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ALTERNATIVES TO ORGANOPHOSPHORUS COMPOUNDS
FOR THE CONTROL OF STORAGE MITES

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1. Introduction

Mites are very common pests of stored grain and oilseeds in the U.K. A survey of commercial grain stores during 1988/89 and oilseed stores in 1995, detected the presence of mites in 81.3 % and 89 % of the stores respectively (Lynch et al., 1991; Prickett, 1997). The most common species in the grain stores were *Acarus siro*, *Lepidoglyphus destructor*, *Tyrophagus longior* and *Tyrophagus putrescentiae*, identified in 59%, 51.2%, 15.9% and 12% of stores respectively (Lynch et al., 1991). In the oilseed stores the predominant species were *Acarus siro* (67%), *Lepidoglyphus destructor* (37%), *Tyrophagus putrescentiae* (31%) and *Tyrophagus longior* (19%) (Prickett, 1997).

Some mites feed on the germ of cereals (Solomon, 1946a) and hollow out rapeseed leaving only the seed coat (Anon, 1982), thus reducing germination and decreasing the value for seed and malting. Heavy infestations can have a strong smell which taints the grain, and makes it unpalatable to livestock and unsuitable for milling (Wilkin and Stables, 1985). Research has found reduced growth rates in pigs fed a diet heavily infested with mites (Wilkin and Third, 1984). Mites in finished cereal products are also a cause of concern. A recent investigation found 22% of cereal based products contained at least one mite (Anon, 1996). Infestations may arise as a result of mites entering the product during any stage in its manufacture, transport and storage (Anon, 1996). There is also the potential risk to the health of workers involved in grain and flour handling by development of serious allergies following exposure to stored product pests (Stengard Hansen et al., 1996). Mites have also been implicated in the transmission of micro-organisms, especially fungi, with recent suggestions of a role as vectors of prions (Sigrianskii, 1940; Griffiths et al, 1959; Wisniewski et al., 1996).

There is a requirement for traded grain to be pest-free; EC regulation 689/92 states in Article 2, that to be accepted for intervention, ‘cereals must be free from live pests (including mites) at every stage of their development’ (Intervention Board, 1996). In the U.K. stored grain protection has relied heavily on bulk admixture with insecticides. A survey of commercial grain stores in 1988/89 found that 67.5% of the sites had used contact pesticides on all or part of the grain, with two thirds treating for prophylactic reasons (Prickett, 1991). The only contact pesticides approved by the Pesticides and Safety Directorate for the treatment of stored grain and oilseed are the organophosphorus (OP) compounds pirimiphos-methyl (Actellic), etrimfos (Satisfar) and chlorpyrifos-methyl (Reldan) (Whitehead, 1997). The survey of commercial stores found that pirimiphos-methyl, chlorpyrifos-methyl and etrimfos were used in 73%, 21% and 12% of sites that treated grain, respectively (Prickett, 1991).

However, none of the pesticides are now particularly effective against field strains of mites. Results from recent surveys have found widespread resistance in populations of *Acarus siro* to one or more of these compounds. Resistance to twice the recommended rate of pirimiphos-methyl was detected in 15% of *Acarus siro* strains from farm stores (1987), 71% of strains from commercial stores (1988/89), 91% from animal feed mills (1992) and 93% from oilseed stores (1995) (Starzewski, 1991; Prickett, 1994; Prickett, 1997). In the latter survey resistance to chlorpyrifos-methyl was also detected in 63% of stores but only in mites from stores where pirimiphos-methyl resistance was found (Prickett and Buckland, 1997). Resistance to etrimfos
was also detected in two pirimiphos-methyl resistant strains (Prickett and Buckland, 1997). Unpublished data from the Central Science Laboratory by Binns and Buckland, found one *Acarus siro* population from a commercial store to be resistant to pirimiphos-methyl, etrimfos and chlorpyrifos-methyl. This indicates the presence of mites resistant to all available compounds used for treating stored grain. Collins and Binns (1996) also found that 8 mg kg⁻¹ of pirimiphos-methyl and etrimfos failed to provide complete mortality of a susceptible strain of *Acarus siro*, when exposed to treated oilseed rape for 14 days.

Thind et al. (1996) also detected cross-resistance to chlorpyrifos-methyl and etrimfos in a pirimiphos-methyl resistant field strain of *Lepidoglyphus destructor*. This suggests that resistance to OPs in this case, has conferred cross-resistance to all three compounds, and it is possible that a single mechanism is responsible (Thind et al., 1996). Therefore, the use of any one compound may lead to selection for resistance to the others.

The ability of some mites to survive treatments with OPs, is due to the development of resistance mechanisms. OPs have been found to inhibit acetylcholinesterase (AChE) in mites and ticks (Errampalli and Knowles, 1990; Roulston et al., 1966). When AChE is inactivated, degradation of the neurotransmitter, acetylcholine, is prevented and hyperexcitation of nerve tissues results in eventual exhaustion and tetany (Dekeyser and Downer, 1994). The first resistance mechanism to OPs developed by the acarina was based on a deviant AChE enzyme (Nolan and Roulston, 1979). In tetranychids, alterations in AChE cause a considerable decrease in the sensitivity to certain OPs (Helle, 1984). AChE insensitivity is the most common type of OP-resistance in the spider mite *Tetranychus urticae* (Helle, 1984). Roulston et al. (1966) also found that death in ticks treated with OPs was highly correlated with the inhibition of AChE. Another type of OP-resistance is based on a detoxication mechanism (Nolan and Roulston, 1979). In phytoseiid mites the most common OP resistance mechanism is based on detoxication by increased activity of glutathion-S-transferases (Helle, 1984).

As well as concerns regarding the development of resistant pests, the costs and consumer resistance to toxic chemicals in food, have led to increasing pressures for a reduction in pesticide use. The Maximum Residue Limits (MRLs) for OPs on stored grain have been reduced in the EU to 5 mg kg⁻¹ (S.I., 1994), which is close to the recommended application rates and there are pressures for further reductions.

Cooling and drying is also used to protect grain from pest infestation. By reducing the temperature of grain to below 5°C mite breeding is prevented; and by drying grain to below 60% rh development can be inhibited (Cunnington, 1976). However, many sale contracts stipulate that the maximum moisture content of grain to be purchased is 15% (McLean, 1989). At 25°C, a moisture content of 15%, depending on variety, is at equilibrium with about 70% rh (Henderson, 1987), which is within the range of conditions required by *Acarus siro*, *Lepidoglyphus destructor* and *Tyrophagus putrescentiae* to complete their development in the laboratory (Cunnington, 1976). Furthermore, during the winter, surface layers may reabsorb moisture from the atmosphere (Burrell and Havers, 1976) locally increasing product moisture content and enhancing the development of surface mite infestations (Armitage, 1984).
Surface grain cannot be kept cool or dry enough to limit mite numbers, so a surface pesticide treatment may be required.

The future of OPs looks bleak. There are strong pressures for their replacement, linked to their reputed involvement in Chronic Fatigue Syndrome (CFS) following use as sheep dips, the possible involvement in Gulf War Syndrome, a suggested link to spongiform encephalopathies by causing prion mutation, claims that they cause autoimmune diseases and continuing concerns over residues in foodstuffs (Vial et al., 1996; Wester et al., 1996; Stephens et al. 1996; Fairhall, 1996; Davies, 1997; Warden, 1996). However, there is also the need for high quality pest-free grain and together with suggestions that mites are implicated in the development of allergies and the spread of prions (Wisniewski et al, 1996), it is obvious that alternatives need to be sought.

There are a number of alternative compounds used effectively against acarine pests in field agriculture, veterinary and public health control programs, which may also prove effective against storage mites. These include insect growth regulators, inert dusts, botanicals, novel compounds and biological control agents. Each of these groups will be discussed including the advantages and disadvantages of their use in a storage environment, together with modes of action; with the aim of identifying potential alternatives that may warrant further investigation.

This review covers results of efficacy testing of a wide range of mite species, so it is probably in order to explain their relationship to the commonly-occurring grain storage species, as it is not unreasonable to expect that different orders or families of mites will have varying susceptibilities to toxicants. The main mite pests of stored products in the UK are all members of the order Astigmata, which rely solely on cutaneous respiration and are thus weakly sclerotised and vulnerable to desiccation. Other Astigmatid mites which are important in other contexts include the house dust mite, *Dermataphagoides* spp. and *Psoroptes* spp., the scab or mange mites. Another commonly occurring UK grain species is *Cheyletus eruditus*, a predatory mite of the order Prostigmata, which are a well-sclerotised group with tracheate systems which open via a pair of stigmata just beneath the mouthparts. Other well-studied Prostigmatid mites include *Tetranychus*, spider mite pests of plants, and *Varroa*, the bee parasite. The Mesostigmata are equally well-sclerotised mites with the stigmata opening mid-way along the body. There are several species of the genera *Haemogamasus*, *Blattisocius* and *Androlaelaps* which occur in association with stored products, in particular with processed cereals. *Amblyseius* sp., a predator of spider mites and *Dermanyssus* sp., the chicken or poultry red mite, are well-studied pests in other contexts. The ticks are external sucking parasites and form the order Metastigmata. They are also well-studied agricultural pests but there are no grain storage representatives. The Mesostigmata and the Metastigmata form the superorder Parasitiformes with the poorly-known unigeneric Tetrastigmata. The Astigmata and the Prostigmata form the superorder Acarifomes with the Cryptostigmata, which are heavily-armoured soil dwellers, sometimes known as ‘beetle mites’.

2. **Insect Growth Regulators (IGRs)**

IGRs are compounds that disrupt the normal development of insects by mimicking the action of insect hormones and/or by interfering with hormone regulated processes.
They have been used in a variety of practical applications, such as for mosquito and cockroach control, and have shown to be effective against stored product insects (Loschiavo, 1976; Kramer et al., 1985 and Bengston, 1987).

The role of hormones in the regulation of development and reproduction in insects has been extensively studied. However, in acarines this regulation is less well understood, although it is believed that hormone-like substances are responsible (Soneshine, 1991). In ticks it has been suggested that the lateral segmental organs and the retrocerebral organ complex are possible endocrine glands (Binnington, 1986), however the nature of their secretions is unknown.

There are three main types of IGRs used in pest control: juvenile hormone analogues, moulting hormone analogues and chitin synthesis inhibitors.

2.1 Juvenile Hormone Analogues (JHAs)

In immature insects, JH affects development by suppressing the formation of adult characteristics. During diapause, development is inhibited by high levels of JH which are thought to inhibit the brain-prothoracic gland system (Eaton, 1985). In adults, JH stimulates ovarian development and yolk production by the fat body. Although no JH or JH-like substance has been identified in the Acarina, many investigators support their existence and physiological role (Soneshine, 1991). Several JHAs appear to affect mite development by disrupting normal morphogenesis to the adult, resulting in abnormal mites, with combined juvenile and adult characteristics, that cannot feed or reproduce and eventually die; these JHAs also appear to affect embryonic development resulting in failure of egg hatch (Dekeyser and Downer, 1994). A wide range of JHAs have been tested for their toxic effects on a variety of acarine species, however, information on the effects on stored product mites is limited.

Czaja-Topinska et al. (1979) listed the effects of 56 JHAs on *Tyrophagus putrescentiae* (Astigmata) and reported a range of morphogenetic, ovicidal and sterilising effects. Although not all had significant action on the mites, effects ranged from reduced fecundity in treated females, to a significant increase in the number of larvae unable to complete development to the adult stage. The most sensitive stage to the JHAs was the egg stage from which larvae emerged but did not feed and soon died.

Thind and Edwards (1990) found that fenoxycarb, a carbamate insecticide with JH-like properties, stimulated egg production in *Acarus siro* (Astigmata). Incorporation into food at 10 mg kg⁻¹ and 100 mg kg⁻¹ increased egg production by 43% and 99% respectively; and total mite populations were significantly higher in the treated media than in controls. It was suggested the effects of fenoxycarb indicated that JH-like compounds may act as gonadotrophins. This gonadotropic effect has also been observed in *Tetranychus urticae* (Prostigmata) when treated with the JH mimic farnesol (Regev and Cone, 1976). Females treated topically with 200 ppm farnesol in 40% ethanol laid more eggs than females treated with only ethanol.

However, Buchi (1990) found that fenoxycarb reduced the number of adult *Acarus siro* (Astigmata) produced by between 37.1% and 94.9%, when added to food media at doses ranging from 0.5 ppm to 8 ppm. The numbers of larvae were also reduced by
between 34.6% and 95.3%. Methoprene, another JHA, also reduced the numbers of adults by 53.4% to 88.1% and larvae by 53.6% to 83.6%, when added to food at doses of between 47.5 ppm and 190 ppm (Buchi, 1990).

Downing et al. (1990) evaluated the effects of fenoxycarb, methoprene and hydroprene, on adult and immature mites of *Dermatophagoides farinae* (Astigmata), when exposed to treated filter papers. Methoprene was most effective at suppressing population growth especially at concentrations of 1% (10 000 ppm) and 5% (50 000 ppm). Hydroprene also suppressed mite populations but not as consistently as methoprene. The numbers of mites exposed to fenoxycarb were only significantly different to the controls at a concentration of 5% after 30 days exposure, however, there was no difference after 90 days.

Downing et al. (1993) also assessed methoprene and hydroprene against adults and immature mites of *Dermatophagoides farinae* (Astigmata) by contact and diet incorporation assays. Both compounds significantly suppressed population growth, with methoprene more effective than hydroprene. When applied at 7.5%, the number of mites over a 13-week period, did not increase significantly compared to the controls, however, the average numbers of mites were significantly higher in the diet incorporated assays compared to the contact assays.

Saleh et al. (1976) found that altosid and altozar (methoprene) affected and retarded the development of tritonymphs of *Dermatophagoides farinae* (Astigmata) to adulthood, when exposed to treated food. There was a reduction of 26.7% to 75.5% with altosid and 28.3% to 91.7% with altozar when exposed to doses between 0.00016 ppm and 0.032 ppm.

El-Banhawy (1979) found that the eggs of the predatory mite *Amblyseius brazilli* (Mesostigmata) were more sensitive to methoprene than females, whereas females of its prey, *Tetranychus desertorum* (Prostigmata), were more sensitive than its eggs. Spraying eggs with methoprene resulted in dead larvae or larvae that died just after emergence. Feeding female *Amblyseius brazilli* on a diet incorporating methoprene caused a depression in reproduction and sterility.

Nelson and Show (1975) showed that compounds containing a cyclopropane moiety provide control of *Tetranychus urticae* (Prostigmata) in the field, having direct ovicidal effects and causing temporary sterilisation of adult females. Several chlorinated JHAs, including 3,3 dichloroallyloxy-alkyl 4-ethyl phenyl ethers, have also showed high ovicidal activity against *Tetranychus urticae* by preventing hatching of eggs (Piccardi et al., 1980). As well as ovicidal activity a moderate toxicity (LD₉₀ ~ 1 g l⁻¹) was observed. Some of the compounds also exhibited good ovicidal effectiveness against *Panonychus ulmi* (Prostigmata) (Piccardi et al., 1980). Also in ticks the effects of various JHAs included a reduction in hatchability, which was shown to be due to desiccation of treated eggs (Soloman and Evans, 1977).

Anti-juvenile hormones also have potential for mite control. They interfere with the synthesis or action of JH and result in precocious metamorphosis (Dekeyser and Downer, 1994). Chicken mites, *Dermanyssus gallinae* (Mesostigmata), produce fewer progeny when treated with the anti-juvenile hormone precocene II, and then recover following treatment with JH III (Oliver et al., 1985). Precocenes have been
proposed as a means to control the bee mite, *Varroa jacobsoni* (Prostigmata) (Nemec et al., 1990). In the tick *Ornithodoros parkeri* (Metastigmata), precocene II blocked yolk production and subsequent embryogenesis (Oliver et al., 1985). Leahy and Booth (1980) also found that precocene II induced sterility and inhibited ecdysis in argasid and ixodid ticks, although precocious metamorphosis was not observed.

### 2.2 Moulting hormone (ecdysone) analogues

Ecdysone is a steroidal hormone secreted by the prothoracic gland in insects, which after release is converted to 20-hydroxyecdysone, which induces moulting (ecdysis) and metamorphosis (Dekeyser and Downer, 1994). Ecdysone analogues may therefore be expected to promote a premature moult (Dekeyser and Downer, 1994). The hormone may also regulate yolk production (Hagdorn, 1983), diapause termination (Wright, 1969), and sex pheromone production (Blomquist et al., 1984).

Although the moulting process in acarines has not been extensively studied, experimental work has indicated that ecdysteroid hormones are involved in the initiation and control of the moulting process in ticks (Soloman et al., 1982), with the moulting cycle appearing to resemble that in insects (Evans, 1992, Mango and Moreka, 1979). Dees et al. (1984) also confirmed the existence of ecdysteroid material in the ticks *Dermacentor variabilis* (Metastigmata) and *Hyalomma dromedarii* (Metastigmata). Chambers et al. (1996) found the highest titres of ecdysteroids in *Dermanyssus gallinae* (Mesostigmata) were present 24 hours after feeding. Sakagami et al. (1992) identified 2-deoxyecdysone (a precursor of ecdysone and 20-hydroxyecdysone in insects) from *Tyrophagus putrescentiae* (Astigmatida) and suggested that the two ecdysteroids may exist in small amounts in the mite, although no biological activity was observed. Ellis and Obenchain (1984) suggest that cells associated with the fat body are the source of ecdysteroids in ticks. Whereas Oliver and Dotson (1993) suggest that the epidermis is the site of ecdysone production, and the fat body the site of 20-hydroxylation in the tick *Ornithodoros parkeri* (Metastigmata). As well as their role in ecdysis, ecdysteroids in ticks have also shown effects on salivary glands (Kaufman, 1991), sex pheromone production (Dees et al., 1984), oogenesis and oviposition (Diehl et al., 1986) and in termination of diapause (Wright, 1969).

Ecdysone analogues have not received as much attention from industry as have JHAs due to their complex structure and difficulty in penetrating the insect cuticle (Piccardi et al., 1980). Also the field use of compounds resembling steroid hormones, which have roles in man and higher animals, need extensive testing for possible side effects (Piccardi et al., 1980).

### 2.3 Chitin synthesis inhibitors

Chitin synthesis inhibitors are another class of IGR which although do not mimic insect hormones, prevent normal moulting of larvae. Although these compounds work by inhibiting chitin synthesis, the precise mechanism of this inhibition remains unclear (Oberlander et al., 1997).

The cuticle in mites serves as an anchorage for skeletal muscles, protects against physical damage, penetration of pathogens and desiccation (Dekeyser and Downer,
The procuticle comprises mainly of chitin and protein (Dekeyser and Downer, 1994), with cuticular synthesis controlled by 20-hydroxyecdysone (Mothes-Wagner, 1986).

Benzoylphenylureas affect the immature stages of mites and also prevent hatching of eggs; they are also relatively non-toxic to mammals (Dekeyser and Downer, 1994). They interfere with the moulting process by inhibiting chitin incorporation into the mite cuticle, but their precise mode of action is unknown, although they do not appear to inhibit the chitin-synthesising enzyme, chitin synthetase (Dekeyser and Downer, 1994).

Lipa and Chmielewski (1976) mixed ‘Dimilin’ (diflubenzuron) with wheat germs at doses of 0.00001 to 100000 ppm and added known numbers of different developmental stages of Tyrophagus putrescentiae (Astigmata). The development time from egg to adult and the percentage of adult mites obtained were used as the criteria of effectiveness. No difference in the development time of mites was observed between those on food treated with low doses of Dimilin, and those on untreated food; there was also no difference in the percentage of adult mites obtained. It was suggested that the inactivity may be due to the lack of chitinous hypostracum in the cuticle of mites belonging to the family Acaridae. The hypostracum is analogous to the endocuticle of insects but since it is lacking in some acarina it may not be as important a structure in mites as in insects. Although there was a lack of effect on moulting of Tyrophagus putrescentiae, only 60-70% of larvae reached adulthood on food treated with 1000 ppm or more. It was suggested that mortality was caused by the mechanical effect of the Dimilin dust which covered the bodies.

Downing et al. (1990) found that diflubenzuron and triflumuron failed to suppress adults and immature mites of Dermatophagoides farinae (Astigmata) when exposed to treated filter papers. It was also suggested that the compounds may, in fact, stimulate reproduction in some cases.

Diflubenzuron has also been shown to be effective for the control of citrus rust mites (Phyllocoptruta oleivora) (Prostigmata) in citrus crops (Grosscurt, 1978); and other benzoylphenylureas e.g. flufenoxuron and flucloxuron are highly effective against a range of spider mites (Anderson et al., 1986; Grosscurt et al., 1988). Flufenoxuron is principally effective against immature stages of mites that are undergoing moults between instars, however, Anderson et al. (1986) demonstrated that adults of Tetranychus urticae (Prostigmata) treated with flufenoxuron laid sterile eggs. Perugia et al. (1986) and El-Atrouzy et al. (1989) found the flufenoxuron containing product ‘Cascade’, to be effective against Panonychus ulmi, Panonychus citri and Tetranychus arabis (Prostigmata). El-Kady et al. (1986) found one-day old eggs of Tetranychus urticae to be more susceptible to ‘Andalin’ than 2 and 3-day old eggs. The larval stage also exhibited high sensitivity to the compound compared to the protonymphal stage.

El-Banhawy (1979) found Dimilin to have activity against eggs and females of Amblyseius brazilli (Mesostigmata) and Tetranychus desertorum (Prostigmata). The eggs of both species were more tolerant than the females, with the females of Amblyseius brazilli the most sensitive. Eggs treated with Dimilin failed to hatch and
when incorporated into the diet of *Amblyseius brazilli* females, Dimilin caused a depression in reproduction and sterility.

Zaki et al. (1990) assessed 4 chitin synthesis inhibitors on mites inhabiting animal dung. In buffalo dung Dimilin was the most toxic compound to mites of the suborders Acaridida and Oribatida while XRD was most toxic to Gamasida and Actinedida. Dimilin was found to have low toxicity to the predacious mites of the Gamasida. In sheep dung, Dimilin appeared the most toxic to Gamasida and Oribatida, while IKI was the most toxic to Acaridida.

Mothes-Wagner (1984) demonstrated the effects of the chitin synthesis inhibitor complex nikkomycin on oogenesis in *Tetranychus urticae* (Prostigmata). In addition to the primary action on chitin synthesis, there were secondary effects on reproduction. The effect on yolk synthesis in oocytes and egg shell synthesis, resulted in inhibition of egg deposition.

The advantages in using IGRs for pest control were originally thought to be their selectivity for insects and consequently low mammalian toxicity, as well as less likelihood for the development of resistance (Oberlander et al., 1997). However, insects have developed resistance to IGRs (Staal, 1975) with cross-resistance shown in OP-resistant strains of stored product insects (Bengston, 1987). Although there is the potential for the development of resistant strains, Bengston (1987) reports no incidences of field failures. IGRs also need to maintain their persistence in the field. To be effective the compounds must persist in the active form for as long as it takes most of the target population to pass through the critical sensitive stage. The effectiveness of IGRs in the field against stored product insects over prolonged periods (Bengston et al., 1990), suggests that biological activity can be maintained within the storage environment and may therefore be effective against mites. The specificity of IGRs against target pests also indicates that they could be used where biological control with parasites or predators are employed, as part of an integrated pest management program.

3. Inert Dusts

Inert dusts have been used traditionally as stored grain protectants (Golob and Webley, 1980), and there is increasing interest in their use as alternatives to chemical control measures. A number of studies on the efficacy of inert dusts against stored product insects have been reported (White et al., 1966; La Hue, 1970; Le Patourel, 1986; Desmarchelier and Dines, 1987; Aldryhim, 1990, 1993 and Subramanyam et al., 1994). They have proved effective as grain protectants (Desmarchelier and Dines, 1987), as structural treatments in empty stores (Bridgeman, 1994) and as surface treatments in conjunction with aeration (Nickson et al., 1994). Diatomaceous earths have been registered for storage use in USA, Canada, Australia, Japan, Indonesia and Saudi Arabia.

The products are based on inert materials such as silica gel or diatomaceous earth, and contain no insecticide or knock down agents. They are residue-free, effective against chemically resistant species, and are stable at high and low temperatures (McLaughlin, 1994). In contrast to chemical insecticides which induce rapid immobilisation and kill, the action of inert dusts is progressive, and extended
exposure to treated grain for 20 days or longer, may reduce the doses of dusts required to kill an insect population (McLaughlin, 1994). Most products, at the appropriate concentration, provide protection for at least 12 months (McLaughlin, 1994).

Inert dusts act by physical means, with insect mortality thought to occur by desiccation as a result of the dust adsorbing lipids from the cuticle (Ebeling, 1971). By their sorptive ability the dusts damage the protective lipid layer and, depending on the relative humidity of the air, the insects lose body moisture through the damaged areas and eventually die (Ebeling, 1971). Insects may die from dehydration due to wicking of hydrocarbons from pores that help slow down water loss (Anon, 1997). In addition to the sorptive ability, some dusts also have abrasive properties (Korunic, 1997). They act through the digestive tract or may cause suffocation, these two effects often work in combination (Korunic, 1997). There are probably other unknown mechanisms (Quarles, 1992b).

Although inert dusts do not affect metabolic pathways by chemical action, they may be chemically active under some circumstances (Golob, 1997). It is also postulated that because the action of the dusts is not dependent on metabolic pathways, insects will not be selected genetically by the action of the dusts, so that physiological resistance is unlikely occur (Golob, 1997). However, it is still conceivable that a mutation conferring enhanced or altered lipid content could confer resistance. It may also be possible for pests to develop a behavioural response to the dust and avoid contact (Ebeling, 1971).

In ticks, lipids on the outer layer of the cuticle (epicuticle) result from secretions of the dermal gland, and are of primary importance in restricting water loss (Soneshine, 1991). Damage to the lipid layer by abrasion, adsorption or dissolution results in desiccation and eventual death. The lipid layer in ticks is very different from that found in insects (Soneshine, 1991). In *Dermacentor variabilis* (Metastigmata) neutral lipids and glycolipids comprise most of the lipid material, phospholipids and unknowns the remainder (Soneshine, 1991). The neutral lipid fraction was found to be a mixture of sterols, triacylglycerols, fatty acids, methyl esters and sterol esters; with triacylglycerols constituting the largest component of the fraction (Soneshine, 1991). Cholesterol and cholesteryl esters were most abundant as sterol/sterol esters. Cherry (1969) also identified cholesterol among the lipids of female *Boophilus microplus* (Metastigmata). Other important components are believed to be saturated long chain acids and alcohols, largely in the form of esters. Leal and Kuwahara (1991) classified astigmatid mites according to their cuticle wax components and identified 4 groups: 1) ester type, 2) insect hydrocarbon type, 3) medium sized hydrocarbon type and 4) all-compounds-from-food type. Three of the groups (1, 3 and 4) were completely different from those of insects.

Several studies have investigated the efficacy of inert dusts against parasitic mites. Tarshis (1964) found that the inert dust Dri-die eliminated the northern fowl mite (*Ornithonyssus sylvarium*) (Mesostigmata) from infested dwellings within 48 hours of application. Residual treatments of Dri-die have been shown to be effective against the snake mite (*Ophionyssus natricus*) (Mesostigmata) (Tarshis, 1960), the tropical rat mite (*Ornithonyssus bacozi*) (Mesostigmata) (Ebeling, 1960), the house mouse mite (*Allodermanyssus sanguineus*) (Mesostigmata) (Ebeling, 1960) and the chicken mite (*Dermanyssus gallinae*) (Mesostigmata) (Melicher and Willomitzer, 1967). Protect-
It, a new Canadian formulation of inert dust, is also recommended for use in the home and garden for mite and tick control (Korunic, 1996).

Knowledge of the effects of inert dusts against stored product mites is very limited. Cook and Armitage (1996) investigated the efficacy of ‘Dryacide’, applied at 1g/kg and 3 g/kg, against Acarus siro (Astigmata) and Lepidoglyphus destructor (Astigmata) at temperatures of 10, 17.5 and 25°C; and moisture contents (mc) of 10, 12, 14 and 16%. No mites survived in treated or untreated grain at 10% mc and 12% mc due to the low relative humidity below their survival threshold. At 14% mc and 17.5°C, both doses were completely effective at controlling both species. At 16% mc and 17.5°C, 3g/kg was fully effective against Acarus siro but not against Lepidoglyphus destructor. At 16% mc, there was some effect against Lepidoglyphus destructor at 10°C and 25°C. However, at 25°C a new generation of mites was observed indicating that the mites were able to reproduce with a lack of efficacy against different mite stages.

Further work by Cook and Armitage (1999) assessed the efficacy of ‘Dryacide’ on wheat against Acarus siro (Astigmata) and Lepidoglyphus destructor (Astigmata) at doses of 1, 3 and 5 g/kg, moisture contents (mc) of 14.5, 15.5 and 16.5% and temperatures of 10, 17.5 and 25°C. After 28 days exposure at 10°C, all doses were effective against Acarus siro (Astigmata) with the exception of 1 g/kg at 16.5% mc. Against Lepidoglyphus destructor (Astigmata) complete control only occurred at 3 g/kg and 14.5% mc and at 5 g/kg at 14.5% and 15.5% mc. At 17.5°C the dust was fully effective against Acarus siro (Astigmata) at 3 and 5 g/kg but only at 14.5% mc, and fully effective against Lepidoglyphus destructor (Astigmata) at 5g/kg and 14.5% mc after 28 days. At 25°C after 14 days exposure, Acarus siro (Astigmata) was completely controlled at 3 and 5 g/kg at 14.5% mc as was Lepidoglyphus destructor (Astigmata) after 28 days exposure. It was suggested that a dose of 3 g/kg may be an effective replacement for organophosphorus pesticide surface treatments in an integrated storage strategy based on grain cooling.

Fields and Timlick (1995) found that the product ‘Super Insecolo’ reduced predaceous and grain feeding mite species by over 98% when applied to wheat at 50 ppm. Tarshis (1960) found that ‘SG67’ (Dry-die 67) had no effect on the eggs of Tyrophagus sp. (Astigmata) when placed in dishes containing 20 mg of the dust. However, the larvae that emerged from the eggs were seen to be completely desiccated. Mixed stages were also seen to die within 3 hours when exposed to 50 mg of the dust with or without culture media. The dead dust-treated mites also appeared shrivelled and well desiccated.

The use of inert dusts as grain protectants may become increasingly more significant as alternatives to conventional chemicals are sought. Their advantages include low mammalian toxicity (e.g. for Insecto the acute oral rat LD50 > 5000 mg/kg; Subramanyam et al., 1994), cost effectiveness, persistence and lack of toxic residues on grain. Disadvantages have included the very high treatment rates required, which affect the physical properties of the grain, particularly bulk density, angle of repose and flow rate (Jackson and Webley, 1994). However, with some of the newer improved formulations, application rates have been reduced, e.g. ‘Insecto’ is effective (under certain temperatures and mc) against several stored-product beetles when applied at 0.5-1.0 g/kg grain (Subramanyam et al., 1994). Also due to the particle size
of some dusts they are considered to be respirable and therefore represent a potential hazard to users (Golob, 1997). However, dusts of larger particle sizes e.g. ‘Dryacide’ and ‘Insecto’, are relatively safe to use with minimum protective equipment (dust mask). Inert dusts are also less effective at high relative humidities and moisture contents (Desmarchelier and Dines, 1987; Ebeling, 1971; Le Patourel, 1986), which is a major consideration for their use as grain protectants in UK. The higher doses that may be required for control may have an adverse effect on the physical properties of the grain. However, these disadvantages would be minimised if used as a surface treatment, in conjunction with cooling as part of an integrated storage strategy.

4. Botanicals

Plant parts and plant extracts have been, and still are used in many parts of the world to kill or repel insects (Secoy and Smith, 1983); with a resurgence of interest during recent years into the use of plant derived pesticides. Some 2400 plant species have been reported to have some pest control properties (Grainge and Ahmed, 1988). The most promising botanical pesticides for use at present and in the future, are derived from species of the families Meliaceae, Rutaceae, Asteraceae, Annonaceae, Labiatae and Canellaceae (Jacobson, 1989). Only 20 plant materials are authorised as plant protection products by the EC, and of these only three botanical insecticide materials, Nicotine, Pyrethrins and Rotenone, are approved by MAFF for use on farms in U.K. (Pinniger et al., 1996; Whitehead, 1997). A commercial product of neem, ‘Margosan-O’ is currently used on certain non-food crops and in nurseries in USA and Europe.

Plants are known to produce a range of secondary metabolites such as terpenoids, alkaloids, polyacetylenes, flavanoids and unusual amino acids and sugars (Benner, 1996), for defence from attack by pests. Plant extracts can possess multiple modes of action, making possible a wide spectrum of use, while retaining selective action within each pest class (Quarles, 1992a). Some may exhibit acute toxicity, while others have repellent, antifeedant or antiioviposition effects, or inhibition of growth, development or reproduction (Coats et al., 1991).

The use of plant derived compounds against stored product insects has been reviewed by Jacobson (1984), Nawrot and Harmatha (1994), Golob and Webley (1980) and Saxena et al., (1989). However, information against stored product mites is again limited.

4.1 Azadirachtin (Neem)

One of the most extensively studied botanical sources of pesticidal compounds is *Azadirachta indica* A. Juss, the neem tree, which is native to arid areas of Asia and Africa. Extracts of various parts of the tree, but especially of the seeds, have been shown to possess pesticidal properties (Jacobson, 1989). Several tetranortriterpenoids have been isolated and identified, but the major entomologically active component is azadirachtin (Jacobson, 1989).

Azadirachtin is effective as a feeding deterrent, repellent, toxicant, sterilant and growth disruptant in insects at dosages as low as 0.1 ppm (Jacobson, 1989). Azadirachtin-containing insecticides act primarily as oral poisons, however, the mechanism of action is unclear. Some authors report a reduction in the ecdysone titre
and/or the delay of ecdysone production (Schmutterer, 1988). An interference with the neuroendocrine system controlling ecdysone and juvenile hormone synthesis is suggested, but also inhibition of ecdysone release (Schmutterer, 1988).

Neem derivatives have been found effective against 123 species of insect pest, including those infesting stored products (Jacobson, 1986; Saxena et al., 1989; Golob and Webley, 1980). However, the efficacy against mite species appears to be concentrated on phytophagous pests. Dimetry et al. (1993), Sundaram and Sloane (1995) and Sanguanpong and Schmutterer (1992), showed that different formulations of azadirachtin, including ‘Margosan-O’ and ‘Neem Azal-S’, affected repellency, feeding rate, oviposition, reproduction and mortality of *Tetranychus urticae* (Prostigmata) females. A significant reduction in the number of eggs laid and hatching was also observed (Dimetry et al., 1993) as well as a reduction in the survival of nymphs hatching from treated eggs (Sanguanpong and Schmutterer, 1992). Mansour et al. (1993), found that ‘Margosan-O’ and ‘Azatin’ were not toxic to *Tetranychus cinnabarinus* (Prostigmata) although they were repellent. However, ‘RD9-Repelin’, which has a lower azadirachtin content, was highly toxic. It was suggested that formulations with higher oil contents were more acaricidally active than formulations with high azadirachtin contents (Mansour et al. 1993; Sanguanpong and Schmutterer, 1992).

Gulati (1998), however, assessed neem products for their effect on fecundity and development of *Tyrophagus putrescentiae* (Astigmata). The number of eggs laid was reduced from 147.6 in untreated wheat to 10.2, 21.4 and 27.6 on treatment with 0.4% neem oil, neemark and neem cake respectively. Other stages showed a similar trend but the neem products were more deleterious to eggs and larvae than mature stages.

‘Margosan-O’ has also been shown to be effective at controlling tracheal mites in colonies of honey bees (Liu, 1995), with azadirachtin found to delay the onset of oviposition in ixodid ticks (Kaufman, 1988).

An important consideration in the use of neem extracts is the lack of adverse effects on predators. Dimetry et al. (1994) tested the effect of ‘Neem Azal-S’ and ‘Margosan-O’ on the predatory mites *Amblyseius barkeri* (Mesostigmata) and *Typhlodromus richteri* (Mesostigmata). Both formulations decreased egg laying and food consumption rate, however were considered safe against *Amblyseius barkeri*, with ‘Margosan-O’ harmless to *Typhlodromus richteri*. Mansour et al. (1993), also found ‘Margosan-O’, and ‘Azatin’ to be harmless to *Typhlodromus athiasae* (Mesostigmata).

Neem derivatives are considered safe to man and warm-blooded animals (Saxena et al., 1989). In sub-acute dermal toxicity tests no overt signs of toxicity or abnormal behaviour were observed in albino rats administered with a daily dose of ‘Neemrich-100’ (technical grade neem oil) at 200, 400 or 600 mg/kg (Qadri et al., 1984).

The residual effect on neem based products is restricted to a few days under field conditions, with temperature, ultraviolet light, pH, rainfall and other environmental factors having negative effects (Schmutterer, 1990). However, persistence may be extended in storage environments to provide adequate protection without the need for repeated applications (Saxena et al., 1989). There is also a delayed effect on insects,
and although feeding continues, the amount of food is considerably reduced owing to secondary antifeedant effects (Schmutterer, 1990). Because of a relatively weak contact effect in insects and the unique mode action on the hormonal system, neem products are quite selective. Attempts to select for resistance in the laboratory with the diamond back moth (*Plutella xylostella*) have been unsuccessful (Vollinger, 1987).

### 4.2 Other plant derived products

An array of plant derived products have been evaluated against storage and domestic mites, with varying degrees of efficacy.

The resin of the Peruvian tree *Myroxylon balsarum* var. *pereirae*, has been used in European medicine since 1853 (Kneist and Bischoff, 1995) against the itch mite, *Sarcoptes scabiei* (Astigmata), the cause scabies in man and mange in domestic and wild mammals (Kettle, 1990). Benzyl benzoate was discovered as the active principle and has been used in pure form since 1912 (Kneist and Bischoff, 1995); and was used during World War II against scabies. In literature from eastern Europe *Sarcoptes scabiei* is sometimes referred to as *Acarus siro* (Kettle, 1990). The reason for the confusion is that Linnaeus thought that the itch mite and the grain mite were identical, and in 1758 he described them as subspecies *scabiei* and *farinae* of *Acarus siro* (Kettle, 1990). Western workers retain *Acarus siro* for the free-living mite associated with grain, and transfer *scabiei* to *Sarcoptes*, while some eastern European workers retain *Acarus siro* for the mange mite (Kettle, 1990).

Benzyl benzoate has also been used as a spasmolytic, antiseptic, vasodilator, emetic, cathartic and amoebicide (Kneist and Bischoff, 1995). As well as its medical uses it has a broad application in the perfume, cosmetic and food industries (Kneist and Bischoff, 1995). Benzyl benzoate and benzyl benzoate containing products are considered relatively safe with no adverse effects when investigated for acute (estimated LD$_{50}$ > 2000 mg/kg in oral and dermal acute toxicity tests) and chronic toxicity, sensitivity and irritation as well as mutagenicity and teratogenicity (Kneist and Bischoff, 1995). Benzyl benzoate has FDA approval for food use, and the Council of Europe listed it with an ADI of 5 mg/kg (Kneist and Bischoff, 1995).

Benzyl benzoate also has acaricidal properties and has been proved effective against house dust mites when used to treat carpets, furnishings and upholstery in the houses of allergic patients (Bischoff et al., 1989; Schober et al., 1987). Kneist et al. (1992) found that ‘Acarosan’, an acaricide based on solidified benzyl benzoate, was 88% more effective than intensive cleaning, at killing house dust mites and removing allergens. Kneist et al. (1996) detailed the use of benzyl benzoate formulated as foam, dust, spray and cold wash treatments. The treatments were found to be effective on fibres, and retreatments were only recommended if allergens were detected.

Elixmann et al. (1991) treated carpets, stuffed furniture and mattresses with a single treatment of ‘Acarosan’. Only after 12 months was a slow recovery of *Dermatophagoides* sp. (Astigmata) observed. Even after 2 years the population only reached 10% of the original density. A slow recolonisation of the mattresses and upholstery by *Cheyletus* sp. (Prostigmata) was observed, however, *Acarus* sp.
(Astigmata), Lepidoglyphus sp. (Astigmata), Tyrophagus sp. (Astigmata) or Tarsonemus sp. (Prostigmata) did not reappear after the treatment.

Koren (1995) found a reduction of 99% of Dermatophagoides pteronyssinus (Astigmata) in 8 weeks on mattresses treated with ‘Acarosan’, whereas ‘Aллерsearch BT’ (containing a benzyltannate complex and alcohol) reduced mite populations by 85%. After 24 weeks reductions of 24% and 78% were recorded for ‘Aллерsearch BT’ and ‘Acarosan’ respectively.

Kalpaklioglu et al. (1996) assessed the contact, short term persistence and residual effects of various concentrations (3.2, 0.8, 0.4, 0.2, 0.1 and 0.5%) of benzyl benzoate against Dermatophagoides farinae (Astigmata) when applied to the surface of wells. The wells consisted of approximately 1cm³ space covered on one side with black filter paper and on the other side with a glass slide. All mites were killed within 15 minutes with 0.8% solution, 1 hour with 0.4% solution and 3 hours with 0.1%. Phenyl salicylate, which has a similar structure to benzyl benzoate, killed most of the mites within 1 hour, with 100% mortality after 3 hours at 0.4%.

Benzyl benzoate has also been shown to be highly toxic to the chigger mite, Eutrombicula hirsti (Prostigmata) when impregnated on cloth. When applied to filter papers ED₅₀ values of 1.42 mg/cm² were recorded, compared to 0.26 mg/cm² with DEET (Frances, 1988).

Although no resistance to benzyl benzoate has been reported in pyroglyphid mites (Astigmata) (Kalpaklioglu et al., 1996) or detected with ‘Acarosan’ after 10 years of use (Kneist - personal communication), in agricultural use, mites have developed resistance to this compound (Kalpaklioglu et al., 1996).

Perrucci (1995) found that the essential oils of 2 lavender species and of peppermint killed 100% of Tyrophagus longior (Astigmata) by contact and inhalation action, when applied to petri dishes at 1.0 µl. Eucalyptus oil was the least active. Among the essential oil constituents, menthol killed all the mites at 0.25 µl by direct contact and at 6µl by inhalation. Linalool, fenchone and menthone also showed good acaricidal activity, with eucalyptol having the lowest activity.

Li et al. (1994) assessed the influence of temperature and modified atmosphere on the effectiveness of Lavandula angustifolia Mill. oil for controlling Tyrophagus putrescentiae (Astigmata). The major factors affecting mite mortality were: plant oil concentration > CO₂ concentration > O₂ concentration. Increasing the CO₂ level or lengthening fumigation time were found to enhance the effects of the plant fumigant against the mite.

Watanabe et al. (1989) found that 52 essential oils had acaricidal properties against Dermatophagoides pteronyssinus (Astigmata), Dermatophagoides farinae (Astigmata) and Tyrophagus putrescentiae (Astigmata). Of these almond bitter oil, caraway oil, dill oil, spearmint oil, ho oil and wintergreen oil were very effective, with LD₁₀₀ values ranging from 1µl to 5µl. Of the essential oil components, benzaldehyde, d-carvone, l-carvone, linalool and methyl salicylate showed very high activities. No correlation was observed between mite killing effect and inhibition of cholinesterase.
Kalpaklioglu et al. (1996) assessed the effectiveness of tea (*Thea sinensis*) leaf extract and the essential oils of eucalyptus and laurel against *Dermatophagoïdes farinae* (Astigmata). Laurel oil at 3.2% killed 77.5% of mites after 24 hours, however the eucalyptus oil was ineffective. The tea extract at 9.5% tannin killed 18.03% mites after 24 hours and 62.3% after 1 week.

Lozzia et al. (1994) evaluated 16 essential oils, at 1% in acetone, against *Dermatophagoïdes pteronyssinus* (Astigmata) and *Glycyphagus domesticus* (Astigmata). All the oils were ineffective against *Dermatophagoïdes pteronyssinus* and partially ineffective against *Glycyphagus domesticus*. With the latter species, eugenia and garlic produced mortalities of 41% and 36% respectively, after 24 hours. The remainder produced mortalities of < 29.5%.

Ottoboni et al. (1992) evaluated the efficacy of 10 essential oils on the mortality of *Dermatophagoïdes pteronyssinus* (Astigmata). The most effective were caraway, garlic, black pepper and Peru balsam. The main components of caraway oil, carvone and carvacrol, were also assessed. Carvone had similar effects as caraway oil while carvacrol was particularly effective after 30 minutes.

Czajkowska (1971) assessed the effect of 29 oils, 18 alkaloids and 11 glycosides on the length of development and mortality of *Acarus siro* (Astigmata), *Acarus farris* (Astigmata), *Tyrophagus putrescentiae* (Astigmata), *Rhizoglyphus echniopus* (Astigmata) and *Carpoglyphus lactis* (Astigmata). With *Acarus siro*, 100% mortality was achieved with 16.8 % parsley oil, 2% caffeine and ergotamine, 10% quinidine and 40% arbutine. With *Tyrophagus putrescentiae*, 100% mortality was observed with 8.4% parsley oil, 0.6% colchicine, 8% caffeine, 40 % quinine and 0.4% digitoxine. Several oils were shown to have a stimulating effect on *Tyrophagus putrescentiae*. The alkaloids showed the strongest inhibitory effects on *Carpoglyphus lactis, Acarus siro* and *Tyrophagus putrescentiae*. Higher doses of some glycosides also inhibited the reproduction of *Acarus siro* and *Tyrophagus putrescentiae*.

Potts and Rodriguez (1978) incorporated spice oils into the diet of *Tyrophagus putrescentiae* (Astigmata) and assessed the effects on inhibition of growth and development. Sassafras and vaniprox were moderately inhibitory at a concentration of 0.001 %. The remainder of the oils influenced moderate to high inhibition at concentrations of 0.01% and 0.1 %. The order of inhibition from high to low, was oils of bitter almond < sage < onion < clove < oleoresin black pepper < mace < black pepper.

Rodriguez et al. (1979) investigated the possible effects of dried spices and flavouring oils on *Tyrophagus putrescentiae* (Astigmata). Whole and ground spices incorporated into pet foods at 2% produced kairomone (phagostimulatory) and allomone (deterrent) effects, when presented to mites in free-choice feeding tests. Curry powder, lemon/pepper seasoning, mace and sage showed particular allomone effects. All the flavouring oils mixed into a standard laboratory casein-wheat germ-agar diet or pet food produced some inhibition of mite growth at levels of 0.1% to 0.00001%. In the laboratory diet at 0.1%, total mite inhibition was produced by all oils except the citrus oils, whereas at 0.01%, the inhibition was less than 50% in most cases, with the exceptions of sage, sassafras, vaniprox and orange. In the pet food at 0.1%, inhibition ranged from 76% for oleoresin black pepper to 92% for clove; at 0.01% from 82.4%
for almond to 96% for sassafras; at 0.001% from 74.2% for oil of black pepper to 94.2% for sassafras.

Afifi and Hafez (1988) assessed the toxicity of different plant extracts against *Tyrophagus putrescentiae* (Astigmata) when mixed with flour. Caraway fruit extracts were more effective than fenugreek and lupin extracts. At 12 ppm, complete mortality was achieved after 48 and 72 hours with the caraway and fenugreek extracts respectively, with more than 72 hours required with the lupin extracts. At 100 ppm, complete mortality was achieved after 24 hours exposure to the fenugreek and caraway extracts, and after 48 hours with the lupin. The mites could also differentiate between treated and untreated flour, being attracted to the untreated.

Gulati and Mathur (1995) showed that different concentrations of powdered leaves of *Eucalyptus* and *Mentha* and rhizomes of *Curcuma* (tumeric) had pronounced effects on the fecundity and development of *Tyrophagus putrescentiae* (Astigmata) when applied to wheat flour. The *Eucalyptus* and *Mentha* powders were effective at concentrations from 100% to 5%, in decreasing mite fecundity and reducing the number of eggs to approximately 52 and 25 per female, for the respective materials (at 5%), compared to approximately 98 eggs in the controls. Rhizomes of *Curcuma* reduced egg laying to approximately 8 eggs per female even at 0.1%, and inhibited adult development at all concentrations. The materials were found to affect the eggs and larval stages more than the nymphs and adults. They were also more effective when mixed with whole grains compared to flour. No antifeedant effects were observed.

There is great potential in the use of botanical pesticides for stored product protection. Natural plant extracts are used in many developing countries to control insect pests in small-farm storages because economic conditions do not justify the use of conventional chemical protectants (Niber, 1994). However, before such products can be used commercially they must meet the following criteria: 1. safe for plant and animal life, 2. biodegradable (environmentally safe), 3. ready availability of the plant or capability for cultivation, 4. determination of isolation procedures of the active component or components from the plant (or of formulation of extracts prepared from plant parts) or 5. establishment of synthetic procedures for the active components (Jacobson, 1989). With the vast array of chemical compounds derived from plants and the many diverse behavioural and physiological effects induced, the possibility of pests developing resistance may be less likely. However, as with other pesticides, over or misuse may increase the possibility. The multiple modes of action possessed by some plant extracts, makes possible a wide spectrum of use, however the effects on beneficial organisms have to be considered. Unfortunately the use of some plant extracts that have proved effective against mites may be limited, due to tainting of grain and cereal products.

**5. Pyrethroids**

One of the best known plant-derived pesticides is pyrethrum, obtained from the flower petals of *Chrysanthemum* sp. such as *Chrysanthemum cinerariaefolium* (Grossman, 1993). However, although natural pyrethrum, which consists of six closely related compounds, is still used commercially, it has been largely superseded by the synthetic pyrethroids, which have greatly improved insecticidal properties and photostability.
Pyrethroids degrade slowly on wheat under normal conditions of storage with increased rate of loss at higher temperatures and moisture levels (Noble et al., 1982). Pyrethroids have shown to be effective against storage insects, and also demonstrate a negative temperature coefficient, i.e. toxicity is greater at lower temperatures (Subramanyam and Cutkomp, 1987; Thaung and Collins, 1986; Longstaff and Desmarchelier, 1983; Watters et al., 1983). Pyrethroids act on the nerve membrane with synapses the initial target site (Narahashi, 1976). They act on the ion channels by keeping sodium channels open, resulting in a continuous slow depolarisation which eventually blocks nerve conduction and causes paralysis (Narahashi, 1976).

Several pyrethroids are effective against stored product mites. Cypermethrin applied to wheat at 2, 4 and 8 ppm, gave 5%, 45% and 66% mortality of *Acarus siro* (Astigmata), at the respective doses, after 4 weeks storage; compared to permethrin where 0%, 20% and 54% mortality was recorded (White, 1984). However, Wilkin et al. (1988) found cypermethrin to be ineffective against *Acarus siro* at doses ranging from 0.125 mg/kg to 2.0 mg/kg, 1 day, 2, 4 and 6 months after treatment. Against *Lepidoglyphus destructor* (Astigmata) all doses, except the lowest, produced ~75% mortality after 1 day and 2 months storage, 100% after 4 months and 75% after 6 months storage.

Wilkin and Hope (1973a) found that bioresmethrin applied to wheat at 2 ppm produced complete mortality of *Acarus siro* and *Lepidoglyphus destructor* (Astigmata) after 14-days exposure, with >75% mortality of *Tyrophagus putrescentiae* (Astigmata). However, when 20 ppm piperonyl butoxide was added to 2 ppm bioresmethrin, the mortality of *Lepidoglyphus destructor* decreased to >75%. Both bioallethrin and pyrethrins, applied to wheat at 2 ppm, were ineffective against all three species. However, pyrethrins plus piperonyl butoxide (20 ppm) produced complete mortality of *Acarus siro* and >75% mortality of *Lepidoglyphus destructor*.

Stables (1984) found that bioresmethrin and piperonyl butoxide applied to wheat at 10 ppm + 10 ppm produced approximately 50% mortality of strains of *Tyrophagus longior*, *Tyrophagus palmarus* and *Tyrophagus putrescentiae* (Astigmata) after 7 days exposure, with mortality increasing to approximately 75% after 14 days exposure. Practical trials showed that bioresmethrin and piperonyl butoxide applied at 4 ppm + 20 ppm, 2 ppm + 20 ppm and 2 ppm + 2 ppm, controlled mites in the fabric of buildings and in stored grain, and also controlled lindane resistant strains (Wilkin, 1975a). Anderson and Wilkin (1984) found that although bioresmethrin and piperonyl butoxide applied at 0.5%, killed large numbers of mites infesting cheeses, considerable survival was observed 3 weeks after treatment.

Chisaka et al. (1984) found phenothrin, fenopropathrin and permethrin to be the most effective pyrethroids against *Tyrophagus putrescentiae* (Astigmata) at 500 ppm. Mortalities of 99.7%, 99.5% and 98% were recorded for the respective compounds 3 weeks after treatment. They also found that the pyrethroids were more effective against *Dermatophagoides farinae* (Mesostigmata) than *Tyrophagus putrescentiae.*

Lozzia et al. (1994) evaluated ‘Pertrin E’ (pure permethrin 5%), ‘Pertrin S’ (permethrin 5% with pyrethrum extract 3%) and ‘Cipertrin T’ (cypermethrin 2.5% with tetramethrin 1%) applied in an aqueous solution of 2%, against various mite
species. All the pyrethroids showed fairly good acaricidal activity against the house and storage mites. ‘Cipertrin’ was significantly more efficacious and had a greater speed of action on all the species. Twenty four hours after treatment, mortalities of 22.3%, 44%, 83%, 64.1%, 97.6% and 96.2% were recorded respectively for *Dermatophagoides farinae*, *Dermatophagoides pteronyssinus*, *Acarus siro*, *Tyrophagus putrescentiae*, *Glycyphagus domesticus* and *Lepidoglyphus destructor* (Astigmata). The sensitivity to the 3 pyrethroids varied considerably from family to family increasing from Pyroglyphidae to Acaridae, Chortoglyphidae, Labidophoridae and Glycyphagidae.

Dekeyser and Downer (1994) suggest that bifenthrin is probably the most effective pyrethroid against mites. Binns (1989) found that emulsifiable concentrate and flowable concentrate formulations of bifenthrin, and a flowable concentrate of deltamethrin were more effective than pirimiphos-methyl against *Acarus siro* (Astigmata) at 17.5°C and 75% rh. Both bifenthrin formulations produced 100% and 75% mortality with 1.0 and 0.5 mg/kg respectively after 1 day. At 4 weeks, 1.0 mg/kg of both formulations produced 50% mortality, however after 12 weeks neither were effective. Deltamethrin was least effective after 1 day, producing 25% and 75% mortality with 0.5 mg/kg and 1 mg/kg respectively. After 4 weeks deltamethrin was as effective as bifenthrin, however, after 12 weeks no mortality was recorded.

One disadvantage of using pyrethroids against some mite species is that at doses which fail to produce complete mortality, there is an increase in egg production, resulting in a sudden increase in mite numbers (B. Thind - personal communication).

6. Novel Compounds

A range of other novel compounds have been evaluated for use against stored product and domestic mite pests. These include compounds that act as chemosterilants, fatty acids, inorganic salts, avermectins and other medicinal products.

6.1 Chemosterilants

Chemosterilants are chemicals that arrest or adversely affect reproductive capacity and are therefore obvious candidates for use in pest control programs. Since 1960 interest in the potential of chemosterilants as a practical means of insect control has increased rapidly, being stimulated by the practical applications of gamma radiation for male sterilisation programmes, and the demonstration that insects could be sterilised chemically (Smith et al., 1964).

Chemosterilants may act in one of three principal ways. They may lead to failure to produce ova or sperm, death of the sperm and ova after they have already been produced, or they may produce multiple dominant lethal mutations or severely injure the genetic material in the sperm and ova (Smith et al., 1964). In the last case, although the sperm and ova remain alive, the zygotes, if formed, do not complete development into mature progeny (Smith et al., 1964). This type of action is desired because males so sterilised compete readily with normal males for females thereby satisfying the mating requirements of the females (Smith et al., 1964). If sterile and normal adults compete for mates, the result is a reduction in the number of progeny in the following F1 generation (Hodges, 1984b). If further sterile adults are available to
compete with the F₁ and subsequent generations, the pest population may be reduced still further to a negligible level (Hodges, 1984b). The speed at which this is achieved is dependent upon the ratio of sterile to normal adults (Hodges, 1984b).

Information on the effect of chemosterilants against stored product insects is limited (Brower and Jurk, 1980; Gangrade and Pant, 1970 a & b; Rizvi et al., 1980). However, against mites, Ignatowicz and co-workers have reported the effects of several potential chemosterilants against *Acarus siro* (Astigmata) and *Tyrophagus putrescentiae* (Astigmata). Under optimum conditions (15°C and 90% rh) in the laboratory, *Acarus siro* can average an output of 435 eggs per female, with a maximum of 858 (Cunnington, 1985). However, in order to achieve maximum egg production repeated matings were required (Cunnington, 1985). Chemosterilants therefore offer an alternative approach for mite control, by preventing or reducing egg laying.

Ignatowicz (1982a) found that potassium iodide (KI) applied to wheat germ at concentrations higher than 0.25% prevented egg laying by *Acarus siro* (Astigmata). Egg production was also suppressed in females which were already laying eggs. Sterility was found to be permanent with females more susceptible than males. Exposure time of the mites to KI was more important than its concentration. It was thought that KI probably concentrates in the ovary of females and prevents formation of the eggs. The activity may be the result of a specific reaction with one or more essential components of cells of the tissue responsible for forming the ova.

Potassium iodate and tin iodide added to wheat germ at concentrations higher than 0.25% prevented most females of *Tyrophagus putrescentiae* (Astigmata) from laying eggs permanently (Ignatowicz, 1986). The compounds also suppressed production of eggs in females which were already laying eggs. However, the concentration of the iodine salts required to produce significant sterility were thought to be too high for direct economic use (Ignatowicz, 1986).

Ignatowicz and Boczek (1979) found that females of *Tyrophagus putrescentiae* (Astigmata) were more susceptible than the males to iodine salts (potassium iodide and iodate). They concluded that this may be due to the effect upon egg formation. Some females laid incompletely formed eggs, though, the viability of normal formed eggs exceeded 90%. Iodine salts induce sterility in *Tyrophagus putrescentiae* by reduction in egg production rather than by reduction in hatchability. The salts also inhibit egg yolk production during oogenesis causing incompletely developed eggs to form. It is suggested that this is caused when the iodine compounds bind proteins during egg formation and inhibit their activities.

Ignatowicz (1982b) found that boric acid applied to food at concentrations higher than 0.5%, was lethal to *Tyrophagus putrescentiae* (Astigmata), sodium borate, however, was less toxic. The concentrations of boric acid and sodium borate required for complete infecundity, and those that resulted in rapid death, were close. The lowered fecundity produced by sub-lethal concentrations of boric acid and sodium borate was temporary. Mites exposed to treated diets partially recovered their reproductive abilities after a return to an untreated food, therefore boric acid and sodium borate appeared to exhibit weak chemosterilant activity against *Tyrophagus putrescentiae*. 
Ignatowicz (1983a) observed that sodium fluoride (NaF) was toxic to *Tyrophagus putrescentiae* (Astigmata) when added to food at doses higher than 1%. At a dose of 2%, 58% of females failed to produce eggs, however, at doses of 0.25% or 0.5% only 6-8% of females did not produce eggs. Exposure to NaF resulted in suppression of fecundity rather than acting as a chemosterilant. Egg laying was recovered to some extent after a return of the females to untreated food. The doses required to give complete sterilisation and high mortalities were very close.

Ignatowicz, (1987a) found that the fecundity and viability of eggs of *Tyrophagus putrescentiae* (Astigmata) and *Acarus siro* (Astigmata) decreased with increasing concentration of thiourea in food. However, mites recovered their reproductive potential to some extent when returned to untreated foods. Females treated with high concentrations of thiourea produced eggs only during the early period of oviposition after which they were infecund. At 1-2% thiourea caused both high mortality and sterility, and also suppressed postembryonic development. At 2%, longevity of mites was significantly affected. Females were more affected than males, with *Acarus siro* more susceptible than *Tyrophagus putrescentiae*.

5-fluorouracil (FU) causes sterility only in the females of *Tyrophagus putrescentiae* (Astigmata) and *Acarus siro* (Astigmata) (Ignatowicz, 1987b). At low concentrations in the diet (0.25%-0.5%), FU fed for one week caused partial sterility, with permanent sterility caused at high concentrations (2%). FU when ingested considerably reduced egg production and viability and suppressed egg production in mites already laying eggs. At concentrations higher than 0.5%, longevity was reduced in males and females. FU is an analogue of uracil and thymine and can be incorporated into RNA as an abnormal nucleotide. The main action is reported to be interference with the thymidylate synthetase system, causing a marked inhibition of DNA synthesis (Heidelberger et al., 1957).

Colchicine, when ingested, reduced fecundity and fertility and produced high mortalities of *Tyrophagus putrescentiae* (Astigmata) and *Acarus siro* (Astigmata) (Ignatowicz, 1987c). When fed at 0.01%, fecundity and fertility of *Acarus siro* were reduced by 24.4% and 63% respectively. Whereas the productivity of *Tyrophagus putrescentiae* was lowered by 89.2%. At 0.1%, colchicine was very toxic to the mites. Rapid death of males and females occurred after the 2nd or 3rd week of treatment. The concentrations required to effect complete sterility and rapid death were close.

Szlendak (1998) assessed the influence of folic acid, methionine and riboflavin on the fecundity and mortality of *Tyrophagus putrescentiae* (Astigmata). Low doses of riboflavin (0.5-2%) and folic acid (1%) applied to the diet were insufficient to cause mite sterility and even had a stimulating effect on fecundity. Only methionine at doses equal to or higher than 5% had a negative influence of fecundity and the population parameters.

The disadvantages of using chemosterilants are that their activity may not be restricted to the target pest and may therefore have adverse effects on non-target organisms. However, they could be used in combination with baits and attractants to ensure only the target pest is affected (Smith et al., 1964). Also chemosterilants are usually highly toxic and therefore should not come into contact with food (Hodges,
1984b). It is therefore unlikely that such compounds would ever be approved for use on stored grain or even for use as fabric treatments.

6.2 Fatty Acids

The use of fatty acids against stored product insects has been reported by House and Graham (1967), Williams and Hurlock (1969) and Simpson (1973).

The short chain fatty acids, propionic, butyric, caproic, caprylic and capric acids have been found to be effective in inhibiting growth and development of *Tyrophagus putrescentiae* (Astigmata) when incorporated into commercial dog food (Rodriguez, 1972). No eggs were oviposited in foods containing a 1% concentration of capric acid and 2% concentration of the other fatty acids. Propionic, caproic and capric acids retarded growth to the extent of a significant loss in weight when incorporated into an agar based diet at 0.05%. It was suggested that the routes of entry of fatty acids are by ingestion, adsorption through the integument and in some cases by vapour action (Rodriguez, 1972).

Simpson (1973) found that *Acarus siro* (Astigmata) did not survive in grain treated with 0.5-0.8% of propionic acid. Williams and Hurlock (1969) also found propionic acid to be an effective acaricide against *Acarus siro* and *Thyreophagus* sp. (Astigmata) when applied to barley. It was suggested that its effects on the mites may have been due to the lethal effect on the moulds on which the mites feed (Williams and Hurlock, 1969). However, it has also been found that the effect of propionic acid wears off with time (D M Armitage - personal communication).

Propionic acid also inhibits growth of mould, bacteria and yeasts and has been used to protect grain stored at high moisture contents (Simpson 1973). The quantity of acid used depends on the moisture content of the grain, but should not exceed 1.5% by weight if grain is for animal feed, or 0.3% if for human consumption (Simpson 1973). Grain so treated loses its germinative capacity and is unsuitable for seed or malting (Simpson 1973).

6.3 Inorganic Salts

Tricalcium phosphate is used as a supplemental mineral additive to processed foods and flour (Baker et al., 1976), however, several studies have shown toxic effects against stored product insects (Majumder and Bano, 1964; Highland, 1975; Baker et al., 1976 and Press et al., 1972). This food additive is unique in that it possesses both nutritional properties for vertebrates and toxicological properties towards insects (Baker et al., 1976). Baker et al. (1976) suggested that tricalcium phosphate acted in a similar way to that of inert dusts and that insect death was probably as a result of water loss. However the exact mechanisms of action are not fully understood (Boczek et al., 1984).

Boczek and Ignatowicz (1979) and Ignatowicz (1980) evaluated the effects of tricalcium phosphate, when mixed with food, on *Tyrophagus putrescentiae* (Astigmata). The fecundity, longevity and mortality of mites was only slightly affected when the salt was added at concentrations of 1-6%. A 50% reduction in fecundity was achieved at 18% in the diet, with an 84% reduction at 31.5%. Egg
viability was only reduced at concentrations of 30 and 31.5%. Mortality during development and egg viability were practically unaffected until a concentration of 31.5%.

Boczek and Ignatowicz (1979) and Ignatowicz (1981) also showed that tricalcium phosphate had a very strong contact action causing 100% mortality of mites after 3-5 hours when in contact with 0.5-1 mm of the salt on wheat germ. During exposure the mites did not feed at all. The finely powdered salts were seen to attach to the mite body forming a thin layer, with dead mites seen to have stretched bodies and legs. It was suggested that the action of tricalcium phosphate was of a physical nature, similar to that of inert dusts, causing scratching and wax adsorption of the cuticle. Resistance of mites to tricalcium phosphate may also be less likely, because, as with inert dusts, the action is physical rather than chemical, and is therefore not dependent on metabolic pathways. Related species, Tyrophagus casei, Tyrophagus similis, Tyrophagus palmarum, Tyrophagus longior, Tyrophagus neiswanderi, Acarus siro and Tyroleophagus entomophagus (Astigmata) were more sensitive to the contact action than Tyrophagus putrescentiae (Boczek and Ignatowicz, 1979; Ignatowicz, 1981).

Eggs, immobile larvae and nymphs were, however, tolerant to the salt and 100% emergence to next developmental stage was observed. It was suggested that the resistance of the inert stages may be due to the fact that the new cuticle originates under the old one and therefore moulting mites have two cuticular layers which may protect more from water loss (Ignatowicz, 1981). In addition, the immobile stages do not move and therefore may not pick up as many particles (Ignatowicz, 1981).

Caustic soda (NaOH) is also added to grain to improve nutritional qualities and is thought to provide a method of preserving damp grain (Thind, 1991). Thind (1991) found that caustic soda added to grain at 3%, 2% and 1% did not suppress populations of the wet grain mite Caloglyphus berlesei (Astigmata), with the exception of grain treated with 3% soda and incubated at 24% rh.

Ignatowicz (1981) also found that ferric phosphate rapidly killed various acarid mites when placed in contact with a 1mm layer of the salt. However, ferric phosphate can be harmful to man and domestic livestock.

Ignatowicz (1983b) and Boczek et al. (1984) evaluated the effects of different mineral salts as food additives, on the fecundity and egg viability of Tyrophagus putrescentiae (Astigmata). Different concentrations of the salts had varying effects on fecundity and egg viability, ranging from stimulation to total suppression. Boczek et al (1984) found the most suppressive salts were those containing the elements Ag, Ba, Cd, Co, Cu, F, I, Li, Mn, Mo and Zn. Ag2SO4 and AgNO3 prevented egg laying at concentrations above 1% and reduced adult longevity above 3%. Some of the salts commonly used as food additives, including tricalcium phosphate, produced only slight to little effect on fecundity and egg viability.

6.4 Antibiotics

Avermectins are macrocyclic (large ring compounds usually containing repeating units) lactones isolated from the soil bacterium Streptomyces avermitilis (Lasota and Dybas, 1991). Avermectins are a family of broad-spectrum, antiparasitic agents.
Originally identified in screens of natural products with antihelmintic activity, these compounds have also demonstrated nematicidal, insecticidal and acaricidal activity (Lasota and Dybas, 1991).

There are 8 components (A1a, A1b, B1a, B1b, A2a, A2b, B2a and B2b) of the avermectin complex, and of these avermectins B1a and B2a are the most promising candidates as agricultural pesticides (Putter et al., 1981). Avermectins are thought to act on the neurotransmitter GABA (4-aminobutyric acid). GABA is a major inhibitory neurotransmitter which activates a chloride ion channel in insect nervous systems, leading to rapid hyperpolarisation (Pitman, 1971). Avermectins are thought to act as agonists or stimulate GABA release or binding of GABA to its receptor, thereby increasing chloride-ion channel conductance and causing paralysis (Wright, 1986). GABA has been found in ticks and it is thought that it may play a similar role as in other arthropods (Binnington and Obenchain, 1982). Avermectins can also inhibit chitin synthesis (Calcott and Fatig III, 1984) and causes histopathological changes in the ovaries of fire ant queens (Glancy et al., 1982).

In ticks the mode of action of avermectins is unknown, however, it has been suggested that they may interfere with hormonal systems (Lundke and Kaufman, 1992). Abamectin is the common name assigned to avermectin B1 and which has been used commercially as an acaricide. Ivermectin (synthetic abamectin) has been shown to suppress engorgement, moulting and reproduction (Campbell et al., 1983). In the ixodid tick *Amblyomma hebraeum* (Metastigmata), an avermectin analogue inhibited ovary maturation and yolk production and also lowered the haemolymph ecdysteroid concentration in engorged females (Lundke and Kaufman, 1992).

Abamectin has shown excellent initial and residual control of immature and adult motile mites, with a broad spectrum of activity against mites in the families Tetranychidae (Prostigmata), Eriophyidae (Prostigmata) and Tarsonemidae (Prostigmata), with LC₉₀ values in the range of 0.02-0.24 ppm (Lasota and Dybas, 1991). Also no cross resistance has been identified in resistant populations (Lasota and Dybas, 1991). It has also shown to be effective against ticks (Drummond and Miller, 1984) and cause mortality and reduce fecundity in *Psoroptes ovis* (Astigmata), the common scab mite (Guillot and Wright, 1984).

Against tetranychid spider mites, abamectin has shown a high contact activity against all motile stages, although no true ovicidal activity has been observed (Lasota and Dybas, 1991). Although avermectin has been found to be significantly more toxic to *Tetranychus urticae* (Prostigmata) than to the predacious mite *Metaseiulus occidentalis* (Mesostigmata) (Hoy and Cave, 1985), its value as a selective acaricide is dependent on the rates applied. In the laboratory, avermectin B1a has demonstrated high toxicity to *Tetranychus urticae* and also against other tetranychids and eriophyids including the citrus rust mite (*Phyllocoptruta oleivora*) (Prostigmata), citrus red mite (*Panonychus citri*) (Prostigmata) and the strawberry spider mite (*Tetranychus turkestanii*) (Prostigmata) (Putter et al., 1981). Laboratory evaluations suggest that avermectin kills *Tetranychus urticae* both by contact and oral action although it has a slow-acting effect (Putter et al., 1981).

Hoy and Conley (1987) reported no resistance to abamectin in field populations of *Tetranychus urticae* (Prostigmata) and *Tetranychus pacificus* (Prostigmata) selected
up to 15 times. Also, no cross-resistance to the sulfite acaricide, propargite, and the organotins, cyhexatin and fenbutatin oxide, was detected (Hoy and Conley, 1987). However, Campos et al. (1995, 1996) detected resistance to abamectin in the laboratory, with field populations of *Tetranychus urticae*, although no field failures had been reported. Roush and Wright (1986) reported a lack of abamectin cross-resistance in houseflies to various insecticides (diazinon, dieldrin, DDT, permethrin); Scott (1989) reported conflicting results of polygenic cross-resistance to abamectin in two pyrethroid resistant strains of houseflies.

Milbemycins belong to the same class of 16-membered macrolides as avermectins and were isolated from *Streptomyces hygroscopicus* f. sp. *aureolacriosus* (Takiguchi et al., 1980). A mixture of milbemycin A₃ and A₄ (milbemectin) has been practically used for the control of *Tetranychidae* on tea trees and egg plants since 1990 (Yamaguchi, 1996). Toxicity to mammals is low, but to fish is high (Yamaguchi, 1996).

Polynactins are macrotetrolide antibiotics produced by *Streptomyces aureus* strain S-3466 (Ando et al., 1971). They have been found effective against the carmine spider mite (*Tetranychus cinnabarinus*) (Prostigmata), two spotted spider mite (*Tetranychus urticae*) (Prostigmata) and European red mite (*Panonychus ulmi*) (Prostigmata) (Yamaguchi, 1996). Polynactins show least activity by direct contact with mites in a dry state, however, they exert marked miticidal activity under wet conditions, therefore, water is an essential factor for their activity (Yamaguchi, 1996). It is suggested that polynactins cause leakage of a basic cation, such as K⁺, through the lipid layer of the membrane in mitochondria (Ando et al., 1974). Acute toxicity to mice and rats is very low, though, toxicity to fish is high (Yamaguchi, 1996).

Natamycin is used in drugs and alimentary products as a broad spectrum fungicide. In addition to fungicidal activity, natamycin also has acaricidal properties. Saint Georges-Gridelet (1987) found that natamycin prevented larval hatching, but not embryonic development, in the house dust mite *Dermatophagoides pteronyssinus* (Astigmata). Schober et al. (1987) found that a 3% natamycin solution induced no significant acaridal effects on 10 house dust mites (*Dermatophagoides farinae*) (Astigmata) soaked in the solution. However, a 10% solution added to food, significantly reduced the numbers of mites after 5 weeks. Koren (1995) found a 40% reduction in *Dermatophagoides pteronyssinus* (Astigmata) when ‘Tymasil’ (3.33% w/v natamycin and 0.02% w/v benzalkonium chloride) was applied to mattresses. Bronswijk et al. (1987) also detected some effect on mite population growth after treatment with ‘Tymasil’. It is suggested that the acaridal mechanism of natamycin is a nutrient effect, caused by suppressing the fungi that predigest essential lipid components for the mites (Koren, 1995). Although storage mites can survive on fungal diets when a grain store is empty of commodities, it is not their ideal diet. However, it is suggested that the fungi may act as substrate enhancers for the mites (Parkinson et al., 1991a and b).

Boczek and Czajkowska (1968) assessed 22 antimicrobial agents and 13 antibiotics mixed with diet against *Carpoglyphus lactis* (Astigmata), *Acarus siro* (Astigmata) and *Tyrophagus putrescentiae* (Astigmata). *Acarus siro* was more sensitive to the antimicrobials and less sensitive to the antibiotics than *Carpoglyphus lactis*. *Tyrophagus putrescentiae* was the most tolerant to the additives studied. Some
antimicrobials not recommended as additives to food products (borax, boric acid, hexamethylene, tetramine and salicylic acid), inhibited the development of the mites. Compounds like potassium sorbate, benzoic acid and calcium propionate, which were considered as suitable food additives, also had a distinct inhibitory effect. As no symbiotic organisms were found in the mite bodies, it was suggested that the compounds had a direct effect on the mites, through their metabolic processes.

Fusariotoxin, isolated from the microfungus *Fusarium sporotrichilla*, showed toxicity to *Tetranychus telarius* (Prostigmata), at concentrations of 0.01, 0.02 and 0.03% (Chhabra, 1971). Sterility was also induced in treated females (Chhabra, 1971). After 10 days the populations of mites on treated plants remained at 28.8, 19.2 and 15.9 % of the control levels for the respective concentrations, whereas after 15 days the populations were 59.6, 18 and 9.1% respectively (Chhabra, 1971).

Benzyl alcohol is a pharmaceutic aid with bacteriostatic properties and is also considered non-toxic to man at low concentrations (oral LD$_{50}$ : 500 mg/kg) (Castagnoli et al, 1996). Its acaricidal effects were evaluated against *Dermatophagoides pteronyssinus* (Astigmata), *Dermatophagoides farinae* (Astigmata), *Euroglyphus maynei* (Astigmata) and *Tyrophagus putrescentiae* (Astigmata) (Castagnoli et al., 1996). Eggs and motile stages were sprayed with 3.25% water solution of benzyl alcohol. Immediately after spraying all mites appeared immobilised. The highest mortalities of the motile stages were recorded after 24 hours: 83% for *Euroglyphus maynei* and *Dermatophagoides farinae*, 84% for *Dermatophagoides pteronyssinus* and 87% for *Tyrophagus putrescentiae*. The effectiveness of benzyl alcohol was lower against eggs with 56% hatchability of *Tyrophagus putrescentiae* and 25-30% of the other species. Benzyl alcohol also appeared to have a repellent effect.

7. Biological Control

The term ‘biological control’ is used here in referring to the use of biological agents, i.e. predators, parasites and pathogens, as a method of reducing pest damage. In a broader sense ‘biological control’ is sometimes used to include the manipulation of other biotic factors of the pest’s life system, such as its reproductive processes, its behaviour, the quality of its food etc. (Evans, 1984).

In the past there have been several constraints placed on the potential use and success of biological control in the stored grain ecosystem. 1) The low level of pest infestation tolerable to grain exporters and consumers makes it very difficult for pest populations to be sufficiently abundant and persistent for biological agents to establish themselves and become effective (Snelson, 1987). 2) Natural enemies are slow to overtake and suppress pest populations and only appear in significant numbers after a product has become heavily infested and severe damage has already occurred (Arbogast, 1984). However, deliberate releases of natural enemies during the early stages of infestation may overcome this problem (Arbogast, 1984). 3) The introduction of predators and parasites would increase contamination of the product as they themselves would be regarded as contaminants (Snelson, 1987). However, the presence of contaminants is of little concern in some products, such as seed grain, animal feed and raw commodities that will be cleaned during processing (Arbogast,
4) The physical conditions, especially low moisture, of well-stored grain are not those which favour the spread of pathogens (Snelson, 1987).

The use of biological agents for the control of stored product pests has been reviewed by Evans (1984), Arbogast (1984) and Wilkin and Cox (1996).

7.1 Parasites, Parasitoids and Predators

A parasite is an organism that benefits by feeding upon, and securing shelter or transportation from one or more organisms, its hosts, which although adversely affected, may not necessarily be killed (Evans, 1984). In contrast, a parasitoid invariably kills its host and requires only one host for development (Evans, 1984). A predator is an organism that feeds on one or more host but seldom obtains shelter or transport from them. They also always kill their hosts (Evans, 1984).

The abundance or density of a parasite or predator generally depends on the abundance of the host, that is, it is density-dependent. Characteristically, the relative numbers of the host and parasite oscillate somewhat out of phase, an increase in the host population is followed by a corresponding, but delayed, increase in the parasite or predator population (Evans, 1984). The reduced host population cannot support the increased parasite population which gradually wanes and allows the pest population to recover and another oscillation to start (Evans, 1984).

7.1.1 Parasitoids

Although predators are the regulating agents of some pest insects, the majority of success in biocontrol of insects have involved parasitoids especially parasitic Hymenoptera (McMurty, 1984). Many species of parasitic Hymenoptera are known to attack stored grain insects. Examples include Anisopteromalus calandrae, Choetospila elegans, Bracon hebetor and Venturia canescens and Trichogramma sp. The two former species attack a range of hosts, including species of Sitophilus, whereas the latter are parasitoids of phycitid moths (Arbogast, 1984). The ability of parasitoids to suppress pest populations has been investigated by Cline et al. (1986), Flinn et al., (1996) and Brower and Press (1990).

However, against pest acarines, predators rather than parasitoids are the most prevalent natural enemies (McMurty, 1984). Several parasitic wasps have evolved to be predators rather than parasitoids in that they make use of more than one host to complete their development (Quicke, 1997). Aprostocetus eriophyes, a member of the Eulophidae family (subfamily Tetrastichinae), is known to be predaceous on gall-mites having has as its hosts the eriophyid mites Acaria rudis, Cecidophyopsis ribis, Phytophthe avellanae and Pytoptus tiliae (Goulet and Huber, 1993; Graham, 1987).

Parasitic Hymenoptera are only known to act as parasitoids on one group of acarines, namely the ticks (McMurty, 1984). The two major parasitoids of ticks that have been widely studied are Ixodiphagus texanus and Ixodiphagus hookeri, which have been reported to infect various species of ticks in different parts of the World (Kaaya, 1992). Mwangi et al. (1994 and 1997) and Kaaya (1992) describe the use of Ixodiphagus hookeri against Amblyomma variegatum (Metastigmata). Over a period of 1 year, 150,000 parasitoids were released and the numbers of ticks decreased from
44 to 2 ticks per animal, with numbers remaining low up to 1 year after parasitoid release, although the numbers of the brown ear tick, Rhiciephalus appendiculatus (Metastigmata), increased (Mwangi et al., 1997).

7.1.2 Nematodes

Nematode parasitism of insects can result in sterility, reduced fecundity, delayed development, aberrant behaviour and very often rapid host mortality (Kaya, 1985). Nematodes from the families Steinernematidae and Heterorhabditidae are used commercially against insect pests in agriculture and in households. The infective nematodes (third stage juveniles) are attracted to the their host by a chemotactic response (Gaugler et al., 1980) and after penetrating, release symbiotic bacteria into the haemolymph, which proliferate and kill the host by septicemia, mostly within 24-48 hours (Gaugler, 1987). The nematodes feed on the bacteria, produce two to three generations within the host, then as the host’s resources are depleted, a new generation of infective juveniles is formed, which emerge in search of new hosts (Gaugler, 1987). As the bacterium kills the host very quickly, its nematode partner need not adapt to any specific host life cycle (Gaugler, 1987). Consequently various insect species including many of economic importance are susceptible to these nematodes. However, so far, their effect on most beneficial insects has been found to be negligible (Kaya, 1985). Despite the large insect host range, the nematode-bacterium complex represents no hazard to mammals (Gaugler and Boush, 1979).

Entomophageous nematodes have been evaluated for their ability to parasitize ticks (Mwangi et al., 1991). Mauleon et al. (1993) found the ticks Boophilus microplus (Metastigmata) and Amblyomma variegatum (Metastigmata) to be tolerant to 17 isolates of nematodes whereas Boophilus annulatus (Metastigmata) was susceptible to all of them. Samish and Glazer (1991) found that strains of Steinernema carpocapsae and Heterorhabditis bacteriophora killed Boophilus annulatus very efficiently. All fully engorged ticks were killed, under laboratory conditions, within 4 days post infestation. However, although the ticks were highly susceptible to nematode infection, they did not appear to be suitable hosts for the development and reproduction of the steinernematid nematodes (Glazer and Samish, 1993). Samish et al. (1996) found that different tick stages varied considerably in their susceptibility to a strain of Steinernema carpocapsae, with fed adults being the most susceptible. Haq (1991) found parasitic nematodes belonging to the genus Rhabditis had potential in controlling the oribatid mite Galumna triquetra (Cryptostigmata), a known intermediary host of cestode parasites of cattle and sheep.

The only known parasitic nematodes for which mites are the definitive host, belong to the family Allantonematidae in the order Tylenchida (Poinar and Poinar, 1998). However, cases of this association are extremely rare, with hosts including gamasid mites (Poinar and Poinar, 1998). The infective free-living stage of these mite nematodes is a fertilised female which penetrates the host cuticle and enters the body cavity (Poinar and Poinar, 1998). This stage matures into a parasitic female that produces eggs and juveniles in her body (Poinar and Poinar, 1998). After the first or second moult the juveniles leave the female through the vulva and enter the host’s body cavity (Poinar and Poinar, 1998). After another moult the juveniles exit from the mite and develop to maturity in the environment (Poinar and Poinar, 1998).
Typically allantonematid nematodes do not kill their host outright but slowly debilitate it by partially or completely sterilising it or shortening its life cycle (Poinar and Poinar, 1998). It is thought that in nature, these nematodes may play an important role in the regulation of gamasid mites (Poinar and Poinar, 1998). However, because these obligate parasites have not been cultured on artificial media, their usefulness as biological control agents is limited (Poinar and Poinar, 1998).

There is no information on the ability of nematodes to parasitize storage mites, though, several species of storage insect have shown to be susceptible (Morris, 1985, Pezowicz and Sandner, 1983). However, the use of nematodes in stored grain protection is thought to be extremely unlikely as nematodes usually require a wet environment to infect their hosts (Cox and Wilkin, 1996). The provision of adequate conditions for free living and infective phases in relatively dry stored grains would therefore be difficult (Evans, 1984).

7.1.3 Predators

The predatory mite, Cheyletus eruditus (Prostigmata), is commonly found in temperate grain stores where it feeds on larvae of moths and beetles, psococids as well as mites of the families Acaridae and Glycyphagidae (Astigmata) (mainly Acarus siro, Tyrophagus putrescentiae and Lepidoglyphus destructor) (Coombs and Woodroffe, 1968 and Zdarkova, 1986). The characteristics possessed by Cheyletus eruditus that make it an efficient mite predator include not having a rapid rate of development or a high capacity for prey consumption (Beer and Dailey, 1956; Solomon, 1969). Fecundity is fairly high - up to 129 eggs per female (Summers and Witt, 1972), it reproduces parthogenetically with almost all progeny being female (Solomon, 1961; Hughes, 1976). It has a high ability to survive and find prey at low densities and cannibalism is a major factor enabling it to survive if there are no prey (McMurty, 1984). As the predator becomes more numerous and the prey scarcer, it spends more time reacting to its own species (Solomon, 1969; Burnett, 1977).

Cheyletus eruditus (Prostigmata) is commonly used for biological control of stored food mites in the Czech Republic (Zdarkova, 1994). The predators are supplied in bags containing 2000-3000 specimens and are applied at a rate of one pack per 100 m² of floor area in an empty store (Zdarkova and Horak, 1990).

Pulpan and Verner (1965) reported successful results on the introduction of the predacious mites to grain. They recommended that the predators be introduced in ratios of between 1 : 100 and 1 : 1000 (predator : prey) by sprinkling over the grain surface between April and June before pest mites become too abundant (i.e. over 1000 mites/kg of grain). The predators can also be added to non infested grain as a preventative measure in the ratio of 1 predator/100kg grain.

Solomon (1946b) and Norris (1958) reported the efficacy of Cheyletus eruditus (Prostigmata) at controlling Acarus siro (Astigmata) and Lepidoglyphus destructor (Astigmata) in bulk grain; and Coombs and Woodroffe (1968) achieved similar results with Acarus farris (Astigmata). Zdarkova and Horak (1990) markedly reduced the numbers of acarid mites in empty stores by releasing 2000-3000 predators per 100m². Application of the biopreparation ‘Cheyletin’ reduced the population density of Astigmatid mites by 8.4 times (Zdarkova, 1991).
However, *Cheyletus eruditus* (Prostigmata) is seldom effective enough to be a reliable controlling agent, due in part, to its inability to breed at relatively low temperatures that still permit its host to multiply (Evans, 1984). Solomon (1969) found the predator to be much less effective at low temperatures and found at 10°C the longest survival of *Cheyletus* (young adults and large nymphs) was 20 days. However, Zdarkova and Pulpan (1973) describe the successful storage of mites at 0 ± 1°C for up to 3 months.

*Blattisocius dentriticus* (Mesostigmata) is another mite predator and attacks both *Acarus siro* (Astigmata) and *Tyrophagus putrescentiae* (Astigmata) (Burnett, 1977). It feeds primarily on larvae and protonymphs, although it attempts to attack all stages of the prey (Burnett, 1964). Eggs 2-4 days old and larger stages of prey were largely immune to attack by the predator (Burnett, 1964). Burnett (1977) found that *Blattisocius dentriticus* could not coexist in the system with *Cheyletus eruditus* and *Acarus siro*. *Cheyletus eruditus* (Prostigmata) apparently outcompetes other species (McMurty, 1984). *Androlaelaps casalis* (Mesostigmata) also predates on acarid mites in stored cereals, and has also been found to feed on the predator *Blattisocius keegani* (Mesostigmata) and the young larvae of the confused flour beetle, *Tribolium confusum* (Barker, 1968).

A major limitation to the use of predatory mites in stored grain in the U.K. is that they themselves are considered as a contaminant and therefore require controlling as much as the pest species. Zdarkova (1994) showed that *Cheyletus eruditus* (Prostigmata) was less susceptible to organophosphorus pesticides than its mite prey and that different field strains had different tolerances to the pesticides (Zdarkova, 1997). However, they may have some practical use in the disinfestation of empty stores.

### 7.2 Pathogens

The successful use of diseases for biological control depends on the biology and characteristics of both host and microorganism (Maddox, 1975). The host must occupy habitats suitable for the introduction of the pathogen and have habits that facilitate its transmission and spread (Evans, 1984). As diseases act in a density dependent manner, pests that aggregate or are abundant are more likely to be suitable for biocontrol with pathogens than those that are well dispersed and seldom attain high density (Evans, 1984).

The success of any pathogen infection is dependent on the ability to overcome the host’s immune system. As in insects, the immune response to pathogens and foreign bodies, is mediated in ticks by the haemocytes, which constitute up to 50-60% of the haemolymph (Soneshine, 1991). In insects, the mechanisms of immune response for which haemocytes are responsible include phagocytosis, nodule formation, encapsulation and haemocytic killing mechanisms (Salt, 1970). Ticks have at least 5 classes of haemocytes: 1. prohemocytes, 2. plasmatocytes, 3. granulocytes, 4. sphenulocytes and 5. oenocytoids, although the knowledge of the function of the cells is incomplete (Binnington and Obenchain, 1982). Prohemocytes are believed to be the essential stem cell from which the other types of haemocyte are formed (Soneshine, 1991). Plasmatocytes are believed to serve as phagocytes perhaps as the major phagocytic cell type in ticks (Soneshine, 1991). It is suggested that
plasmatocytes exhibit non-specific responses to corpuscular antigens and inert particles as well as to foreign cells (Soneshine, 1991). In insects, plasmatocytes are usually the most numerous haemocyte type (Lackie, 1988). Granulocytes also have a role in phagocytosis as well as serving to encapsulate foreign material (Soneshine, 1991).

In ticks, as in many other arthropods, a well developed capability for phagocytising microbes and other foreign organisms appears to exist (Soneshine, 1991). Particles too large to be phagocytised may be encapsulated with layers of haemocytes removing them from contact with the tissues and rendering them harmless (Soneshine, 1991). Encapsulation in the tick *Dermacentor variabilis* (Metastigmata) was shown to be similar to that in insects having two phases, a recognition phase and a capsule-forming phase (Eggenberger et al. 1990). In insects, the first phase of recognition is mediated by granulocytes which lyse within minutes of implantation of the foreign body, producing a modified clot and probably releasing some chemotactic factor which initiates the second phase (Schmit and Ratcliffe, 1977). During the capsule-forming phase, plasmatocytes are specifically attracted to the implant forming the capsule. Necrotic haemocytes and coagulated haemolymph form a layer at the surface of the implants thus forming the capsule and removing the foreign body from contact with the host’s tissues (Schmit and Ratcliffe, 1977).

Ticks also produce the protein, lysozyme, which acts as an antibacterial and antirickettsial agent in tick-microbe interactions (Podboronov, 1991). Lectins are sugar-binding proteins or glycoproteins (Schooneveld and Veenstra, 1988). It is not known whether serum lectins of arthropods are present in the plasma as well as being released from haemocytes, and there is no clear understanding of their role (Lackie, 1988). However, it seems that lectins are important molecules in reactions of recognition and defence of invertebrates (Renwrantz, 1983). It is thought that they play a role in the destruction non-self objects as well as in transmission of pathogens by invertebrate vectors (Grubhoffer et al., 1991). They can react either with self glycoconjugates or with glycosylated components of viral, bacterial or protozoan pathogens (Grubhoffer et al., 1991). Grubhoffer et al. (1991) found that lectins in the haemolymph of four tick species, *Ixodes ricinus* (Metastigmata), *Ornithodorus tartakovskyi* (Metastigmata), *Ornithodorus papillipes* (Metastigmata) and *Argas polonicus* (Metastigmata), had agglutination activities, and supposed that the lectins played an important role in the processes of self-non-self recognition and defence reaction.

Stored product insects are subject to infections by numerous pathogenic organisms including protozoa, bacteria, fungi and viruses (Arbogast, 1984). Transmission of pathogens may occur in several ways: by larvae feeding on cadavers of infected larvae or adults, by the consumption of infected stored food, during mating or from the female to its progeny during oviposition (Kellen and Lindgren, 1971; Schwalbe et al. 1974; Shapas et al., 1977). Pathogens may be more suitable for use in stores than in open fields where they run the risk of being inactivated by high temperatures and excessive exposure to ultra violet light (Hodges, 1984a). However, the only diseases likely to be effective in the management of stored product pests are those that have hardy, long lived dormant stages capable of infecting in dry conditions (Hodges, 1984a).
Insect pathogens may be admixed with bulk grain or disseminated by insects lured to a source of pathogens by an attractant; however, due to their specific nature they may have to be integrated with other control procedures for the protection against a wide range of pests (Hodges, 1984a). Control of stored product mites by pathogens appears to have received very little attention compared to stored product insects. The number of micro-organisms that are known to be pathogenic to mites, may not exceed 30 species.

### 7.2.1 Bacteria

One of the most extensively studied insect-pathogenic bacteria is *Bacillus thuringiensis* (Berliner), a gram positive rod-shaped bacterium that forms toxic protein crystals during sporulation, which when ingested are transformed to an active diamond shaped toxin (Arbogast, 1984). The toxins generate pores in the midgut epithelial cell membrane leading to osmotic imbalance, causing the cells to swell and lyse (Mummigatti et al., 1994). Damage to the cells of the insect midgut cause inhibition of feeding which leads to eventual death (Evans, 1984).

*Bacillus thuringiensis* is a complex species existing in numerous different varieties which are pathogenic to different types of insects (Drummond and Pinnock, 1994). These varieties produce different amounts of several types of toxins, the two most commonly used as pesticides are the crystal (δ-endotoxin) proteins and the thuringiensin (β-exotoxin) nucleotide (Drummond and Pinnock, 1994). Most varieties of *Bacillus thuringiensis* are toxic to larvae of certain members of the Lepidoptera (Pathotype-A), some are toxic to Diptera (Pathotype-B) or Coleoptera (Pathotype-C) (Mummigatti et al. 1994). The use of *Bacillus thuringiensis* against stored product beetles and moths has been discussed by McGaughey, 1980; McGaughey and Dicke, 1980; Subramanyam and Cutkomp, 1985 and Mummigatti et al. 1996. However, there are no references on the use of *Bacillus thuringiensis* against stored product mites.

To date, no mite-specific bacteria have been isolated (Poinar and Poinar, 1998). However, Hoy and Ouyang, (1987) found that the β-exotoxin of *Bacillus thuringiensis* (thuringiensin) was toxic to adult female *Tetranychus pacificus* (Prostigmata) and the predatory mite, *Metaseiulus occidentalis* (Mesostigmata), within 48-96 hours of treatment at 0.125-fold to 4-fold the proposed field rate. Egg production by treated females declined, treated larvae were unable to develop to adults and treated eggs hatched but larvae failed to develop. Thuringiensin was found to be effective but unselective at the rates used. Royalty et al. (1990) found immature instars of *Tetranychus urticae* (Prostigmata) were more susceptible to thuringiensin than the adults, although activity was shown to be slow acting initially. However, it was suggested that the high activity against immature stages and sublethal effects, such as reduction in fecundity and feeding inhibition, may offset the initial low mortality observed.

Neal et al. (1987) also found the β-exotoxin of *Bacillus thuringiensis* to be highly effective against *Tetranychus urticae* (Prostigmata) and *Tetranychus cinnabarinus* (Prostigmata) at 0.18% a.i. Autoclaved *Bacillus thuringiensis* var. *thuringiensis* supernatent killed all spider mites (*Tetranychus urticae*) (Prostigmata) within 35 days when sprayed on bean leaves (Kreig, 1968) and application of β-exotoxin at 1.0 %
dilution to orange tree leaves killed citrus red mites (Panonychus citri) (Prostigmata) including eggs and immature stages (Hall et al., 1971).

Chapman and Hoy (1991) tested Bacillus thuringiensis var. tenebrionis wettable powders in the laboratory, to determine the relative toxicity against Tetranychus urticae (Prostigmata) and its predator Metaseiulus occidentalis (Mesostigmata). At 0.1 x, 0.5 x and 1.0 x the recommended field rate (0.9 kg ai /75.7 l / acre), little mortality of female Tetranychus urticae was achieved (90.0 ± 14.2 % survival at field rate), however, mortality was greater with Metaseiulus occidentalis (26.0 ± 23.4 % survival at field rate). Neither predator nor spider mite eggs treated at the field rate suffered depression in hatch rate. However, only 65% of the resulting immature predators reached adulthood compared to 88.8% of immature spider mites.

Hassanain et al. (1997) evaluated 3 varieties of Bacillus thuringiensis (kurstaki, israeliensis and thuringiensis) against the soft tick Argas persicus (Metastigmata) and the hard tick Hyalomma dromedarii (Metastigmata). Argas persicus died within 36 hours to 5 days post treatment, with Hyalomma dromedarii dying between 48 hours and 10 days, depending on dose. LC50 values indicated that ‘Dipel 2x’ (var. kurstaki) was the most potent, followed by ‘Vectobac’ (var. israeliensis) and ‘HD703’ (var. thuringiensis). The soft tick was more affected than the hard tick. Eggs were mostly affected at 16 and 25 days after deposition for the soft and hard ticks respectively.

Advantages in the use of Bacillus thuringiensis in stored product environments is that the bacteria are invisible, they can be cultured in artificial media, the toxin protein crystals rapidly halt feeding, they are easy to use in the dry conditions of stores and the crystals are not toxic to humans (Cox and Wilkin, 1996). However, use of the β-exotoxin may be limited due to its unselectivity and concerns about toxicity to bees, poultry and mammals (Keller and Langenbruch, 1993). Another major limitation in the use of Bacillus thuringiensis is the development of resistance to the toxins. High levels of resistance to Bacillus thuringiensis δ-endotoxins have been demonstrated in at least 6 insect species (McGaughey, 1994a), including field populations of the diamond back moth (Plutella xylostella) (Iqbal et al., 1996), and laboratory populations of the Indian meal moth (Plodia interpunctella) and almond moth (Ephestia cautella) (McGaughey and Beeman, 1988), with high levels of resistance after only a few generations (McGaughey, 1985). The mechanism of resistance involves a change in the binding affinity of the insect’s gut membrane that is specific for the particular toxin type (McGaughey, 1994b). Changes in fitness have also been observed in resistant pests (Jonhson and McGaughey, 1996).

7.2.2 Viruses

Viral infections have been identified in almost 200 insect species, mostly Lepidoptera and also in arachnids, with the main types of virus being polyhedroses and granuloses (Evans, 1984). Important viruses of stored product insects include granuloses of Plodia interpunctella (PGV) and Ephesia cautella (CGV) and a nuclear-polyhedrosis of Ephesia cautella (Arbogast, 1984). McGaughey (1975a) used surface applications of a granulosis virus to control Ephesia cautella in bins of stored maize and wheat; and Vail et al. (1991) demonstrated high levels of control of Plodia interpunctella with a granulosis virus in the laboratory.
Few viral diseases of mites are known, with no records of viral infections in stored product mites. All mite viruses belong to the non-inclusion group (Lipa, 1971). The earliest record of a viral infection of a mite was made by Muma (1955) who observed specimens showing low activity and diarrhoea in a population of red citrus mites (*Panonychus citri*) (Prostigmata). The symptoms and signs of disease in *Panonychus citri* are complex and characteristic (Lipa, 1971). The most striking symptoms are complete immobilisation with stiffened legs (Lipa, 1971). Diarrhoea frequently occurs and dead mites are often fixed to the feeding surface by faeces (Lipa, 1971). A characteristic feature are numerous birefringent crystals which accumulate in the haemocoel of infected mites (Smith and Cressman, 1962). The presence of crystals is a sign of infection, and is apparently a result of metabolic disturbances (Lipa, 1971). The virus is not transmitted transovarially (Lipa, 1971), but by contact with the virus in faeces and debris on the plant surface (Reed et al., 1975). Smith et al. (1959) showed that the infection could be easily transmitted to healthy populations. Shaw et al. (1967) found no differences in the consumption of diseased or healthy mites by predators and no apparent reduction in longevity or activity of the predator. Reed (1981) discusses the practical considerations for the use of the virus.

Another viral disease of mites was identified in the European red mite (*Panonychus ulmi*) (Prostigmata) by Steinhaus (1959). Diseased mites are seen to be dark red with black spots (Lipa, 1971). They gradually become immobile and cannot return to a normal position when put on their backs (Lipa, 1971). Mites in the last stage of the disease exhibit diarrhoea and become fixed to the surface by faecal material (Lipa, 1971).

Boudreaux (1959) described virus-like substances transmitted to the offspring of *Tetranychus cinnabarinus* (Prostigmata) and *Tetranychus urticae* (Prostigmata). These substances were responsible for the absence of certain chemosensory setae on the foreleg of females, but otherwise seemed to have no detectable effect on the host organism.

Resistance to viral infections may also occur, for example, resistance to a granulosis virus in *Plodia interpunctella* resulted in reduced egg viability, larvae that took longer to develop and increased pupal weight (Boots and Begon, 1993).

### 7.2.3 Protozoa

Protozoa are single-celled microscopic organisms. Those that are insect pathogens belong to the Class Sporozoa (Orders Gregarinida, Coccidia and Microsporidia) and are common and widespread among natural populations of stored product insects (Arbogast, 1984). The pathogens usually enter the host insect by ingestion of spores (Cox and Wilkin, 1996). The Gregarinida and Coccidia are parasites of the fat body, malpighian tubules or gut of the insect and are characterised by a resistant spore-like or encysted stage (Cox and Wilkin, 1996). The microsporidia *Nosema* spp. are found in the fat body and can be spread by ingestion of spores, during mating or through the ovaries (Khan and Selman, 1989).

The important sporozoans infecting stored product beetles are *Adelina tribolii*, *Farinocystis tribolii*, *Lymphotropha tribolii*, *Nosema whitei*, *Nosema oryzaephilli*, *Nosema weiseri*, *Nosema ptinidorium* and *Nosema transitellae* (Khan and Selman,
Khan and Selman (1989) review the potential of *Nosema* spp. as control agents for stored product beetles. Amongst the most promising would seem to be *Nosema whitei* for *Tribolium castaneum* and *Tribolium confusum*, *Nosema whitei* and *Nosema oryzaephilii* for *Oryzaephilus surinamensis* (Burges et al., 1971) and *Mattesia trogodermae* for *Trogoderma* spp (Schwalbe et al. 1974; Shapas et al., 1977). *Nosema plodei* has also been isolated for *Plodia interpunctella* (Kellen and Lindgren, 1971), but its use as a control agent has not been studied.

Lipa (1971) reviews the little information that is known regarding protozoan diseases of mites. Weiser (1956) reported the first case of microsporidiosis in mites and described *Nosema steinhausi* from *Tyrophagus putrescentiae* (Astigmata). Three microsporidian species have been found in mass rearings of the predatory mites *Amblyseius cucumeris* (Mesostigmata) and *Amblyseius barkeri* (Mesostigmata) (Beerling et al., 1993). One species was detected in predatory mites as well as in the stored product mites *Acarus siro* (Astigmata) and *Tyrophagus putrescentiae* (Astigmata), which are the prey in mass rearings of *Amblyseius cucumeris* (Mesostigmata) and *Amblyseius barkeri* (Mesostigmata) (Beerling and van der Geest, 1991). This microsporidium has small oblong spores (1.8µm x 0.9µm) and belongs to the Pleistophoridae family (Beerling et al., 1993). A second species which occurs regularly in mass rearings has small oval spores (1.4µm x 0.8µm) and has been found exclusively in prey mites (Beerling et al, 1993). A third species occurs occasionally in mass rearings and has large spores (2.6µm x 1.3µm), and is only found in prey mites and is thought to be *Nosema steinhausi* (Beerling et al., 1993). Bjørnson et al. (1996) described the pathology of *Microsporidium phytoseiuli* infecting the predatory mite *Phytoseiulus persimilis* (Mesostigmata).

Rehacek et al. (1996) isolated *Nosema slovaca* from a male *Dermacentor reticulatus* (Metastigmata) tick, which was seen to cause acute infection in partly engorged females, with death occurring within 5-15 days post-infection. *Nosema parkeri* has also been detected in a laboratory colony of the tick *Ornithodorus parkeri* (Metastigmata) (Krinsky, 1977).

Protozoa have received relatively little attention as biocontrol agents mainly because they cause chronic rather than acute infections (Evans, 1984). Protozoa are not as fast acting as some bacteria, viruses or chemical pesticides. However, the reproduction of the host is often curtailed with resultant long-term reduction of the host population rather than a high initial mortality (Evans, 1984). Another disadvantage is the difficulty in production (Khan and Selman, 1989). However, their debilitating sub-lethal effects on the host, the large numbers of species found, their frequently high prevalence and array of transmission routes are advantageous for use in inoculative augmentation (Khan and Selman, 1989). The use of protozoa in controlling storage pests may therefore be most beneficial in long-term storage since they produce slow-acting chronic infections and also show promise when integrated into existing control systems (Khan and Selman, 1989).

### 7.2.4 Fungi

The performance of entomaphagous fungi is often erratic due to the necessity for suitable temperature and humidity conditions to prevail before the spores can germinate and infect their hosts (Evans, 1984). In addition, because of the density-
dependence of the pathogens, adequate levels of control are only achieved when the pest has done considerable damage (Evans, 1984).

Two species of entomopathogenic fungi, *Beauveria bassiana* and *Metarrhizium anisopliae*, have been evaluated against stored product insects (Ferron and Robert, 1975; Searle and Doberski, 1984; Hluchy and Saminakov, 1989; Thuy et al., 1994). Infection is initiated by germination of a microscopic spore which penetrates the insect cuticle and spreads through the haemocoel and fills the insect’s body with fungal mycelia (Cox and Wilkin, 1996). Hyphae then grow out of the insect and produce spores which disperse to infect other insects (Cox and Wilkin, 1996).

Fungi of the Order Entomophthorales appear to be important pathogens of mites, with species recorded on mites belonging to the genus *Neozygites (Entomophthora)* (Lipa, 1971). It is suggested that *Neozygites* spp. play a major role in the regulation of natural spider mite populations (Carner and Canerday, 1968). *Neozygites floridana* and *Neozygites fresenii* have been found to significantly reduce field populations of *Tetranychus urticae* and *Tetranychus cinnabarinus* (Prostigmata) (Carner and Canerday, 1968; Smitley et al., 1986; Mietkiewski et al., 1993); and Fisher (1951) and Muma (1955) reported *Neozygites* sp. on *Panonychus citri* (Prostigmata). A number of species of *Triplosporium* are also known to parasitise mites, mainly tetranychids (Prostigmata) and their relatives (O’Connor, 1984).

*Hirsutella thompsonii*, a Basidiomycete, is a specific fungal pathogen of Acarina, particularly eriophyids and tetranychid mites (McCoy, 1981). Fisher (1950) found a significant reduction in the citrus rust mite (*Phyllocoptruta oleivora*) (Prostigmata) by *Hirsutella thompsonii* in a grapefruit grove. Gerson et al. (1979) found *Hirsutella thompsonii* to be highly pathogenic to the carmine spider mite (*Tetranychus cinnabarinus*) (Prostigmata) and the oriental spider mite (*Eutetranychus orientalis*) (Prostigmata). The fungus penetrated the mites’ integument mainly through the legs and formed hyphal bodies in chains in the haemolymph. Hyphae on which the spores were produced began to emerge through the genital and anal apertures and then all over the body. Representatives of other mite Orders namely the Astigmata (*Rhizoglyphus robini, Tyrophagus palmarium*), Cryptostigmata (*Nothrus biciliatus*), Mesostigmata (*Parasitus timetionum*) and Metastigmata (*Argas persicus*) were not infected by *Hirsutella thompsonii*, suggesting a specificity for the Prostigmata. Although another Prostigmatid mite, the mycophagous *Tarsoneumus* sp., was not affected by the fungus.

The effects of *Hirsutella thompsonii* and *Verticillium lecanii* have been evaluated against storage mites (Anon, 1983). Doses of $1 \times 10^7$ spores/ml of *Hirsutella thompsonii* and $1.4 \times 10^7$ spores/ml of *Verticillium lecanii* on a mixed culture of Astigmatid mites: *Acarus siro, Acarus chaetoxysilos, Acarus farris, Lepidoglyphus destructor* and *Tyrophagus putrescentiae*, had no detectable effect on any of the mite species (Anon, 1983).

In the U.S. *Hirsutella thompsonii* was registered for control of eriophyid mites on citrus and turf, however, production was terminated in 1985 due to many factors including the sensitivity of the infective unit to available water, fungal survival in the field which influenced its reliability and limitations in storage and transportation to maintain fungal stability (McCoy et al., 1988). The use of the fungus is limited as it is...
most effective during hot and humid periods when mite populations peak and is best suited to tropical and subtropical regions and in glasshouses with special humidity regimes (McCoy et al., 1988).

Of the infections caused by the Fungi Imperfecti, the most important species are those belonging to the genera Penicillium, Aspergillus and Beauveria, which have been found infecting mites and ticks (Lipa, 1971; Cerepanova, 1964). Leatherdale (1965) also found that Paecilomyces eriophytes was infective to Panonychus ulmi (Prostigmata).

Mycotoxins are the natural but highly toxic by-products of growth and development of several species of fungi, and some of these, produced by species of Penicillium and Fusarium, are toxic to storage pests (Cox and Wilkin, 1996). However, they can also be acutely toxic or carcinogenic to higher animals (Rodriguez et al., 1984). Rodriguez et al (1984) challenged Tyrophagus putrescentiae (Astigmata) and Caloglyphus rodriguezi (Astigmata) with species of Pencillium, Aspergillus, Fusarium and Calviceps purpurea. Tyrophagus putrescentiae egg hatch was generally not adversely affected by contact with the fungi, however, larvae were sensitive to the toxic effect of some fungi. Tyrophagus putrescentiae females did not develop or lay eggs when cultured with Aspergillus versicolor, Aspergillus flavus, Aspergillus nidulans and Pencillium islandicum; and their longevity was significantly shortened. Aspergillus ochraceus, Aspergillus versicolor, Aspergillus nidulans, Fusarium poae and Pencillium rubrum were most toxic to Tyrophagus putrescentiae. Rodriguez et al. (1980) found that certain mycotoxins (aflatoxin, citrinin, ochratoxin and penicillic acid) exhibited mild acute toxicity in the developing generation of Tyrophagus putrescentiae that were lethal to the F1 progeny.

Solomon et al. (1964) found that the xerophilic fungi Sporendonema (Wallemia) sebi and Aspergillus restrictus caused premature failure of Acarus siro (Astigmata) populations when incorporated into the food supply. Reduced reproduction, high mortality and retarded development were observed. Parkinson et al. (1991a and b) found that Acarus siro, Lepidoglyphus destructor (Astigmata) and Tyrophagus longior (Astigmata) always produced fewer eggs on fungal diets of Cladosporium cladosporiodes, Aspergillus repens, Aspergillus ruber and Pencillium cyclopium. The fungal diets usually shortened male lives. No mycotoxin activity was detected in the experiment, although, the fungal species used have been found to produce mycotoxins (Parkinson, 1991a).

The main advantages in the use of pathogens are that they are fairly host specific and therefore harmless to non-target organisms, they are compatible with, and even at times, synergistic with pesticides, they are relatively easy and cheap to culture and are not associated with rapidly developing mechanisms for host resistance (Evans, 1984). The main disadvantages are their requirement for careful timing of applications relative to incubation periods, their specificity, which may limit their effectiveness where a complex of pest species are involved, and the maintenance of virulence and infectivity may depend greatly on favourable climatic conditions (Evans, 1984). Due to the rather specific nature of pathogens, the future for biocontrol agents may therefore lie in an integrated approach by combining with other control measures, to achieve protection to a wide range of pests. The effect of fumigation on Bacillus thuringiensis and granulosis virus have been investigated (Hodges, 1984a). Bacillus
*thuringiensis* is compatible with several grain fumigants (McGaughey, 1975b). Methyl bromide inactivated granulosis virus and affected *Bacillus thuringiensis* so that when cultured it failed to produce colonies, however, the bacteria was still potent against *Plodia interpunctella* (Hodges, 1984a).

8. Alternatives to admixture treatments

Although this review has concentrated on alternatives to OPs for admixture treatments, it is important to mention other alternative methods that have been assessed for the protection of stored commodities from mite infestation.

8.1 Hygiene

Cleaning bin surfaces by steam treatments or vacuuming and removing residues from harboursages will reduce the initial mite inoculum and it is undoubtedly good practise from the point of view of insect control. However, no quantitative studies on the benefits of this approach have been carried out and it is likely only to delay the onset of mite infestation, since these animals are carried by air currents throughout the environment.

8.2 Cooling

Most Astigmatid storage mites cannot breed below 5°C (Cunnington, 1984) but can survive lengthy periods of sub-zero exposure (Sinha, 1964). Nevertheless, Armitage (1980, 1984) showed that mite populations in cooled rapeseed were many times less numerous than in uncooled seed, and Hurlock et al. (1980) achieved a delay in mite increase in cooled bins of wheat. However, temperatures are not well-controlled at the grain surface which is where mites increase in the winter when atmospheric moisture is absorbed by surface grain (Burrell and Havers, 1976). Therefore a surface pesticide treatment is required (Armitage et al., 1994).

8.3 Heating

Although no practical attempt has apparently been made to use heat as a disinfestation measure against mites, most die rapidly above 30°C. *Acarus siro* will only survive 1-4 days at 30°C, 10 hours at 35°C and 35 minutes at 40°C (Cunnington, 1984).

8.4 Drying

Mites cannot complete their development below 65-70% r.h., depending on the temperature, which is in equilibrium with a wheat moisture content of about 15% (Henderson, 1987). This can be achieved by ‘continuous driers’ when the grain is dried at high temperature in a short time, which allows no increase of mites during the process. However, approximately half of the grain is dried ‘on-floor’ using ambient air or air heated by a few degrees Celsius, which may take several weeks. This allows mites to increase in undried, surface layers of grain as the ‘drying front’ passes slowly through the bulk. Armitage et al. (1982, 1984) and Armitage (1986) showed that mites increase rapidly during drying and that numbers then decline more gently, at a rate that depends on the final moisture content achieved.
8.5 Cleaning and Conveying

Burrell and Havers (1973, 1975) showed mite numbers in cleaned barley were 46 times lower than in uncleaned grain, while Armitage (1994) showed that mite populations in cleaned grain were halved and that mite numbers increased with the increasing proportion of dust. Armitage et al. (1996) showed cleaning achieved a 90% mite reduction and that populations in cleaned grain only achieved 20% of those in uncleaned. Mite populations can be reduced by 69-98% by conveying (Megalov, 1934, Wilkin 1975b, Wilkin and Hope, 1973b, Armitage, 1994), however, populations normally build up quickly afterwards so the solution is purely short-term.

8.6 Fumigation

Eggs of the commonest Astigmatid storage mites are tolerant of most fumigants (Bowley and Bell, 1981), especially at low temperatures, although the mobile stages are susceptible. Complete control can most easily be achieved by two fumigations at moderate to low doses, separated by between 2 weeks at 20°C and 7 weeks at 10°C, during which time the eggs hatch but do not reach adult stage.

8.7 Modified Atmospheres

The use of modified atmospheres (MA) involves a change in the proportions of the atmospheric gases, nitrogen (N\textsubscript{2}), oxygen (O\textsubscript{2}) and carbon dioxide (CO\textsubscript{2}), to produce conditions lethal for pests (Banks and Fields, 1995). CO\textsubscript{2} is more toxic than N\textsubscript{2} (Navarro and Donahaye, 1990) and does not rely solely on anoxia to be lethal as it causes acidification of the body fluids and subsequent inhibition of glycolysis (Adler, 1994).

Greatest tolerance of low O\textsubscript{2} is found in mite eggs as it is related to low O\textsubscript{2} consumption. In 99.5\% CO\textsubscript{2} at 85\% r.h., eggs and mobile stages died in 6 days and 1 day respectively (Stepien, 1974). At 15°C and 70\% r.h., *Tyrophagus longior* was the most tolerant species, surviving for 22 days in 99.5\% N\textsubscript{2} (Conyers et al. 1996). Burner gas was most effective with 0.5\% O\textsubscript{2} but with an increase to 2\% O\textsubscript{2}, CO\textsubscript{2} became the more effective. At 15°C and 75\% r.h., Navarro et al (1985) killed *Acarus siro* adults in 4 days using 30\% CO\textsubscript{2} while 2\% O\textsubscript{2} in N\textsubscript{2} killed all *Acarus siro* in 6 days at 15°C and in 2 days at 26°C. White and Jayas (1991) controlled all mites after 42 days with CO\textsubscript{2} at 40\% and between 12 and 15°C.

9. Conclusions

This review has demonstrated the wide range of compounds available for use as acaricides. However, the relatively limited information on the efficacy against storage mites emphasises the need for further research. Table 1 summarises the results of previous research on the use of alternative compounds against storage mites, giving details on the test species, doses, test conditions and methods of application. As seen from the table, it is difficult to directly compare results, as different researchers have used different methods of evaluation.
For compounds to be considered as potential alternatives to OPs, as well as being effective against storage mites, they must also meet the following criteria:
1. effective against storage insects
2. available as commercial products, preferably already cleared for use on grain
3. easy to apply
4. have low mammalian toxicity
5. provide prolonged protection over extended storage periods
6. effective under typical U.K. storage conditions, i.e. low temperatures, high r.h.
7. can be incorporated into an integrated pest management programme e.g. as a surface treatment

Table 2 provides a summary of the advantages and disadvantages in the use of alternative compounds against storage mites.

The aim of this review was to identify compounds which would seem to warrant further investigation as potential alternatives to OPs for the control of storage mites. Of the IGRs, methoprene, appears the most promising, as previous research with fenoxycarb has produced contradictory results, and dimilin is not particularly effective against some storage mites. Inert dusts, such as ‘Dryacide’, are already used as grain protectants in some countries, however their efficacy under typical U.K. storage conditions may limit their use; although some of the newer products, e.g. ‘Protect-It’, may prove more efficacious. Pyrethroids have shown varying degrees of efficacy against storage mites, with bifenthrin, bioresmethrin and deltamethrin seeming to warrant further investigation. Azadirachtin containing products have proved effective against storage insects, although efficacy against mites appears to be concentrated on phytophagous pests. Benzyl benzoate has FDA approval for food use and although effective against Astigmatid mites in a domestic environment, has not been assessed for storage use. Although other plant derived products have proved effective, their main limitation may lie in the tainting of grain.

Of the novel compounds, chemosterilants have proved effective against storage mites, however, they are also usually highly toxic. Propionic acid has also proved effective, although treated grain loses its germinative capacity. Tricalcium phosphate is commonly used as a food additive, but high doses are required to be effective against storage mites. Abamectin has been used commercially as an acaricide and has a wide spectrum of activity against Prostigmatid mites, although it has not been assessed against storage mites.

Of the biological control agents, the predator *Cheyletus eruditus*, appears the most promising and is already used in storage facilities overseas. However, the predators themselves would be considered as grain contaminants and therefore need controlling. *Bacillus thuringiensis* may also be promising, as commercial products have been shown to be effective against phytophagous mites and storage insects. Nematodes are unsuitable for use in a dry storage environment, viruses and protozoa are not easily available and fungi produce mycotoxins that may be toxic to mammals.

More than 20 million tonnes of grain is stored annually in the U.K., valued in excess of £2 billion/year. During storage, grain is at risk of spoilage from infestation which is estimated to cost £50 million annually. With increasing concerns over the use of OPs, it is vitally important to investigate the efficacy of alternative compounds as grain protectants.
10. Future Work

The aim of initial experiments will be to evaluate approximately a dozen compounds that appear to be promising alternatives to OPs for the treatment of stored grain against mite infestation. Commercially available formulations will be used, where possible, and applied to grain at a wide range of doses, as determined from the literature. Mixed stages of OP-susceptible strains of *Acarus siro*, *Tyrophagus putrescentiae* and *Lepidoglyphus destructor* will be exposed to treated grain for periods long enough to encompass at least two generations. The numbers of live mites will be assessed using the technique of Solomon (1962), which counts actual mite numbers.

Compounds to be evaluated may include the IGRs: methoprene, fenoxycarb and diflubenzuron; the inert dusts: ‘Dryacide’, ‘Protect-It’ and ‘Insecto’; the pyrethroids: bifenthrin, bioresmethrin and deltamethrin; the botanicals: azadirachtin and benzyl benzoate; as well as abamectin and *Bacillus thuringiensis*.

These experiments will provide information as to which of the compounds show promise as acaricides for stored grain protection and therefore warrant further investigation.

11. Acknowledgements

The author would like to thank David Armitage, Bhushy Thind, Nick Renn, Gay Marris and Simon Conyers for their advice and contributions to the writing of this review; and also the staff in the Information Centre at CSL, York for their help in providing copies of the literature. This review was funded by the Home Grown Cereals Authority.

12. References


Binns, T. J. (1989). The laboratory assessment of 3 pyrethroid formulations and a formulation of pirmiphos-methyl, admixed with grain, on laboratory susceptible strains of 5 major storage pests. MAFF, CSL report No. C/89/0467. 29 pp..


Third, B. B. (1991). Assessment of some of the physical changes occurring in grain following treatment with caustic soda and the effects of these changes on the infestability of the grain by *Calogyphus* sp. MAFF CSL Report 19 pp.


Table 1 - Summary of efficacy of different admixture compounds against storage mites

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>MITE SPECIES</th>
<th>DOSE (mg kg⁻¹)*</th>
<th>APPLICATION</th>
<th>MORTALITY *</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Growth Regulators</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenoxycarb</td>
<td>A. siro</td>
<td>10</td>
<td>Food</td>
<td>+ 43 % eggs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td>99 % eggs</td>
<td>Third &amp; Edwards (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(20°C / 80%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenoxycarb</td>
<td>A. siro</td>
<td>0.5 - 8</td>
<td>Food</td>
<td>Adults 37%</td>
<td>Buchi (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- 99%</td>
<td></td>
</tr>
<tr>
<td>Methoprene</td>
<td>A. siro</td>
<td>47.5 - 190</td>
<td>Food</td>
<td>Adults 53%</td>
<td>Buchi (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- 88%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(25°C / 85%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56 JHAs</td>
<td>T. putrescentiae</td>
<td>0.0001% - 10%</td>
<td>Topically</td>
<td>Ovicidal, morphogenetic &amp; sterilising effects</td>
<td>Czaja-Topinska et al (1979)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(25°C / 85%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diflubenzuron</td>
<td>T. putrescentiae</td>
<td>1000 &amp; 100,000</td>
<td>Wheat</td>
<td>60-70% of larvae reached adulthood</td>
<td>Lipa &amp; Chmielewski (1976)</td>
</tr>
<tr>
<td>(Dimilin)</td>
<td></td>
<td>(25°C / 85%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Inert Dusts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dryacide</td>
<td>A. siro</td>
<td>1000 &amp; 3000 (17.5°C / 60 %)</td>
<td>Wheat</td>
<td>100% at 14% mc</td>
<td>Cook &amp; Armitage (1996)</td>
</tr>
<tr>
<td></td>
<td>L. destructor</td>
<td>3000 (17.5°C / 75 %)</td>
<td>Wheat</td>
<td>100% at 16% mc</td>
<td></td>
</tr>
<tr>
<td>Dryacide</td>
<td>A. siro</td>
<td>3000 &amp; 5000 (10, 17.5 &amp; 25°C)</td>
<td>Wheat</td>
<td>100% at 14.5 % mc</td>
<td>Cook &amp; Armitage (1999)</td>
</tr>
<tr>
<td></td>
<td>L. destructor</td>
<td>5000 (10, 17.5 &amp; 25°C)</td>
<td>Wheat</td>
<td>100% at 14.5 % mc</td>
<td></td>
</tr>
<tr>
<td>Super Insecolo</td>
<td>Astigmata &amp; Prostigmata</td>
<td>50 (Field)</td>
<td>Wheat</td>
<td>98%</td>
<td>Fields &amp; Timlick (1995)</td>
</tr>
<tr>
<td>Dri-die 67</td>
<td>Tyrophagus sp.</td>
<td>20 mg (24-26°C/75&amp;100%)</td>
<td>Dishes</td>
<td>No effect on eggs, larvae desiccated</td>
<td>Tarshis (1960)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 mg (25-26°C / 25,50,75 &amp; 100 %)</td>
<td>With/without culture media</td>
<td>Killed mixed stages in 3 hours</td>
<td></td>
</tr>
<tr>
<td><strong>Pyrethroids</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cypermethrin</td>
<td>A. siro</td>
<td>2, 4 &amp; 8 (22°C / 100 %)</td>
<td>Wheat</td>
<td>5%, 45% &amp; 66% after 4 weeks</td>
<td>White (1984)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.125 - 2 (17°C / 75 %)</td>
<td>Wheat</td>
<td>Ineffective after 1 day - 6 months</td>
<td>Wilkin et al (1988)</td>
</tr>
<tr>
<td></td>
<td>A. siro</td>
<td>2 % (25°C / 75 %)</td>
<td>Potter Tower</td>
<td>83 % after 24 hours</td>
<td>Lozza et al (1994)</td>
</tr>
<tr>
<td></td>
<td>L. destructor</td>
<td>2 % (25°C / 75 %)</td>
<td>Potter Tower</td>
<td>96.2 % after 24 hours</td>
<td>Lozza et al (1994)</td>
</tr>
<tr>
<td></td>
<td>L. destructor</td>
<td>0.25 - 2 (17°C / 75 %)</td>
<td>Wheat</td>
<td>75% after 1 day - 6 months 100 % after 4 months</td>
<td>Wilkin et al (1988)</td>
</tr>
<tr>
<td></td>
<td>G. domesticus</td>
<td>2% (25°C / 75 %)</td>
<td>Potter Tower</td>
<td>97.6% after 24 hours</td>
<td>Lozza et al (1994)</td>
</tr>
<tr>
<td></td>
<td>T. putrescentiae</td>
<td>2% (25°C / 75 %)</td>
<td>Potter Tower</td>
<td>64% after 24 hours</td>
<td>Lozza et al (1994)</td>
</tr>
<tr>
<td>Permethrin</td>
<td>A. siro</td>
<td>2, 4 &amp; 8 (22°C / 100 %)</td>
<td>Wheat</td>
<td>0%, 20% &amp; 54% after 4 weeks</td>
<td>White (1984)</td>
</tr>
<tr>
<td>COMPOUND</td>
<td>MITE SPECIES</td>
<td>DOSE (mg kg⁻¹)* (TEMP / RH)</td>
<td>APPLICATION</td>
<td>MORTALITY *</td>
<td>REFERENCE</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>-------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Permethrin</td>
<td><em>T. putrescentiae</em></td>
<td>500</td>
<td>Culture</td>
<td>98% after 3 weeks</td>
<td>Chisaka et al (1984)</td>
</tr>
<tr>
<td>Bioresmethrin</td>
<td><em>A. siro</em> L. destructor</td>
<td>2</td>
<td>Wheat</td>
<td>100% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td><em>T. putrescentiae</em></td>
<td>(17.5°C / 75 %)</td>
<td></td>
<td>100% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Bioresmethrin + piperonyl butoxide</td>
<td><em>A. siro</em> L. destructor</td>
<td>2 + 20</td>
<td>Wheat</td>
<td>100% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td><em>T. putrescentiae</em></td>
<td>(17.5°C / 75 %)</td>
<td></td>
<td>&gt; 75% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td><em>T. destructor</em></td>
<td></td>
<td></td>
<td>&gt; 75% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td><em>T. longior</em> T. palmarum</td>
<td>10 + 10</td>
<td>Wheat</td>
<td>~ 75% after 14 days</td>
<td>Stables (1984)</td>
</tr>
<tr>
<td></td>
<td><em>T. putrescentiae</em></td>
<td>(17.5°C / 80 %)</td>
<td></td>
<td>~ 75% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Bioresmethrin + piperonyl butoxide</td>
<td><em>A. siro</em></td>
<td>4+20, 2+20 &amp; 2+2</td>
<td>Wheat</td>
<td>&gt; 75% after 14 days</td>
<td>Wilkin (1975a)</td>
</tr>
<tr>
<td></td>
<td>(15°C)</td>
<td></td>
<td></td>
<td>~ 75% after 14 days</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Bioallethrin</td>
<td><em>A. siro</em> L. destructor</td>
<td>2</td>
<td>Wheat</td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td><em>T. putrescentiae</em></td>
<td>(17.5°C / 75 %)</td>
<td></td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Bioallethrin + piperonyl butoxide</td>
<td><em>A. siro</em></td>
<td>2 + 20</td>
<td>Wheat</td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td>L. destructor T. putrescentiae</td>
<td>(17.5°C / 75 %)</td>
<td></td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Pyrethrins</td>
<td><em>A. siro</em> L. destructor</td>
<td>2</td>
<td>Wheat</td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td><em>T. putrescentiae</em></td>
<td>(17.5°C / 75 %)</td>
<td></td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Pyrethrins + piperonyl butoxide</td>
<td><em>A. siro</em></td>
<td>2 + 20</td>
<td>Wheat</td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td></td>
<td>L. destructor T. putrescentiae</td>
<td>(17.5°C / 75 %)</td>
<td></td>
<td>Ineffective</td>
<td>Wilkin and Hope (1973a)</td>
</tr>
<tr>
<td>Phenothrin</td>
<td><em>T. putrescentiae</em></td>
<td>500</td>
<td>Culture</td>
<td>99.7% after 3 weeks</td>
<td>Chisaka et al (1984)</td>
</tr>
<tr>
<td>Fenopropathrin</td>
<td><em>T. putrescentiae</em></td>
<td>500</td>
<td>Culture</td>
<td>99.5% after 3 weeks</td>
<td>Chisaka et al (1984)</td>
</tr>
<tr>
<td>Bifenthrin</td>
<td><em>A. siro</em></td>
<td>1 &amp; 0.5</td>
<td>Wheat</td>
<td>100% &amp; 75% after 1 day</td>
<td>Binns (1989)</td>
</tr>
<tr>
<td>Bifenthrin</td>
<td><em>A. siro</em></td>
<td>1</td>
<td>Wheat</td>
<td>50% after 4 weeks, ineffective after 12 weeks</td>
<td>Binns (1989)</td>
</tr>
<tr>
<td>(17.5°C / 75 %)</td>
<td></td>
<td></td>
<td></td>
<td>~ 50% after 14 days</td>
<td>Binns (1989)</td>
</tr>
<tr>
<td>Deltamethrin</td>
<td><em>A. siro</em></td>
<td>1 &amp; 0.5</td>
<td>Wheat</td>
<td>75% &amp; 25% after 1 day</td>
<td>Binns (1989)</td>
</tr>
<tr>
<td>Deltamethrin</td>
<td><em>A. siro</em></td>
<td>1</td>
<td>Wheat</td>
<td>50% after 4 weeks, ineffective after 12 weeks</td>
<td>Binns (1989)</td>
</tr>
<tr>
<td>Botanicals</td>
<td><em>T. longior</em></td>
<td>1.00 %</td>
<td>Petri dishes</td>
<td>100%</td>
<td>Perrucci (1995)</td>
</tr>
<tr>
<td></td>
<td><em>T. putrescentiae</em></td>
<td>(25°C / 70 %)</td>
<td>Petri dishes</td>
<td>100% with 1-5 µl</td>
<td>Watanabe et al (1989)</td>
</tr>
<tr>
<td>COMPOUND</td>
<td>MITE SPECIES</td>
<td>DOSE (mg kg⁻¹)*</td>
<td>APPLICATION</td>
<td>MORTALITY *</td>
<td>REFERENCE</td>
</tr>
<tr>
<td>----------</td>
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<td>-----------</td>
</tr>
<tr>
<td>Essential oils of Eugenia &amp; Garlic</td>
<td><em>G. domesticus</em></td>
<td>1% (25°C / 75%)</td>
<td>Potter tower</td>
<td>41% &amp; 36% after 24 hours</td>
<td>Lozzia et al (1994)</td>
</tr>
<tr>
<td>Parsley oil</td>
<td><em>A. siro</em></td>
<td>16.80%</td>
<td></td>
<td></td>
<td>Czajkowska (1971)</td>
</tr>
<tr>
<td>Caffeine</td>
<td><em>T. putrescentiae</em></td>
<td>8.40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ergotamine</td>
<td><em>A. siro</em></td>
<td>2%</td>
<td>rye germs</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Quinine</td>
<td><em>A. siro</em></td>
<td>10%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Arbutine</td>
<td><em>T. putrescentiae</em></td>
<td>40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colchicine</td>
<td><em>T. putrescentiae</em></td>
<td>8.40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ergotamine</td>
<td><em>A. siro</em></td>
<td>2%</td>
<td>rye germs</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Quinine</td>
<td><em>A. siro</em></td>
<td>10%</td>
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<tr>
<td>Arbutine</td>
<td><em>T. putrescentiae</em></td>
<td>40%</td>
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<tr>
<td>Colchicine</td>
<td><em>T. putrescentiae</em></td>
<td>0.6%</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Digitoxine</td>
<td><em>T. putrescentiae</em></td>
<td>0.4%</td>
<td></td>
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<tr>
<td>Spice oils of:</td>
<td></td>
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</tr>
<tr>
<td>Sassafras</td>
<td></td>
<td>0.001%</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Vaniprox</td>
<td></td>
<td>0.001%</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Bitter almond &lt; sage</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>&lt; onion &lt; clove &lt; oreosin black pepper &lt; mace &lt; Black pepper</td>
<td></td>
<td>(0.01% &amp; 0.1%) Diet</td>
<td></td>
<td></td>
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<tr>
<td>Curry powder,</td>
<td></td>
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<tr>
<td>Lemon/pepper seasoning, mace, Sage</td>
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<tr>
<td>Oreosin black pepper</td>
<td><em>T. putrescentiae</em></td>
<td>0.1%</td>
<td>Pet food</td>
<td>76% growth inhibition</td>
<td></td>
</tr>
<tr>
<td>Clove</td>
<td></td>
<td>0.1%</td>
<td></td>
<td></td>
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<tr>
<td>Almond</td>
<td></td>
<td>0.01%</td>
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</tr>
<tr>
<td>Sassafras</td>
<td><em>T. putrescentiae</em></td>
<td>0.01%</td>
<td>Pet food</td>
<td>96% growth inhibition</td>
<td></td>
</tr>
<tr>
<td>Sage</td>
<td>Oil of black pepper</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Sassafras</td>
<td></td>
<td>(0.001%)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Caraway extracts</td>
<td><em>T. putrescentiae</em></td>
<td>0.1%</td>
<td>Pet food</td>
<td>76% growth inhibition</td>
<td></td>
</tr>
<tr>
<td>Fenugreek extracts</td>
<td></td>
<td>0.1%</td>
<td></td>
<td></td>
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<tr>
<td>Caraway extracts</td>
<td><em>T. putrescentiae</em></td>
<td>0.01%</td>
<td>Pet food</td>
<td>96% growth inhibition</td>
<td></td>
</tr>
<tr>
<td>Fenugreek extracts</td>
<td></td>
<td>0.01%</td>
<td></td>
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<tr>
<td>Lupin extracts</td>
<td></td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus powder</td>
<td></td>
<td>0.5%</td>
<td></td>
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</tr>
<tr>
<td>Mentha powder</td>
<td><em>T. putrescentiae</em></td>
<td>5%</td>
<td>Flour</td>
<td>Eggs ↓ to 52 / female</td>
<td>Gulati &amp; Mathur (1995)</td>
</tr>
<tr>
<td>Curcumia rhizomes</td>
<td></td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Novel Compounds</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chemosterilants</td>
<td><em>A. siro</em></td>
<td>&gt; 0.25% (25°C / 85%)</td>
<td>Wheat germ</td>
<td>Egg laying suppressed, permanent sterility</td>
<td>Ignatowicz (1982a)</td>
</tr>
<tr>
<td>Potassium iodide</td>
<td><em>T. putrescentiae</em></td>
<td>&gt; 0.25% (85%)</td>
<td>Wheat germ</td>
<td>Egg laying suppressed</td>
<td>Ignatowicz (1986a)</td>
</tr>
<tr>
<td>Potassium iodate &amp; tin iodide</td>
<td><em>T. putrescentiae</em></td>
<td>&gt; 0.5% (85%)</td>
<td>Food</td>
<td>Egg laying suppressed</td>
<td>Ignatowicz (1982b)</td>
</tr>
<tr>
<td>Boric acid</td>
<td><em>T. putrescentiae</em></td>
<td>2%</td>
<td>Food</td>
<td>100%</td>
<td>Ignatowicz (1983)</td>
</tr>
<tr>
<td>Sodium fluoride</td>
<td><em>T. putrescentiae</em></td>
<td>0.25% or 0.5%</td>
<td>Food</td>
<td>58% did not lay eggs</td>
<td>Ignatowicz (1987a)</td>
</tr>
<tr>
<td>Thiourrea</td>
<td><em>A. siro</em></td>
<td>1-2%</td>
<td>Food</td>
<td>6-8% did not lay eggs</td>
<td>Ignatowicz (1987b)</td>
</tr>
<tr>
<td>5-fluorouracil</td>
<td><em>T. putrescentiae</em></td>
<td>0.25% - 0.5%</td>
<td>Food</td>
<td>High mortality &amp; sterility</td>
<td>Ignatowicz (1987b)</td>
</tr>
<tr>
<td>A. siro</td>
<td></td>
<td>2% (85%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPOUND</td>
<td>MITE SPECIES</td>
<td>DOSE (mg kg⁻¹)* (TEMP / RH)</td>
<td>APPLICATION</td>
<td>MORTALITY *</td>
<td>REFERENCE</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>Colchicine</td>
<td>T. putrescentiae</td>
<td>0.01 % Food 0.01 % (25°C / 85 %)</td>
<td>Food</td>
<td>Fecondity ↓ 89 %</td>
<td>Ignatowicz (1987c)</td>
</tr>
<tr>
<td></td>
<td>A. siro</td>
<td>0.01 % Food</td>
<td></td>
<td>Fecondity ↓ 24 %</td>
<td></td>
</tr>
<tr>
<td>Fatty Acids</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Capric acid</td>
<td>T. putrescentiae</td>
<td>1 % Dog food</td>
<td>No eggs</td>
<td></td>
<td>Rodriguez (1972)</td>
</tr>
<tr>
<td>Propionic, butyric, caproic &amp; caprylic acids</td>
<td>T. putrescentiae</td>
<td>2 % Dog food</td>
<td>No eggs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propionic acid</td>
<td>A. siro</td>
<td>0.5 - 0.8 % Wheat</td>
<td>100 %</td>
<td></td>
<td>Simpson (1973)</td>
</tr>
<tr>
<td>Inorganic salts</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Tricalcium phosphate</td>
<td>T. putrescentiae</td>
<td>18 % Food 31.5 % (25°C / 85 %)</td>
<td>Food</td>
<td>50 % ↓ Fecondity</td>
<td>Boczek &amp; Ignatowicz (1979)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 - 1mm</td>
<td></td>
<td>84 % ↓ Fecondity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(25°C / 85 %)</td>
<td></td>
<td>100 % after 3-5 hours</td>
<td></td>
</tr>
<tr>
<td>Ag₂SO₄, AgNO₃</td>
<td>T. putrescentiae</td>
<td>1 % Food</td>
<td>Suppressed egg laying ↓ adult longevity</td>
<td>Boczek et al (1984)</td>
<td></td>
</tr>
<tr>
<td>Antibiotics</td>
<td>T. putrescentiae</td>
<td>3.25 % Direct 1.0 x 10⁷ spores / ml (20°C / 70, 90 &amp; 100 %)</td>
<td></td>
<td>87 % after 24 hours of motile stages 56 % egg hatch</td>
<td>Castagnoli et al (1996)</td>
</tr>
<tr>
<td>Benzyl alcohol</td>
<td>A. putrescentiae</td>
<td>18 % Food 31.5 % (25°C / 85 %)</td>
<td>Food</td>
<td>100 % after 3-5 hours</td>
<td></td>
</tr>
<tr>
<td>Biological control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predators</td>
<td></td>
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<tr>
<td>Cheyletus eruditus</td>
<td>Astigmata</td>
<td>2000-3000 predators / 100m² (Field)</td>
<td>Empty store</td>
<td>Markedly reduced mites</td>
<td>Zdarkova &amp; Horak (1990)</td>
</tr>
<tr>
<td></td>
<td>Astigmata</td>
<td>1 : 100 &amp; 1 : 1000 (Predator : Prey) (Field)</td>
<td>Grain surface</td>
<td>Successful control</td>
<td>Pulpan &amp; Verner (1965)</td>
</tr>
<tr>
<td>Cheyletin</td>
<td>Astigmata</td>
<td>2000-3000 predators / 100m² (Field)</td>
<td>Empty store</td>
<td>Population ↓ by 8.4 x</td>
<td>Zdarkova (1991)</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Protozoa</td>
<td></td>
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</tr>
<tr>
<td>Nosema steinhausi</td>
<td>T. putrescentiae</td>
<td>(22-24°C / ~ 90 %)</td>
<td>Empty store</td>
<td>Markedly reduced mites</td>
<td>Weiser (1956)</td>
</tr>
<tr>
<td>Pleistophora sp.</td>
<td>T. putrescentiae</td>
<td>(22°C / ~ 90 %)</td>
<td>Empty store</td>
<td>Markedly reduced mites</td>
<td>Beerling et al (1993)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beerling &amp; van der Geest (1991)</td>
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<tr>
<td>Fungi</td>
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<tr>
<td>Hirsutella thompsonii</td>
<td>A. siro</td>
<td>1.0 x 10⁷ spores / ml (20°C / 70, 90 &amp; 100 %)</td>
<td>Wheat, cheese &amp; filter papers</td>
<td>No detectable effect</td>
<td>Anon (1983)</td>
</tr>
<tr>
<td></td>
<td>A. chaetosilosis</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>A. farris</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>L. destructor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T. putrescentiae</td>
<td></td>
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</tr>
<tr>
<td>Verticillium lecanii</td>
<td>A. siro</td>
<td>1.4 x 10⁷ spores / ml (20°C / 70, 90 &amp; 100 %)</td>
<td>Wheat, cheese &amp; filter papers</td>
<td>No detectable effect</td>
<td>Anon (1983)</td>
</tr>
<tr>
<td></td>
<td>A. chaetosilosis</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>A. farris</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>L. destructor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T. putrescentiae</td>
<td></td>
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</tr>
<tr>
<td>COMPOUND</td>
<td>MITE SPECIES</td>
<td>DOSE (mg kg⁻¹)* (TEMP / RH)</td>
<td>APPLICATION</td>
<td>MORTALITY *</td>
<td>REFERENCE</td>
</tr>
<tr>
<td>---------------------------------</td>
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</tr>
<tr>
<td><em>Aspergillus versicolor</em></td>
<td>T. putrescentiae</td>
<td>(27°C / 85 %)</td>
<td>Culture</td>
<td>Females did not develop or lay eggs, longevity shortened</td>
<td>Rodriguez et al (1984)</td>
</tr>
<tr>
<td><em>Aspergillus flavus</em></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><em>Aspergillus nidulans</em></td>
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</tr>
<tr>
<td><em>Pencillium rubrum</em></td>
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<tr>
<td><em>Aspergillus versicolor</em></td>
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</tr>
<tr>
<td><em>Aspergillus nidulans</em></td>
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<tr>
<td><em>Fusarium popae</em></td>
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<tr>
<td><em>Pencillium rubrum</em></td>
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<tr>
<td><em>Sporendonema sebi</em></td>
<td>A. siro</td>
<td>(20°C / 75 %)</td>
<td>Food</td>
<td>↓ reproduction, high mortality &amp; retarded dev.</td>
<td>Solomon et al (1964)</td>
</tr>
<tr>
<td><em>Aspergillus restrictus</em></td>
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<td></td>
</tr>
<tr>
<td><em>A. siro</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>L. destructor</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>T. longior</em></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><em>Cladosporium cladosporiodes,</em></td>
<td>A. siro</td>
<td>(20°C / 90 %)</td>
<td>Food</td>
<td>Fewer eggs produced Male longevity ↓</td>
<td>Parkinson et al (1991 a &amp; b)</td>
</tr>
<tr>
<td><em>Aspergillus repens</em></td>
<td></td>
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<tr>
<td><em>Aspergillus ruber</em></td>
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<tr>
<td><em>Pencillium cyclopium</em></td>
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</tbody>
</table>

* - Unless otherwise indicated
Table 2 - Advantages and disadvantages in the use of some alternative compounds for the control of storage mites

<table>
<thead>
<tr>
<th>COMPOUND / TYPE</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Growth regulators</strong></td>
<td>• Specific for target pests</td>
<td>• Vary in efficacy against mites</td>
</tr>
<tr>
<td></td>
<td>• Low toxicity to beneficial organisms and mammals</td>
<td>• Cross resistance in OP resistant insects</td>
</tr>
<tr>
<td></td>
<td>• Persistant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Effective against insects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Commercial compounds available</td>
<td></td>
</tr>
<tr>
<td><strong>Inert dusts</strong></td>
<td>• Resistance will not occur</td>
<td>• Behavioural avoidance may occur</td>
</tr>
<tr>
<td></td>
<td>• Persistant</td>
<td>• Less effective at high r.h.</td>
</tr>
<tr>
<td></td>
<td>• Effective against insects</td>
<td>• Small particle dusts are a respirable hazard</td>
</tr>
<tr>
<td></td>
<td>• Large particle formulations safe</td>
<td>• Slow-acting</td>
</tr>
<tr>
<td></td>
<td>• No toxic residues</td>
<td>• Affects grain flow</td>
</tr>
<tr>
<td></td>
<td>• Low mammalian toxicity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Commercial compounds available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Cost effective</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Registered for storage use in some countries</td>
<td></td>
</tr>
<tr>
<td><strong>Botanicals</strong></td>
<td>• Effective against insects</td>
<td>• Delayed effect</td>
</tr>
<tr>
<td>Azadirachtin</td>
<td>• Possible increased persistance in store.</td>
<td>• No information on efficacy against storage mites</td>
</tr>
<tr>
<td>Others</td>
<td>• Quite selective</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low mammalian toxicity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Resistance not detected</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Commercial compounds available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Vast array of products</td>
<td>• Some extracts may taint grain</td>
</tr>
<tr>
<td></td>
<td>• Efficacy against mites varies</td>
<td></td>
</tr>
<tr>
<td><strong>Pyrethroids</strong></td>
<td>• Multiple modes of action</td>
<td>• Toxic residues</td>
</tr>
<tr>
<td></td>
<td>• Reduced resistance threat</td>
<td>• Resistance potential</td>
</tr>
<tr>
<td></td>
<td>• Degradation slowly under UK conditions</td>
<td>• Degradation increases as temperature increases</td>
</tr>
<tr>
<td></td>
<td>• Toxicity increased at lower temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Effective against mites and insects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Commercial compounds available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Registered for use in some countries</td>
<td></td>
</tr>
<tr>
<td><strong>Novel compounds</strong></td>
<td>• Efficacy against storage mites well known</td>
<td>• Usually highly toxic</td>
</tr>
<tr>
<td>Chemosterilants</td>
<td>• Used with attractants to target pest</td>
<td>• Activity not specific to target pest</td>
</tr>
<tr>
<td>Fatty acids</td>
<td>• Effective against storage mites</td>
<td>• Short-lived protection</td>
</tr>
<tr>
<td>Inorganic salts</td>
<td>• May be food additives</td>
<td>• Grain killed</td>
</tr>
<tr>
<td></td>
<td>• Some effective against mites</td>
<td>• Efficacy against mites varies</td>
</tr>
<tr>
<td></td>
<td>• Resistance unlikely</td>
<td>• High doses required</td>
</tr>
<tr>
<td>Antibiotics</td>
<td>• Avermectins effective at low doses</td>
<td>• Resistance potential</td>
</tr>
<tr>
<td></td>
<td>• against phytophagous mites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Commercial compounds available</td>
<td></td>
</tr>
<tr>
<td>COMPOUND/TYP</td>
<td>ADVANTAGES</td>
<td>DISADVANTAGES</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Biological control Parasitoids, nematodes and predators</td>
<td>No toxic residues</td>
<td>Predators considered contaminants</td>
</tr>
<tr>
<td></td>
<td>Predators already used in storage overseas</td>
<td>Parasitoids of storage mites unknown</td>
</tr>
<tr>
<td></td>
<td>Predators more tolerant of OPs than pests</td>
<td>Storage conditions too dry for nematodes</td>
</tr>
<tr>
<td></td>
<td>Harmless to non-target organisms</td>
<td>Slow to act at low temperatures</td>
</tr>
<tr>
<td></td>
<td>Compatible with pesticides</td>
<td>Specificity may limit usefulness</td>
</tr>
<tr>
<td></td>
<td>Cheap and easy to culture</td>
<td>Careful application timings needed</td>
</tr>
<tr>
<td></td>
<td>Longevity enhanced in grain storage</td>
<td>Virulence depends on climate</td>
</tr>
<tr>
<td></td>
<td>Suitable for admixture</td>
<td>Control achieved slowly</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Invisible</td>
<td>Resistance potential</td>
</tr>
<tr>
<td></td>
<td>Effective against storage insects</td>
<td>Few mite viral diseases</td>
</tr>
<tr>
<td>Bacteria</td>
<td>Pest feeding halted rapidly</td>
<td>Resistance potential</td>
</tr>
<tr>
<td></td>
<td>Easy to use</td>
<td>Not evaluated against storage mites</td>
</tr>
<tr>
<td></td>
<td>Commercial compounds available</td>
<td>β-exotoxins toxic to bees, poultry &amp; mammals</td>
</tr>
<tr>
<td>Viruses</td>
<td>Large number of species available</td>
<td>Sub-lethal effects</td>
</tr>
<tr>
<td></td>
<td>Many modes of transmission</td>
<td>Slow-acting</td>
</tr>
<tr>
<td></td>
<td>Some effective against storage mites</td>
<td>Difficult to produce</td>
</tr>
<tr>
<td>Protozoa</td>
<td>Mycotoxins may be toxic to mites</td>
<td>Storage too dry for fungal growth</td>
</tr>
<tr>
<td>Fungi</td>
<td></td>
<td>Mycotoxins also toxic to mammals</td>
</tr>
</tbody>
</table>