CHAPTER 11

PESTICIDES IN IPM: SELECTIVITY, SIDE-EFFECTS, APPLICATION AND RESISTANCE PROBLEMS

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11.1. Importance of Selective Pesticides in IPM Programmes

The success of released or naturally occurring biological control agents in preventing pest outbreaks in protected crops has led the greenhouse industry to be particularly conscious of the necessity of applying selective pesticides. The activity of a selective pesticide is confined to a narrow range of specific pests (Heitefuß, 1975). In IPM, the process of developing the selectivity of a pesticide aims to maximize its specific effect against pests and diseases and minimize its effect on non-target organisms (Hull and Beers, 1985). Thus the selectivity of a pesticide is often used to express its harmlessness for beneficial organisms. The selectivity of the action and of the toxicity of a pesticide is dependent on its physiological selectivity and/or on the application procedures (Poehling, 1989). Physiological selectivity is expressed by reduced sensitivity of an organism to the pesticide due to pesticide metabolism and to the availability of the appropriate enzymes in the target organisms (Hassall, 1982). Application procedures comprise the dose rate, mode of action, method and timing.

The use of chemical pesticides that cause undesired side effects on non-target beneficial organisms may lead to pest outbreaks. In tomatoes, multiple application of the broad-spectrum carbamate methomyl for the control of leafminer infestation *(Liriomyza sativae* Blanchard) eliminated the naturally occurring beneficial parasitoid complex, which, without chemical treatment, reduced the pest population to 50% of the level found in pesticide-treated plots (Oatman and Kennedy, 1976). To avoid these consequences the harmful effects of pesticides on the natural enemies of target pests must be avoided or minimized for successful implementation of biological control agents within IPM strategies. Some pests and pathogens have developed resistance towards certain chemical pesticides, and this must also be considered in order to prevent misuse of pesticides.

In this chapter we will deal with the selectivity of pesticides in relation to effects on beneficial organisms that can be used in greenhouses, the potential for improving applications for better performance and selectivity, and the problems of resistance of the pests or diseases to the chemicals used in greenhouses.

11.2. Types of Side-Effects on Beneficial Organisms

Pesticides can exhibit primary or secondary effects on predators, parasitoids and pathogens of target pests. Primary effects are direct or indirect, depending on their

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exposure and on the biological parameter influenced. Direct mortality of beneficial organisms may be caused by direct contact during application, pesticide residues, taking up contaminated prey, intoxication by fumigants, and contact or contamination with soil disinfectants.

Indirect or sublethal effects on beneficial arthropods include decreases in reproduction, oviposition, parasitization, predation, longevity and egg viability, and a delay in development and shifting of the sex-ratio. Morphological and behavioural changes may also occur (Elzen, 1989).

Secondary effects due to pesticides include killing the prey/host of a beneficial organism or of species which produce alternative food like honeydew (Huffaker, 1990), taking up contaminated food (Sell, 1984; Celli *et al.,* 1997), and directly stimulating the pest; for example, some pyrethroids enhance reproduction in *Tetranychus urticae* Koch.

Pesticides directly affect entomopathogenic fungal biocontrol agents by inhibition of spore germination and vegetative development (mycelial growth), and they also reduce the viability of conidia (McCoy *et al.,* 1988) and their survival and activity on plant surfaces. Viability and infectivity of the infective juveniles (J3) of entomopathogenic nematodes are also adversely affected (Rovesti *et al,* 1988).

Side-effects of pesticides on natural enemies may vary between and within taxonomic groups. From their comprehensive data on the side-effects of pesticides, Theiling and Croft (1988) concluded that predators were more tolerant to pesticide treatment than parasitoids, except for fungicides, towards which susceptibility was not greatly affected. The tolerance of aphid natural enemies decreases from Coccinellids > Chrysopids > Syrphids > Hemiptera > Hymenoptera (Hodek, 1973). Evaluation of effects within taxonomic groups revealed that the classification of the effects of 74 compounds tested against the parasitoids *Encarsia formosa* Gahan, *Aphidius matricariae* Haliday and *Leptomastix dactylopii* Howard corresponded by more than 78% (Hassan *et al.,* 1983, 1987, 1988, 1991, 1994). In a comparison of trial results with 81 test compounds for predatory mite species occurring in orchards and vineyards with *Phyloseiulus persimilis* Athias-Henriot, the same level was reached in 64% of the test compounds.

Differences in susceptibility have been recorded between taxonomically close species, and even between strains within the same species. *Eretmocerus mundus* Mercet adults were less susceptible to residues of amitraz, thiodicarb and cypermethrin than *E. formosa* or *Encarsia pergandiella* Howard (Jones *et al.,* 1995). Among *Aphidius* species, *A. matricariae* was more tolerant to dimethoate than *Aphidius rhopalosiphi* de Stefani Perez or *Aphidius colemani* Viereck (Maise *et al.,* 1997). The response of several species of entomopathogenic fungi to copper incorporated in agar differed. *Paecilomyces farinosus* (Holmsk.) A.H.S. Brown & G. Sm. was more tolerant than *Verticilium lecanii* (A. Zimmerm.) Viégas, *Beauveria bassiana* (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metschnikoff) Sorokin (Baath, 1991). The entomopathogenic nematodes *Steinemema carpocapsae* (Weiser), *Steinemema feltiae* (Filipjev) and *Heterorhabditis* HP88 exhibited different tolerance levels to 9 tested pesticides (Zimmerman and Cranshaw, 1990). Repeated exposure of local strains to chemicals may cause natural enemies to develop tolerance to pesticides. This is the case of *P. persimilis* and organophosphorous compounds (OPs) (Goodwin and Welham, 1992) and of *Aphidoletes aphidimyza* (Rondani) and azinphos-methyl (Warner and Croft, 1982). Developmental stage may greatly influence the response of natural enemies to pesticides. The susceptibility of *A. aphidimyza* and *Chrysoperla cornea* (Stephens) to pesticides with contact mode of action increased from the egg stage to the adults (Bartlett, 1964). In contrast, pesticide susceptibility was lowest in treated adults of *Coccinella septempunctata* L. (Zeleny *et al.,* 1988) and in eggs of *P. persimilis,* while in the coccinellid the egg stage and in the predatory mite the larvae or protonymph stage were the least tolerant (van Zon and Wysoki, 1978; Blümel and Stolz, 1993). However, compounds with modes of action that regulate or inhibit insect growth resulted in high mortality of *C. carnca* larvae, but not of the adults, whose fertility was only slightly affected (Vogt, 1992).

The host may offer parasitoids different degrees of protection against pesticides; unprotected stages of parasitoids (e.g. adult hymenoptera) and protected stages (e.g. different developmental stages in aphid mummies) show different levels of mortality after the same pesticide treatment. Avermectin B killed 50% of *E. formosa* protected in the whitefly scales in a direct contact test, but 79% of the adult wasps after contact with the dried residue (Zchori-Fein *et al.,* 1994). *Leptomastix dactylopii* protected in *Planococcus citri* (Risso) were barely affected by topical treatment of endosulfan, while the adults were severely damaged in residual tests (Reddy and Bhat, 1993). Even sexes of the same species may present different susceptibility against pesticides. In 5 different populations of *Diglyphus begini* (Ashmead) (Rathman *et al.,* 1992) and in predatory mites, males are less tolerant than females.

11.3. Tests and Approaches to Detect Side-Effects of Pesticides

One of the most comprehensive programmes to test side-effects of pesticides on beneficial organisms was set up by the IOBC/WPRS working group "Pesticides and Beneficial Organisms" (Hassan, 1989). In the first step, arthropod species and microorganisms that were regarded as the most important natural enemies in the different crops were identified. For these species test methods at different levels were developed. Pesticide screening is based on a sequence of three steps in laboratory, semi-field and field conditions, as shown in Fig. 11.1. The sequential programme assumes that pesticides that are harmless in the laboratory will also be safe in semi-field and field conditions, and do not need to be evaluated in further steps. When a chemical, however, is categorized as harmful in one step, its effect at the next step cannot be inferred, and the sequence must be continued until it finishes at field conditions or displays no negative effects.

The pesticides are usually tested at the highest recommended field rate as commercial formulations. The laboratory methods aim to evaluate the direct, initial toxicity of pesticide residues on susceptible and protected developmental stages of the test arthropods and are thus classified as lab-a- and lab-b-tests. The aim of the first test is the detection of pesticides which are harmless to the test organism after worst case exposure to dried pesticide residue on a defined test surface (glass or sand) after a single application of the test compound. The results of the tests should include the mortality (direct effect) and the reproduction (sublethal effect) of the test organism. Information about the duration of the effect of a pesticide is provided by the persistence test. Plant material (e.g. leaves) is sprayed with the test pesticide and left on the plant under greenhouse conditions for residue aging. Leaf samples undergo a further test, similar to the lab-a-test. The next test is the semi-field test which is carried out on pesticide residues or as a direct application on the plants with the test arthropods, and is kept under more natural conditions. Sublethal effects, behavioural changes, and the effect of more than one application of the test product are thus evaluated. The range of tests developed for a selection of organisms important in greenhouse crops is presented in Table 11.1. Most of the information that follows in this section may be found in the IOBC/WPRS Bulletin 1988,11(4); 1992,15(3); 1994,17(3).

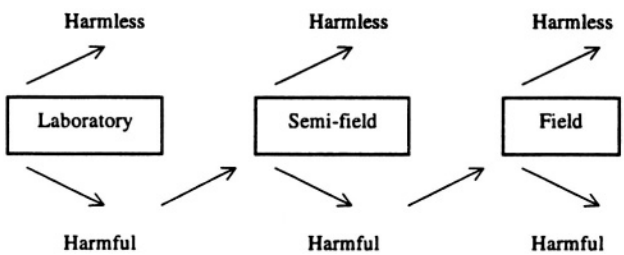

Figure 11.1. **Sequential IOBC/WPRS procedure for testing effects of pesticides on natural enemies (after Hassan, 1989).**

The lab-a-test for parasitoids (*E. formosa, A. matricariae*) and for A. *aphidimyza* adults (on leaf material) is carried out as a residual contact test with adult wasps or gall midges. Mortality and reproduction (parasitization of the host or number of eggs deposited) are evaluated. In the lab-b-test, the protected stages of the parasitoids in their hosts (aphid mummies; whitefly scales) are directly sprayed with the pesticide solution and the emergence rate from the hosts is assessed. The lab-a-test for predatory mites is a residual contact test starting with predatory larvae or protonymphs. During the test the mortality rate, escaping rate and reproduction per female are evaluated.

The same testing procedure is used as in the lab-a-test for *Orius niger* (Wolff), and the emergence from the deposited eggs is also assessed. The lab-b-test for *O. niger* is the same as the lab-a-test, but uses predatory bug adults. The lab-b-test for *A. aphidimyza* is carried out with larvae as a residual contact test on leaves and is also appropriate for a persistence test. Laboratory tests for *C. carnea* and *Syrphus corollae* Fabricius follow the same principles. Larvae are tested in a residual contact test to assess the mortality and reproduction of the test organisms. A laboratory test for Coccinellids has also been described in detail for *Hippodamia oculata* (Thunberg). A residual contact test with larval stages is carried out to evaluate mortality and duration of development. The adults deriving from this first testing phase are used to check reproduction, duration of sexual maturation of females, and emergence from the deposited eggs.

Persistence tests or tests to detect the duration of harmful effects of the pesticide residue are very similar for nearly all test organisms. Suitable plants are sprayed and kept under greenhouse conditions for different periods. Leaf samples are collected at regular intervals and are used as test surfaces, as in the lab-a-test or the lab-b-test. Mortality and reproduction are again assessed. In this case persistence must be considered as an extended laboratory test. For *C. carnea* and *Episyrphus balteatus* (DeGeer) the test is carried out on treated plants and, in addition to the above mentioned parameters, changes in the behaviour of *E. balteatus* can be examined.

TABLE 11.1. Test methods on different test levels of the sequential testing scheme developed within the IOBC/WPRS working group "Pesticides and Beneficial Organisms"

Test organism	Lab-a-test	Lab-b-test	Extended laboratory test/ persistence	Semi-field test initial tox.	Semi-field test persistence/ greenhouse
Parasitoids					
Encarsia formosa	X[1]	X	X	X	
Aphidius matricariae	X	X	X		
Leptomastix dactylopii	X				
Aphytis melinus	X				
Predatory mites					
Phytoseiulus persimilis	X		X	X	
Others	X		X		
Predators					
Chrysoperla carnea	X		X	X	X
Syrphus corollae	X				
Episyrphus balteatus				X	X
Coccinellids (*Semiadalia, Harmonia, Coccinella*)	X				
Orius niger	X	X	X	X	
Aphidoletes aphidimyza	X	X	X		
Entomopathogenic fungi					
Beauveria bassiana, Beauveria brongiartii	X	X	X	X	
Metarhizium anisopliae	X	X	X	X	
Verticillium lecanii	X				
Entomopathogenic nematodes					
Steinernema sp.	X				

[1]X: existing test methods

The sequential IOBC testing scheme for *B. bassiana* and *M. anisopliae* comprises all three test levels. In the lab-tests the mycelial growth on agar containing pesticides is measured. The production and viability of conidia is assessed with a bioassay to check virulence. It has been proposed to switch from tests on solid medium to a worst case test for growth inhibition in liquid medium, where the mycelium, as the most sensitive stage of the fungus, is immersed into the pesticide solution. In the semi-field test conidia are mixed with standard soil and treated with the test pesticide. The soil is then incubated and the number of spores per unit of soil is determined. To check the virulence of the tested fungus at each step of the sequential scheme the *Galleria*-bait-method may be used. The results of an *in vivo* assay, in which leaf discs are sprayed with the conidial suspension of the beneficial fungus on a dried residue of the test pesticide have been described. Side-effect testing at the infective juvenile J3 stage of entomopathogenic nematodes is carried out in a 2-step scheme. First, the viability and the behaviour *in vitro* in pesticide solutions is checked. In the next step, mobility and infectivity are examined in a bioassay in soil.

Compatibility of pesticides with bumble-bees used as natural pollinators in greenhouses is classified in four categories, which allow or exclude the use of bumble-bees or recommend a certain period after pesticide application during which the hives should be removed from the greenhouses.

Comprehensive data collections about side-effects of pesticides on natural enemies are available from commercial suppliers of beneficial organisms (Biobest, 1998) and also in the tables published by the IOBC/WPRS working group.

11.4. Effects of Chemical Pesticides on Beneficial Organisms Used in Greenhouses

Information on specific pesticide effects on natural enemies and pathogens may be found in the published results of the Joint Testing Programmes by the IOBC/WPRS Working Group "Pesticides and Beneficial Organisms" (Hassan *et al.,* 1983, 1987, 1988, 1991, 1994; Croft, 1990; Sterk *et al.,* 1998) and in many other references. Some examples selected from the literature are included in Table 11.2.

Generally herbicides, acaricides and fungicides have less effect than insecticides, although mycopesticides are highly susceptible to fungicides.

(i) Effect on beneficial predators. For predatory mites most pyrethroids and carbamates were harmful, both in initial toxicity and in reproduction and persistence trials with the susceptible juvenile predators. *Aphidoletes aphidimyza* showed a similar susceptibility to insecticide/acaricide treatments, and was also affected by OPs. OPs caused varying levels of mortality in predatory mites (see Section 11.3). In coccinellids, high mortality rates were caused by nearly all tested compound groups, except the microorganisms and soap. Chrysopids were not harmed by acaricides, most pyrethroids, soap or microorganisms, but were affected by most of the insect growth regulators (IGRs) and most of the OPs. For predatory bugs, pyrethroids, carbamates, most OPs and few of the IGRs proved to be harmful. Fungicides and herbicides were relatively harmless for coccinellids, chrysopids and predatory bugs, but partly harmful to predatory mites.

(ii) Effects on beneficial parasitoids. Synthetic pyrethroids and pyrethrin were very harmful to adults, regardless of the test species. In tests with the protected stages, several pyrethroids were only slightly harmful, but in combination with a persistence of more than one week this advantage was neutralized. OPs were very harmful to the unprotected stages and with few exceptions also to the protected life stages, and showed high persistence as residues. Carbamates were harmful in both types of laboratory tests, but some had a persistence shorter than three days. IGRs and most of the acaricides were harmless to both the susceptible and the protected developmental stage of the parasitoids. Plant extracts (except pyrethrin), soap and microorganisms were harmless. Fungicides belonging mainly to the group with a broad-spectrum and protective mode of action were harmful to adult parasitoids and revealed detrimental effects which persisted over one week. In tests with the protected life stage, however, all fungicides were considered harmless. Very few herbicides were harmful to adult wasps, but not for other developmental stages.

TABLE 11.2. Effects of pesticides on natural enemies. The type of tests are indicated in column headings: 1, lab-a-test; 2, lab-b-test; 3, persistence test; 4, semi-field or greenhouse test (see Section 11.4 in this chapter for further explanations on these types of tests). Effects have been categorized according to the following criteria. In laboratory and semi-field tests: –, <50% total effect; o, total effect between 51 and 99%; +, >99% total effect. In persistence tests: –, effect on <50% for lesser than one week; o, effect on 51–99% for lesser than one week; +, effect on >99% for more than one week. More than one effect classification indicates different test results. Compiled from published results of the Joint Testing Programmes by the IOBC/WPRS Working Group "Pesticides and Beneficial Organisms" (Hassan *et al.*, 1983, 1987, 1988, 1991, 1994; Croft, 1990; Sterk *et al.*, 1998) and also from many other references

Pesticide common name	Groups of natural enemies and types of test																				
	Predatory mites				Coccinellids/ Chrysopids				Predatory bugs				Parasitoids				Entomopathogens				
																	Nemat.		Fungi		
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	1	2	4
Organophosphorus																					
Chlorpyrifos	o+			+	+	+		o+	+	+			+	o	+		–	o	–		
Diazinon	–+			+	–+	o+		–o	–	o			+	o	+		o	o	–		
Heptenophos	–+	–			o+	o	–	–o	–o	o			+o	–	–	o	–	+	–+		
Phosmet	o+			o+	+	o+		–	o				+	o			–		o		
Triazophos	–+			+	+	+		o+	+	+			+	o+	+				o		
Organochlorines																					
Endosulfan	o		o		o+	–o							+o	–	o		–				
Lindane	–				o								+	–	+		–				
Carbamates																					
Methomyl	+		o+	+	o+	+			+	+			+	o		o	o	o			
Oxamyl	+	o		+	+	o		o	+				+	o		+	–		o–		
Pirimicarb	–o		–	o	–o	–				o			+	–	–	–					
Propoxur	o+			o	+				+				+				–				
Pyrethroids																					
Deltamethrine	+			+	o+			o	+				+	+	+	+	–		–		
Fenpropathrin	+		+	+	+	o		o	+				+	+o	+	–	o		–		
IGR's																					
Diflubenzuron	–			–	–+	o		o+	o–	–+			–				–		–		
Fenoxycarb	–			–	–+	–		–o	+				–	–					o		
Teflubenzuron	–			–	o+	+		+	o+				–	–	–		–	–	–		
Natural origin																					
Azaridachtin	–	–											–	–							
Bacillus thuringiensis ssp. *kurstaki*, *Bacillus thuringiensis* ssp. *tenebrionis*	–			–	–	–		–	–				–				–	–	–		
Nicotine					–+	o	–														
Pyrethrum + rotenone	+	o			o																
Verticillium lecanii	–			–	–			–					–				–	–			

TABLE 11.2. Effects of pesticides on natural enemies. The type of tests are indicated in column headings: 1, lab-a-test; 2, lab-b-test; 3, persistence test; 4, semi-field or greenhouse test (see Section 11.4 in this chapter for further explanations on these types of tests). Effects have been categorized according to the following criteria. In laboratory and semi-field tests: –, <50% total effect; o, total effect between 51 and 99%; +, >99% total effect. In persistence tests: –, effect on <50% for lesser than one week; o, effect on 51–99% for lesser than one week; +, effect on >99% for more than one week. More than one effect classification indicates different test results. Compiled from published results of the Joint Testing Programmes by the IOBC/WPRS Working Group "Pesticides and Beneficial Organisms" (Hassan *et al.*, 1983, 1987, 1988, 1991, 1994; Croft, 1990; Sterk *et al.*, 1998) and also from many other references (cont.)

Pesticide common name	Groups of natural enemies and types of test																				
	Predatory mites				Coccinellids/ Chrysopids				Predatory bugs				Parasitoids				Entomopathogens				
																	Nemat.		Fungi		
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	1	2	4
Other insecticides																					
Abamectin	o	+		o					–	o			o	–o			–				
Amitraz	+				–o			o	–	–			+	o	o	+	–		o		
Buprofezin	–o				–o	–o		o–	–	–			–	–		–	–		–		
Cyromazine	–+			–+	+o	o		o–	o	–			o	–		–	–		–		
Imidacloprid	+			–					+								–				
Pyriproxifen	–	–		–					–	–			–	o							
Acaricides																					
Dicofol	o+		o	+	o	–				o			+o		+	–	–				
Fenbutatin oxide	–				–	–							–			–			–		
Fungicides																					
Bitertanol	–			–	–	–		–	–				–			–			+–		o
Chlorothalonil	–o				–	–		–					–				–		o+	+	+
Copper oxychloride	–			–	–o	–		–	–				+	–	–				–+		
Iprodione	–		–		–	–		–	–				–	–		–			o–		
Quinomethionate	o			o	o								+	–	–				–		
Sulphur	–+	o		o+	–+	o		–	–o				+–	–	+–		–o		–		
Triforine	–			–	o–	–		–					–				–		o		o
Herbicides																					
Glyphosate	–o				o–				–				–				–		–		
2,4 D	–				–	–		–	–				–						–		

(iii) Entomopathogens. Only a small number of carbamates out of the tested insecticides/acaricides affected entomopathogenic nematodes, while fungicides proved to be mainly harmless. Insecticides, acaricides and herbicides in most cases did not adversely influence the mycelial growth or the sporulation of the fungal species *V. lecanii, B. bassiana,* and *M. anisopliae* in laboratory tests or during infectivity tests in the greenhouse. Half of the fungicides examined in all types of tests affected at least one of the three test fungi, whereas one fourth of the fungicides were harmless for all of them. Effects could not generally be attributed to the mode of action of the fungicides. *Verticilium lecanii* was slightly more affected than *B. bassiana.*

(iv) Sublethal effects on natural enemies. Besides direct toxicity caused by a number of "classical" insecticides, sublethal effects were also demonstrated in several investigations. Among sublethal effects of pesticide application on natural enemies which are reported in the literature are: development prolongation, reduced egg production or its total inhibition, decrease in prey consumption, changes in searching or foraging behaviour, alteration of pathogenicity in entomopathogens, and increased tendency to escape from treated surfaces. The importance of repellence of pesticide compounds for beneilcials is difficult to classify. On the one hand, repellence may negatively influence natural enemies by expelling them from their host or prey which they need for further population development; on the other, beneficials can be protected from possibly hazardous contact with contaminated plant surfaces or prey/hosts. Both effects are undesirable, especially in greenhouses, where mass reared arthropods are intentionally introduced as biological control agents, and because the natural enemies would cease to be effective as control agents, particularly when untreated refuges are scarce.

Insect growth regulators, like diflubenzuron, chlorfluazuron, fenoxycarb, flufenoxuron and teflubenzuron, which are incorrectly considered as harmless to many beneficials, in fact interfere with the viability of eggs, the moulting process, and the reproduction of several predators.

The influence of different formulations of pesticides on their effects on natural enemies was shown for endosulfan, which as an emulsifiable concentrate (EC) formulation resulted in up to 17% less mortality of *P. persimilis* than the wettable powder (WP) formulation in a residual laboratory test (Blümel *et al.,* 1993). For *E. formosa* the EC formulation of tebufenpyrad was more toxic than the WP formulation (van de Veire, 1995).

11.5. Influence of Pesticide Application on the Selectivity of a Pesticide

The relatively small areas in greenhouses - compared to arable agriculture - and high plant density dictate in many cases the use of manually operated spraying equipment. In an enclosed structure, good ambiental conditions can exist for applying very small particles and using artificial air movement to improve pesticide distribution and pest control. Conversely, improved chemical control can adversely affect bio-agents such as bumble-bees, antagonistic fungi and beneficial arthropods, factor which has to be considered when choosing a pesticide. Pesticide application in enclosed areas also imposes the risk of breathing air that contains small particles of pesticides. Personal protective clothing is often hot and uncomfortable, and farmers tend to spray unprotected.

Unfortunately, many growers continue to use high volume (HV) spraying (>1000 1/ha of spraying solution). HV spraying to run off leads to wastage to the order of 70–90% of the chemical dripping to the ground (Matthews, 1992). The low concentration of a.i. with HV applications reduces the hazard to the operator, who is often heavily contaminated by the pesticide, but may not give adequate control, and growers are thus forced to repeat sprays at frequent intervals. The whole area becomes contaminated with pesticides, making it impossible to integrate biological control with chemicals. The volume of spray and wastage due to runoff can be reduced significantly by changing nozzles to produce small droplets which do not coalesce on the target (Matthews, 1992). A widely used piece of equipment is the knapsack mistblower.

As an alternative to HV spraying, the use of thermal or cold foggers gives the grower clear savings in time and labour, although they are only suitable in totally enclosed greenhouses. Deposition is improved with cold fogging, but persistence is less. The shorter persistence obtained with cold foggers allows the introduction of natural enemies quicker after treatment than when a thermal fogger is used, and a greenhouse can be treated when parasitoids are protected inside the infested host stages (Lingappa *et al.,* 1972). Additionally, cold fogging allows the use of a wider range of pesticides, e.g. insecticides perhaps with higher selectivity, such as *Bacillus thuringiensis* Berliner which has been used successfully by cold fogging.

Another technique, vaporization, is suitable for small areas (approximately $100\ m^2$). The pesticide (e.g. sulfur) is placed on a small heater installed inside a wide pipe. After evaporation or sublimation, the pesticide condenses to small particles (e.g. 2–8 μm) and is carried up by the heated air directed by the pipe. The dispersion and settling of particles of this size is influenced by the inside air circulation systems and they fall mainly on the upper side of the leaves, rendering minimal residual effect.

Alternatives to spray treatments include application of granules or drenches and chemigation by drip irrigation to the soil, when systemic pesticides can be used. Specific treatments can be combined with a pesticide or other types of lure, e.g. yellow cards in a "lure and kill" method. Thrips have been controlled with a polybutene sticky surface combined with an insecticide (Thripstick). Specific baits cause only minimal damage to non-target organisms, as their chance of exposure is very low.

The timing of the pesticide treatment is crucial in order to avoid the susceptible life stage of the non-target organism. Where chemical pesticides adversely affect the entomopathogenic fungus *V. lecanii,* they should not be applied at the same time, but after a delay (Schuler, 1991). Similarly, the alternation of chemical fungicides with the fungal biocontrol agent *Trichoderma harzianum* Rifai T39 is preferred to the use of a tank mix of this biocontrol agent with chemicals for the control of foliar pathogens (Shtienberg and Elad, 1997). Selective application can also be carried out by considering spatial factors and using the systemic pesticides as granules or seed treatment to preserve plant-inhabiting beneficials. Limited areas can be treated with hand-held air-assisted spinning disc sprayers. Multiple applications of a pesticide may cause a severe reduction in the number of natural enemies, without achieving a satisfactory control of the target pest. In contrast, a single, better timed application of the same pesticide can control the pest to the same extent, without seriously damaging the natural enemies, thus improving overall control. Keeping the pest below the economic threshold has been achieved with different use of oxamyl and methamidophos against *L. sativae* and its parasitoid complex in tomatoes (Schuster *et al.,* 1979).

Systemic fungicides, which were harmful to *V. lecanii* when applied as sprays, did not affect the fungus pathogenecity against *Aphis gossypii* Glover on cucumber when applied as a soil drench (Wilding, 1972). Another possibility for the partial preservation of natural enemies is the treatment of selected strata of the plants, e.g. flowers, and leaving the lower part of the canopy untreated, thus maintaining a significant population of natural enemies (Scopes and Biggerstaff, 1973). These localized treatments are gaining acceptance where insects are used to pollinate crops and growers release natural enemies such as *E. formosa.* In one study, the application of pyriproxifen to the upper parts of tomato plants infested with greenhouse whitefly effectively reduced the pest, but did not damage the parasitoid *E. formosa,* which, though susceptible to this compound, was situated in the whitefly pupae on the lower parts of the plants (van de Veire, 1995).

11.6. Pesticide Resistance and Anti-Resistance Strategies in IPM

Pests and pathogens may overcome the toxic effect of pesticides by metabolizing the active ingredient into less toxic components, developing a change in the target site, reducing the absorption of the chemical or by avoiding exposure to the compound. Resistance development is the most severe challenge to pesticide. In greenhouses, pesticide-resistant strains of fungi and pests have appeared frequently. This phenomenon occurs because the greenhouse is a closed system in which the population of selected strains is not diluted by the outdoor wild population. Usually, the existence of epidemic conditions in greenhouses is a prerequisite for the development of resistant populations of pathogens and pests. Moreover, the optimal conditions for their development in greenhouses prevail for long periods. The number of life cycles is increased due to the optimal conditions or the extended time they prevail, and control necessitates frequent pesticide applications. The latter result in high selection pressure towards resistance to pesticides. The main pathogens which are known to develop resistance to fungicides in greenhouses are *Botrytis cinerea* Pers.:Fr., *Pseudoperonospora cubensis* (Berk. & M.A. Curtis) Rostovzev (downy mildew of cucurbits), *Didymella bryoniae* (Auersw.) Rehm (gummy stem blight of cucurbits), *Sphaerothecafusca* (Fr.) Blumer. [= *Sphaerothecafuliginea* (Schlechtend.:Fr.) Pollacci] (powdery mildew of cucurbits), *Puccinia horiana* Henn., *Uromyces dianthi* (Pers.:Pers.) Niessl (= *Uromyces caryophyllinus G.* Wint.) and *Fusarium oxysporum* Schlechtend.:Fr. f. sp. *gladioli* (L. Massey) W.C. Snyder & H.N. Hans.

The benzimidazole fungicides (benomyl, carbendazim, thiophanates) have a high resistance potential against pathogens because they have a specific mode of action. The resistance is usually not associated with a significant loss of fitness of the pathogen. It occurs in populations of *B. cinerea, D. bryoniae, Fusarium* and powdery mildews. Mixtures and alternations with multi-site contact fungicides may delay this selection, before resistance becomes apparent.

Acute problems of resistance to dicarboximide fungicides (e.g. iprodione, procymidone, vinclozolin) have arisen when fungicides are used intensively and exclusively over many seasons (Gullino *et al.,* 1989). Isolates are moderately resistant and tend to be almost as fit as sensitive strains in the absence of fungicides. It is recommended to restrict the number of dicarboximide treatments to no more than three per crop in greenhouses where resistance is found, and even in the absence of detectable resistant strains. When infection pressure is high, it is usually recommended to alternate or mix these fungicides with protectants such as chlorothalonil, captan, TMTD, or with biocontrol which do not usually select for resistance. However, TMTD may interfere with natural enemies (Section 11.4).

Ergosterol biosynthesis inhibitors (EBIs) are a group of fungicides which include triazole, imidazole and pyrimidine fungicides which inhibit C14 demethylation and morpholines. Unlike the sharp, significant nature of resistance towards benzimidazoles and dicarboximides mentioned above, the resistance towards EBIs develops in the form of slow shifts in the pathogen population. For instance, powdery mildews in greenhouses were controlled for several years by benzimidazoles, hydroxypyrimidines, pyrazophos, and EBIs. Resistance is known in populations of *S. fusca* but the alternation of fungicides, which is practised in many countries, is helping to deal with the problem. It is generally recommended to rotate or mix EBI fungicides with fungicides from other groups as well as with biocontrol.

The failure of disease control in greenhouses is exemplified by the history of gray mold epidemics. Multiple resistant isolates occur in greenhouses that bear the resistance towards benzimidazole, diethofencarb, dicarboximides and ergosterol biosynthesis inhibitors (Pommer and Lorenz, 1982; Elad *et al.,* 1992). The extreme summer conditions do not interfere with the survival of fungicide-resistant isolates (Yunis and Elad, 1989). Table 11.3 illustrates the situation for Israeli vegetable greenhouses sampled in 1997 by exposing plates of *Botrytis* selective medium containing test fungicides from various groups (for method, see Elad and Shtienberg, 1995).

TABLE 11.3. Resistance towards fungicides in greenhouse populations of *B. cinerea* (number of colonies grown on exposed plates containing Botrytis selective medium indicating comparable levels)

Crop	Place	Group of fungicides, test fungicide in plate and concentration (µg/ml)			
		None	Benzimidazoles	Dicarboximides	EBIs
			Benomyl (5)	Iprodione (5)	Fenbuconazole (1)
Cucumber	Ahituv	100	98	29	21
	Yama A	23	18	3	22
	Yama B	59	7	4	72
	Tzafit	6	7	1	6
Tomato	Bet Shikma	77	100	10	100
	Sde Moshe	18	16	1	14
	Yama	46	48	1	47
	Ibtan	10	3	2	1

Phenylamide fungicides that inhibit RNA synthesis were introduced in the late 70s for Phycomycetes control. During the 70s *P. cubensis* was controlled mainly with protective applications of dithiocarbamates and chlorothalonil. In the early 80s the phenylamide metalaxyl was released and soon afterwards resistant strains were selected. Metalaxyl-resistant strains seem to be more competitive than wild-type strains (Cohen *et al.,* 1983). Resistance was found also in *Phytophthora infestans* (Mont.) de Bary on tomato and *Bremia lactucae* Regel on lettuce. Anti-resistance mixtures of metalaxyl with protectant fungicides were developed to cope with phenilamide resistance.

In order to reduce the pressure towards development of resistance in pathogen populations, it is usually better to limit the exposure of the pathogen to a group of fungicides. The number of applications of fungicides of the same mode of action has to be limited, especially against fungi with many cycles during the growing season. Moreover, the application of non-chemical methods is also recommended.

Insecticide and acaricide resistance of nearly all important arthropod greenhouse pests is well documented (Georghiou and Mellon, 1983). Besides genetic and operational factors that influence the selection of resistant individuals, biotic reasons such as generation turn-over, number of offspring per generation and type of reproduction have a major impact on resistance development. Most of the pest species on greenhouse crops favour resistance selection with regard to these biological parameters.

Recently *Bemisia tabaci* (Gennadius) and *Bemisia argentifolii* Bellows & Perring have developed resistance against a range of conventional insecticides as well as against IGRs and juvenile hormone analogs (Cahill *et al.,* 1994; Horowitz *el al.,* 1994), and *Frankliniella occidentalis* (Pergande) developed resistance against most pesticide groups (Anonymous, 1988), resulting in severe economic losses in the affected crops. Pesticide resistance can also develop in natural enemies and has been found in all taxonomic groups (Croft and Strickler, 1983). The differences in the occurrence and the level of pesticide resistance in predators and parasitoids can be explained by the influence of the factors such as food limitation and differential susceptibility to the chemical.

Chemical resistance management strategies for pests comprise different approaches classified as management by moderation (low dosages, reduced number of applications), management by saturation (suppressing detoxification) and management by multiple attack (application of mixtures) (Georghiou, 1983). For IPM programmes additionally non-target effects on natural enemies have to be considered, which might not always correspond with the aforementioned strategies.

11.7. Future Aspects

Modern techniques used in greenhouses for pesticide application allow a low input of chemicals while achieving good coverage of the right part of the plant. Selective application can also direct the active ingredient to the right target, with lowered effect on beneficial organisms. However, it is important to know the undesired side effects of chemical use in greenhouses. The use of side effect data by advisory services or growers may lead to problems due to contradictory information about the effects of the same pesticides resulting from differences in test methods, different test laboratories carrying out the tests and the formulation of the pesticide used in different countries. Therefore, uniform labelling of the non-target effects of plant protection products already during the process of authorization as proposed in the European Plant Protection Legislation (EU-Directive 414/91, including all annexes) is desirable. The basic requirements to fulfil the legislative demands were formulated during the "Workshop of European Standard Characteristics of Beneficial Arthropod Testing" (Barrett *et al.,* 1994). Resulting from this workshop 11 different ring test groups for the standardization and harmonization of existing test methods and for the development of new test methods were formed. As an outcome of this joint initiative by governmental research centres, industry, commercial test laboratories and contributions from the European and Mediterranean Plant Protection Organization (EPPO), a harmonized labelling of plant protection products concerning the non-target effects is expected.

Other topics for the implementation of side-effect data into IPM practice still need to be addressed. Most of the data about side-effects of pesticides on beneficials is derived from laboratory tests or even higher test levels with only one application of the product. However, in practice, even when natural enemies are used against arthropod pests, chemical treatment can be necessary against fungal diseases. Often these fungicides have to be applied not once, but several times at certain intervals. These applications can lead to an accumulation of the product on the plants, affecting the beneficial organisms. This situation becomes more complicated when mixtures of different active ingredients are used.

Very few chemical pesticides are selective for natural enemies. Improvements in the compatibility of beneficial organisms with pesticide application by selecting beneficials with some resistance towards chemical pesticides have been attempted, but this is often a cumbersome procedure as the pesticides used may change quickly. Besides the degree of resistance, its stability and its possible influence on the fitness of the tolerant organisms are features that must be assessed before the selected organisms can be used in pest or disease control. For phytoseiids development of pesticide resistance against several insecticide groups, acaricides and fungicides, and even against sulphur has been extensively described (Fournier *el al.,* 1985; Croft and van den Baan, 1988). Alternatively, pesticides are applied spatially to selected areas or in frequencies which reduce the target pest to a sufficient extent, but minimize harm to natural enemies and thus allow a combination or synergized effect of both the chemical and the biological controls (Theiling and Croft, 1988; Zhang and Sanderson, 1990).

Another important topic in the assessment of side-effects is examining whether natural pesticides or natural enemies themselves affect beneficial organisms, as reported in studies of the impact of entomopathogenic nematodes on non-target organisms (Bathon, 1996). Fransen and van Lenteren (1993) could not find detrimental effects of the entomopathogenic fungi *Aschersonia aleyrodis* Webber on the parasitoid *E. formosa,* while Sterk *et al.* (1995) observed no effect of a commercial strain of *Paecilomycesfumosoroseus* (Wize) Brown & Smith on *P. persimilis, E. formosa* and *Onus insidiosus* (Say). However, Pavlyushin (1996) detected direct and sublethal effects of entomopathogenic fungi on Chrysopids in the laboratory.

The present status of resistance of pests or pathogens in greenhouses is often unknown; growers tend to apply excess amounts of chemical, and control is not achieved. The development of tools for monitoring resistance should facilitate the assessment of different management options.

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