Applied Ecology of Stored-Product Pests

Gamila S. A. Aspaly

PhD Thesis, 2008

Supervisor: Prof Vojtěch Jarošík

Co-Supervisor: Dr. Vaclav Stejskal and Dr. Jan Hubert

Acknowledgements

In the name of Allah

I thank Allah so much, who gave me the patience to finish this work. Then, I am very grateful to Prof. Vojtěch Jarošik for his support and I would like to thank Dr. Vaclav Stejskal and Dr. Jan Hubert for their advice and helpful in numerous suggestions on preliminary version of the manuscripts. I would also like to thank Šárka Tučková and Marta Nesvorná for their technical assistance and all the staff of Stored product Department in Crop Research Institute (VURV, vvi) in Prague, for their kindness and help. Also, I am grateful to my family and my husband for their encouragement.

Finally, I thank my country for providing support and this opportunity.

Jamila Aspaly

Index

1- Introduction

Stored grain is usually stored for a minimum period of one year, and in national famine reserves for 3-4 years. In most regions there is only one annual cereal harvest. Cereals are the staple crops on which we depend so seed grains are stored about 6-8 months, on average, till the start of the next growing season. The main sources of protein in many human diets are dried pulse (beans, peas, etc.). Linnean Society report 1989 by Prof. Bunting estimated the average amount of cereal grains in storage worldwide about half of the crop biomass for the harvest of 1984 (Dennis 2002).The Food Agriculture Organization of the United Nations (FAO) estimated the world wide losses of foodstuffs, due to insects and rodents, at about 25%. (www.iaea.org/nafa/d5/public/foodirradiation.pdf). More attention was given to stored-product pests in the 1960s, while the post harvest protection has been neglected for the last 40 years. Pest control is an applied ecology (Dent 2000).

The word ecology means home or estate and it comes from the Greek “Oikos”. Hence, ecology is the study of the home, or how the household of nature is kept in order (Clarke, 1966).The stored-product ecosystem is a man made system in which determination is an ongoing process, resulting from interaction among physical, chemical and biological variables. The success of any organism depends on many factors; including environmental conditions, human factors and presence of food, places to hide and the status of competitors, predators and parasites (Sinha, 1995). Recently, the concept of the ecosystem approach to managing product systems was proposed (Arbogast and Throne 1997). Generally, the rate of development is governed by a combined effect of the relative humidity (or moisture) content of the food and the nutritive value of the diet. The optimal conditions, in terms of temperature and relative humidity, have to be equated to the tolerance limits.

Many species are quite cosmopolitan due to the transportation, in trade between different regions, of these species over several centuries. For example, Synanthropic rodents (rats and mice, family *Muridae*) are regular and serious pests in stored products. One side effect of rodent infestation of human food and water supplies is the transmission of disease organisms. Also, arthropods contain large groups of insects and mites, which are considered stored-product pests. For example Class Arachnida, especially order Acarina (Mites) contains several pest species. However, only a small number of mites are serious pests in stored products. *Acarus siro* L. (Flour mites, family Acaridae) is a serious international pest of stored grain products and other foodstuffs. This pest impairs germination and reduces the nutritive value, and can also cause a dermal irritation known as bakers itch. *Tyrophagus putrescentiae* L. attacks foods rich in fat and protein (Dennis 2002). These insects also cause losses in weight and value of the products, in addition to the allergies, which are caused by insect feces and fragments. Psocids and beetles constitute serious problems in the food industry, as their infestation of grain and flour decreases the food quality. They also produce allergens that endanger public health (i.e. the food industry workers and the final consumers) (Arlian,2002). In the Czech Republic, allergenic-mites are abundant and frequent pests in cereal stores, under the local conditions, and *Tribolium* is a key pest in horizontal grain stores (Stejskal et al. 2003). Currently, chemical control of storage mites and insects is facing serious problems. Resistance to some insecticides and acaricides has been recorded (Thind and Muggleton, 1998) and several classes of potent acaricides, organophosphates in particular, are under consideration and may be excluded from use in urban and storage environments (Collins, 2006). Apart from the problem with potent acaricide and insecticide availability, in developed countries, customers tend to refuse grain containing any chemical residues. Thus physical control, which includes management of grain moisture and temperature, is likely to remain the major viable option for the control of mites and insects in stored grain (Arthur and Flinn, 2000). Moisture and temperatures are known to limit population growth of stored-product mites (Solomon, 1962). Burks, et al. (2000) gave a comprehensive overview on the effects of temperature and thermal treatments for stored product protection. Also, the use of botanical insecticides was starting to control stored pests, as a safe alternative for humans. Higher plants are considered to be a rich source of novel insecticides (Prakash and Rao, 1997).

Historically, botanicals were used long before other kinds of pesticides. The ancient Chinese, Greeks and Romans used plants or plant extracts with sulfur and arsenic as insecticides (NAS, 1969; Tschirley, 1979). More than 2000 plant species with insecticidal properties have been characterized (Grainge and Ahmaed, 1988). Legumes contain a wide range of allelochemicals with toxic and deterrent affect against many stored-product insects (Bell, 1978; Harborne et al., 1971). These chemicals reduce the reproduction of many stored-product insect pests and it is unlikely to have negative effects on mammals (Bodnaryk et al. 1999). Peas (*Pisum sativum* L.) are toxic to some stored-product insects (Fields, et al. 2001). The use of botanicals, for the sake of human health, has expanded greatly in recent years; as most insect deterrents in nature work by softer modes of action than do acutely toxic insecticides, using behavior modifying and growth reducing effects (Catherine et al 2005).

2. Literature review

Ecology refers to the environmental factors surrounding stored products, such as temperature, humidity (stored product moisture), and nutritional quality of the food. These ecological factors have a tremendous influence on the biological performance of product pests (Clarke, 1966).

2.1. Stored-product pests- arthropods: characteristics and ecology

Arthropods include insects and arachnids.

2.1.1 Insects

Insects have infested stored food products since the beginning of human civilization. Many of the pest species found in stored products do not normally occur on wild host plants or in non-human habitats, but are fully adapted to storage systems. Most pests have a worldwide distribution because they have been spread by people. The exact origins of stored-product insects are unknown. They are assumed to be tropical or subtropical in origin, because of their ability to thrive under warm conditions. Insects associated with stored products belong primarily to three insect orders: Coleoptera, which includes beetles; Lepidoptera, which includes moths; and Psocoptera which includes the psocids. Insect bodies are differentiated into three parts: the head, thorax and abdomen; and have three pairs of legs. Depending on the type of damage caused, the insects are discriminated into two groups of pests. Primary pests are species capable of initiating injury on previously undamaged grain, such as adults of Saw-toothed Grain Beetle (*Oryzaephilus surinamensis* L.) and Rice weevil (*Sitophilus oryzae* L.). Whereas secondary pests, such as Grain Weevil *(Sitophilus granaries* L.), Mediterranean Flour Moths *(Ephestia kuehniella Zell.*) and Rust-red Flour Beetles *(Tribollium castanem* Herb.), tend to feed on already damaged grain.

2.1.1.1 Order Coleoptera (Beetles)

This is the largest order, which contains about 370,000 named species (Harde, 1984). Beetles vary in habitat and are found almost everywhere in the world and feed on all sorts of plant and animal material (Borrer et al.1989). About 40 beetle's families are associated with stored foods. There are more than 60 species worldwide which feed on stored food products, however only the members of seven families are considered economically important. These families are Bostrichidae, Bruchidae, Curculionidae, Dermestidae, Laemopholidae (Previously Cucujidae), Silvanidae, and Tenebrionidae. The beetles undergo complete metamorphosis and the life cycle varies in length. Most species have one generation a year; overwintering, depending on the species, can occur at any life stage. Both larvae and adult beetles cause damage to stored products. Their folded hind wings are used for flying with the hard elytra as a modified forewing. Stored-product beetles are mostly small; some of them only 2-3 mm in length.

Adult can be short or long lived and may or may not feed; their mouth parts are generally unspecialized biting and chewing types with well developed toothed mandibles and thus may not cause any damage. Some adults feed on nectar from flowers, some feed on fungi etc. Larvae of course all feed and thus may be pests. Weevil larvae are mostly quite legless.The mouth parts have biting mandibles, and typically biting and chewing are the primary forms of damage (Dennis, 2002).

The common beetles in stored grain, which first evolved as saprophytic insects and have been adapted to the stored-products environment for more than 4000 years (Levinson and Levinson, 1985) are: Red and Confused Flour Beetles (Tribolium *sp),* Saw Toothed (Oryzaephilus sp.) and Flat Grain Beetles (Cryptolestes sp.). Also, the more dangerous internal grain feeders on rice and maize are granary weevils of the genus (Sitophilus sp.) and Lesser, Larger Grain borers (Bostrichid sp.), which riddle stored grains with their tunneling activities.

2.1.1.2 Order Lepidoptera (Moths)

About 70 species of Lepidoptera from the families of Pyralidae, Tineidae, Oecophoridae and Gelechiidae, have been reported in various stored products. Of these, a few members of Pyralidae are frequently encountered infesting cereal grain, feed plants, and feed products. Unlike beetles, only the larvae stages of moths cause damage to stored products. It is a very large group of insects and only a few are stored-products pests, but those species are very important because they are abundant and widespread and can be very damaging. Around 70 species of moths have been recorded infesting stored products, but the actual number of obligate stored-product pests is low less than a dozen.

There are a number of other species that feed on fruits and vegetables and it is mostly field crop pests that are carried into produce stores, where they may live for a while. Adults have two large pairs of wings that overlap medially, and both the wings and body are covered with tiny overlapping scales. The primitive biting and chewing mouthparts (mandibles) have gradually been lost during evolution and replaced by long coiled (at rest) suctorial proboscis with which they suck nectar from flowers, and imbibe other juices.

The larvae are known as caterpillars and they inflict the most damage at this stage. Its body shape is characteristic of the order; its mouthparts include mandibles used for biting and chewing. Some have modified salivary glands, which produce a continuous thread of silk, used for making the pupae cocoon. Caterpillars have a well-developed head capsule and three pairs of thoracic legs, which are clawed. The abdomen consists of ten segments bearing short fleshy prologs on segments 3-6 and a pair of terminal claspers. Eggs can be globular, fusiform, upright, sculptured, flattened or ovoided and they are laid singly or in small groups. The common pests related to this order are Flour mills *(E. kuehniella*- family Pyralidae) the major pest in European and Indian Meal Moth (*Plodia interpunctella* Hub. Family Pyralidae)

2.1.1.3 Order Psocoptera (Book lice, Bark lice)

Members of this order are commonly called psocids. It includes about 1000 species, divided into 26 families, of which about 15 psocids are associated with stored products. It has worldwide distribution, with a number of species that are truly tropical, and other restricted to temperate regions. They are small, fragile insects capable of causing severe damage to stored grains. In size they range from around 1 to 10 mm in length and are often cryptically colored. Some of are winged and some wingless; the antennae are long and filiform; the body is rounded and soft, with protruding eyes. The biting mouthparts are modified, in that they have been developed into elongated “picks”. Most of them feed on fungi and lichens, or epiphytic algae, but a few eat dried animal material and stored flours and cereal products. Occasionally, when conditions are humid, psocids can be serious pests of stored foodstuffs and large populations can develop. Most species cannot survive more than 2-3 weeks at less than 58% RH. As an example of this order, *Lepinotus patruelis* (Pearman) a round bodied , 2-3 mm long, dark chocolate brown psocid is a minor pest of stored grain used in the milling and brewing industries (Finlayson 1949). And *Liposcelis bostrychophila* Badonnel is the principal psocid pest species in Europe. It is probably the most publicized species, and now quite cosmopolitan, but thought to be African origin. It reproduces parthenogenically, can feed on a wide range of foods and, despite being wingless, has a very wide distribution in the rest of the world. It's lifespan is relatively long and varies with temperature, humidity and available food sources.

Turner (1994) recorded the maximum lifespan, 53 weeks, for psocids feeding on skim milk powder. It lays eggs singly or in small batches. The eggs are large, about 1/3rd female body size; 3-4 eggs per day maximum can be laid. It has 4 nymphal stages; the nymphs are almost colourless and difficult to see on light coloured background. The population can rapidly increase unnoticed, until the nymphs mature to brown adults. The generation time (from egg to egg-laying adult female) depends on temperature. It takes approximately 56 days at 20ºC and 22 days at 30ºC. In the UK the patterns of complaints related to psocids show a strong seasonality, peaking in autumn and being lowest in the spring (Turner, 1998) *L. bostrychophilus* Badonnel is an extremely difficult insect to control, as it is able to survive without food for considerable periods of time (Turner and Maude-Roxby, 1988).

2.1.2 Mites: order Acarina

The first record of stored-product mites was in Canada, by Saunders (1880), who mentions that *Tyrophagus farinae* (*A. siro*) reproduces on flour and chess, and recorded 4 species of Acaridae that infected stored products. Stored-product mites infest food during its storage (Sinha 1979, Iversen et al.1990; Franz et al 1997; Arlian 2002; Stejskal et al. 2003). A mite infestation decreases food safety because mites are allergen producers (Van Hage-Hamsten and Johansson 1992). Some cause itching (grocer's itch etc.) and diarrhea in humans. Also, they transmit mycotoxin producing fungi (Franzolin et al. 1999; Hubert et al. 2003).

Those mites which belong to the families Pyroglyphidae, Glycyphagidae, Acaridae, and Cheyletidae are still considered the most detrimental to human health (Maunsell et al.1968, Cohen 1980, Feldman-Muhsam et al. 1985, Galvao and Guitton 1986, Geller 1999). Mites are one of the most common triggers of allergies. Several families of mites occur in stored grain, including grain feeders, fungus feeders, predators, and parasites. These can cause occupational health problems for grain industry workers; including skin contact dermatitis, inhalant allergies and asthma, and painful irritation caused by direct bites from mites to human skin (Halliday, 2003). Not only Living mites, but also the fecal pellets and cuticle fragments contain allergens (Tovey, et al. 1981).

Table2 - Acaridae and related mites associated with skin conditions

(Southcott1976)

Condition	Causal mites
Baker´s itch	*Acarus siro (* L.)
Copra itch, grocer´s itch	*Tyrophagus putrescentiae* (Schrank)
Wheat pollard itch	*Suidasia nesbitti* (Hughes)
grocer´s itch	*Glycyphagus domesticus* (De Geer)
Dried fruit dermatitis	*Carpoglyphus lactis* (L.)

Sinha (1963) mentions that the recorded number of species of the order Acarinea, which are associated with stored products, increased from one species (*A. siro*) in 1873 to 90 species in 1960. Mites are very small insects of microscopic size, their bodies consisting of two parts. A larva with 6 legs hatches from the egg and passes through two nymphal stages with 8 legs. The mouthparts of most mites consist of a pair of tiny, toothed chelicerae, which are used in for scraping. Most of the family Acaridae (Tyrophagidae, Astigmata partim) are free living, but a few damage growing plants and bulbs, and some are stored-product pests. The gnathosoma is adapted for biting. The deutonymph is often adapted into a hypopus. An inert hypopus develops at a resting stage (with reduced limbs) and the active hypopus is adapted for active dispersal, often using a mammal or an insect as transporting host. The best example of this order is the flour mite (*A. siro*), which is a serious international pest of stored grain products. This pest causes direct damage by biting and eating the products, though it only attacks grains damaged by primary beetle pests. It causes impaired germination and reduces the nutritive value, and also causes dermal irritation and baker's itch. Most mites that occur in grain and other stored foods belong to the Acaridae and related families.

These mites are 0.5-1 mm long, slow moving, are usually white or pale brown, often shiny, and usually with visible long hairs, especially at the posterior end. Hughes (1976) identified and gave the biology of these mites. There may be as many as 50 species that fit the general description. The symptoms of allergens are probably caused by a combination of direct skin contact with mites, or their products, and inhalation of mite fragments. Mites are attracted to higher moisture (Ždarkova 1973, 1979) and prefer the humid part of the grain (Sinha,1979a). House–dust mites (*Dermatophagoides farina* Hugh., *D. pteronyssinus* -family Pyroglyphidae) and stored-product mites (Glycyphag*us domestic* De Geer, *Lepidoglyphus destructor* (Schrank)- Family Glycyphagidae , *A.siro* and *T. putrescentiae*- Family Acaridae) are the main groups of mites.

2.2 Occurrence of stored-product pest arthropods in grain storage

2.2.1 Czech conditions

In recent fauna research of stored grain in the Czech Republic, 31 insect species and 25 mite species were found (Werner,et. al.1999). Pests of the order Lepidoptera are now economically unimportant in stored grain in the Czech Republic (Stejskal, 2002). Mites and fungi heavily infest stores in the Czech Republic. Both vertical silo-stores (VSS) and horizontal flat-stores (HFS) were infested with three major groups of storage arthropods: mites (25 species), psocids (8 species) and beetles (23 species). Mites were found to infest about 60% of the grain sample and were the most abundant group of pests. Psocide and beetle infestation was lower (20% of grain samples).

Moths were not observed. The most economically important species of mite and beetle grain pests occurred in both types of storage. The only an exception was a higher occurrence of *T. castaneum* and *S. granarius* in HFS, which provides better conditions for this beetle species than VSS. due to higher surface to volume ratio of grain mass in flat stores than in silos. The most abundant and frequent group was mites, followed by psocids and beetles (Stejskal. et. al 2003). Ninety-four fungal species were isolated from mite-infested seed samples taken from Czech stores. Storage mites may play an important role in the spread of some medically hazardous micromycetes, which may cause a high risk of mycotoxins in food, and cause mixed contamination by fungal and mite allergens (Hubert et al 2004). *A. siro* is the most frequent and abundant pest of stored grain in the Czech Republic (Stejskal et al.2003).

2.2.2 Libyan conditions

In general, the work of Zavatari (1934) provided early information on Libyan fauna. His list includes the species known to be associated and infesting stored products. Alabed (2003) mentioned in her thesis introduction that Martelli (1940) reported three Lepidoptera species and one Coleoptera species infesting stored products. Martin (1956) recorded 25 species attacking stored foodstuffs in his list. Damiano and Ben Saad (1959) reported 20 species of beetles and moths attacking stored products.

Also. Damiano (1961) included in his list of insects recorded in Libya, 35 species that were associated with stored products. Goura (1977) reported 12 species attacking wheat. Ben-Saad et al. (1981) listed 30 species of insects as being pests of stored products. Ben Othman (1998) recorded 40 species of insects infesting stored products in Tripoli, in which three species of are recorded for the first time. In Eastern Libya (2002) Hamed recorded 4 species of mites in flour: A. *siro, A. farris, T. putrescentiae and T. longior*. She also mentioned that *A. siro* was the most distributed species, with high density. Goura (1977) estimated the average loss of wheat at 38.8%. Abozeidah and Naje (1982) stated that losses are generally great. Alabed (2003) identified four species of mites (Table 1) in western Libya.

Table 1 - Mite species in western Libya, according to Al-Abed, (2003).

Mesostegmata	Ascida	Blattisocius tarsalis (Berlese)
Prostigmata	*Cheyletidae*	*Cheyletidae Malaccensis (Oudemans)*
Prostigmata	*Tarsonemidae*	*Tarsonemus granaries (Lindquist)*
Astigmata	*Acaridae*	*Tyrophagus entomophagus (Laboulbene)*

She mentions that *C. malaccensis* and *T. granarius* were the most abundant compared with the other species, especially during the summer season, while they were less in the winter. All recorded species in this region were found on wheat flour and rice. The complete list of Libyan storage-product pest arthropods in Libya is shown in Appendix A.

2.3 The protective mechanisms in integrated pest management of stored-product arthropods

There is zero tolerance for live insect pests in bulk, stored grain. Control measures for arthropods include chemical pesticides, fumigation, controlled atmosphere, physical methods, and biological control. Integrated pest management (IPM) is the use of a combination of methods to manage a whole spectrum of pests within a particular cropping system. Its history dates back to the beginnings of agriculture, where it has been defined as a pest management system (Dent, 2000). However, even in the best-regulated systems, integrated strategies incorporating pesticide surface treatments are required to achieve pest-free grain (Armitage et al. 1994).

2.3.1 Chemical control

Although pesticides are valuable tool in pest management, chemical control is sometimes the last tactic considered due to negative impacts on human health and the environment.

2.3.1.1 Synthetic pesticides

Since the early 1950s, when the organchlorine insecticides where first widely introduced, chemical insecticides have been considered an essential component of insect pest control.

Synthetic insecticides, such as malation, pirmiphos-methyl, chlorpyrifos-methyl, pyrethrum, deltamethrin methoprene and fumigant phosphine are currently the main products (Bond, 1984; Snelson, 1987) used by many grain storage managers to reduce losses of stored grain to insect pests (Arthur, 1996). Its use is considered the only option when a pest population in stored grains reaches the economic threshold (White and Leesch 1996).

Traditional management of stored-product mites and insects relies on chemical acaricides and insecticides, and on good husbandry. In the past two decades the USA and EU legislative bodies have increasingly restricted the use of methyl bromide and organophosphorus, leaving the food industry without its only efficient class of registered acaricides, since most pyrethroids do not control mites satisfactorily (Wilkin and Hope 1973). Various methods have been used to control stored mites.They include the use of grain protectants as acaricides, as cypermethrin (Wilkin et al. 1988). The range of chemicals permitted for pest control is declining. Carbon dioxide (CO2) can replace methyl bromide as a fumigant in some situations. High concentration carbon dioxide retained in well-sealed enclosures has been used to control stored-product insects in food commodities, particularly grain (Jay 1986). The duration of exposure to carbon dioxide necessary for complete control varies. Seven days' exposure is needed for complete mortality on *T. castaneum. S. oryzae* and *A. siro* require 14 days (Newton 1991).

The results of Emekci (2001) showed that the respiration rate of immature stages of *T. castaneum* increased with the increase of O_2 levels.

Desiccants or inert dusts are candidates to replace organophosphorus compounds, particularly when used as a surface treatment. They are based on silicon dioxide and their advantage comes from their low levels of mammalian toxicity; they are non-reactive, leave no chemical residues, are effective against insecticide-resistant pests and are long lived (Golob. 1997). Pheromones are chemical substances generated by the insects themselves.Pheromones specifically disrupt the reproductive cycle of harmful insects. They also can be used to lure the pests into traps that help farmers track insect population growth and stages of development. In this way, farmers can reduce the amount of insecticide they need– spraying only when the insects are in a vulnerable stage or when their numbers exceed certain levels.

2.3.1.2 Bio-pesticides

The most recent products tend to be of a lower toxicity, more environmentally friendly and more specific to the pests they control. Some older products such as insecticidal soaps and horticultural oils are environmentally safe as well. Organic or botanical insecticides are also popular, but these too must be applied properly and handled with care. Bio-pesticides include botanical insecticides, which are extracts of some plants like the neem tree (*Azadiracha indica* A. Juss), which has shown insecticidal activity (deterrent, anti-feed, anti-ovipositional, growth regulating and with fecundity effects) against more than 400 insect species (Schmutterer and Singh, 2002; Schmutterer, 1990). Another example is *T. castanium* (Jilani and Su 1983, Jilani et al. 1988) and garlic *(Allium sativum* L.), which have been reported to be effective in controlling spider mites. The leaves of *Lansium domesticum* Corr.Serr. (Meliaceae), which is a tree native of Southeast Asia, have been used by people in the Philippines for the control of mosquitoes (Monzon et al. 1994). Also, the bark of this tree is traditionally used as an anti-malarial remedy by the native people of Borneo (Leaman et al., 1995).

Many plants and their extracts have been investigated for control of stored-product insects (Weaver and Subramanyam, 2000), the most effective plants being medicinal plants (Golob et al, 1999). Some foods, such as legume seeds, contain a wide range of allelochemicals with toxic and deterrent effects against insect pests (Harborne et al 1971; Bell 1977). Most stored-product insects are unable to develop on legumes (Singh and Wilbur, 1966, Sinha and Watters, 1985). Yellow split peas (*P. sativum*) are particularly effective in reducing survival and reproductive output of S. *oryzae* (Fabaceae) (Coombs et al 1977; Holloway, 1986). Also protein-rich pea flour causes adult mortality and interferes with reproduction Bodnaryk et al 1999, Fields et al 2001), and the extract from protein-rich pea flour reduced feeding of *S. oryzae*

(Xingwei et al 2004). Juvenoids, plant oils and diatomaceous earth represent the only chemical alternatives to methyl bromide and organophosphorus insecticides for control of the storage mites (Thind and Edwards 1990; Cook and Armitage 2000).

In addition, the boom in genetic engineering techniques raises the possibility of using insecticidal and acaricidal biomolecules in GMO crops. The inhibitors of digestive enzymes (namely inhibitors of proteases and ά-amylase) are among the biomolecules that are currently being investigated intensively to combat the insect and mite pests (Schuler, 1999). The ά- amylase inhibitors were tested in natural and laboratory experiments with insects (Gatehouse et al. 1986; Pueyo et al. 1995; Chrispeels et al. 1998; Gatehouse and Gatehouse 1998; Hou and Fields 2003).

It also has an effect on the digestive apparatus of the stored-product mites (Hubert et al 2005). Another possibility, is the use of entomopathgenic fungi, such as *Beauveria bassiana* (Balsamo) and *Metarhizium* sp., which adhere to, germinate on, and penetrate through their host's integument to achieve infection. Also *Bacillus thuringiensis*.(Bt), which has became a major insecticide, because genes that produce Bt toxins have been genetically engineered into major crops grown on 11.4 million ha worldwide in 2000 (Shelton et al. 2002).

2.3.2 Physical control

Many factors, such as temperature, species, life stage, acclimation, relative humidity, etc., determine the length of time needed to kill all individuals.

2.3.2.1 Temperature

There are number of alternatives to chemical control of stored-product insects, including low or high temperature (Fields, 1992). Insects are ectotherms (their body temperature is in large part determined by temperature of the environment). The most economically important insect pests of stored products develop and reproduce over a narrow optimal range of temperature, between 20-35ºc (White 1995). Low temperatures reduce the rates of development, feeding, fecundity and survival (Longstaff and Evans 1983, Flinn and Hagstrum 1990). Temperatures between 13-25ºc will slow development. *S. granaries* is only the major stored-product insects that can develop below 20ºc and down to 13ºc, in grain with optimal moisture content (Banks and Fields 1995).

The range of temperature in which stored-product insects can normally survive lies between 8-41ºc (Sinha and Watters 1985). Mites in damp grain only stop developing at 2ºc. Although no development occurs at these temperatures, insects and mites remain alive for long periods and will cause damage if the temperature rises. Granary Weevils and Indian Meal Moths are among the most cold-hardy, while Red Flour Beetles are among most cold susceptible (Fields, 1992 and Howe 1965). Several species of stored-product insects and mites can be controlled by exposure for 14 days or less to an atmosphere containing 60% carbon dioxide at 23 or 25 ºc (Newton 1991). Generally development and multiplication are optimal near 30ºc and 50-70% RH (Howe 1965). At temperatures above 45ºc both the insects and their eggs are killed within a few hours. Most insects cannot reduce their body temperature by perspiring or breathing. They will simply die due to coagulation of their body proteins. Lethal exposure times for certain species at certain temperatures are quite scarce. Wilkin and Nelson (1987) found that 15 min exposure to 60ºc killed all stages of *T. castaneum, O. surinamensis Cadra cautella* (Walker) and *Plodia interpunctela* (Hübner). Al-azawi et al. (1984) mention that adults of the dried fruit beetle *Carpophilus hemipterus* (L.) were quite heat tolerant and required up to 60 min exposure to 50 ºc for complete control.

2.3.2.2 Humidity

High moisture content of grain at harvest rapidly leads to spoilage and occasionally to the production of the mycotoxins sterigmatocystin, ochratoxin A, or citrinin (Jayas, 2003). Generally development and multiplication are optimal at 50-70% RH. *T. castaneum* has a greater tolerance for low humidity, even as low as 1% (Howe 1965). Desmarchelier (1988) showed that populations of insects and other pests increase linearly with wet-bulb temperature of inter-granular air in bulk of grains. Thorpe (2002a) points out that, when grains are ventilated, most of the grains acquire a thermodynamic state that is strongly dependent on the wet-bulb temperature of the air and the initial moisture content of the grains.

2.3.3 Biological control

Insect pests in stored products are attacked by a variety of natural enemies; such as predatory insects and mites, hymenopterous parasitoids, other vertebrates and pathogenic microorganisms. Despite this, the use of these natural predators against post-harvest pests was very limited until recently. During the last decade, however, biological control gradually began to occupy a significant part in stored-product IPM. This was due to many reasons; such as its many advantages over traditional chemical methods, pest resistance to conventional pesticides, the phase-out of methyl bromide, the favorable conditions for beneficial insects of a stored-product environment (protection from wind, rain, extreme temperature fluctuations, insects prevented from leaving, high concentration of habitat and host within a limited area, etc.) and its compatibility with other IPM methods (Arbogast, 1984; Haiens. 1984; Gordh and Hartman, 1991; Brower et al., 1996; Scholler et al., 1997; Scholler and Flinn. 2000)

The use of parasitoids in biological pest control is already common in several agricultural and horticultural fields. However, only a few alternatives to biological protection are given for stored products. Important natural enemies include parasitoid wasps of the families Braconidae, Ichnemonidae, Pteromalidae and Bethylidae, such as the wasp *Lariophagus distinguendus,* which seems to be a promising candidate for biological pest control in stored grain (Steidle and Scholler 2001). The superfamily Ichneumonoidea (consisting of two families: the

Ichneumonidae and the Braconidae) has been estimated to contain well over 80,000 different species. Some members use many different insects as a host; others are very specific in the choice of host. Various ichneumons are used successfully as biological control agents for controlling pests, such as flies, beetles, predatory pirate bugs, assassin bugs, hister beetles, pseudoscorpions, and predatory mites. An example is *Blattisocius tarsalis* (Berlese), which is a polyphagous predator that has been recorded world-wide in association with insects and mites infesting stored products (Graham, 1970; Haines, 1981) such as *Ephestia, plodia* L. and *Tribolium* sp. (Darst and King, 1969, Nielsen, 1998). Sinha 1984 reported 37 species of predatory mites in stored products. Also, pathogenic bacteria and viruses occur naturally within storage insect communities, such as *Bacillus thuringiniensis*.

2.3.4. Cultural control

Host plant resistance is one of the basic steps in an integrated approach to pest management. It is a type of genetic control, which means using plants that have been selected or genetically manipulated to become resistant or less susceptible to pests. In some plants phenolics serve to protect against insect attack by metabolism inhibition when ingested by insects, and producing abnormal growth and development (Reese 1979). As example sorghum is resistant to *S. oryzae* (Ramputh et al. 1999).

3. Problems

Insecticides can be used to protect grain, but few are labeled for use on grain, and insects are evolving resistance to some of these.

The massive overuse of chemical insecticides has resulted in various measurable problems to the environment. Their misuse has lead to such disadvantages as pest resistance to the pesticide, outbreaks of secondary pests and adverse effects on non-target organisms, unwanted pesticide residues, and direct hazards to the user.The range of chemicals permitted for pest control is declining. Insects have developed resistance to some and others have been removed for safety and environmental reasons. Meanwhile, the process of developing and registering replacements becomes more demanding and costly (Arthur 1994), such as methyl bromide which has an alleged role in ozone depletion (Anon 1992b). It is important to determine the best time for control of stored-product pests, relative to the indoor and outdoor temperature, in order to be effective and economically feasible.

4. Aims

The general aims of this study are: control of stored-product pests, by using physical control (temperature), bio-control (botanical insecticides) and biological control (natural enemies), which are considered safe methods for humans and the environment.

4.1 Particular goals were:

Investigating the effect of temperatures ranging from 5-35ºC on population growth of storage mites .

Testing the toxicity and exploring the potential of Bean flour *(Phaseolus vulgaris*) as novel botanical acaricide under optimal conditions for mites.

5. Results

5.1 Scientific papers

5.1.1 Temperature-dependent population growth of three species of stored- product mites (Acari: Acaridida).

5.1.2. The toxicity of bean flour (*Phaseolus vulgaris*) to stored-product mites (Acari: Acaridida).

5.1.3 The suppressive effect of bean flour (*Phaseolus vulgaris*) on five species of stored-product mites (Acari: Acaridida).