5% at 70% r.h., but 42% at 30% r.h. (approximately 9% m.c.). However, at 20°C mortality is 46% at 70% r.h., but as much as 99% at 30% r.h. Not only is there a significant level of disinfestation, but development time is also extended by 10 and 12 d respectively, affording additional protection in terms of slower population growth. Drying is particularly important as a means of controlling psocids and mites as both are particularly sensitive to aridity and can not survive at any temperature below about 60% r.h. for psocids (Rees, 2004) and 65% r.h. for mites (Navarro et al., 2002). However, maintenance of such conditions at the grain surface can be a challenge particularly in a maritime climate (Armitage and Cook, 2003).

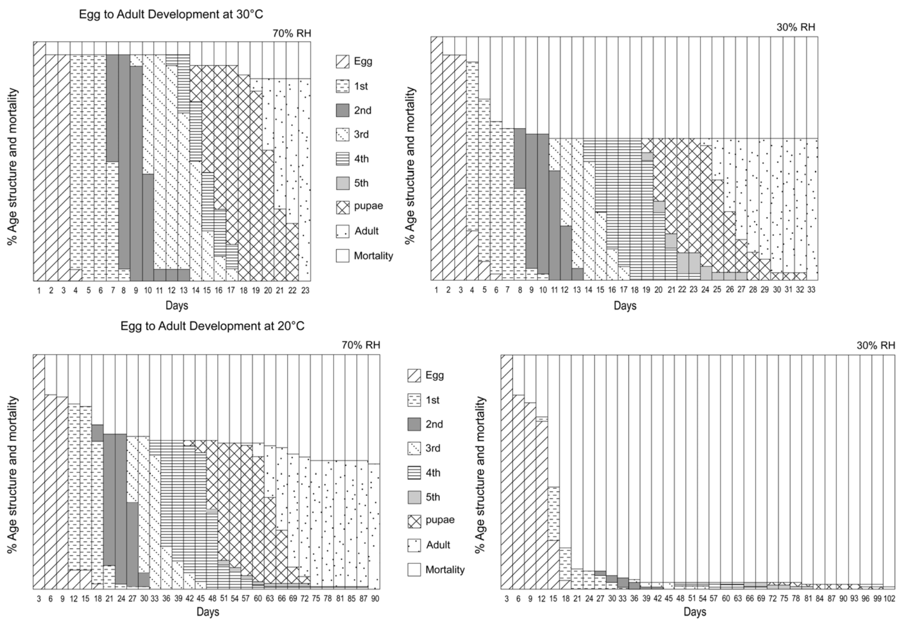

Figure 1 The effect of temperature and relative humidity on immature mortality and development time of *Oryzaephilus surinamensis* (from Beckett and Evans (1994)).

When heat is used, grain drying can be an effective method of thermal disinfestation. Insect mortality can be achieved at grain temperatures as low as 43°C, which is the maximum recommended for malting and seed barley, seed wheat, canola, and grain legumes at high moisture contents (Metz, 2006; Hill, 1999) (Table 1). Heat tolerance at moderately high temperatures is species-dependent so it is valuable to identify a particular infestation. The time required for disinfestation at these conditions can be prolonged, so any opportunity for grain to hold heat before active cooling would increase efficacy.

Table 1 Time (h) required for 99% mortality of the most heat tolerant life stage of a range of major insect pests at different temperatures and recommended grain temperatures during drying for different grain types (from Beckett et al., (2007), Metz (2006) and Hill (1999)).

		LT_{99} (h) for the most heat tolerant insect life stage at different temperatures					
	Moisture conditions	**43°C**	**45°C**	**50°C**	**55°C**	**60°C**	**65°C**
Sitophilus oryzae	12%mc	19	8.6	2.4 (49°C)	-	<0.01	<0.01
Sitophilus granarius	13%mc	-	3.3	0.5	<0.01	<0.01	<0.01
Rhyzopertha dominica	12%mc	-	70.8	8.9	0.3	0.01	<0.01
Tribolium castaneum	22% rh	83.7 (42°C)	13.0 (46°C)	7.2	1.4	0.5	<0.01
Tribolium confusum	22% rh	-	-	1.5	1.0 (54°C)	0.4	<0.01
Psocids	70%rh	40.4	19.9 (46°C)	2.5	-	<0.01	<0.01
Trogoderma variabile	0% rh	-	-	3.6	0.07	0.04	<0.01
Recommended grain temperatures for different grains types	malting/ seed barley	Maximum					
	seed wheat	Maximum					
	canola	Maximum					
	Grain legumes	Maximum					
	milling wheat			Optimum	Maximum		
	feed grains					Optimum	Maximum

There have been a few investigations into the used of grain dryers as a practical means of rapid heat disinfestation, which would allow the capital cost of equipment to be offset (Bruce et al., 2004; Qaisrani and Beckett, 2003a,b). At higher temperatures required for heat tolerant species, potential grain damage due to drying temperature variation was a concern, while disinfestation of other species with lower heat tolerance at moderate temperatures could be achieved successfully. More research is required, but the development of dependable dryer/disinfectors holds some promise.

2.2. Cooling

Cooling grain with ambient or refrigerated aeration has particular advantages for insect and mite control as lower temperatures have considerable effect on population parameters (Aspaly et al., 2007; Beckett et al., 1994). Using the example of immature mortality and development in *O. surinamensis* (Beckett and Evans, 1994), Fig. 1 shows mortality increase from 14.5% at 30°C and 70% r.h. to 46% at 20°C and 70% r.h. and 42% at 30°C and 30% r.h. to 99% at 20°C and 30% r.h., with eggs and first instar larvae most vulnerable. The difference in development time between 30 and 20°C is 23d compared with 90 d and 33 d compared with 102 d for 70 and 30% r.h., respectively. The threshold temperatures for population growth can vary considerably. For mites it can be as low as 7°C (i.e. for *Acarus siro* (L.)(Astigmata: Acaridae)), but for major stored-product beetles it is considerably higher. For example, it is about 14°C for *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) at 70% r.h. (calculated from Nakakita and Ikenaga, 1997), and 15, 17.5, 19 and 20°C for *Sitophilus oryzae* (L.), *Rhyzopertha dominica* (F.)(Coleoptera: Bostrichidae), *O. surinamensis* and *Tribolium castaneum* (Herbst)(Coleoptera: Tenebrionidae), respectively, at relative humidities ranging from 45 to 65% (Beckett et al., 1994). Populations of *Trogoderma granarium* Everts (Coleoptera: Dermestidae) have also been shown to decline at 20°C and 70% r.h. (Burges, 2008). Major stored-product moths start breeding at 15°C or above, but *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae) and *Ephestia elutella* (Hübner) are reported to start breeding at 12 and 10°C, respectively (Rees, 2004).

Predictive models for rates of population growth in relation to temperature and grain moisture have been developed for the major stored-product pests (Aspaly et al., 2007; Driscoll et al., 2000; Kawamoto et al., 1989). The relatively low rate of population growth at dry, cool conditions near the threshold of population growth may allow storage for some time with minimal risk, if the grain is initially insect-free or the population is very small. A simple demonstration of this is by considering population doubling times (Dt) at such conditions (Table 2) ($Dt = \log_e(2)/\log_e(\lambda)$, where λ is the weekly finite rate of population growth). For example, at 18°C *S. oryzae* can double its numbers in 3.4 weeks at 50% r.h. but can not tolerate 35% r.h. at this or any temperature. *Rhyzopertha dominica* and *O. surinamensis* take about 3 and 6 months to double at 20°C and 35% r.h., and about 1.5 and 2.25 months at 20°C and 50% r.h., respectively. Data for *T. castaneum* are limited, but of the four species it appears to have the slowest rates of population growth at moderately low temperatures. In comparison, at 30°C and 50% r.h., all species will double in number in about a week.

Table 2 Population doubling times (weeks) for four major stored-product insect pests at a range of temperatures at 35 and 50% r.h. (negative numbers refer to population halving times) (Calculated from Beckett et al. (1994)).

	Temperature (°C)							
	18		**20**		**22**		**30**	
	35% r.h.	**50% r.h.**	**35% r.h.**	**50% r.h.**	**35% r.h.**	**50% r.h.**	**35% r.h.**	**50% r.h.**
Sitophilus oryzae	-34.3	3.4	-6	2.3	-3.5	1.9	-1.5	1.2
Rhyzopertha dominica	-69	∞	11.9	5.7	4	2.8	1.6	1
Oryzaephilus surinamensis	-	-	23.5	9	3.6	3.3	1.2	1
Tribolium castaneum	-	-	-	-	-	9	6.6	1.3

Where lower temperatures can be obtained, disinfestation can be achieved, but the process is slow unless temperatures are subzero. For example, Evans (1987) determined the rate of immature mortality over 12 months of six major stored product beetle species on Australian Standard White wheat at typical refrigerated aeration conditions of 13.5 and 9°C, and 11% m.c. The species tested were *Cryptolestes ferrugineus* (Stephens)(Coleoptera: Laemophloeidae), *O. surinamensis*, *R. dominica*, *Sitophilus granarius* (L.), *S. oryzae* and *T. castaneum*. After 3 months there was 100% mortality of *C. ferrugineus* at both temperatures and *O. surinamensis* at 9°C. After 9 months there was 100% mortality of *R. dominica* at both temperatures and the two *Sitophilus* species at 9°C. Mortality at 13.5°C was 97.5% for *S. granarius* and 99.8% for *S. oryzae* and *T. castaneum*. At temperatures such as these, low grain moisture content continues to have a substantial effect on mortality (Evans, 1983). Rapid cooling counteracts the development of cold tolerance through acclimation, which has been observed in several insect species, particularly *C. ferrugineus* (Fields and White, 1997), where 5% of an acclimated adult population is estimated to survive 75 days at -10°C (Fields, 1990).

Achievable outcomes and whether cooling is with ambient or refrigerated air, are determined by climate, target conditions and cost. Recent studies have shown the potential of aerating Japanese rice to 15°C using ambient autumn temperatures to control *S. zeamais* (Arthur et al., 2003), and demonstrated the ability to achieve that temperature using chilled aeration to control *S. zeamais* in stored maize in the United States (Ileleji et al., 2007). Kaliyan et al. (2007) determined the cost of disinfesting *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) using ambient aeration in regions in the United States where winter temperatures were below -10°C, and Rulon et al. (1999) developed an economic model which demonstrated that chilled aeration in some circumstances could compete with phosphine fumigation as a disinfestation method with a high value crop such as popcorn.

3. Disinfestation during handling

3.1. Grain cleaning

Quantitative disinfestation studies of specific grain cleaning machinery are limited. This author is aware of only two studies in the last 14 years, however, these reports indicate that substantial levels of insect mortality can be achieved. Armitage et al. (1996) evaluated aspirated sieving using a laboratory scale apparatus. The process successfully removed *O. surinamensis*, *S. granarius* and *C. ferrugineus* adults, and 90% of mixed development stages of two species of mites, *A. siro* and *Lepidoglyphus (Glycyphagus) destructor* (Schrank) (Astigmata: Glycyphagidae) with a grain weight loss of 4.5%. However, there was no reduction in the numbers of immature stages of *S. granarius*. Weller et al. (1998) evaluated a commercial laminar air-flow grain cleaner where the process removed 99.5% of mixed aged *T.*

castaneum and 93.5% of mixed-age *R. dominica* with a grain weight loss of less than 1.5%. It was suggested that death by physical shock or impact must play a large part in the reduction of immature *R. dominica* numbers. While cleaners could be modified to disinfest more effectively (Weller et al., 1998) and are generally successful at removing major secondary invaders such as *Tribolium* and *Cryptolestes* spp., *O. surinamensis* and psocids, it is likely that a proportion of internal developers such as *R. dominica* and *Sitophilus* spp. will remain. Subsequent cooling or fumigation is essential with infestations of these species.

3.2. Mechanical disinfestations

The challenge for mechanical disinfestation, ultimately, has been impacting the eggs and larvae of insects such as *Sitophilus* spp. and *R. dominica* that are protected within kernels without causing seed damage. Entoleters, for example, are effective as disinfesters, but they destroy a large proportion of the kernels and so are used prior to milling or for treating flour (Stratil et al., 1987). Bailey (1962; 1969) was able to demonstrate a relationship between grain impact velocity, moisture content and grain breakage on one hand, and impact velocity, impact repetition and insect mortality on the other. Recent trials have further explored the relationship between impact velocity and repetition, and grain damage and insect mortality to determine if a treatment range exists where sufficient mortality can be achieved before grain damage commences.

4. Physical impact trials

4.1. Materials and methods

An apparatus was constructed to discharge a given quantity of grain at a known velocity at a surface so that each grain kernel hit the surface unobstructed (Fig. 2). The grain could then be collected and the process repeated. The apparatus consisted of an aluminium cylinder 82-cm diameter by 60-cm high, in the centre of which was a Perspex grain container/releaser or 20-cm diameter by 1.5 cm impellor attached to a vertically mounted 2.2-kW electric motor. Grain was fed into the container through small holes in the lid. While the container spun on the motor shaft, the lid was forced down onto it by hydraulic pressure. When the container was revolving at an appropriate speed, the lid was lifted and a mono-layer of grain which had formed around the circumference was projected out against the inside wall of the cylinder. The grain was then funnelled down into a collecting bin. The speed of the grain on impact (ms ^{1}) was $2\pi r_{impellor}$rpm/60.

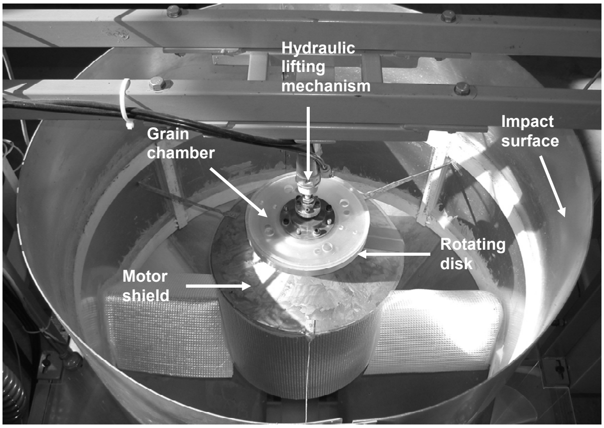

Figure 2 Vertical view of experimental grain impact apparatus.

Mortality data were collected for adults and four immature cohorts of *S. oryzae* and *R. dominica*. The cohorts progressed in age such that cohort 1 was mainly eggs and first instar larvae and cohort 4 was mainly late larvae and pupae. Mortality data were also collected for adults and late larvae of *T. castaneum*. Each replicate tested for *S. oryzae* and *R. dominica* consisted of 10 g of grain infested with 100 adults or an immature cohort, while each replicate for *T. castaneum* consisted of 10 g of grain infested with either 100 adults or larvae.

Experiments were conducted using Australian soft wheat, variety Rosella at grain velocities of 10, 15 and 20 ms^{-1} over a range of repetitions from a single impact to 45 continually repeated impacts. The time between impacts was less than 1 min. Three replicates of each development stage of each species in wheat at 11% m.c. were tested for each impact treatment. Experiments using wheat at 14% m.c. were also conducted on *S. oryzae*. Adult mortality in all three species was assessed against controls after 24 h and 7 d, while immature cohorts were incubated at 30ºC and 55% r.h., and emerging adults assessed on a weekly basis against controls. Grain quality was monitored by subjecting three replicates of 10 g of uninfested wheat at 12 and 14% m.c. to a similar range of treatments. Quality response was determined by observing the levels of germinative energy and germinative capacity (Ghaly and Taylor, 1982; Ghaly and van der Touw, 1982), following the procedure set out by the International Seed Testing Association (Anonymous, 1993). A reduction in germination due to treatment ≥3% was considered to be excessive damage.

4.2. Results

At 20 ms^{-1}, 100% mortality of all development stages of all species in grain at 11% m.c could be achieved by 7 repetitions. However, unacceptable grain damage occurred at 3 repetitions. At 15 ms^{-1}, mortality was at least 99% for all stages of *S. oryzae* and *R. dominica* by 7 repetitions, except for immature cohort 1 of *R. dominica* where mortality was 91%. In this treatment, grain quality was still acceptable, but declined rapidly with subsequent repetitions. At 10 ms^{-1}, 45 repetitions were performed before 100% mortality was achieved in all stages except for immature cohort 2 of *S. oryzae* with 98% mortality, and immature cohort 1 of *R. dominica* with 96% mortality. At this treatment, grain quality still remained acceptable (Tables 3 and 5). In general, early immature stages of *S. oryzae* and *R. dominica* were the most tolerant stages with *R. dominica* slightly more tolerant that *S. oryzae*. Conversely, *S. oryzae* adults were more tolerant than *R. dominica* adults, which were even more susceptible that *T. castaneum* adults. *T. castaneum* adults proved slightly more tolerant than larvae.

The mortality response of *S. oryzae* in grain at 14% m.c. to all impact velocities was less than that in grain at 11% m.c., particularly for immature cohort 1 (91% compared with 100% at 45 repetitions of 10 ms^{-1} and 83% compared with 99% at 7 repetitions of 15 ms^{-1}). However, there was no discernible difference detected in grain quality response (Tables 3 and 4).

Table 3 Percent mortality of *Sitophilus oryzae* in Australian soft wheat at 11% m.c. in response to a range of repeated impacts at three velocities.

		Repetitions									
	Velocity m/s	**1**	**3**	**5**	**7**	**10**	**15**	**20**	**25**	**40**	**45**
Adults	10					42	76	90	95	100	
	15		71	82	99						
	20	70									
Immature cohort 4	10					95	100		100	100	
	15			99	100						
	20	92	100	100							
Immature cohort 3	10			80	91	97	99	100	100	100	
	15	82	95	99	100	100					
	20	95	100								
Immature cohort 2	10				91	95	99	98	97	100	98
	15		95	99	100	100					
	20	88	98	99	100						
Immature cohort 1	10				58	77	85	91	92	96	100
	15		78	90	99	98	100				
	20	55	95	99							

Shaded area: ≥3% germination loss

Table 4 Percent mortality of *Sitophilus oryzae* in Australian soft wheat at 14% m.c. in response to a range of repeated impacts at three velocities.

		Repetitions									
	Velocity m/s	**1**	**3**	**5**	**7**	**10**	**15**	**20**	**25**	**40**	**45**
Adults	10					60	78	88	88	100	100
	15		73	90	99	100					
	20	69	98	100							
Immature cohort 4	10				94	97	98	99	97	100	
	15		96	99	100	100					
	20	92	100								
Immature cohort 3	10					89	96	99	99	100	
	15		95	99	99	100					
	20	90	100								
Immature cohort 2	10				79	85	94	97	97	100	
	15		91	97	99	100					
	20	77	95	99							
Immature cohort 1	10				45	60	68	72	84	87	91
	15		61	81	83						
	20	48	86								

Shaded area: ≥3% germination loss

Table 5 Percent mortality of *Tribolium castaneum* and *Rhyzopertha dominica* in Australian soft wheat at 11% m.c. in response to a range of repeated impacts at three velocities.

		Repetitions									
	Velocity m/s	**1**	**3**	**5**	**7**	**10**	**15**	**20**	**25**	**40**	**45**
Tribolium castaneum											
Adults	10				51	71	93	100	100		
	15		85	97	100	100					
	20	51	100								
Large larvae	10	5	33	45	71	92	99	100	100		
	15	19	97	100	100						
	20	99	100								
Rhyzopertha dominica											
Adults	10				56	83	100	100			
	15		98	100	100						
	20	99									
Immature cohort 4	10			97	100	100	100				
	15	96	100	100							
	20	98	100								
Immature cohort 3	10				99	100	100	100	99		
	15		99	100	99	100					
	20	96									
Immature cohort 2	10				94	98	99	99	100	100	
	15		96	98	99	100					
	20	89	99	99							
Immature cohort 1	10				76	82	91	95	98	96	96
	15		80	90	91						
	20	69									

Shaded area: ≥3% germination loss

Treatments at 3 and 5 impacts at 15 ms^{-1}, which gave moderate levels of mortality, were repeated for both *S. oryzae* and *R. dominica* in grain at 11% m.c. so that a subsequent period of cooling at 15 and 20°C could be included to determine the effects of aeration on mortality after mechanical impact treatment. Results showed 99 to 100% mortality can be achieved within 5 weeks at 15°C and even 97% mortality can be achieved at the higher temperature of 20°C (Table 6). This may in part be due to eggs and first instar larvae being particularly sensitive to cool, dry conditions similar to that exhibited by *O. surinamensis* (Fig. 1).

Table 6 The effects of cooling to 15 and 20°C for 35 days on mortality of *Sitophilus oryzae* and *Rhyzopertha dominica* after 3 and 5 repetitions of impact at 15 ms^{-1}.

Insect		*Treatment*	*Repetitions*	*Insect*
			3	*5*
Sitophilus oryzae	Cohort 1	Impact only	78	90
		+ cooling 20°C	92	99
		+ cooling 15°C	100	100
	adults	Impact only	71	82
		+ cooling 20°C	91	97
		+ cooling 15°C	97	99
Rhyzopertha dominica	Cohort 1	Impact only	80	90
		+ cooling 20°C	90	97
		+ cooling 15°C	99	100
	adults	Impact only	98	-
		+ cooling 20°C	100	-
		+ cooling 15°C	100	-

5. Discussion and conclusions

The degree to which stored grains are kept dry and cool will determine the level and range of infestation problems. If commodities are kept below 65% r.h., mites should not present a problem, and below 60% r.h. psocids should also be controllable. Below 17°C at 45 to 65% r.h., most stored-product beetles will also cause little problem, and if relative humidity is at or below 35%, *Sitophilus* spp. should also be controllable at any temperature. A few moth species will breed at temperatures below 17°C at relative humidities as low as 20% r.h.; this may be a concern. If commodities with little or no infestation can be held in well sealed facilities at appropriate storage conditions, then their status should change little y time of out-loading. However, in the areas of increased moisture (by moisture migration) with possibly increased temperatures, populations of some insects may develop rapidly.

The process of drying using elevated grain temperatures and rapid cooling to relatively low temperatures can cause disinfestion to occur if sufficient time is available. For most stored product beetles 99% mortality can be achieved at 50°C in less than 9 h. Moths are more susceptible with 100% mortality at 50°C usually reached in 2 h (Fields, 1992). Under cool conditions, 9°C for 3 months will kill *C. ferrugineus* and *O. surinamensis*, and after 9 months will kill *R. dominica*, *S. oryzae* and *S. granarius* and *T. castaneum*. However, a practical difficulty with temperature control, as it is with fumigation, is variability, particularly at the periphery of a storage structure. The financial cost of drying and cooling can also be a serious impediment which must be accounted for.

Like drying, grain cleaning also gives the opportunity to in-load grain free of most stored-product pests with the exception of those whose immature stages develop within the kernels. This could be managed if adequate cooling is possible. The removal of dockage also reduces easily accessible food sources for certain pest species (Song et al., 1990).

The use of mechanical impact combined with aeration at moderately cool conditions (20°C) is promising as a way to in-load insect-free grains such as wheat and barley. This technology may not be practical for commodities such as maize which is highly susceptible to breakage during harvesting and handling, especially at lower moisture contents (Hagstrum et al., 1996). Mechanical impact could also be used as a post-storage treatment, particularly if further research shows that complete disinfestation of eggs and first instar larvae can be achieved without the added effect of cooling. A drawback is that mechanical impact treatment requires specific grain-handling equipment designed to provide controlled grain velocities at impact; it may be difficult to achieve uniformity of treatment in commercial grain industries that are provided by drying, cooling and cleaning technologies.

Some stored-product pests show more susceptibility than others to dry, cool conditions, or drying, cooling or handling, either in terms of survival or population growth. With current developments in these technologies, it may become possible in the future to reliably store certain major commodities without chemical treatment. Adding judicious mechanical treatment may deliver them sufficiently pest-free. Moreover, any reduction or break in the use of pesticides is widely regarded as one of the best ways of managing development of pest resistance (Subramanyam and Hagstrum, 1996); this is becoming particularly urgent due to the major reliance on phosphine.

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