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Insecticide resistance in five major insect pests of cotton in India

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Abstract

Insecticide resistance to representatives of commonly used insecticide groups (pyrethroids—cypermethrin; organophosphates—chlorpyriphos; cyclodienes—endosulfan) was determined in five major insect pests of cotton from the main cotton growing regions of India with emphasis on Andhra Pradesh and Maharashtra. The cotton bollworm *Helicoverpa armigera* (Hubner) exhibited widespread resistance to cypermethrin with 23–8022-fold resistance being recorded in field strains. Resistance to endosulfan and chlorpyriphos was low to moderate in *H. armigera*. The overall resistance of the pink bollworm *Pectinophora gossypiella* (Saunders) to pyrethroids was low. However, high resistance levels of 23–57-fold to endosulfan were recorded in some areas of Central India. Resistance to chlorpyriphos was high in the Medak, Bhatinda and Sirsa strains from North India. The majority of the *Spodoptera litura* (Fab.) strains collected in South India exhibited high resistance levels of 61–148-fold to cypermethrin. Resistance to endosulfan was high only in two strains, collected from Bhatinda and Karimnagar in North India. The *S. litura* strains from South India exhibited high levels of resistance at 45–129-fold to chlorpyriphos. Insecticide resistance in *Earias vittella* (Fab.) was low to moderate in the Sirsa and Sriganganagar strains from North India. *Bemisia tabaci* (Genn.) exhibited moderately high levels of resistance to cypermethrin, but resistance to endosulfan and chlorpyriphos was negligible in the field strains tested. The implications of resistance for cotton pest management in India are discussed.

Keywords: Insecticide resistance; *Helicoverpa armigera*; *Pectinophora gossypiella*; *Earias vittella*; *Spodoptera litura*; *Bemisia tabaci*

1. Introduction

The cotton bollworm *Helicoverpa armigera* (Hubner), pink bollworm *Pectinophora gossypiella* (Saunders), spotted bollworm *Earias vittella* (Fab.), tobacco caterpillar *Spodoptera litura* (Fab.) and the whitefly *Bemisia tabaci* (Genn.) are major pests of cotton that have the potential to reduce yields by 20–80% (Mukherjee, 1982). Cotton crop failures during 1987 and 1997 resulted in heavy economic losses in many cotton growing states of India, particularly Andhra Pradesh, Maharashtra and the Punjab. The pest management difficulties in the coastal belt of Andhra Pradesh in 1987 were shown to involve pyrethroid resistance in *H. armigera* (Dhingra et al., 1988; McCaffery et al., 1989). However it had not been demonstrated whether the heavy crop damage caused by insect pests of cotton during the 1997–1998 cropping season was due to poor pest control which, in turn, may have been influenced by the development of insect resistance to insecticides.

The insecticide resistance position of *H. armigera* has received considerable attention (Armes et al., 1992a, b, 1996; Kranthi et al., 2001a, b and the references therein). However, there are few data on changes in insecticide susceptibility in other important insect pests of cotton in India. Armes et al. (1997) consider resistance in *S. litura* in Andhra Pradesh. Kranthi et al. (2001b) explore the resistance to carbamate (methomyl) and organophosphate (quinalphos and monocrotophos) insecticides *H. armigera*, *P. gossypiella*, *E. vittella*, *S. litura* and *B. tabaci*. This paper reports the extent of resistance development in these five major cotton insect pests to representatives of the major groups of insecticides (cypermethrin—a pyrethroid, endosulfan—a cyclodiene, and chlorpyriphos—an organophosphate) in use during 1997–1998, which was a major outbreak season

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for *H. armigera*, in important cotton growing regions across the country, with emphasis on the states of Andhra Pradesh in South India and Maharashtra in Central India.

2. Materials and methods

2.1. Insects

A survey to assess the levels of resistance was carried out in major cotton growing regions of India, with emphasis on the states of Andhra Pradesh and Maharashtra, during February 1998, to coincide with the final phase of the 1997–1998 cropping season. A key to the areas mentioned in the paper is provided in Fig. 1. Larvae of *H. armigera, S. litura, P. gossypiella, E. vittella* and pupae of *B. tabaci* were collected from cotton, pigeonpea, chickpea and sunflower crops. The lepidopteran larvae were reared individually on a wheat-germ based semi-synthetic diet (Armes et al., 1992a; Barlett and Wolf, 1985, Paul et al., 1987) in 7.5 ml cells in 12 well tissue culture plates. Laboratory cultures of the lepidopteran insects were established for each population from 150 to 200 moths. An insecticide susceptible strain of *H. armigera* which had been maintained at Reading Univ. (UK) for over 15 years ('Reading susceptible') was used as a reference strain. An insecticide susceptible laboratory strain of *B. tabaci* ('Sudan-S'), collected from cotton in Sudan in 1997 and cultured at Rothamsted Agricultural Experimental Station (UK) was used as the reference strain for this species. Indian field populations of *B. tabaci* were maintained separately in cages on 3–4 week old cotton plants. Some field populations of *H. armigera, S. litura, P. gossypiella* and *E. vittella* collected from traditionally

Fig. 1. Districts from which field collections were made: (1) Bhatinda; (2) Dabwali; (3) Sirsa; (4) Sriganganagar; (5) Buldana; (6) Akola; (7) Parbhani; (8) Amaravati; (9) Nagpur; (10) Wardha; (11) Yavatmal; (12) Nanded; (13) Karimnagar; (14) Rangareddy; (15) Warangal; (16) Medak; (17) Mahbubnagar; (18) Khammam; (19) Guntur; (20) Prakasam; (21) Dharwad; (22) Coimbatore.

unsprayed regions of the Nagpur and Wardha districts of Maharashtra, exhibited low levels of resistance to almost all the groups of insecticides tested. These were maintained at the Central Institute for Cotton Research, Nagpur for at least seven generations as reference strains.

2.2. Insecticides and chemicals

Cypermethrin is the most commonly used chemical for bollworm control in India. Endosulfan is the sole cyclodiene used and its use is very widespread, as is that of chlorpyriphos and quinalphos amongst organophosphates. The following technical grade insecticides were used for bioassays on lepidopteran insects: cis : trans (c. 50:50 ratio) cypermethrin (90% w/w; Zeneca Agrochemicals, UK); endosulfan (94% w/w; Excel Industries, India) and chlorpyriphos (97.8%; DeNocil, India). The following formulated insecticides were used for bioassays on *B. tabaci*: cypermethrin (Ripcord 10% EC, DeNocil), endosulfan (Thiodan 35% EC, Hoechst) and chlorpyriphos (Ruban 20% EC, DeNocil).

2.3. Log dose probit assays

The field strains were maintained in the laboratory for at least 2 generations and used for bioassays using a topical application procedure described previously (Kranthi et al., 1997) as recommended by the Entomological Society of America (Anon, 1970). Third instar larvae of *H. armigera* and *S. litura* and fourth instar larvae of *P. gossypiella* and *E. vittella* were used for bioassays. Serial dilutions of technical insecticides in acetone were applied with a Hamilton repeating dispenser, as 1.0 µl drops on the thoracic dorsum of at least 40 larvae at each of five or more concentrations in three replicates plus controls. Larvae were held individually in 12-well tissue culture plates containing semi-synthetic diet, at 25 ± 2°C for six days, when mortality assessments were made.

Bioassays on whiteflies were based on the adult leaf-dip method used by Cahill et al. (1995). *Gossypium hirsutum* cotton (hybrid Ankur 651) was grown in the glass house. Leaf discs 38 mm in dia. were cut from 2 week old plants and immersed in serial dilutions with a five to six fold range of concentrations in three replicates, and air dried after draining off the excess solution. The leaf discs were then placed adaxial side down on a bed of agar gel (1.3%) in a plastic Petri dish (39 mm dia. $\times$ 5 mm deep). Control leaves were dipped in the diluent only. Female *B. tabaci* were separated under a binocular microscope from 2–4 day old groups of flies anaesthetised with CO_2. Thirty female whiteflies were released on each of the leaf discs and each Petri dish was sealed with a transparent, close fitting ventilated lid. When the adult flies had recovered from anaesthesia, the Petri dishes were inverted to allow the whiteflies to orient normally. Mortality was scored 72 h after treatment.

All rearing and bioassay operations were carried out at 25 ± 2°C. Data from the replicates were pooled and dose-mortality regressions were computed by probit analysis (Finney, 1971). When required, corrections for control mortality were made using Abbott's formula (Snedecor and Cochran, 1989). Resistance factors (RF) were calculated as the LD_{50} of the field strain divided by the LD_{50} of the susceptible strain.

3. Results

3.1. Insecticide resistance in H. armigera (Table 1)

The Reading susceptible strain exhibited the lowest LD_{50} values with the three insecticides tested. The high slopes of 2.0–2.3 were typical of homozygous susceptible strains.

Pyrethroid: Resistance to cypermethrin was found to be widespread in India with resistance levels of 23–8022-fold being recorded in the field strains. Resistance was >100-fold in 12 out of 21 strains tested. Resistance was high at c.8000 in the Amaravati and Akola strains of Central India, followed by 500–2000-fold in the Khammam, Guntur and Warangal strains from Andhra Pradesh.

Cyclodiene: Resistance to endosulfan was fairly high at 16–31-fold in 5 out of the 9 strains collected in Central India and was moderate at 10–17-fold in 5 out of 10 strains from South India. Resistance was <10-fold in strains from other places in the country.

Organophosphate: Compared to the susceptible strain, all the 22 field strains were found to be significantly resistant at 4–82-fold to chlorpyriphos. Resistance was highest at 82-fold in the Guntur strain, followed by 21–32-fold in the Karimnagar, Khammam, Amaravati and Akola strains.

3.2. Insecticide resistance in P. gossypiella (Table 2)

The susceptible strain from Wardha in Maharashtra, recorded the lowest LD_{50} values, with moderately steep slopes of 1.2–1.7.

Pyrethroid: The overall resistance to pyrethroids was low. Only 5 out of the 18 strains tested were found to exhibit moderate resistance levels of 10–27-fold. The highest RF of 15–27-fold were recorded in strains from Bhatinda, Parbhani and Warangal. Resistance in 11 out of the14 strains from Central India was low at 1–3-fold.

Cyclodiene: High resistance levels of 23–57-fold were recorded with endosulfan in six out of the 19 strains tested. Five of these were from Nagpur and the other from Yavatmal, both in Central India. Resistance was negligible in all strains collected from North India. The

Table 1
Log dose probit response of field strains of *H. armigera* to insecticides

District	Collection date	Cypermethrin						Endosulfan						Chlorpyriphos					
		n	LD_{50}	95% FL	LD_{90}	Slope ± SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope ± SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope ± SE	RF
Reading susceptible		240	0.009	0.007–0.01	0.040	2.0±0.2		228	0.55	0.38–0.76	1.98	2.3±0.3		446	0.02	0.01–0.024	0.07	2.2±0.2	
Wardha susceptible		160	0.053*	0.015–0.09	0.28	1.7±0.4	**6**	118	0.57	0.35–0.91	3.04	1.7±0.2	**1**	240	0.08*	0.06–0.13	0.53	1.6±0.1	4
Central India																			
Nagpur	Oct '97	176	0.88*	0.65–1.16	2.90	2.5±0.4	**98**	324	13.00*	11.0–17.0	64	1.9±0.3	**24**	240	0.11*	0.07–0.18	1.01	1.3±0.1	**5**
	Feb '98	242	2.73*	1.85–4.48	62.9	0.9±0.1	**303**	221	17.00*	14.0–22.0	66	2.2±0.4	**31**	284	0.16*	0.03–0.49	5.57	0.8±0.1	**8**
Wardha	Oct '97	396	0.85*	0.65–1.14	9.01	1.2±0.2	**94**	168	0.58	0.34–0.77	4.1	1.4±0.2	**1**	245	0.08*	0.05–0.13	0.92	1.2±0.1	**4**
Amaravati	Feb '98	169	69.59*	24–926	17974	0.5±0.1	**7732**	179	2.57*	1.71–3.48	13.9	1.7±0.2	**5**	328	0.44*	0.28–0.69	3.17	1.5±0.1	**22**
Akola	Feb '98	144	72.20*	32–417	4173.7	0.7±0.2	**8022**	121	4.52*	3.45–5.99	16.8	2.2±0.4	**8**	344	0.55*	0.27–1.13	11.3	0.9±0.1	**27**
Parbhani	Oct '98	166	0.80*	0.52–1.31	9.12	1.2±0.2	**89**	221	5.73*	2.93–8.0	45.0	1.4±0.3	**10**	196	0.19*	0.10–0.37	3.12	1.1±0.1	**9**
Yavatmal	Feb '98	148	2.59*	1.66–13.2	10.34	2.1±0.4	**288**	146	12.00*	8.0–17.0	64	1.6±0.3	**22**	220	0.13*	0.07–0.24	1.68	1.1±0.1	**6**
Buldana	Feb '98	171	0.21*	0.15–0.29	1.03	1.8±0.2	**23**	252	5.60*	3.0–8.10	72	1.2±0.2	**10**	168	0.15*	0.08–0.27	1.77	1.2±0.1	**7**
Nanded	Feb '98	118	0.46*	0.28–0.79	5.16	1.2±0.2	**51**	176	9.90*	7.0–13.0	64	1.6±0.2	**18**	268	0.11*	0.07–0.17	0.84	1.5±0.1	**5**
South India																			
Warangal	Feb '98	177	7.38*	5.05–10.47	60.7	1.4±0.2	**820**	116	9.09*	6.17–16.1	67.6	1.4±0.3	**17**	224	0.30*	0.05–0.83	4.39	1.1±0.1	**15**
Medak	Feb '98	210	1.08*	0.62–1.67	9.4	1.4±0.2	**120**	105	2.53*	1.58–3.74	16.5	1.5±0.4	**5**	430	0.24*	0.15–0.38	3.57	1.1±0.1	**12**
Karimnagar	Feb '98	216	4.70*	3.10–7.10	65.0	1.1±0.2	**522**	168	6.60*	4.8–9.0	31.5	1.9±0.3	**12**	338	0.42*	0.25–0.72	6.65	1.1±0.1	**21**
Khammam	Feb '98	144	18.0*	10.0–34.0	47.0	3.1±0.5	**2000**	168	8.00*	5.6–11.6	56	1.5±0.2	**15**	320	0.65*	0.30–1.3	5.69	1.3±0.1	**32**
Guntur	Feb '98	192	4.70*	3.10–7.00	48.0	1.3±0.2	**522**	120	6.10*	2.70–8.80	26.4	2.0±0.5	**11**	286	1.64*	0.83–2.7	10.1	1.6±0.2	**82**
Prakasam	Feb '98	144	1.20*	0.30–2.50	10.0	1.4±0.3	**133**	168	3.70*	2.0–5.60	27.8	1.5±0.3	**7**	294	0.31*	0.15–0.62	6.45	1.0±0.1	**15**
Rangareddy	Feb '98	212	0.89*	0.57–1.50	40.6	0.8±0.1	**99**	138	3.31*	2.35–4.61	16.5	1.8±0.2	**6**	336	0.27*	0.13–0.53	5.54	1.0±0.1	**13**
Mahbubnagar	Feb '98	220	0.82*	0.67–1.07	2.9	2.3±0.4	**91**	144	3.37*	1.54–8.69	11.4	2.4±0.3	**6**	286	0.18*	0.10–0.31	2.06	1.2±0.1	**9**
Coimbatore	Mar '98	168	0.64*	0.35–2.33	42.76	0.7±0.2	**71**	143	6.17*	4.21–8.43	68.2	1.2±0.1	**11**	224	0.18*	0.11–0.29	2.22	1.2±0.2	**9**
Dharwad	Jan '96	212	0.91*	0.48–3.74	42.98	0.8±0.2	**101**	112	2.90	0.59–6.08	21.1	1.5±0.3	**5**	344	0.34*	0.18–0.65	5.23	1.1±0.1	**17**
North India																			
Bhatinda	Nov '98	240	0.38*	0.14–1.11	3.6	1.3±0.2	**42**	192	2.52*	1.51–4.41	31.9	1.1±0.3	**5**	266	0.16*	0.08–0.29	2.04	1.2±0.1	**8**
Dabwali	Nov '98	220	0.56*	0.41–0.87	6.6	1.2±0.2	**62**	194	3.17*	1.65–6.05	40.7	1.1±0.3	**6**	196	0.12*	0.07–0.21	1.58	1.1±0.1	**6**
Sirsa	Nov '98	159	0.54*	0.16–2.51	4.1	1.4±0.2	**60**	190	2.35*	0.32–4.91	84.5	0.8±0.3	4	236	0.23*	0.14–0.38	3.52	1.1±0.1	**11**

*Designated LD_{50} values are significantly different from the LD_{50} of the susceptible strain through non-overlap of fiducial limits.
Abbreviations: LD = lethal dose expressed as μg/larva, FL = fiducial limits, *n* = number of larvae treated, df = degrees of freedom, SE = standard error, RF = resistance factor.

Table 2
Log dose probit response of field strains of *P. gossypiella* to insecticides

District	Collection date	Cypermethrin						Endosulfan						Chlorpyriphos					
		n	LD_{50}	95% FL	LD_{90}	Slope±SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope±SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope±SE	RF
Wardha susceptible		267	0.75	0.57–0.98	4.34	1.7±0.1		300	20.48	11.7–63.06	188	1.3±0.2		310	0.12	0.07–0.19	1.33	1.2±0.1	
Central India																			
Nagpur	Dec '95							186	912*	407–18062	6780	1.5±0.5	**45**						
	Jan '96	287	2.12*	1.33–3.69	24.39	1.2±0.2	**3**							284	1.15*	0.84–1.49	5.27	1.9±0.2	**9**
	Nov '96							290	460*	123–13792	17074	0.8±0.2	**23**						
	Jan '97	264	2.67*	1.88–4.0	33.64	1.1±0.1	**4**												
	Dec '97							305	1177*	223–59888	31360	0.9±0.3	**57**						
	Feb '98	264	1.44	0.92–2.57	15.59	1.2±0.2	**2**	164	750*	217–480488	9978	1.1±0.4	**37**	295	1.78*	1.31–2.30	9.76	1.7±0.2	**15**
	Dec '98							287	771*	160–6136	43801	0.7±0.2	**38**						
	Feb '99							305	341*	106–6406	9252	0.9±0.2	**17**						
Wardha	Dec '97	286	0.90	0.51–1.58	6.8	1.5±0.1	**1**	289	54	21–677	1045	1.0±0.2	**3**						
	Feb '98	196	0.82	0.36–1.89	26.59	0.8±0.2	**1**	208	24	13–44	342	1.1±0.3	**1**	300	0.24	0.03–1.01	2.13	1.5±0.1	**2**
	Jan '99	305	1.02	0.62–1.67	7.11	1.5±0.1	**1**												
Amaravati	Feb '98	156	2.06*	1.02–5.89	37.27	1.0±0.2	**3**	198	307*	124–8227	3722	1.2±0.4	**15**	300	29.10*	23–39.	102.5	2.3±0.3	**242**
	Dec '98							305	70	22.37–954	3155	0.7±0.1	**3**						
Akola	Feb '98	156	5.81*	3.02–18	51.99	1.3±0.3	**8**	196	125*	68.6–675.3	890	1.5±0.4	**6**	300	15.55*	13–20	44.36	2.8±0.4	**130**
	Dec '98	310	2.88*	1.97–4.52	45.94	1.1±0.1	**4**												
Parbhani	Feb '98	172	12.43*	3.88–11.20	538.0	0.8±0.2	**17**	122	181*	89–1255	2432	1.1±0.3	**9**	240	1.99*	1.18–2.93	8.29	2.1±0.2	**17**
Yavatmal	Feb '98	200	2.16*	1.36–4.19	15.87	1.5±0.3	**3**	140	892*	239–165480	28198	0.8±0.3	**44**	290	3.47*	1.61–6.35	17.62	1.8+ 0.2	**29**
Buldana	Feb '98	196	1.04	0.67–1.70	7.06	1.5±0.3	**1**	140	10	3.5–18	276	0.9±0.2	**1**	284	9.59*	8.00–11.81	31.53	2.5±0.3	**80**
	Dec '98	301	1.18	0.85–1.66	13	1.2±0.1	**1**	309	39	16–253	1369	0.8±0.1	**2**						
Nanded	Feb '98	186	9.51*	4.48–53	94.68	1.3±0.3	**13**	160	260*	114–2417	4075	1.1±0.3	**13**	240	2.45*	1.35–3.79	10.44	2.0±0.2	**20**
South India																			
Warangal	Feb '98	212	20.03*	10–66.86	503	0.9±0.1	**27**	286	85	26.2–2778	1905	0.9±0.2	**4**	240	56.39*	38–117	322.82	1.7±0.3	**470**
Medak	Feb '98	234	8.03*	5.28–14.6	95	1.2±0.1	**11**	309	41	17.8–390	521	1.1±0.3	**2**	300	56.02*	37–117	331.06	1.7±0.3	**467**
North India																			
Bhatinda	Nov '97	284	11.03*	6.69–23.8	168	1.1±0.1	**15**	310	24	13.0–87.7	226	1.3±0.3	**1**	240	102.25*	54–430	927.21	1.3±0.3	**852**
Sirsa	Nov '97	124	6.86*	4.35–12.9	120	1.0±0.1	**9**												

*Designated LD_{50} values are significantly different from the LD_{50} of the susceptible strain through non-overlap of fiducial limits.
Abbreviations: LD = lethal dose expressed as μg/larva, FL = fiducial limits, *n* = number of lar

Table 3
Log dose probit response of field strains of *S. litura* to insecticides

District	Collection date	Cypermethrin						Endosulfan						Chlorpyriphos					
		n	LD_{50}	95% FL	LD_{90}	Slope±SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope±SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope±SE	RF
Nagpur susceptible	Sept '97													324	0.048	3–0.06	0.17	2.3±0.4	
Bangalore susceptible	July '97	288	0.029	0.02–0.03	0.09	2.6±0.3		240	1.2	1.0–1.4	3.1	3.1±0.4							
Central India																			
Nagpur	Dec'95	242	0.12*	0.08–0.16	1.26	1.2±0.1	**4**	359	6.67*	4.4–10.8	17	0.9±0.1	6	256	0.09	0.03–0.23	1.38	1.1±0.1	**2**
	Dec'97	256	0.14*	0.09–0.21	2.86	1.0±0.1	**5**												
	Feb '98	182	0.02	0.01–0.05	0.29	1.3±0.2	**1**							256	0.13	0.03–0.34	3.25	0.9±0.1	**3**
	Sept '98							324	1.47	1.2–1.8	5.3	2.3±0.3	1						
	Feb '99							242	3.66	1.4–9.4	32	1.4±0.1	3						
Wardha	Feb '98	287	0.19*	0.13–0.26	1.73	1.3±0.1	**7**	267	9.27*	6.8–13.1	71	1.5±0.1	8						
Amaravati	Feb '98	242	0.25*	0.18–0.35	2.45	1.3±0.1	**9**	312	9.45*	6.8–13.8	94	1.3±0.1	8	284	0.15	0.01–0.53	3.78	0.9±0.1	**3**
Yavatmal	Feb '98	234	0.79*	0.45–1.61	13.4	1.0±0.1	**27**							244	0.27*	0.08–0.63	2.43	1.3±0.1	**6**
South India																			
Warangal	Feb '98	265	1.78*	1.2–2.93	21.7	1.2±0.1	**61**	143	7.31*	4.9–9.6	30	2.1±0.3	6	252	6.21*	1.76–64.9	326	0.7±0.1	**129**
Karimnagar	Feb '98	174	0.34*	0.26–0.42	1.07	2.5±0.3	**12**	167	92.46*	48–571	727	1.4±0.3	77	240	4.39*	2.00–11.9	304	0.7±0.1	**91**
Mahbubnagar	Feb '97	240	4.3*	3.1–7.2	19.0	2.0±0.4	**148**												
	Feb '98	148	3.86*	2.76–5.45	17.7	1.9±0.3	**133**	144	12.8*	8.6–19.9	31	3.2±0.5	11	280	6.12*	2.94–16.5	635	0.6±0.1	**127**
Rangareddy	Feb '98	192	1.98*	1.49–2.60	9.26	1.9±0.2	**68**	191	6.52*	4.4–8.3	31	1.9±0.4	5	240	2.41*	1.02–4.54	15.7	1.5±0.2	**50**
Khammam	Nov '98	146	2.60*	2.03–3.26	7.23	2.9±0.4	**90**	143	15.1*	7.6–29.8	58	2.2±0.3	13	274	2.16*	0.83–5.97	91.9	0.8±0.1	**45**
North India																			
Bhatinda	Nov '98	231	0.31*	0.18–0.52	3.52	1.2±0.1	**11**	213	27.3*	13.8–99	242	1.1±0.1	23	264	1.91*	0.42–5.14	15.5	1.6±0.2	**40**

*Designated LD_{50} values are significantly different from the LD_{50} of the susceptible strain th
Abbreviations: LD = lethal dose expressed as μg/ larva, FL = fiducial limits, *n* = number of larvae treated, df = degrees of freedom, SE = standard error, RF = resistance factor.

Table 4
Log dose probit response of field strains of *E. vittella* to insecticides

District	Collection date	Cypermethrin						Endosulfan						Chlorpyriphos					
		n	LD_{50}	95% FL	LD_{90}	Slope± SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope± SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope± SE	RF
Nagpur susceptible	Dec '95	210	0.008	0.006–0.01	0.06	1.5±0.1		238	2.19	1.37–3.2	10.6	1.8±0.2		296	0.09	0.05–0.14	0.93	1.3±0.1	
Central India																			
Nagpur	Feb '96	212	0.022*	0.013–0.03	0.09	2.0±0.4	**3**												
	Feb '98	154	0.008	0.006–0.01	0.05	1.6±0.2	**1**	213	2.04	1.3–3.6	30.4	1.1±0.1	**1**	240	0.13	0.07–0.21	1.56	1.2±0.1	**1**
Wardha	Dec '98	242	0.01	0.007–0.01	0.05	1.6±0.1	**1**							264	0.22	0.09–0.45	2.38	1.2±0.1	**2**
Parbhani	Feb '98	186	0.012	0.008–0.02	0.08	1.5±0.1	**1**	221	4.51	3.2–6.9	45.5	1.3±0.1	**2**	284	0.16	0.05–0.41	2.26	1.1±0.1	**2**
Nanded	Feb '98	141	0.012	0.008–0.02	0.11	1.3±0.1	**1**	231	2.61	2.0–3.4	12.6	1.9±0.2	**1**						
Akola	Feb '98	156	0.046*	0.034–0.06	0.35	1.5±0.1	**6**	220	7.42*	4.6–14.3	136	1.0±0.1	**3**	240	0.19	0.07–0.44	3.58	1.0±0.1	**2**
North India																			
Sriganganagar	Feb '98	176	0.079*	0.059–0.10	0.53	1.5±0.1	**10**	187	3.50	1.6–16.2	96	0.9±0.1	**2**	252	0.66*	0.27–1.41	17.2	0.9±0.1	**7**
Sirsa	Feb '98	212	0.093*	0.069–0.12	0.78	1.4±0.1	**12**	238	11.41*	6.4–27.8	310	0.9±0.1	**5**	264	0.74*	0.28–1.63	11.5	1.1±0.1	**8**

*Designated LD_{50} values are significantly different from the LD_{50} of the susceptible strain through non-overlap of fiducial limits.
Abbreviations: LD = lethal dose expressed as μg/larva, FL = fiducial limits, *n* = number of larvae treated, df = degrees of freedom, SE = standard error, RF = resistance factor.

Table 5
Log dose probit response of field strains of *B. tabaci* to insecticides

District	Collection date	Cypermethrin						Endosulfan						Chlorpyriphos					
		n	LD_{50}	95% FL	LD_{90}	Slope± SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope± SE	RF	*n*	LD_{50}	95% FL	LD_{90}	Slope± SE	RF
Sudan susceptible		575	7.0	5.7–10.1	30.5	2.0±0.4		241	2.0	—	38.1	1.0±0.2			2.90[a]	2.00–3.8	—	3.3±0.4	
South India																			
Rangareddy	Nov '97	336	32.8*	21–55	346	1.3±0.1	**5**												
	Dec '97	353	263*	95–265	35481	0.6±0.1	**38**	336	1.8	0.5–5.7	645	0.5±0.1	**1**						
	Dec '97							325	1.3	0.4–3.6	467	0.5±0.1	**1**						
	Jan '98	289	98.8*	55–145	457	1.9±0.3	**14**												
	Feb '98	331	313*	417–548	776	3.2±0.7	**45**							320	5.70	3.70–8.20	35.9	1.6±0.2	**2**
	May '98							485	3.2	1.1–4.4	11	2 3±0 5	**2**	348	4.5	3.10–5 60	12.4	2.9±0.5	**2**
	June '98							398	3.5	2.6–4.4	13	2.2±0.2	**2**						
	Nov '98	379	109*	78–145	778	1.5±0.2	**16**												
Mahbubnagar	Dec '98	402	75*	56–95	380	1.8±0.2	**11**							309	2.0	0.77–3.50	19.3	1.3±0.2	**1**
Guntur	Dec '98	392	106*	78–138	755	1.5±0.2	**15**							288	4.1	2.40–6.20	21.1	1.8±0.3	**1**

[a] Data from Cahill et al. (1995).
*Designated LD_{50} values are significantly different from the LD_{50} of the susceptible strain through non-overlap of fiducial limits.
Abbreviations: LD = lethal dose expressed as ppm, FL = fiducial limits, *n* = number of larvae treated, df = degrees of freedom, SE = standard error, RF = resistance factor.

slopes were shallow at 0.7 to 1.1 in the majority of the strains, probably indicating a heterogeneous response to the insecticide.

Organophosphate: Six of the 12 tested strains were found to express high resistance levels to chlorpyriphos (RF 80–852). Resistance was highest at 852 and 467-fold in the Sirsa and Bhatinda strains from North India and 470-fold in the Medak strain from Central India.

3.3. *Insecticide resistance in S. litura (Table 3)*

The Bangalore (South India) and Nagpur (Central India) susceptible strains exhibited the lowest LD_{50} values and steep slopes of 2.2–3.1.

Pyrethroid: All strains collected in South India, except from Karimnagar, exhibited high resistance levels of 61–148-fold to cypermethrin. Resistance was low at 1–9-fold in the majority of strains from Central India.

Cyclodiene: Resistance levels to endosulfan were high at 27 and 92-fold in only two strains, collected from Bhatinda (North India) and Karimnagar (Central India) respectively. Otherwise resistance was low to moderate at 5–13-fold.

Organophosphate: All the strains collected from South India exhibited high levels of resistance to chlorpyriphos (45–129-fold). The highest resistance levels in Central India were recorded in the Warangal (RF 129) and Mahbubnagar (RF 127) strains. Otherwise resistance was low at 2–6-fold in Central India. Resistance was moderate, at 40-fold, in the single strain (Bhatinda) tested from North India.

3.4. *Insecticide resistance in E. vittella (Table 4)*

The Nagpur susceptible strain exhibited low LD_{50} values with slopes of 1.3–1.8.

Pyrethroid: Resistance to cypermethrin was moderate at 10–12-fold only in the Sirsa and Sriganganagar strains of North India. There was no indication of significant resistance in the other strains tested.

Cyclodiene: Resistance to endosulfan was low (1–5-fold) in the six strains tested.

Organophosphate: Only two of the six strains tested were found to express significant resistance to chlorpyriphos. Both were from North India.

3.5. *Insecticide resistance in B. tabaci (Table 5)*

The Sudan susceptible strain exhibited the lowest LD_{50} values to cypermethrin and a steep slope of 2.0 suggesting a homogeneous response. Measurements on field strains were made only in Central India.

Pyrethroid: Resistance levels to cypermethrin were significant at 5–45-fold in the field strains.

Cyclodiene and organophosphate: Resistance to endosulfan and chlorpyriphos was negligible in the strains tested.

4. Discussion

4.1. *History of insecticide resistance and crop failure in India*

In India, cotton consumes over half the total insecticides, although it occupies only 5% of the cropped area. Andhra Pradesh alone consumes more than 33% of all insecticides used in the country, with over 54% of this on cotton (Puri et al., 1999). Over the past 30 years, the cost of insecticides has constituted 30–40% of the growing costs of cotton in Andhra Pradesh (Parthasarathy and Shameem, 1998) and is now around 44% in India as a whole (ICAC, 1998). A good deal of this material is of poor quality. Although insecticide quality is officially regulated in India, in practice much of the insecticide sprayed is both of poor quality and is inadequately formulated. The field control problem is exacerbated by poor selection of chemicals for control (often under advice from inadequately trained dealers) and sub-standard application practices. Around 80% of Indian cotton is sprayed with hand-pumped knapsack sprayers and a further 15% from motorised back-pack sprayers, leaving only 5% sprayed from tractor mounted equipment, mainly in North India (ICAC, 1999). The quality and maintenance of these machines and nozzles is very poor, resulting in inadequate delivery rates and encouraging the use of insecticide mixtures. In *H. armigera* outbreak years, over 70% of all cotton insecticide applications in North India and 33% in Central India are mixtures (Iyengar and Russell unpublished). Most of these are tank mixes, most lacking any coherent rationale. The same active ingredient is often sprayed repeatedly.

Partly as a consequence of these practices, over the past two decades, cotton pest management in India has been complicated by the evolution of insecticide resistance by pests.

When describing the difficulty in assigning the causes of poor field control to resistance, Sawicki (1987) stated that "There is a wide gap between suspicion and proof, and it is often difficult or even impossible to pin control failure to resistance." More often the reasons for poor insecticide efficacy are attributed to adulteration or spurious chemicals (Parthasarathy and Shameem, 1998). Nevertheless, we feel that data on the levels of resistance to major groups of insecticides can help in assessing the relative importance of resistance in causing field control failures. Cypermethrin, endosulfan and chlorpyriphos, as representative of the pyrethroid, cyclodiene and organophosphate insecticides respectively, rank amongst the most commonly used insecticides on cotton in India and account for at least 40% of all insecticides used on cotton.

E. vittella and *S. litura*, were major pests of cotton when pyrethroids were first introduced into India in 1982. Pyrethroids were found to be highly effective for the control of these pests resulting in significantly higher cotton yields. The use of pyrethroids is believed to be one of the major reasons for the historically highest cotton yields being obtained in 1983–1984 (1100 kg seed cotton/ha in Andhra Pradesh). Subsequently, the use of pyrethroids increased strongly and farmers were soon overusing the compounds. For the first few years after the introduction of pyrethroids in India, boll damage in the pyrethroid treated cotton fields was consistently <12% (Rao et al., 1994). Insecticide resistance in *H. armigera* in the in-land districts of Andhra Pradesh was negligible until the mid 1980s (A. Phokela, Indian Agricultural Research Institute, New Delhi, pers. comm.). However during the 1987–1988 cropping season pest control problems due to a reduced efficacy of pyrethroids on *H. armigera* were experienced in Andhra Pradesh (Armes et al., 1992b). The yields dropped dramatically to an all time low, especially in the coastal belt of Andhra Pradesh (460 kg seed cotton/ha). Resistance to pyrethroids was soon confirmed in *H. armigera* strains from Andhra Pradesh (Dhingra et al., 1988; McCaffery et al., 1989). By 1995 *H. armigera* resistance to pyrethroids was found to be widespread in the Indian sub-continent (Armes et al., 1996). Pyrethroid resistance continued to be high subsequently (Jadhav et al., 1999; Kranthi et al., 2001a, b).

Particular control problems were experienced in the 1997–1998 season. The incidence of *H. armigera* was high in September to November in almost all cotton growing areas in the country including Andhra Pradesh and Maharashtra. During this time the farmers could not take proper crop protection measures due to an early drought followed by unseasonal cyclonic rains in September which caused a heavy pest flare-up. Reports of poor control of cotton bollworms, were common from almost all parts of Andhra Pradesh. Additionally, in most parts of Andhra Pradesh, the infestation of *S. litura* was severe after October and continued to be high until the end of December. This worsened the crisis and farmers resorted to more insecticide, using up to 30 applications. The excessive use of insecticides led to problems of insecticide resistance in some of the major pests of cotton, which further necessitated the repeated application of insecticides. Poor insect pest control on account of resistance caused yield losses. The indiscriminate use of insecticides forced farmers to incur debts and over 300 committed suicide out of desperation (Vandana et al., 1999; Parthasarathy and Shameem, 1998); at least 174 in Andhra Pradesh (Vaartha Newspaper, Hyderabad, Feb 16, 1998) and 40 in Maharashtra (Indian Express Newspaper, Nagpur, May 16, 1998).

4.2. Resistance in H. armigera

Insecticide resistance in *H. armigera* was high in almost all the sites surveyed in February 1998, especially in Andhra Pradesh and the parts of Central India from which cases of cotton farmer suicides were reported. Resistance to pyrethroids was exceptionally high in parts of Central India and almost all districts of Andhra Pradesh. Armes et al. (1996) reported that the most highly resistant populations of *H. armigera* were generally found in the central and southern regions of India. They stated that it was primarily from these regions that reports of inadequate control were most frequent and concomitant numbers of insecticide applications were high. The present study indicated high levels of resistance to all three insecticides tested on *H. armigera* from the Warangal, Karimnagar and Khammam districts of in-land Andhra Pradesh. Resistance to cypermethrin was high at 500–2000-fold in the three districts. Considering the fact that pyrethroids constituted almost 70% of all sprays used on cotton in Andhra Pradesh (Jayswal, 1989) and are still intensively used, the high levels of resistance are not surprising.

Pyrethroid: Resistance to cypermethrin in *H. armigera* from Andhra Pradesh in South India was reported at 40–750-fold during 1987–1998 (McCaffery et al., 1989). It had risen to 7–2100-fold during 1989–1990 (Armes et al., 1992b) and 20–6500-fold between 1991 and 1994 (Armes et al., 1996). In the current study, resistance levels in Andhra Pradesh were found to range from 23–2000-fold.

Prior to this study, the highest level of resistance to cypermethrin recorded in Central Indian strains of *H. armigera* was 480-fold in a Central Indian (Maharashtran) strain (Armes et al., 1996). The current study revealed that pyrethroid resistance in Central India can potentially cause severe problems in pest management. For example, the highest levels of resistance to cypermethrin (c.8000-fold) were recorded in Akola and Amaravati and the use of pyrethroids in the two districts was the highest in Central India during 1997–1998 (Kranthi et al., 2001a). Armes et al. (1996) reported pyrethroid resistance levels of 37–140-fold in *H. armigera* strains from North India and Coimbatore in South India, during 1991 to 1994. Our study indicates that resistance to pyrethroids in these regions continues to be moderate, at between 60 and 101-fold.

Cyclodiene: Resistance levels to endosulfan in *H. armigera* were low at <31-fold in the strains tested. McCaffery et al. (1989) stated that endosulfan resistance levels of 13-fold could be correlated with poor control of *H. armigera* in coastal Andhra Pradesh. Armes et al. (1996) reported the highest resistance levels of 28-fold in

H. armigera strains from Andhra Pradesh, but felt that even low levels of 5–10-fold resistance to endosulfan were sufficient to compromise the efficacy of the chemical for *H. armigera* control under field conditions. Endosulfan resistance levels of 11–15-fold in the Warangal, Karimnagar and Khammam districts could have thus reduced the chemical's effectiveness under field conditions thereby necessitating repeated applications of insecticides. Endosulfan is the single largest selling insecticide in Central India, with an estimated 85% of it used on cotton. This high level of use of the compound on cotton presumably contributed to the high levels of resistance.

Organophosphate: Resistance to chlorpyriphos was moderate at 4–32-fold in majority of the strains tested in the current study, with the exception of 82-fold resistance recorded in a Guntur (coastal Andhra Pradesh) strain. Resistance to organophosphates was reported to have been low (RF 2–9) for quinalphos, and 2–3 for monocrotophos in *H. armigera* in India until 1990 (McCaffery et al., 1989; Armes et al., 1992b). Later, Armes et al. (1996) reported low to moderate levels of resistance (2–59-fold) against quinalphos in *H. armigera* field strains in India. It is not known what levels of resistance actually cause a significant reduction in field efficacy of organophosphates. However, low levels of 10–15-fold resistance in *H. armigera* have been found to result in poor field control at the Central Institute for Cotton Research farm at Nagpur. Resistance levels of 15–32-fold in the *H. armigera* strains from Andhra Pradesh and some parts of Central India could have certainly caused difficulties in cotton pest management thus leading to an increase in the use of insecticides.

4.3. Resistance in P. gossypiella

Reports of *P. gossypiella* resistance to insecticides have been relatively rare. Resistance to azinphosmethyl and permethrin was reported from strains collected in Arizona and California (Osman et al., 1991). From experience in China, Tang et al. (1988) did not consider *P. gossypiella* as a pest prone to develop resistance to insecticides. However Li et al. (1997) describe the recent development of resistance in this species in China. The current study shows significant resistance in India too.

Pyrethroid: Cypermethrin resistance was the highest at 27-fold in the Warangal strain.

Cyclodiene: Endosulfan resistance was high at 15–58-fold in the Central Indian strains, which could have been a result of the indiscriminate use of endosulfan in Central India throughout the season.

Organophosphate: Resistance to chlorpyriphos was almost ubiquitous, with the highest levels of 130–852-fold in strains from Central and North India (Akola, Amaravati, Medak, Warangal and Bhatinda districts). The high levels of resistance to chlorpyriphos in these regions could be due to the high intensity of use of organophosphates in the late reproductive phase of cotton crop. Although these compounds are intended to target *H. armigera*, they would also have an impact on populations of *P. gossypiella* which occurs late in the cotton season in Central and Southern India. This species is an early season pest in North India, but there it is subjected to organophosphate sprays primarily aimed at sucking pest control, probably accounting for the resistance observed in strains from Bhatinda.

4.4. Resistance in S. litura

Resistance to endosulfan, carbaryl and malathion has been reported in field strains from of *S. litura* from Haryana (Verma et al., 1971), West Bengal (Mukherjee and Shrivastava, 1970) and Andhra Pradesh (Ramakrishnan et al., 1984). Ramakrishnan et al. (1984) reported a 56-fold increase in endosulfan resistance between the early 1970s and 1983 and concluded that endosulfan resistance levels in Andhra Pradesh were high. However by the mid 1990s Armes et al. (1997) reported that resistance was low in Andhra Pradesh, at 1–13-fold to endosulfan and quinalphos. Our data indicates that insecticides are likely to again have reduced efficacy on *S. litura* in Andhra Pradesh and some parts of North India, and that significant problems are emerging with the use of endosulfan in some areas.

High levels of resistance were detected to all three insecticides tested with *S. litura*, in strains from both north and South India. Resistance levels to cypermethrin and chlorpyriphos were high, at 45–148-fold, in the majority of the Andhra Pradesh strains. Resistance to endosulfan was highest at 77-fold in the Karimnagar (North India) strain but <23-fold in rest of the strains tested. The Central Indian strain from Mahbubnagar exhibited the highest RF to cypermethrin and chlorpyriphos. Both insecticides were heavily used for the management of *S. litura* on the groundnut crop in Mahbubnagar.

4.5. Resistance in E. vittella

Under field conditions, generations of *E. vittella* are rarely synchronised. There are usually mixtures of eggs, larvae and pupae on cotton crop simultaneously, thus making the timing of insecticide application crucial and management of epidemics more difficult (Reed, 1994). Out of the seven strains of *E. vittella* that were assayed, only two were found to exhibit resistance to cypermethrin and chlorpyriphos. Both strains were from North India and the resistance was low (RF 6–12). Endosulfan resistance was not above RF5 in any of the strains tested Organophosphates which were earlier found to be effective for the control of *E. vittella*, have been showing poor field efficacy in recent times in North India, especially in Punjab (J. Singh, Punjab Agricultural University, pers comm.) Pyrethroids are still very effective for the management of *E. vittella*, but are not preferred as early or mid-season sprays in IPM programmes due to their broad-spectrum effects on beneficial insect species and in order to avoid pyrethroid resistance problems consequent on season long usage, as they are widely used for *H. armigera* control late in the cotton season. With limited chemistry available as early season sprays to combat the problem of *E. vittella*, bollworm management may pose a persistent problem in times to come.

4.6. Resistance in *B. tabaci*

All the *B. tabaci* field strains exhibited resistance to cypermethrin and susceptibility to chlorpyriphos and endosulfan. Organophosphates are still widely used on cotton and other crops in Andhra Pradesh to keep whitefly populations under control. *B. tabaci* resistance to cypermethrin and chlorpyriphos has been widely reported in strains from USA, Central America, Europe, Pakistan, Sudan and Israel, (e.g. Cahill et al., 1996), and high *B. tabaci* resistance levels to organophosphates in Sudan were demonstrated by Dittrich et al. (1985). Our data suggests that endosulfan and some organophosphates still have a major role to play in contrast to the decreasing importance of pyrethroids (RF 5–38) in whitefly management. Similar results were found for Andhra Pradesh by Jadhav et al. (1999). In addition they found no resistance to imidocloprid, but detected 6–7-fold resistance to monocrotophos. Singh et al. (1999), working in Punjab of North India, found incipient resistance to Cypermethrin (RF 11–64) but not to deltamethrin. Amongst the organophosphates, oxydemeton methyl was quite strongly resisted (RF 59–66) and dimethoate and acephate were beginning to show problems. *B. tabaci* was still susceptible to monocrotophos and quinalphos and showed only incipient resistance against chlorpyriphos and phosphamidon. Resistance to endosulfan, profenofos and ethion was very low.

4.7. Resistance management

Based on the results obtained from the survey, it is suggested that pyrethroid use on cotton should be discouraged in Andhra Pradesh until susceptibility in the major pests is restored. Resistance to organophosphate insecticides was also high in Andhra Pradesh in almost all the insect pests except *B. tabaci*. There is a need to exercise caution in the use of these compounds to prevent further selection for resistance. Endosulfan resistance appeared to be low to moderate, but it may be possible futher reduce the resistance levels by restricting its use.

The majority of the *P. gossypiella* and *E. vittella* strains of Maharashtra, were susceptible to pyrethroids. Hence these compounds may be used to target these pests in this area but only after October, in order to avoid any unintentional targeting of *H. armigera* which occurs as a key pest until late October. Resistance to endosulfan and organophosphates was low to moderate in most of the bollworm strains of Maharashtra and hence these compounds may still be effectively used here.

The current results demonstrate that insecticide resistance is prevalent in the majority of the areas surveyed. Unless a strong resistance management plan is implemented, the problem is likely to become even more severe. Apart from regulation and restriction of the use of insecticides, it may be useful to consider exploring other options such as the use of new molecules that are effective on resistant insects or alternative methods of pest control such as biopesticides and biocontrol agents. Such strategies can reduce the selection pressure of insecticides on the target pests and may help in delaying the further development of resistance.

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References

Anon, 1970. Standard method for detection of insecticide resistance in *Heliothis zea* (Boddie) and *H. virescens* (Fab.). Bull. Entomol. Soc. Am. 16, 147–153.

Armes, N.J., Bond, G.S., Cooter, R.J., 1992a. The laboratory culture and development of *Helicoverpa armigera*. Natural Resources Institute Bulletin 57, Natural Resources Institute, Chatham, UK, 1992, 22pp.

Armes, N.J., Jadhav, D.R., Bond, G.S., King, A.B.S., 1992b. Insecticide resistance in *Helicoverpa armigera* in South India. Pestic. Sci. 34, 355–364.

Armes, N.J., Jadhav, D.R., De Souza, K.R., 1996. A survey of insecticide resistance in *Helicoverpa armigera* in the Indian subcontinent. Bull. Entomol. Res. 86, 499–514.

Armes, N.J., Wightman, J.A., Jadhav, D.R., Ranga Rao, G.V., 1997. Status of insecticide resistance in *Spodoptera litura* in Andhra Pradesh, India. Pestic. Sci. 50, 240–248.

Barlett, A.C., Wolf, W.W., 1985. *Pectinophora gossypiella*. In: Moore, R., Singh, P. (Eds.), Handbook of Insect Rearing, Vol. 2, Elsevier, Amsterdam, pp. 415–430.

Cahill, M., Byrne, F.J., Gorman, K., Denholm, I., Devonshire, A.L., 1995. Pyrethroid and organophosphate resistance in the tobacco whitefly, *Bemisia tabaci* (Homoptera: Aleyrodidae). Bull. Entomol. Res. 85, 181–187.

Cahill, M., Denholm, I., Byrne, F.J., Devonshire, A.L., 1996. Insecticide resistance in *Bemisia tabaci*—current status and implications for management. In: Proceedings, Brighton Crop Protection Conference—Pests and Diseases—British Crop Protection Council, pp. 75–80.

Dhingra, S., Phokela, A., Mehrotra, K.N., 1988. Cypermethrin resistance in the populations of *Heliothis armigera*. National Academy of Sciences, India. Sci. Lett. 11, 123–125.

Dittrich, V., Hassan, S.C., Ernst, G.H., 1985. Sudanese cotton and the whitefly: a case study of the emergence of a new primary pest. Crop Protection 4, 161–176.

Finney, D.J., 1971. Probit Analysis, 3rd Edition. Cambridge University Press, Cambridge.

ICAC, 1998. Survey of the costs of production of raw cotton. International Cotton Advisory Committee, Washington, USA.

ICAC, 1999. Survey of cotton production practices. International Cotton Advisory Committee, Washington, USA.

Jadhav, D.R., Kranthi, K.R., Tawar, K.B., Russell, D.A., 1999. Insecticide resistance scenario on cotton pests in India. Proceedings, ICAC-CCRI Regional Consultation on Insecticide Resistance Management in Cotton. 28 June–1 July 1999, Central Cotton Research Institute, Multan, Pakistan, pp. 103–117.

Jayswal, A.P., 1989. Management of American bollworm on cotton in Andhra Pradesh. Indian Farming, July, 6–7.

Kranthi, K.R., Armes, N.J., Rao, N.G.V., Raj, S., Sundaramurthy, V.T., 1997. Seasonal dynamics of metabolic mechanisms mediating pyrethroid resistance in *Helicoverpa armigera* in Central India. Pestic. Sci. 50, 91–98.

Kranthi, K.R., Jadhav, D., Wanjari, R., Kranthi, S., Russell, D., 2001a. Pyrethroid resistance and mechanisms of resistance in field strains of *Helicoverpa armigera* (Lepidoptera: Noctuidae). J. Econ. Entomol. 94 (1), 254–263.

Kranthi, K.R., Jadhav, D.R., Wanjari, R.R., Shaker Ali, S., Russell, D., 2001b. Carbamate and organophosphate resistance in cotton pests in India, 1995–1999. Bull. Entomol. Res. 91, 37–46.

Li, X.C., Wang, Y.C., Zhang, Q.S., Yu, G.J., Zhang, D.Y., Yang, Y.T., Zhi, Z., Zhang, J.P., Luo, S.S., Chan, C.X., Ding, S.Y., 1997. Insecticide resistance in field strains of *Pectinophora gossypiella* (Saunders) in China and the effect of synergists on deltamethrin and parathion methyl activity. Pestic. Sci. 50 (3), 183–186.

McCaffery, A.R., King, A.B.S., Walker, A.J., El-Nayir, H., 1989. Resistance to synthetic pyrethroids in the bollworm, *Heliothis armigera* from Andhra Pradesh, India. Pestic. Sci. 27, 65–76.

Mukherjee, S.K., 1982. Agrochemicals in India. In: Agrochemicals: Fate in Food and Environment. Symposium proceedings, Rome 7–11 June 1982, IAEA, Vienna, pp. 3–21.

Mukherjee, A.B., Shrivastava, V.S., 1970. Bioassay of relative toxicity of some pesticides to the larvae of *Spodoptera litura* (Fab.) (Lepidoptera: Noctuidae). Indian J. Entomol. 32, 251–255.

Osman, A.A., Watson, T.F., Sivasupramaniam, S., 1991. Susceptibility of field populations of Pink bollworm (Lepidoptera: Gelechiidae) to azinphosmethyl and permethrin and synergism of permethrin. J. Econ. Entomol. 84, 358–362.

Parthasarathy, G., Shameem, 1998. Suicides of cotton farmers in Andhra Pradesh—an exploratory study. Economic and Political Weekly March 28, pp. 720–726.

Paul, A.V.N., Prasad, B., Gautam, R.D., 1987. Artificial diets for *Pectinophora gossypiella* and *Earias vittella* bollworms of cotton. Indian J. Agric. Sci. 57, 89–92.

Puri, S.N., Murthy, K.S., Sharma, O.P., 1999. Integrated pest management for sustainable cotton production. In: Sundaram, V., Basu, A.K., Narayanan, S.S., Krishna Iyer, K.K., Rajendran, T.P. (Eds.), Handbook of Cotton in India. Indian Society of Cotton Improvement, Mumbai, India, pp. 233–245.

Ramakrishnan, N., Saxena, V.S., Dhingra, S., 1984. Insecticide resistance in the population of *Spodoptera litura* (Fab.) in Andhra Pradesh. Pesticides 18, 23–27.

Rao, N.V., Rajasekhar, P., Venkataiah, M., Rama Rao, B., 1994. Cotton pest control problems in Andhra Pradesh, India: optimising pest management options for a more sustainable approach to cotton cultivation. In: Constable, G.A., Forrester, N.W. (Eds.), Proceedings: Challenging the Future, World Cotton Research Conference-1, 14–17 February 1994. Brisbane, Australia, pp. 563–568.

Reed, W., 1994. *Earias* spp. (Lepidoptera; Noctuidae). In: Mathews, G.A., Tunstall, J.P. (Eds), Insect Pests of Cotton. Commonwealth Agricultural Bureau International, UK, pp, pp. 151–176.

Sawicki, R.M., 1987. Definition, detection and documentation of insecticide resistance. In: Ford, M.G., Holloman, D.W., Khambay, B.P.S, Sawicki, R.M. (Eds.), Combating Resistance to Xenobiotics. Ellis Horwood, Chichester, UK, pp. 105–117.

Singh, J., Singh, S., Sohi, A.S., Brar, D.S., Kapoor, S.K., Russell, D.A. 1999. Management of resisitant pests of cotton in North India—an analysis. Proceedings ICAC-CCRI Regional Consultation on Insecticide Resistance Management in Cotton. 28 June–1 July 1999. CCRI, Multan, Pakistan, pp. 131–142.

Snedecor, G.W., Cochran, W.G., 1989. "Statistical Methods", 8th Edition. Iowa State Univ. Press, USA.

Tang, Z.H., Gong, K.Y., You, Z.P., 1988. Present status and countermeasures of insecticide resistance in agricultural pests in China. Pestic. Sci. 23, 189–198.

Vandana, S., Emani, S., Jafri, A.H., 1999. Globalisation and threats to seed security. Case of transgenic cotton trials in India. Economic Political Weekly. March 6–13, pp. 601–613.

Verma, A.N., Verma, N.D., Singh, R., 1971. Chemical control of *Prodenia litura* (Fab.) (Lepidoptera: Noctuidae) on cauliflower. Indian J. Hortic. 28, 240–243.