Proc. Indian natn. Sci. Acad. B52 No 1 pp 148–164 (1986)

Pesticide Resistance in Agricultural Pests in India

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Development of resistance to pesticides is now acknowledged as one of the most serious problems in pest control. From the first ever published instance in 1914, the number of species of arthropods with reported cases of resistance to pesticides through 1980 has risen to 428 all over the world. Of these, 260 species i.e., 60.7% are of importance to agriculture and include many major crop pests. Barring a dozen species, these cases pertain to the post-DDT era i.e., after the introduction of newer synthetic insecticides. Alarmingly, resistance has emerged to almost all the insecticides employed in pest control. In some cases the situation is, indeed, serious as the world-wide occurrence of malathion resistance in the flour beetle, *Tribolium castaneum.*

The phenomenon has made its appearance in India too, though so far it has not posed a serious challenge to the pest control programmes. The total number of species reported resistant is less than ten. Occurrence of pesticide resistance is more widespread in stored product pests; prominent among them being *Tribolium castaneum, Sitophilus oryzae, Rhyzopertha dominica* and *Trogoderma granarium* resistant to malathion or phosphine. Of the crop pests, the only species with repeated reports of resistance to BHC and other insecticides from different areas is the polyphagous tobacco caterpillar, *Spodoptera litura.* The occurrence and spread of insecticide resistance in stored product pests has generated interest in the problem and as a result studies on various fundamental aspects like laboratory selection of resistant strains, inheritance of resistance and cross resistance have been carried out. In *Tribolium castaneum,* resistance to DDT, malathion and lindane has been shown to be governed, in each case, by an incompletely dominant autosomal single factor.

The reasons that the problem has not been reported as serious in agricultural pests in our country may be due either to the lack of proper tests for detection of resistance or that the application of insecticides is yet not intensive or extensive enough for resistance to emerge widely. Development of resistance serves as an index to the extent of use of insecticides in a country. Development of resistance in agricultural pests to pesticides is inevitable. We are bound to contend with the problem in the years to come in view of the expected increase in the use of pesticides for pest management in order to achieve the projected targets of agricultural production in the country. However, on the basis of available knowledge it is necessary, from now onwards, to resort to discreet Pesticide Management so that the problem can be contained.

Introduction

Insecticide resistance in insects made its appearance 70 years ago. Reporting occurrence of the phenomenon for the first time, Melander (1914) asked, "Can insects become resistant to sprays?" Little did one realize that the problem thus posed, would during the course of time grow and proliferate to constitute one of the major challenges in applied entomology. The rapid succession with which cases of pests developing resistance surfaced following introduction of the newer synthetic insecticides, the very basis of the Age of Pesticides, heralded with fanfare by the advent in 1946 of the wonder chemical DDT, began to be shaken. Indeed, this development alone provided ample evidence that the scientific principles were generally at a discount during this period of intense preoccupation with the insecticides as insect killer. Smallman (1964) singled out, "the failure of entomologists generally to anticipate the development of resistance to insecticides as a consequence of one of the basic tenets of biology—the principle of natural selection." The world-wide experience of chemical control of insect pests shows that resistance in pests almost invariably develops through sustained insecticide usage and selection. Resistance is not limited to insects or pests. Often, the insecticides have exceeded their targets and have selected for resistance in non-target organisms of practically every type, from bacteria to mammals. The development of resistance to chemicals is an evolutionary phenomenon.

Global Status of Insecticide Resistance in Pests

It is, indeed, the introduction and extensive use of modern insecticides that has aggravated the problem of resistance. From the first report (Melander 1914) of resistance to lime sulphur in San Jose Scale, *Aspidiotus perniciosus*, the number of arthropods developing resistance to insecticides rose steadily in the pre-DDT era (11 species). In the post-DDT era there has been a virtual onslaught of resistance and the number based on carefully documented cases was: 12 by 1948, 16 by 1951, 25 by 1954, 76 by 1957, 137 by 1960, 159 by 1963, 224 by 1968, 364 by 1976 (Metcalf 1980), and 428 through 1980 as listed by Georghiou and Mellon (1983) who reviewed pesticide resistance in time and space. Their analysis shows that, of these, 260 species (60.7%) are of agricultural importance and 168 (39.3%) are of medical and veterinary importance or other pests. Amongst them, the maximum number belongs to Diptera (153 species) predominantly of medical importance. A large number of species belong to agriculturally important orders: Lepidoptera and Coleoptera (64 species each), Acarina (53 species), Hemiptera (42 species), Heteroptera (20 species). The resistant species include many of the major pests.

If the problem is viewed from the point of insecticides involved, it is evident that the situation is equally alarming. Resistance has been reported to almost every insecticide that has been employed in pest control. The number of species resistant to each of the insecticide group are: DDT 229, cyclodienes 269, organophosphates 200, carbamates 51, pyrethroids 22, fumigants 17 and others 41. Many species have in practice become resistant to more than one insecticide. Hence, if the number of species versus individual insecticide is considered, the total number of cases reported through 1980 rises to 1640 (Georghiou & Mellon 1983).

Insecticide resistance problem is growing fast involving more and newer cases, areas, species and insecticides. Considering the exponential rate of growth of resistance since 1948, Metcalf (1983) observed that the number of cases doubled about every six years

and suggested that in 10 years the number of examples may exceed 1500 species, and "by the turn of the century, man will have succeeded in producing some degree of insecticide resistance in nearly all pest insects".

The enumeration of resistance is essential, but now it is not merely the numbers. The gravity of the situation manifests when the implications are considered from the practical standpoint and the complexities brought about by the phenomena of cross- and multiple-resistance; spread of resistance through international trade; many-fold increase in the cost of pest control; development and production of newer insecticides; piling of insecticide residues; compelling search for alternative methods of control and a host of other interrelated problems.

Insecticide Resistance in India

Perusal of literature shows that, so far, resistance has developed in only eight species of insects of agricultural importance—three crop pests and five pests of stored products. Out of these, six belong to Coleoptera and two to Lepidoptera. The reported cases are listed in table 1.

Field pests

The first case was reported in 1963 by Pradhan et al. who found the singhara beetle, *Galerucella birmanica* collected from villages around Delhi to be resistant to DDT and *gamma* BHC. It is a serious pest of singhara crop, *Trapa bispinosa* Roxb. and the two insecticides had been used effectively since 1952 to save the crop. Further tests (Pradhan et al. 1964, Jotwani & Sarup 1966) showed that many cyclodiene insecticides also i.e. chlordane, aldrin, dieldrin, isodrin and toxaphene were ineffective against the resistant population. Jotwani (1967) tested mixed formulations of some insecticides in combination with DDT and lindane and found synergism in a number of cases.

Srivastava and Joshi (1965) observed failure of BHC to control tobacco caterpillar, *Spodoptera litura* infesting cauliflower around Jaipur and Ajmer (Rajasthan) and on the basis of laboratory tests established that the resistance was of the order of $\times 7$. Verma et al. (1971) found that the pest was resistant to endrin in Hissar. More recently, Ramakrishnan et al. (1984) have shown that the pest collected from Andhra Pradesh is resistant to a wide range of insecticides—malathion, pyrethrum, lindane, endosulfan and carbaryl. Georghiou and Mellon (1983) have listed *S. littoralis** on cotton having developed resistance to cyclodiene insecticides in India. The occurrence of *littoralis* in India is doubtful, therefore, the species involved seems to be *litura* only, as outbreaks of *S. litura* on cotton in Gujarat and certain other areas have been reported. These reports show that resistance in this polyphagous pest, involving insecticides of different groups, is fairly widespread.

Another crop pest in which resistance has developed to a range of insecticides, mainly in Punjab and to a limited extent in Haryana, is the diamond back moth, *Plutella xylostella*, a serious pest of cauliflower. First reported as failure of DDT and parathion to control the pest in Ludhiana (Verma & Sandhu 1968), it is now prevalent in more areas and involves besides these two insecticides, fenitrothion, malathion and endrin (Deshmukh & Saramma 1973, Verma et al. 1972, Chawla & Kalra 1976).

Storage pests

The problem is, indeed, serious in the case of stored product insects. The possible occurrence of resistance to lindane and

*The report actually pertains to *S. litura*; Georghiou G P, Jan., 1985 (Personal communication)

Table 1 *Insecticide resistance in agricultural pests in India*

S. No.	Species	Insecticide	Resistance factor	State/Area	Reference
1	2	3	4	5	6
1.	*Galerucella birmanica* Jacoby (Singhara Beetle)	DDT, BHC	Control failure	Delhi	Pradhan et al. (1963)
2.	*Spodoptera litura* (F.) (Tobacco Caterpillar)	BHC	×7	Rajasthan (Ajmer, Jaipur)	Srivastava and Joshi (1965)
		BHC	Control failure	Haryana (Hissar)	Verma et al. (1971)
		Malathion	×5.7	Andhra Pradesh	Ramakrishnan et al. (1984)
		Pyrethrum	×14.7		
		Lindane	×16.3		
		Endosulfan	×85.9		
		Carbaryl	Resistant		
3.	*Plutella xylostella* (Linn.) (Diamond Back Moth)	DDT	Control failure	Punjab (Ludhiana)	Verma and Sandhu (1968)
		Parathion	Resistant	Haryana (Hissar)	Verma et al. (1972)
		Endrin			
		Parathion	High tolerance	Punjab (Ludhiana Amritsar Jullunder)	Chawla and Kalra (1976)
		Fenitrothion			
		Malathion			
		DDT			
		Endrin			
4.	*Tribolium castaneum* (Herbst) (Flour Beetle)	DDT	×2.3	Delhi	Bhatia et al. (1971)
			×3-10	Punjab (8 locations)	Kalra et al. (1975)
		Lindane	Resistant	Punjab (widespread)	Kalra et al. (1975)
		Malathion	×37.8	Delhi	Bhatia et al. (1971)
			×16-21	Uttar Pradesh (Hapur Meerut)	Rajak et al. (1973)
		Malathion	Resistant	Maharashtra (Bombay, Borivli)	Champ and Dyte (1976)
		Lindane		Rajasthan (Kota)	
				Uttar Pradesh (Hapur, Kaili Meerut, Mathura)	
				Delhi	

1	2	3	4	5	6
		Phosphine	Resistant	Maharashtra (Borivli, Bombay)	Champ and Dyte (1976)
5.	*Sitophilus oryzae* (L.) (Rice Weevil)	Malathion	×5.8	Uttar Pradesh (Kanpur)	Rajak et al. (1973)
			Resistant	Maharashtra (Bombay) Haryana (Karnal)	Champ and Dyte (1976)
		Lindane	Resistant	Maharashtra (Bombay) Haryana (Karnal, Faridabad) Uttar Pradesh (Mathura) Delhi	Champ and Dyte (1976)
		Phosphine	Resistant	Maharashtra (Bombay) Haryana (Karnal)	Champ and Dyte (1976)
6.	*Rhyzopertha dominica* (F.) (Lesser Grain Borer)	Malathion	Resistant	Maharashtra (Bombay, Borivli) Haryana (Karnal) Rajasthan (Kota) Uttar Pradesh (Meerut)	Champ and Dyte (1976)
		Lindane	Resistant	Maharashtra (Bombay) Haryana (Karnal) Rajasthan (Kota) Delhi Uttar Pradesh (Hapur, Meerut)	Champ and Dyte (1976)
		Phosphine	Resistant	Uttar Pradesh (Hapur, Kaili)	Champ and Dyte (1976)
			×7	Maharashtra (Bombay, Borivli)	

1	2	3	4	5	6
7.	*Oryzaephilus surinamensis* (L.) (Saw-toothed Grain Beetle)	Malathion	Resistant	Maharashtra (Bombay, Borivli)	Champ and Dyte (1976)
		Lindane			
8.	*Trogoderma granarium* Everts. (Khapra Beetle)	Phosphine	×40	Punjab	Borah and Chahal (1979)

malathion in the flour beetle, *Tribolium castaneum* was first demonstrated by Dyte and Blackman (1970) and Champ and Campbell-Brown (1970) on the basis of tests with insects collected from cargoes of Indian origin and unloaded alongwith those from other countries at English, Scottish and Australian ports. However, the resistant insects may not have arisen in the country of loading as cross infestation could occur on board ship (Dyte 1970), hence these reports needed confirmation. With a strain collected from Food Corporation of India godown at Naraina, Delhi, Bhatia et al. (1971) showed presence of resistance to malathion (×37.8) in *T. castaneum*. The strain did not show cross-resistance to lindane but was 2.3 times resistant to p,p'DDT. Subsequently, on the basis of collections made from eight locations in Punjab, prevalence of resistance to lindane and DDT in this species was established (Kalra et al. 1975). However, no resistance to malathion was detected in *T. castaneum*, nor was there any evidence of resistance to lindane, malathion and DDT in *Sitophilus oryzae* or *Rhyzopertha dominica* in the Punjab. But significant resistance to malathion both in *T. castaneum* and *S. oryzae* in some samples collected from Uttar Pradesh was reported by Rajak et al. (1973). It was through the FAO global survey that wide scale prevalence of resistance to lindane and malathion and on a limited scale to phosphine in four species, *T. castaneum*, *S. oryzae*, *R. dominica* and *Oryzaephilus surinamensis* was actually revealed (Champ & Dyte 1976). In fact, phosphine resistance in one of the strains of *R. dominica* was one among the highest in the world. A recent report (Borah & Chahal 1979) shows that Khapra beetle, *Trogoderma granarium* has developed a high level of resistance (× 40) to the fumigant, phosphine, in certain areas of Punjab.

Thus resistance to one or more insecticides has developed in all the major coleopterous storage pests in India. The emergence of resistant strains under practical conditions are of global interest as resistance travels with the international trade (Bhatia 1971). In view of the seriousness of the problem with regard to storage pests, a great deal of interest was evoked and many laboratory studies have been conducted.

Laboratory selection of resistant strains: Studies on resistance to insecticides in *T. castaneum* were initiated in 1958 at the Indian Agricultural Research Institute, New Delhi with a view to exploring the possibility of development of resistance to DDT and BHC, the then most commonly used insecticides (table 2). By rearing the insect in insecticide treated medium, two strains, each resistant to p,p'DDT (>236×) and Lindane (>86×) were selected (Bhatia & Pradhan 1968, 1971). The high degree of resistance developed in a short period of nine generations demonstrated the success of the method which ensured a constant selection pressure to all developmental stages of the insect, and survivors of the treatment alone had a chance to propagate. Starting, respectively, with 7.5 and 20 ppm of p,p'DDT and lindane

in the first generation, concentrations of 250 and 600 ppm were reached in the ninth. Since then, i.e., for the last 25 years, *T. castaneum* has been continuously reared in insecticide treated medium at these concentrations as also several colonies have been isolated which successfully breed at higher concentrations (600 ppm, p,p'DDT and 1500 ppm, lindane) without any detrimental effect on their development and the resistant strains have passed through 90 to 100 generations. These strains have been used for various studies referred to in the article subsequently.

Similarly, strains resistant to malathion, phosphine and pirimiphos methyl in *T. castaneum* (Pasalu & Bhatia 1974a, Kem 1977, Saxena & Bhatia 1980a, Desh Bandhu 1982), to pirimiphos methyl in *T. confusum* (Desh Bandhu 1982), to malathion in *S. oryzae* (Bansode & Bhatia 1976), to phosphine in *R. dominica* (Bakwad 1984) and to lindane in *Corcyra cephalonica* (Shukla & Srivastava 1982) have been selected (table 2).

Biological characteristics of resistant strains:
Selection for resistance to insecticides has often resulted in changes in the biological characteristics of the selected strains (table 3). In most of the cases, fecundity of the selected strain was adversely affected. In the p,p'DDT-resistant strain of *T. castaneum*, combined with reduced fecundity longer developmental period was observed which made the resistant strain inferior in competition to the normal susceptible insects and explained the resistant genotypes being fewer in number in a natural population (Bhatia & Pradhan 1968). However, it appears after a prolonged exposure, the insect is able to adjust to the new environment as has been seen in case of the lindane-resistant strain of *T. castaneum*. Bhatia and Pradhan (1971) reported that after 10 generations of selection with lindane, the resistant females had 36.7% lower fecundity but there was no difference in the preimaginal development duration. However, recent studies showed that after 69 generations of selection the fecundity of the resistant insects was not impaired and its preimaginal development was significantly faster than that of the susceptible strain (Kumar & Bhatia 1983). It thus seemed that after the initial set-back due to exposure to lindane, biological characteristics were restored with the continuous and prolonged rearing in lindane treated medium and the species had stabilized in its new toxic environment. This observation has practical implications i.e., the resistant insects may remain abundant in nature even when the use of lindane has been withdrawn. These results offer a possible explanation of the predominance of lindane resistance in *T. castaneum* in India as stated above and especially when viewed in the light of results of genetical studies (Kumar & Bhatia 1982) which showed that lindane resistance is inherited as a dominant factor and the reversion in resistance, therefore, will not be a quick process.

Another significant finding is that phosphine-resistant *T. castaneum* has 22–25% lower fecundity as compared to the susceptible. When the adults (susceptible and resistant) were exposed to phosphine fumigation, there was reduction in the oviposition which was dose dependent; the higher the dose, more the reduction. At a dose (4 mg/l) which caused 77% mortality of the resistant insects, the reduction in oviposition was 64%. Thus the fecundity was adversely affected both due to the development of resistance as well as treatment with phosphine and this phenomenon is likely to hamper the emergence of resistance to phosphine in practice (Saxena & Bhatia 1980b).

Genetical studies:
In spite of the worldwide prevalence of insecticide resistance in storage pests, very little work on the inheritance of resistance has been attempted.

Table 2 *Laboratory selection of insecticide resistant strains of storage pests*

S. No.	Species	Insecticide	Resistance factor	Reference
1.	*Tribolium castaneum*	p,p'DDT	127.7 × (Rearing medium) >236 × (Films) 44.9 × (Direct spray)	Bhatia and Pradhan (1968)
2.	,,	Lindane	90.2 × (Rearing medium) >86 × (Films) 12.5 × (Direct spray)	Bhatia and Pradhan (1971)
3.	,,	Malathion	53.7×	Pasalu and Bhatia (1974a)
4.	,,	Phosphine	11.9×	Kem (1977)
5.	,,	Phosphine	5.9×	Saxena and Bhatia (1980a)
6.	,,	Pirimiphos methyl	18.7×	Desh Bandhu (1982)
7.	*T. confusum*	Pirimiphos methyl	8.5×	Desh Bandhu (1982)
8.	*Sitophilus oryzae*	Malathion	39.0×	Bansode and Bhatia (1976)
9.	*Rhyzopertha dominica*	Phosphine	18.0×	Bakwad (1984)
10.	*Corcyra cephalonica*	Lindane	38.4×	Shukla and Srivastava (1982)

Table 3 *Biological characteristics of insecticide resistant strains of storage pests*

S. No.	Species	Strain	Dev. period	Fecundity	Reference
1.	*Tribolium castaneum*	p,p'DDT-resistant	22.7% longer larval period	Reduction (59.5%)	Bhatia and Pradhan (1968)
2.	,,	Lindane-resistant	No change	Reduction (26.7%)	Bhatia and Pradhan (1971)
3.	,,	Lindane-resistant	Shorter (3-4 days)	No change	Kumar and Bhatia (1983)
4.	,,	Malathion-resistant	Shorter	Higher	Verma and Ram (1973)
5.	,,	Phosphine-resistant	—	Reduction (22%)	Saxena and Bhatia (1980b)
6.	*Sitophilus oryzae*	Malathion-resistant	No change	Reduction (20%)	Bansode and Bhatia (1981)

Inheritance of resistance to p,p'DDT, lindane and malathion in three laboratory selected strains of *T. castaneum* has been studied at the Indian Agricultural Research Institute, New Delhi by making crosses between each of the resistant strains with the susceptible strain. The results showed that resistance to p,p'DDT, lindane and malathion is controlled, in each case, by an autosomally inherited single gene which is incompletely dominant (Bhatia & Panicker 1976, Kumar & Bhatia 1982, Pasalu & Bhatia 1983). In addition, these studies have also outlined experimental procedure to be adopted in genetical analysis of resistance. Kumar and Bhatia (1983) evaluated different bioassay techniques and showed importance of the choice of one that gives a suitable measurement of the degree of resistance and allows use of ld-p regression lines for proper interpretation of the results.

Cross-resistance studies:

The phenomenon of cross-resistance has been investigated in a number of insecticide-resistant strains of storage pests. The results are summarized in tables 4a and 4b.

The general picture of cross-resistance is that a selected strain shows resistance to a compound chemically related to the selecting agent but not to the unrelated compounds. However, there are several exceptions to this generalization. The most prominent among these being cross-resistance to carbaryl and O-P compounds in p,p'DDT-resistant strain and to carbaryl in the lindane-resistant strain of *T. castaneum*, to DDT and carbaryl in malathion-resistant strain of *S. oryzae* (Bhatia & Pradhan 1970, 1972, Bansode & Bhatia 1978). These studies thus highlight the importance of carrying out tests with each resistant strain with a view to finding out the most suitable alternative insecticide for its control.

One of the most consistent findings in these studies is that strains resistant to contact insecticides do not show cross-resistance to the fumigants and conversely resistance to the fumigants does not extend to the contact insecticides. This finding is of great practical importance with regard to the control of storage pests. However, there are very few insecticides which are safe for use against the storage pests and one that has dominated in practice is malathion. Two types of malathion resistance, one specific and the other non-specific, are known in the case of the flour beetle, *T. castaneum* throughout the world. Tests with the malathion-resistant *T. castaneum* collected originally from the field have shown that resistance to malathion in this case is suppressed by triphenyl phosphate (TPP) and is, therefore, of a specific nature (Pasalu & Bhatia 1974b). In the case of laboratory-selected *S. oryzae* although no tests using TPP were carried out, malathion resistance seems to be of non-specific type as it involved resistance to other O-P compounds (Bansode & Bhatia 1978).

The global spread of insecticide resistance in storage pests has led to greater emphasis for finding and developing alternative methods of control. One such method, often proposed is the use of gamma radiation. Therefore, radiosensitivity of insecticide resistant strains was investigated. Studies with a phosphine-resistant strain of *T. castaneum* showed that resistance to phosphine ($\times$ 5.9) did not involve any change in the sensitivity to radiation (Saxena & Bhatia 1981). Similar results were reported by Bhatia and Sethi (1978) for lindane-resistant ($\times$ 59), DDT-resistant ($\times$ 150) and malathion-resistant ($\times$14) strains of *T. castaneum* and resistance to these insecticides did not show any significant change in susceptibility to gamma radiation. Also studies on the combined effect of gamma radiation and treatment with these insecticides showed that pretreatment of the resistant insects with radiation did not alter their response to the insecticide treatment (Bhatia & Sethi 1979).

Table 4a *Cross-resistance spectra of insecticide-resistant strains of storage pests*

Insecticide	*T. castaneum* p,p DDT-R (94.3 ×)	*T. castaneum* Lindane-R (>86 ×)	*T. castaneum* Malathion-R (53.7 ×)	*T. castaneum* Lindane-R (45.1 ×)	*T. castaneum* Lindane-R (180.6 ×)	*T. castaneum* Malathion-R (160.5 ×)	*S. oryzae* Malathion-R (39.0 ×)	*C. cautella* Lindane-R (38.4 ×)	*T. castaneum* Phosphine-R (11.9 ×)
	1	2	3	4	5	6	7	8	9
p,p'DDT...		0.7 ×	0.9 ×		2.4 ×		11.5 ×	2.6 ×	1.3 ×
Lindane	1.2 ×		1.2 ×				2.6 ×		1.5 ×
Dieldrin	2.0 ×	>291 ×			128.8 ×		3.6 ×	52.3 ×	
Aldrin	1.3 ×	>147 ×			14.8 ×				
Endrin	1.7 ×	>165 ×			26.9 ×		2.8 ×	7.3 ×	
Isodrin							1.5 ×		
Heptachlor	2.7 ×	>232 ×			19.9 ×			31.1 ×	
Chlordane	1.6 ×	>34 ×							
Endosulfan	1.7 ×	>8 ×			>4.4 ×		0.9 ×	2.1 ×	
Toxaphene	1.2 ×	>9 ×							
Methoxychlor					0.9 ×				
Parathion	8.5 ×	2.0 ×	(Ethyl)			(Ethyl)	32.8 ×		
			>1.8 ×			(Methyl)	26.0 ×		1.5 ×
Diazinon	9.1 ×	1.1 ×	1.5 ×				17.7 ×	1.1 ×	
Malathion	3.1 ×	1.0 ×		4.09 ×	3.9 ×			1.1 ×	1.8 ×
Mevinphos	8.3 ×								
Disulfoton			2.5 ×				7.4 ×		1.3 ×
Phosphamidon			1.0 ×				6.0 ×		1.0 ×
Dichlorvos			1.2 ×		1.1 ×		8.6 ×	1.1 ×	
Fenitrothion			1.1 ×	1.8 ×	1.1 ×		39.0 ×		2.9 ×
Iodofenfos			1.3 ×				8.8 ×		1.4 ×
Monocrotophos								1.0 ×	
Pirimiphos methyl				2.2 ×		0.9 ×			
Phenthoate				3.7 ×					
Etrimphos				1.7 ×					
Phorate			1.9 ×						1.3 ×
Bromophos						0.6 ×			
Tetrachlorvinphos						0.9 ×			
Baythion						0.6 ×			
Carbaryl	>12 ×	>12 ×	2.1 ×		16.6 ×		>5.3 ×	4.2 ×	1.5 ×
Carbofuran					13.5 ×				
Propoxur					2.7 ×				
Pyrethrins	1.9 ×	1.5 ×	4.6 ×				3.5 ×	2.1 ×	1.0 ×
Allethrin					2.0 ×				
Permethrin				1.5 ×					
	(1) Bhatia and Pradhan (1970)	(2) Bhatia and Pradhan (1972)	(3) Pasalu and Bhatia (1974a)	(4) Kumar and Bhatia (1981)	(5) Barwal and Kalra (1982)	(6) Verma and Ram (1973)	(7) Bansode and Bhatia (1978)	(8) Shukla and Srivastava (1982)	(9) Kem (1979)

Overview and Resistance Management Strategies

Assessment and prospects

The foregoing account shows that the problem of insecticide resistance in agricultural pests in India is not yet serious when viewed against the background of the alarming situation that prevails elsewhere in the world. Resistance has so far been reported in eight species of agricultural pests, five amongst them being pests of storage. In the three crop pests, resistance is confined to certain areas while in the case of storage pests, resistance to malathion and lindane is fairly widespread.

Considering that the insecticides have been used in crop protection for over three decades, the number of cases of resistance are few: three species and 7 cases only. This shows that the overall use of insecticides in crop protection has not been intensive and extensive enough for resistance to develop in general. The consumption of pesticides in India is low as compared to other countries in which resistance has developed extensively; the consumption per year per hectare of cultivated land for 1980 was: India 336 gm, U.S.A. 1490 gm, Europe 1870 gm and Japan 10,790 gm (Rangaswamy 1983). Further, it seems, in two of the three species, namely, *S. litura* and *P. xylostella* resistance has developed because of intensive use of insecticides primarily on vegetable crops (cabbage and cauliflower). Recently, however, multiple resistance has been detected in *S. litura* which infests many crops including cotton. Areawise, resistance is mainly prevalent in Punjab and Andhra Pradesh; to a limited extent in Haryana and a single instance from Rajasthan. Multiple resistance in *G. birmanica* was reported from Delhi without any further recent report to show the present level of resistance.

It is surprising that resistance has not developed in any of the major pests of cotton or in any pest of paddy so far, despite the fact that pest control recommendations involve repeated application of insecticides to both the crops. The two crops account for nearly 70% of our total crop insecticide market. The pesticide share in cotton and

Table 4b *Cross-resistance to fumigants of insecticide-resistant strains of storage pests*

	T. castaneum	*S. oryzae*	*T. castaneum*	*T. castaneum*		
Fumigant	p,p'DDT-R (166.8 ×)	Malathion-R (39.0 ×)	Phosphine-R (11.9 ×)	p,p'DDT-R (150 ×)	Lindane-R (59 ×)	Malathion-R (14.4 ×)
Carbon tetrachloride	1.4 ×	0.87 ×	0.93 ×			
Ethylene dichloride	0.8 ×	1.1 ×	1.06 ×			
EDCT mixture	0.8 ×	0.99 ×	1.00 ×			
Carbon disulphide	1.2 ×	0.95 ×	0.96 ×			
Ethylene dibromide	0.9 ×	1.29 ×	1.25 ×			
Acrylonitrile	1.2 ×					
Methyl bromide		2.06 ×	1.17 ×			
Phosphine	0.8 ×	1.72 ×		1.17	1.18	1.04
	Bhatia and Bansode (1971)	Bansode and Bhatia (1980)	Kem (1978)	Saxena and Bhatia (1985)		

paddy is 54 and 17%, respectively (Rangaswamy 1983) showing that the insecticide application is quite intensive to select for resistance especially in major cotton and paddy growing areas. Though resistance has not developed but another consequence of insecticide application has been the pest resurgence. Resurgence of the brown plant hopper, *Nilaparvata lugens* (Stal) and blue leaf hopper, *Zygina maculifrons* (Motch.) on paddy and *Aphis gossypii* Glov. on cotton following insecticide application was observed (Chelliah & Heinrichs 1978, Mani & Jayaraj 1976, Sithanantham et al. 1973).

An important feature that emerges from the overall consideration of the situation is that insecticide resistance has received very little attention from the point of view of investigation. This is apparent from the few publications on the subject originating from India (11 in all) reporting development of resistance in practice; in some merely control failure of a particular insecticide has been recorded. It is indicative, in general, of a tendency preferring a switch over to another insecticide influenced by the quick introduction and availability of newer insecticides in the market and thus be in trend with a new recommendation rather than investigate and document control failure of the insecticide in use earlier. In other words, change over to a new insecticide has been effected on various considerations other than reaching the end-point due to development of resistance with the earlier one ignoring the correct moment for a change. This preferential avoidance has led to lack of careful documentation of resistance as also of information on changes in pest susceptibility during the course of application of different insecticides over the years. It may be emphasized that undoubtedly pest susceptibility to insecticides has been continuously undergoing changes as a result of introduction of insecticides in the agro-ecosystem and the prior base-line levels of susceptibility may not be obtainable now in many cases and there does not seem any possibility that these will be restored in future.

The fact that monitoring for resistance has received little attention in our country is very well brought out by referring to the developments in respect of storage pests. The possible occurrence of resistance in *T. castaneum* to malathion and lindane was first detected in insects intercepted from cargos of Indian origin unloaded at ports abroad. Again it was the global survey in mid-seventies and tests carried out in U.K. that established widespread occurrence of resistance in storage pests in India. Following these reports there have been some studies carried out in the country, but relatively few and even now precise information on the present level of insecticide susceptibility of these pests is not available.

The above points highlight the need for greater attention and research on insecticide resistance especially keeping in view that in the next 15 years there will be greater reliance, as ever before, on insecticides in crop pest control programmes to achieve the targets of agricultural production envisaged for 2000 A.D. to meet the growing demands of food, fibre and other produce. Hence, we are bound to encounter insecticide resistance problem in greater intensity and extent in future. But at the same time, opportunity is afforded, to take advantage of the vast fund of experience and knowledge on insecticide resistance and to adopt measures that the arising problem may be managed.

Pesticide management

From the very beginning of the emergence of the problem, countermeasures to the development of resistance have been suggested (Brown 1964). The guiding principles for evolving countermeasures as proposed by FAO Working Party of Experts on Pest Resistance to Pesticides in Agriculture (FAO 1970) are: (*i*) to avoid unnecessary selection

for resistance, and (*ii*) to anticipate the problem of resistance. It is now fully recognised that one of the best ways of circumventing the problem lies in practising the whole range of measures included in the terms of Integrated Pest Management (Brown 1976). While it is advisable to use alternatives to chemical pest control whenever possible, it might not be possible to do without the pesticides altogether, hence the strategy has to be based on continued use of pesticides i.e., pesticide management, in dealing with the problem. Georghiou (1983) discussed in detail chemical strategies for management of resistance under three principal categories i.e., (*i*) management by moderation, (*ii*) management by saturation, and (*iii*) management by multiple attack.

However, the most obvious and practicable countermeasure to the development of resistance is ensuring reduced selection pressure. The components generally agreed upon are: (1) reduce the frequency of insecticide treatments by treating only when necessary, (2) reduce the extent of treatments, (3) avoid insecticides with prolonged environmental persistence and slow release formulations, (4) reduce use of residual treatments, (5) avoid treatments that apply selection pressure on larval and adult stages, and (6) avoid use of mixtures of insecticides (Metcalf 1983). These practices should be kept in mind while recommending chemical pest control measures.

Countermeasures to development of resistance in storage pests:

The perusal of literature shows that the resistance problem under practical conditions in storage pests is serious with respect to contact insecticides, mainly malathion and lindane and the use of fumigants has not been seriously challanged. The reasons for this situation are in the very nature of these groups of insecticides. The contact insecticides are long persisting and once applied continue to select the insects till their residual toxicity lasts whereas the fumigants are non-persistent. Another important factor that seems to have led to the situation that prevails at present is the use of some of the contact insecticides, especially malathion and to a certain extent lindane, as grain protectants. Because of the 'safety' involved in their use, these are often mixed with the grain in some countries. This practice, undoubtedly, has hastened the emergence of resistant strains by intensifying the selection. Earlier, the use of contact insecticides was restricted due to the fear of contamination of grain and residue hazards. The introduction of 'safe' chemicals has changed this situation; their use has become increasingly common over the years, and are even gradually replacing fumigation. Bhatia (1978) suggested the following strategy to be adopted for storage pest control.

The contact insecticides should not be recommended for mixing with the grain howsoever 'safe' these might be, as this treatment is likely to hasten the process of emergence of resistance. Besides, this has other implications as well. The earlier the resistance to an insecticide develops even though in a relatively less important pest, the sooner its application will be discontinued from the control programmes. Since there are a few contact insecticides that qualify for use in storage, efforts should be directed to prolong their 'life' by delaying development of resistance and this measure will be a step in that direction.

The use of fumigants should be encouraged for insect disinfestation. Although the insects possess inherent ability to become resistant to fumigants, yet in field populations it is not yet common. The reasons for this may be that, in practice, intensive selection so very essential for induction of resistance does not result due to the very nature of fumigants and the manner of their application. Firstly, fumigants are nonpersistent

and are used only to kill spot insect infestation. Secondly, due to their ability to penetrate, they most often bring about complete kill and resistant individuals are not left for propagation. In case, however, there are a few survivors of the treatments, they are not subjected to any further selection until fumigation is repeated which may be after such length of time as to allow sufficient population build-up warranting another treatment. The insect may pass through more than one generation meanwhile and this process would seem not to let selection pressure become too intense for selection of resistant strains. Further, the use of fumigants is in keeping with the modern approach advocating use of less persistent chemicals in control programmes. Winteringham (1966) discussing the need for an integrated approach to the problem of pest resistance to pesticides stated that with fumigation the selection is minimal. Hence, wherever possible, fumigation should be preferred over treatment with contact insecticides.

Both the contact insecticides as well as the fumigants should be employed in control programmes, the former preferably superficially and the latter for killing spot-infestation. These two alternative treatments will reduce the chances of development of resistance as resistant individuals selected by one treatment will be eliminated by the other since resistance to one group of insecticides does not extend to the other. Studies have shown that DDT-resistant *T. castaneum* and malathion-resistant *S. oryzae* are susceptible to various common fumigants (Bhatia & Bansode 1971, Bansode & Bhatia 1980). Conversely, fumigant resistant strains seem to be fully susceptible to lindane and malathion (Kem 1979). Multiple resistance may arise but the possibility of occurrence of a common mechanism governing resistance to both fumigants and contact insecticides seems to be remote. Hence, this phenomenon offers unique opportunity for delaying or overcoming resistance in storage pests.

Regular monitoring of resistance and development of standardized tests: An essential requirement for pesticide management is to regularly monitor the insect populations in order to detect the resistance early. Once occurrence of resistance has been established, it is important to assess it quantitatively and determine its geographical extent. Also, tests for cross-resistance should be carried out, in each case, for evolving suitable recommendations of alternative insecticides in the event of development of resistance. For this purpose it is essential to evolve standardized testing methods suited to our requirements keeping in view those recommended by the FAO for a series of pests (FAO 1974, 1975). Further, on the basis of tests it is necessary to generate information in the country on insecticide susceptibility levels and genetic variability of our pest populations for valid comparisons subsequently. Any comparison based on susceptibility levels estimated in other countries or with populations collected from elsewhere can be misleading as insects thriving under different environmental conditions show variability with respect to susceptibility to insecticides. It has been reported that a standard susceptible strain of *T. castaneum* from Slough (U.K.) had a different susceptibility pattern to 15 insecticides as compared to a local susceptible strain from Palampur. The Palampur strain was found to be significantly more tolerant than the Slough strain to a number of chlorinated hydrocarbons although it did not have any history of exposure to an insecticide (Barwal & Kalra 1982). Higher tolerance to lindane was also indicated in a laboratory-maintained susceptible strain of *T. castaneum* tested by the FAO recommended method (Kumar & Bhatia 1983). This study also showed importance of the choice of a bioassay technique for evaluation of resistance. It is pertinent to invite reference to

the information published on several insect species by the Indian Agricultural Research Institute, New Delhi which can provide a starting base for surveillance of resistance and standardization of testing methods. Bioassay of relative toxicity of insecticides has been carried out since 1952 and one of the objectives has been to use the data for detection of resistance to insecticides in agricultural pests (Pradhan 1960).

The work on insecticide resistance needs to be organised on All India level taking up first such crop pests in which development of resistance to insecticides seems imminent e.g., pests of cotton, paddy and vegetables and also to intensify work on stored product pests in which the problem is known to exist. An Advisory Body of Experts may be constituted to prepare guidelines for resistance detection and to suggest measures for resistance management in agricultural pests.

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