

Status of Pesticide Resistance in Arthropod Pests in Israel

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A complex of events and factors, pertinent to a specific insect and insecticide, governs the development of resistance to insecticides. In Israel, resistance to conventional and novel insecticides occurred in insect pests such as *Bemisia tabaci* and *Spodoptera littoralis* (that damage agricultural crops), *Tribolium castaneum* and other flour beetles (that contaminate stored products), and *Pediculus humanus* spp., house flies and mosquitoes (that threaten public health). In the mid-1980s an insecticide resistance management (IRM) strategy was established for all cotton grown in Israel and is being adjusted on a yearly basis as needed. At present, insect pest management and IRM strategies are being developed and implemented area-wide for three regions in Israel: Bet She'an Valley, western Galilee, and western Negev. There are several research groups now working in Israel on various aspects of resistance including occurrence, mechanisms, and management practices. This paper offers a tentative review of the status of insecticide and acaricide resistance in pests in Israel.

KEY WORDS: Insect management strategies; insecticide resistance; control failures; agricultural pests; public health pests; Israel.

INTRODUCTION

The evolution of resistance to insecticides is governed by a complex of events and factors: mainly, intense and repeated applications of insecticides which belong often to the same chemical group or which employ the same mode of action. The mechanisms of resistance due to specific biochemical changes that occur and the speed with which resistance develops, vary according to the specific insect concerned (*e.g.* the frequency of alleles for resistance inherent in the population), and the chemical group, application rate and selection pressure (frequency of application) of the insecticide. Resistance evolves in pests of agricultural crops in the field, stored products, and public health.

Agriculture in the semi-arid Israeli climate has developed into intensive cropping systems including irrigated field crops, orchards, and greenhouses. Israel has been plagued by many insect and mite pest species that have seriously damaged yields, including: *Bemisia tabaci* (Gennadius), *Spodoptera littoralis* (Boisduval), *Helicoverpa armigera* (Hübner), *Pectinophora gossypiella* (Saunders), *Earias insulana* Boisduval, *Aphis gossypii* Glover, *Tetranychus* spp., *Frankliniella occidentalis* (Pergande) and *Liriomyza* spp. in cotton, vegetable and ornamental crops; *Cydia pomonella* (Linnaeus) and spider mites in apple and pear orchards; *Lobesia botrana* (Schiffermüller) and *Drosophila melanogaster* (Meigen) and *D. simulans* Sturtevant in vineyards; *Ceratitis capitata* (Wiedemann),

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Aonidiella aurantii (Maskell), *Phyllocoptruta oleivora* (Ashmead) and *Phyllocnistis citrella* Stainton, in citrus groves.

In order to reduce losses caused by these pests, numerous pesticides are applied to the crops. Aside from generating environmental and health problems, these treatments have resulted in evolution of resistance to various groups of conventional and non-conventional insecticides.

Some stored-product pests, *Tribolium castaneum* (Herbst), *Rhyzopertha dominica* (Fabricius) and *Oryzaephilus surinamensis* (Linnaeus), have developed resistance due to intense insecticide application. Similarly, public health pests, such as *Pediculus humanus capitis* De Geer, *P.h. humanus* Linnaeus, *Musca* spp. and *Culex pipiens* Linnaeus, have also been subjected to intense insecticide applications and have developed resistance.

Today, there are only a few groups working on resistance in Israel; a group at The Volcani Center, with the assistance of the Israeli Cotton Board, has focused research on resistance in cotton pests such as whiteflies (*B. tabaci*), Egyptian cotton leafworm (*S. littoralis*), and cotton bollworm (*H. armigera*). Groups from the Department of Zoology at Tel-Aviv University, and the Department of Entomology at The Hebrew University of Jerusalem Faculty of Agriculture in Rehovot, are studying mechanisms of resistance to conventional insecticides. Other groups from the Entomological Laboratory of the Ministry of Health in Jerusalem, and from the Department of Parasitology and Entomology at The Hebrew University of Jerusalem, are working on insecticide resistance of public health pests such as house flies, mosquitoes and human lice.

This paper offers a brief, tentative review of the status of insecticide resistance, mainly in the agricultural pests, in Israel, although stored-product and public health pests will also be addressed.

INCIDENTS OF INSECTICIDE CONTROL FAILURES IN AGRICULTURAL PESTS

In Israel, insecticide resistance management (IRM) was not implemented until late in the 1980s. Furthermore, until the 1990s, most vegetable and flower growers in Israel seldom used even simple practical techniques for combating insecticide resistance (such as pesticide mixtures or short-term alternation of two or more insecticides). Tomato growers use a deleterious practice in their battle against *B. tabaci*-transmitted geminiviruses (4): In the past, two applications of organophosphates (OPs) or pyrethroids *per week* were sufficient to control whiteflies and to prevent virus damage to the young tomatoes. Recently, one or two insecticide applications *per day* have not been enough, and the plots are, in some cases, totally infected with tomato yellow leaf curl (TYLC) virus.

A number of failures to control insects have been observed during field surveys over the past 20 years, as seen in Table 1. This table was constructed according to data collected by the late Haim Shoham, the former head of the Plant Protection Division in the Extension Services. Because these failures were not correlated with bioassay data, and since other factors, such as poor application or climatic conditions, could have been involved in such field failures, this table should be read with caution. Furthermore, years in which the failures first occurred are based on the recollections of Extension Services personnel. However, in most cases, after incidents in which a particular insecticide failed to control the pest population, its use was terminated by the growers. Failures occurred more or less simultaneously in cotton and vegetable crops.

TABLE 1. Failures of Insecticides to Control Pests in Israel*

Crop	Pest	Insecticide
Cotton	<i>Bemisia tabaci</i>	Bifenthrin (1990), butocarboxim (1988), cypermethrin (1985), fenpropathrin (1990), fenvalerate (1983), pirimiphos- methyl (1985)
	<i>Earias insulana</i>	Azinphos-methyl (1970)
	<i>Spodoptera littoralis</i>	Chlorpyrifos (1980), cypermethrin (1985), methomyl (1980), monocrotophos (1975), parathion-ethyl (1967)
Vegetables	<i>Bemisia tabaci</i>	Bifenthrin, cyhalothrin, cypermethrin, fenpropathrin, fenvalerate, pirimiphos-methyl
	<i>Spodoptera littoralis</i>	Chlorpyrifos, cypermethrin, fenvalerate, monocrotophos, parathion-ethyl, trichlorfon (1967)
	<i>Tetranychus</i> sp.	Binapacryl, bromopropylate (1977), Cyhexatin (1990), dicofol (1982), monocrotophos, propargite, pyrazophos, tetradifon (1982)
	Aphids	Pirimicarb (1985)
	<i>Chrysodeixis chalcites</i>	Chlorpyrifos (1987), dichlorvos (1990), methamidophos, methomyl (1990)
Apple & Pear	<i>Tetranychus</i> sp.	Benzoximate, dicofol, quinomethionate, tetradifon
	<i>Eriosoma lanigerum</i>	Vamidothion
Grapes	<i>Lobesia botrana</i>	Cypermethrin

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Some of the listed failures were probably caused by resistance in pests to conventional insecticides such as organochlorines, OPs, carbamates and pyrethroids. Among the primary pests that have developed resistance to these insecticides are *B. tabaci*, *S. littoralis*, spider mites and aphids. Sometimes insecticide failure to control a particular pest has occurred very quickly. For example, failure of the carbamate triazamate to control *A. gossypii* occurred one year after growers started using it on cotton. Moores *et al.* (18) have shown that in other aphid species there is cross-resistance between pirimicarb (another carbamate insecticide that was used in Israel for ~20 years) and triazamate. Failure to control the pea leafminer, *Liriomyza huidobrensis* (Blanchard), with various conventional insecticides was observed just after the pest was identified in Israel (27), indicating that it entered the country from Europe as a resistant pest.

TABLE 2. Incidents of resistance (*resistance ratio at LD₉₀) to common insecticides in the house fly *Musca domestica*, and the northern house mosquito, *Culex pipiens*

Year and Location	Azamethiphos	Insecticides		
		Chlorpyrifos	Cypermethrin	Permethrin
<i>Musca domestica</i>				
1994 Mevasseret Ziyyon	7		24	21
1996 Shuval	5			68
<i>Culex pipiens</i>				
1994 Geva		58	7	5
Omer		5	22	18
1995 Aroer		115	5	15
1996 Yavne		>>**	47	>150
Nataf		>>	>>	>>

Based on unpublished data of Dr. H. Pender from the Central Laboratories of the Israel Ministry of Health in Jerusalem.

* Resistance ratio – obtained by dividing the LD values of the field populations by those of the susceptible strains;

** >> Very high levels of resistance; 90% mortality was not achieved at the dosages tested.

AGRICULTURAL PEST RESISTANCE

Field Crops and Ornamentals

In 1987, cotton growers were introduced to an IRM program (7,12). The main goal was to delay the onset of resistance by optimizing the use of insecticides. The tactics were to restrict the use of still-effective conventional insecticides, such as endosulfan and pyrethroids, to a short period during the cotton season, and to preserve beneficials during the early season (May–July) by reducing chemical treatments to a minimum.

During the cotton-growing season, a central pest control committee (comprised of representatives from the Cotton Board of Israel, the Extension Services, and researchers and growers) meets weekly to evaluate reports on plant-growth development, occurrence of pests, and changes in susceptibility of the pests to the insecticides (8). This evaluation can lead to slight modifications of the IRM program during the growing season. The strategy is modified each year according to reports of pre-season resistance levels and the availability of new compounds.

Bemisia tabaci: Although the first outbreak of whiteflies occurred in the mid-1970s, almost a decade elapsed before the first documentation of resistance. Perry (25) found 55-fold resistance to phosfolan and 60-fold resistance to endosulfan from field-collected whiteflies. Since 1990, *B. tabaci* has been monitored for resistance to conventional insecticides by collecting whitefly adults from various locations, and exposing them to diagnostic doses of endosulfan, bifenthrin, methomyl and methidathion. Bioassay results have indicated an increase in tolerance of whitefly adults to endosulfan and bifenthrin, which was correlated with immigration from sources of intensive treatments (such as vegetable and flower greenhouses) (8,10). The mechanisms of resistance and inheritance of resistance to the OP methidathion in field populations of whiteflies have been investigated (5,29).

Monitoring of resistance to insecticides with novel modes of action (such as buprofezin, pyriproxyfen, diafenthiuron and acetamiprid) began with the introduction of these

compounds to cotton fields and other crops. Bioassays for these compounds were conducted twice per season: in early summer before any of the insecticide applications, and in late season after the various insecticide applications. In greenhouse vegetables or flowers without a resistance management policy, successive applications of buprofezin caused an approximately 15-fold increase in resistance in whiteflies; control failures occurred subsequently (8). The results of 7 years (1989–1996) of buprofezin use in cotton with an IRM program indicated that the susceptibility of *B. tabaci* to this compound was not appreciably altered; in 1989–1991, the regression lines were not significantly different from those of a susceptible strain. In 1992, an approximately fourfold increase in resistance was observed (9), which has increased to about tenfold today (A.R.H., unpublished data). While only small changes (in general, tenfold or greater is considered significant resistance) in the bioassay data from field-collected *B. tabaci* were observed in the laboratory, field effectiveness of buprofezin in controlling high populations was more significantly reduced (A.R.H., unpublished data).

Susceptibility to pyriproxyfen in an IRM program remained constant from year to year until 1995; there was a slight increase in tolerance in the late season testing, but populations tested at the beginning of the following season returned to baseline susceptibility. Since the 1995 season, moderate to high levels of resistance have been observed in some locations; however, the susceptibility of whiteflies has remained unchanged in most locations (A.R.H., unpublished data). In contrast, after successive applications, very high resistance to pyriproxyfen (approximately 500-fold to egg-hatch inhibition) was observed in *B. tabaci* from some ornamental greenhouses without IRM programs (11).

If we summarize the history of resistance to pyriproxyfen, one can see that this insecticide is very resistance-prone (probably due to the high frequency of alleles conferring resistance in a wild population), especially following successive applications. While even the restriction of use to a single application per year outdoors could not prevent the ultimate onset of resistance, it could delay it for an additional 5 years of use.

Monitoring of resistance to the new chloronicotinyl insecticides (imidacloprid and acetamiprid) started in 1996 in cotton fields and greenhouse ornamentals. No apparent resistance to imidacloprid or acetamiprid was observed after 2 years of use, although the pest developed a fivefold tolerance to the former insecticide in some greenhouses (A.R.H., unpublished data).

Spodoptera littoralis: Since the 1970s, this pest has apparently developed high levels of resistance, as evidenced by failure of many insecticides to control populations in the field, and substantiated by laboratory trials. Field-collected populations showed much higher resistance levels to OPs such as chlorpyrifos (LC_{50} about 20-fold higher), and pyrethroids such as deltamethrin (500-fold higher) and cypermethrin (approximately 100-fold higher) than susceptible strains (2,14).

Monitoring of resistance in *S. littoralis* to insect growth regulators (IGRs; chlorfluazuron and teflubenzuron) started late in the 1992 season, following their introduction into cotton, with the collection of eggs and larvae from cotton fields and greenhouses. The results indicated that the susceptibility of the larvae to chlorfluazuron was not altered in either 1992 or 1993. A slight increase in tolerance was observed for teflubenzuron; however, this was not significant and the pest is apparently still susceptible to this compound (9).

Helicoverpa armigera: Pheromone-trapped male moths were exposed to diagnostic

concentrations of four conventional insecticides (endosulfan, cypermethrin, methidathion, and methomyl) to determine levels of resistance. The results indicated that susceptibility of the cotton bollworm to these insecticides was not appreciably altered from 1987 to 1991, although fluctuations during the season were observed (13). The results from 1992 and 1993 show a decline in *H. armigera* resistance to the four insecticides tested, which apparently correlates with the general reduction in insecticide applications (9).

Aphis gossypii: Ishaaya and Mendelson (15) reported on the susceptibility of the melon aphid (*A. gossypii*) to various conventional insecticides in cotton fields during the 1985 and 1986 seasons. They found that resistance to insecticides gradually increased during the cotton-growing season; late in the 1985 season, 85-fold resistance was observed to bifenthrin, tenfold to monocrotophos, and threefold to methomyl. Their 1986 results indicated that during the winter, part of the resistance developed during the previous cotton season was lost.

Frankliniella occidentalis: Monitoring of resistance in the western flower thrips began in 1996 in various commercial greenhouses. The results indicated moderate resistance to carbosulfan and methiocarb and strong resistance to cypermethrin (S. Kontsedalov, P.G. Weintraub, A.R. Horowitz and I. Ishaaya, unpublished data).

Tetranychus cinnabarinus: As reported by Mansour and Plaut (17), resistance to various pesticides (dicofol, malathion, tetradifon, phosphamidon and phenkapton) in mites collected from field and ornamental crops has been observed since the mid 1950s. These workers tested resistant and susceptible strains of mites collected in 1973 from a rose greenhouse and *Viola odorata* L., respectively, and found resistance factors of 167-fold to dicofol and 24-fold to bromopropylate.

Vineyards

Drosophila melanogaster and *D. simulans*: Because of their importance in spreading grape sour rot, vineyards infested with these two species have received multiple applications of insecticides. Ringo *et al.* (26) demonstrated resistance in field-collected flies to chlorpyrifos and elucidated the mechanism of resistance.

Orchards

Control programs were initiated in northern Israel deciduous orchards approximately 20 years ago. However, only in 1991 was a state-wide IPM project started that now includes *ca* 25% of the total acreage (3). While there has been a reduction of *ca* 30% in the total amount of pesticides used, there are almost no published data on the status of insecticide resistance in these deciduous orchards. In citrus groves, however, much work has been done on insecticide resistance at the laboratory of the Citrus Marketing Board of Israel (B.A. Peleg, personal communication).

Aonidiella aurantii: Peleg and Bar-Zakay (24) demonstrated high levels of resistance to various OPs (such as chlorpyrifos, methidathion and omethoate) in the California red scale. Growers now use very selective combinations of IGRs which do not harm the natural enemies.

Phyllocoptruta oleivora: The citrus rust mite has been shown to be resistant to chlorobenzilate (B.A. Peleg, personal communication), which is now reserved exclusively for outbreak situations.

Ceroplastes floridensis Comstock: The Florida wax scale became very highly resistant

to carbaryl (LC₅₀, >100,000-fold) (23) and then to carbosulfan (24). As a result, these insecticides are no longer used for control; growers selectively use IGRs and oils to control this scale.

Cadra cautella (Walker): Work by Wool *et al.* (28) on the almond moth in orchards established that malathion resistance was inherited co-dominantly. By releasing malathion-susceptible males, these workers were able to decrease the incidence of malathion resistance in field populations in general.

Stored Products

Tribolium castaneum: The genetics of the red flour beetle and its mechanisms of resistance to malathion were reported by Cohen (6) and Wool *et al.* (30). The resistant strains had relatively high mixed-function oxidase, esterase and epoxide hydrase activities. Levels of resistance of 538-fold were reported by Navarro *et al.* (22). The malathion-resistant strain was less susceptible to the IGR diflubenzuron, apparently because of a higher enzymatic metabolism (16).

Rhyzopertha dominica: Navarro *et al.* (22) demonstrated malathion resistance levels of up to ninefold from field-collected specimens, as compared with susceptible laboratory colonies of the lesser grain borer.

Oryzaephilus surinamensis: Similar to the lesser grain borer, the sawtoothed grain beetle was found to have malathion resistance levels of up to eightfold (22).

PUBLIC HEALTH PEST RESISTANCE

Pediculus humanus capitis: Comprehensive studies on human head lice were conducted by the group of Dr. K.T. Mumcuoglu from The Hebrew University of Jerusalem. They reported that in spite of the introduction of effective insecticides for the treatment of lice (such as malathion, carbaryl, pyrethrum and some pyrethroids) the number of cases of lice infestation has increased (19). One of the main reasons for this phenomenon is the development of resistant strains of lice.

Although organochlorine insecticides such as DDT have not been used for decades, lice have maintained their resistance to this and lindane in Israel. DDT-resistant lice have been reported in other countries worldwide.

Permethrin-based pediculicides were introduced in the 1970s. Baseline susceptibility studies were conducted in Israel 2 years before their introduction into Israel in 1991 (21). The first incidence of resistance to permethrin in Israel occurred in 1993, and a study conducted in 1994 showed a fourfold increase in resistance (20); cross-resistance to other pyrethroids (such as bioallethrin and phenothrin) was also observed.

The rapid development of resistance to permethrin was attributed to several factors (20): cross-resistance between permethrin and both DDT and bioallethrin (both of which were previously used in Israel), the almost exclusive use of permethrin-based pediculicides after their introduction into Israel, and the lack of synergists in the permethrin formulations.

Musca domestica and Mosquitoes: In the 1940s and the 1950s following control failures against mosquitoes and house flies, a research group established by Prof. Mer (Rosh Pinna Malaria Research Station, The Hebrew University of Jerusalem, and later, Medical Research Laboratories, Medical Corps, Israel Defense Forces) developed methods for area-wide monitoring of resistance to the main insecticides used against insects of medical importance. The insecticides monitored were DDT and gamma-BHC (1). This

research on resistance in house flies and mosquitoes continued until the 1960s. Thereafter, the laboratories of the Ministry of Health in Jerusalem conducted research on insecticide resistance.

Routine tests to detect resistance in pests detrimental to human health, such as house flies and mosquitoes, are currently being conducted by Dr. Hedva Pener's group in the Central Laboratories of the Ministry of Health in Jerusalem. Their efforts are part of traditional resistance monitoring work conducted during the past 30 years. Recent reports have shown that various field populations of the house fly and the mosquito *Culex pipiens* have developed very high levels of resistance to the insecticides commonly used (Table 2).

CONCLUSIONS

Israel, as every other country, is faced with serious problems of development of resistance to insecticides. In the past, growers rarely used any tactics to prevent insecticide resistance, and some of their practices actually enhanced insecticide failures, especially in vegetable and flower crops. More rational practices adopted recently have helped in delaying the onset of resistance to conventional and new insecticides. Even with an insecticide such as pyriproxyfen, which is very sensitive to resistance, the restriction to one application per year could delay the onset of resistance in open fields for about 5 years.

Adding to the problem of insecticide resistance was the fact that only one growers' group (cotton) had an IRM program. Other growers' groups lacked coordinated efforts in IRM and this precluded the reduction or control of insecticide resistance. Recently, area-wide insecticide management, covering most of the major agricultural crops, has gradually come under supervised control (3). At present, IPM and IRM strategies are being developed and implemented area-wide for three regions in Israel: Bet She'an Valley, western Galilee, and western Negev. This program has resulted in an approximately 30% reduction in the use of pesticides and, no doubt, has also improved the situation with regard to insecticide resistance. Because the costs of developing new insecticides are enormous, emphasis must be placed on developing management practices which will not only prolong the life of current insecticides, but will also prevent the development of resistance to insecticides which have not yet been introduced. Such management practices cannot stand alone; more research is needed in areas of developing new and novel insecticides to maintain diversity of insecticides available for use, determining the mechanisms of resistance, and monitoring its occurrence.

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