Chapter 11
Insect Resistance to Insecticides and Bt Cotton in India

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Abstract Yield losses in cotton are often attributed, worldwide, to biotic factors, of which insect pests, categorized as sucking pests and bollworms, are dominant. Insecticides are the most potent tools used against them. Pest management was severely affected when bollworms developed resistance to commonly used insecticides. Transgenic Bt cotton Bollgard and Bollgard II were introduced in India in 2005 and 2006, respectively, to control lepidopteran pests. Cotton crop protection in India, supported by strategic research, made strides beginning in the late 1990s. From a less-rational, calendar-based schedule in the 1980s, today insecticide use is integrated with other components of pest management in a "windows" approach to ensure sustainability, and these programs are comparable with cotton crop protection programs across the world. This chapter briefly documents the advances made in the field of insecticide resistance, including Bt resistance. Stewardship of Bt cotton in India did not facilitate a delay in the development of resistance in target pests. Bt cotton, a promising tool in crop protection, stands threatened with the development of field-evolved resistance to both toxins, Cry1Ac and Cry2Ab, in Bollgard II, by the pink bollworm. In addition, sucking and emerging pests have been reported to limit yields of BGII cotton in specific locations. Dissemination of crop protection strategies is still inadequate. Cotton crop protection needs to be strengthened quickly through an effective network that includes stakeholders, exploiting recent technologies to ensure that rational strategies are disseminated and implemented in the right place and at the right time, for effective pest and crop management, before

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a powerful, expensive, and useful technology such as genetically modified (GM) cotton is rendered unsustainable.

Keywords Cotton · Insecticide · Bt · Resistance · Insect pests

Abbreviations/Terms

$	US dollar
BHC(HCH)	Hexachlorocyclohexane
Bollgard II	Cotton contains two genes derived from the common soil bacterium *Bacillus thuringiensis*
Bt	*Bacillus thuringiensis*
CICR	Central Institute for Cotton Research, Nagpur, India
Cry1Ac	Cry1Ac toxin is a crystal protein produced by the bacterium Bacillus thuringiensis (Bt) during sporulation. Cry1Ac is one of the delta endotoxins produced by this bacterium which acts as an insecticide
Cry2Ab	Pesticidal crystal protein Cry2Ab
DDT	Dichlorodiphenyltrichloroethane
Dissemination	Active spread of innovations/new practices to the target audience using planned strategies
g	Gram
ha	Hectare
HDPS	High density planting system
IARI	Indian Agricultural Research Institute, New Delhi
IPM	Integrated pest management
IRM	Insecticide resistance management
LC_{50}	Lethal concentration 50 (LC_{50}).
Mt.	Metric tons
NPV	Nuclear polyhedrosis virus
RIB	Refuge in Bag, cotton hybrid seeds mixed with the Bt cotton seeds
Rs	Indian Rupee: the official currency of the Republic of India
USA	The United States of America

11.1 Introduction

Cotton is a key commercial crop, the cultivation of which is usually affected by many insect pests and diseases. Insect pests are dominant and occur throughout the season, often requiring input of intensive management, particularly in the tropics. Cotton is cultivated in an area of 12 million ha in India that constitutes 38% of the global cotton acreage. More than 90% of the cotton cultivated in the country comprises Bt cotton (Bollgard II) that expresses Cry1Ac and Cry2Ab toxins of *Bacillus* *thuringiensis* (Bt). Prior to the introduction of Bt cotton, whiteflies and bollworms were the major insect pests. After the introduction of Bt cotton, bollworm infestation became negligible, until 2010, during which pink bollworm developed resistance to the Cry1Ac toxin (Dhurua and Gujar 2011), but jassids, thrips, and whiteflies, however, continued to cause damage. Cotton cultivated in North India was severely affected by insecticide-resistant whiteflies that caused serious economic losses, around an estimated US$ 636 million (Kranthi 2016). Whiteflies transmit the dreaded leaf curl virus disease, which accentuates the damage. Pink bollworm *Pectinophora gossypiella* developed resistance to the two gene variants of Bt cotton, in Central and South India, where it has been causing yield losses since 2013 (Naik et al. 2018). It is now acknowledged that the pink bollworm, whitefly, and the cotton leaf curl virus disease are the major biotic factors affecting cotton production in the country.

11.2 Insecticide Use in India

Insecticide use in India started in the 1950s. Estimates indicate that about 35–50% of the annual average insecticide used was applied on cotton during 1970–2000. Insecticide usage (active ingredients) on cotton varied from 6,863 to 13,176 Mt. at an annual average of 10,665 Mt. during 1996–2004. About 58–71% of the total insecticide use during this period was for bollworm control. As the area under Bt cotton increased after 2004, insecticide usage declined to an average of 6,863 Mt. (4,623–11,598 Mt) during 2005–2013. Insecticide use on cotton during 1996–2004 was 26–40% of the total insecticides used in agriculture in India. The proportion decreased to 15–25% during 2005–2013. Insecticide usage on cotton was reported to have increased during 2014–2017, mainly due to enhanced sucking pest infestation and pink bollworm's resistance to Bt cotton.

11.3 Insecticide Influenced Changes in Insect Pest Dynamics

Prior to 1980, the pink bollworm (*Pectinophora gossypiella*), jassids (*Amrasca biguttula biguttula*), and cotton leafworm (*Spodoptera litura*) were the major insect pests of cotton in India. The main insecticides used on cotton in India during 1950–1990 were BHC, DDT, endosulfan, carbaryl, carbofuran, parathion, dimethoate, monocrotophos, acephate, triazophos, metasystox, chlorpyrifos, and quinalphos. Synthetic pyrethroids were introduced in India in 1981 and used on cotton to control pink bollworm and the cotton leafworm. Indiscriminate use of pyrethroids during the 1980s replaced these pests with the American bollworm *Helicoverpa armigera* and whitefly *Bemisia tabaci*. Outbreaks of American bollworm notably intensified over time and were confirmed in 1978, 1983, 1990, 1995, 1997, 1998, and 2001 (Dhawan et al. 2004). By the early 1990s, *H. armigera* and *B. tabaci* showed high levels of resistance to almost all insecticides recommended for their control. Efforts were stepped up to develop and implement integrated pest management (IPM) and insecticide resistance management (IRM) strategies, mainly to combat the American bollworm and the whitefly. During the mid-1990s, chloronicotinyl insecticides such as imidacloprid, acetamiprid, and thiamethoxam were introduced, initially as seed treatment and later on as foliar sprays for sucking pest control. These insecticides were found to be very effective as seed treatment in protecting seedlings against sap-sucking insects for the first 2 months and as foliar sprays for 15–20 days. Cotton yields started increasing due to the effective protection of the vegetative stage of the crop from sucking pest infestation. During the late 1990s, new chemicals such as rynaxypyr, novaluron, spinosad, indoxacarb, emamectin benzoate, and lufenuron were introduced for the control of the *H. armigera* and *S. litura*. However, with the introduction of Bt cotton in 2002 the demand for these insecticides declined.

11.4 Bt Cotton and Changes in Insect Pest Dynamics

Transgenic Bt cotton containing the crystal (Cry) toxin Cry1Ac, derived from the insect pathogenic bacterium *B. thuringiensis*, was introduced in India in 2002. Bt cotton that expressed two crystal toxins, Cry1Ac and Cry2Ab, was introduced in the country in 2006. In India, the Bt technology was introduced in only hybrid varieties and not in pure line, open-pollinated varieties. Because of their responsiveness to nitrogenous fertilizers and excessive vegetation due to hybrid vigor, hybrid cotton varieties in general were known to be susceptible to aphids, jassids, and a few other sap-sucking insect pests. Experimental evidence showed that, without seed treatment, a vast majority of the Bt cotton hybrids would not have survived the damage caused by sap-sucking insects. Thus, it is widely believed that the chloronicotinyl group of insecticides may have played a major role in the adoption of Bt cotton hybrids and their subsequent near saturation of cotton cultivated area in the country. The introduction of more than 1,000 Bt cotton hybrids, most of which were susceptible to sap-sucking insect pests, led to the emergence of new insect pests such as mirid bugs, tea mosquito bugs, flower bud maggots, thrips, and mealybugs, during 2006–2011. By the mid-2000s, mainly after 2007, the main sap-sucking pests, aphids, jassids, and whiteflies developed resistance to the chloronicotinyl insecticides and other major insecticide groups, thereby leading to enhancement in insecticide use for their control. By 2011, more than 75% of India's cotton area was covered by Bollgard II Bt cotton. The intensive selection pressure led to the development of resistance to Cry toxins in the oligophagous pest, the pink bollworm, which prompted the use of insecticides for its control on Bt cotton. Currently, Gujarat resorts to 6–7 rounds of sprays on BGII cotton.

A similar situation was seen in other countries cultivating Bt cotton. The green mirid (*Creontiades dilutus*), green vegetable bug (*Nezara viridula*), leafhoppers (*Austroasca viridigrisea* and *Amrasca terraereginae*), and thrips (*Thrips tabaci*, *Frankliniella schultzei*, and *Frankliniella occidentalis*) increased in importance in

Australia on Bt cotton (Lei et al. 2003; Wilson et al. 2006). The bug *Lygus hesperus*, which is a sucking insect pest not susceptible to *Bt* proteins, is considered to be the number one pest of cotton in Arizona on the basis of the proportion of the total insecticide sprays targeting it (Ellsworth and Jones 2001; Ellsworth et al. 2007). Wu et al. (2002) observed that populations of a complex of mirid plant bugs (*Adelphocoris suturalis*, *A. lineolatus*, *A. fasciaticollis*, *Lygus lucorum*, and *L. pratensis*) arose dramatically in association with reduced insecticide use in Bt cotton in northern China.

11.5 Insecticide Resistance in Sucking Pests

Among aphids, *Aphis gossypii* was reported to have developed high levels of resistance to the synthetic pyrethroids, organophosphates, and carbamates in China, Hawaii, Australia, France, Pakistan, and other countries (Kung et al. 1961; Furk et al. 1980; Wei et al. 1988; Robert et al. 1994; Deguine 1996; Cheng et al. 1997; Delorme et al. 1997; Zhang et al. 1997; Villatte et al. 1999, Herron et al. 2001; Nibouche et al. 2002; Ahmad et al. 2003; Herron et al. 2003, 2014; Herron and Wilson (2011); Bass et al. 2015).

The jassid *A. biguttula biguttula* was reported to have developed resistance to endosulfan and a range of organophosphate insecticides in India (Santhini and Uthamasamy 1997; Challam and Subbaratnam 1999; Jeyapradeepa 2000; Challam et al. 2001; Praveen 2003). Studies conducted from 2008 to 2017 at CICR Nagpur showed high levels of jassid resistance to neonicotinoids and organophosphates.

Whitefly *Bemisia tabaci* showed high levels of resistance to dimethoate and monocrotophos (Dittrich and Ernst 1983) to buprofezin, imidacloprid, and other organophosphate insecticides in the USA, China, Egypt, Europe, Pakistan, Sudan, and Israel (Cahill et al. 1996; Ahmad et al. 2002; El-Kady and Devine 2003; Horowitz et al. 2004; Dennehy et al. 2005; Wang et al. 2010), as well as to BHC, endosulfan, organophosphates, and carbaryl in India (Prasad et al. 1993), and to methomyl and monocrotophos, with moderate resistance to cypermethrin, in India (Kranthi et al. 2002a, b).

Resistance in the leafhopper and whitefly were quantified more recently against the commonly used insecticides. Insecticide resistance to selected organophosphates, pyrethroids, and neonicotinoids in seven Indian field populations of *B. tabaci* genetic groups Asia-I, Asia-II-1, and Asia-II-7 was reported (Naveen et al. 2017). The variability of the LC_{50} values was 7 times for imidacloprid and thiamethoxam, 5 times for monocrotophos, and 3 times for cypermethrin among the Asia-I, whereas they were 7 times for cypermethrin, 6 times for deltamethrin, and 5 times for imidacloprid within the Asia-II-1 populations. When compared with the most susceptible population, PUSA (Asia-II-7), a substantial increase in resistant ratios was observed in both the populations of Asia-I and Asia-II-1. Evidence of potential control failure was detected using probit analysis estimates for cypermethrin, deltamethrin, monocrotophos, and imidacloprid. Studies conducted at CICR (Rishi Kumar et al., unpublished) during 2014–2017 showed that whitefly populations in North India have acquired resistance to the commonly used insecticides. Resistance ratio varied from 98- to 1,400-fold for bifenthrin 10EC, 14- to 137-fold for dinotefuran 20SG, 60- to 131-fold for acephate 75SP, 21- to 331-fold for acetamiprid 20SP, 153- to 340-fold for fipronil 5SC, 371- to 2,237-fold for triazophos 40EC, 51- to 706-fold for buprofezin 25SC, 9- to 512-fold for imidacloprid 17.8SL, 40- to 347-fold for diafenthiuron, 2- to 19-fold for chlorpyrifos 20EC, 1- to 2-fold for thiamethoxam 30FS, 2- to 7-fold for clothianidin 50WDG, 2- to 23-fold for pyriproxyfen, and 1- to 6-fold for flonicamid.

Resistance ratio to imidacloprid was high, up to 2,089-fold, in leafhopper populations from Jalna, in Maharashtra (Central India), and 7,264-fold with leafhopper populations in the Haveri district of Karnataka (South India). The highest resistance ratio to thiamethoxam was 6,554-fold in the populations of leafhoppers from the Indore district of Madhya Pradesh (Central India) and 13,945-fold in the populations of leafhopper from the Haveri district of Karnataka (South India). Broadly, leafhopper populations in Central and South India were resistant to neonicotinoids, imidacloprid, and thiamethoxam as compared with that in the populations from North India (K.R. Kranthi et al., unpublished). The level of resistance in *A. biguttula biguttula* from Tamil Nadu as revealed by the percent survival, varied from 6.67 (Salem) to 15.38 (Srivilliputhur) for imidacloprid, 3.33 (Salem) to 15.09 (Srivilliputhur) for thiamethoxam, 5.00 (Bhavanisagar) to 20.00 (Srivilliputhur) for acetamiprid, and 5.00 (Bhavanisagar) to 9.09 (Srivilliputhur) for thiacloprid (Preetha et al. 2014).

11.6 Bollworm Resistance to Insecticides and Bt Cotton

The American bollworm, *H. armigera* was found to be resistant to parathion, endosulfan, DDT, organophosphates, pyrethroids, and endrin in Australia (Forrester et al. 1993; Gunning 1993); to carbamate and pyrethroids in Thailand (Ahmad and McCaffery 1988); to organophosphate insecticides (Cheng and Lieu 1996) and spinosad in China (Wang et al. 2009); to deltamethrin in South Africa (Martin et al. 2003); to cypermethrin in Turkey (Ernst and Dittrich 1992); to pyrethroids in Central Africa (Djihinto et al. 2009); and to organophosphates and pyrethroids in Pakistan (Ahmad et al. 1995, 1997). In India, *H. armigera* was reported to have developed high levels of resistance to endosulfan, carbamates, organophosphates, and pyrethroids (Armes et al. 1996; Dhingra et al. 1988; McCaffery et al. 1989; Mehrotra and Phokela 1992; Sekhar et al. 1996: Kranthi et al. 2001a, b; 2002a, b). The corn earworm *Helicoverpa zea* was reported to have developed resistance to Bt cotton in the USA (Tabashnik et al. 2008). Fourteen populations from northern China showed very strong resistance to fenvalerate (from 43- to 830-fold) and low levels of resistance to phoxim (3.0- to 8.9-fold) when compared with the susceptible SCD strain of *H. armigera*, whereas two populations from Northwestern China showed low levels of resistance to fenvalerate (3.0- and 10-fold) and no resistance to phoxim (0.7- and 0.9-fold). In comparison with the resistance in field populations before Bt cotton adoption, a maintenance of high levels of fenvalerate resistance was observed in northern China, with a reversion of phoxim resistance from high levels to low levels, in field populations of *H. armigera* (Yang et al. 2013).

Studies on insecticide resistance in cotton bollworms have been carried out since the 1990s in India (Kranthi et al. 2002a). Pyrethroid resistance was found to be high and constant throughout the cotton season in *H. armigera*. Resistance in the pest built up over the seasons to some insecticides, such as endosulfan, and was correlated with excessive use of that molecule (Kranthi et al. 2002b). Mechanisms and genetics of inheritance of resistance were worked out, and strategies of insecticide resistance management were developed and validated. Protocols were standardized for systematic studies on metabolic enzymes mediating insecticide resistance (Kranthi 2005). Robust repeatable protocols were developed for insecticides and Cry toxin bioassays and for maintaining healthy lab cultures of bollworms (Kranthi et al. 2000).

Resistance of the pink bollworm, *P. gossypiella*, to organophosphates and pyrethroids was reported in the USA (Osman et al. 1991) and China (Xianchun et al. 1997). Spotted bollworm *Earias vittella* was found to be resistant to monocrotophos in India (Kranthi et al. 2002a).

In India, resistance to Cry1Ac-based Bt cotton (Dhurua and Gujar 2011) and to Cry1Ac + Cry2Ab-based Bt cotton (Naik et al. 2018) were reported for the pink bollworm. First evidence, found in 2011, of field-evolved resistance of pink bollworm to Cry1Ac and lack of cross-resistance to Cry2Ab2 suggested that plants producing this toxin were likely to be more effective against resistant populations than plants producing only Cry1Ac. In less than 2 years, field resistance to the 2 gene Bt cotton was reported by Naik and coworkers (2018), where high PBW larval recovery on BGII in conjunction with high LC_{50} values to both Cry1Ac and Cry2Ab were recorded.

Laboratory studies showed that *H. armigera* resistance to Cry1Ac increased by 76-fold at the end of the tenth generation, whereas the unexposed population remained susceptible (Kranthi et al. 2000). Temporal and spatial variations in the expression of Cry1Ac were studied in Bollgard cotton (Kranthi et al. 2005). A decline in toxin expression was recorded as the plants aged. Also certain plant parts, such as the square bracts and boll rind, had significantly lower toxin expression as compared to expression in leaves.

F_2 screening method was used to estimate the frequency of Cry1Ac-resistant alleles in *H. armigera* populations collected from Bangalore, Dharwad, Raichur, and New Delhi (IARI). The F_2 screening results showed that the expected Bt resistance allele frequency in the collected populations was 0.085 with 95% confidence interval of 0.009–0.256, indicating that the F_2 screening method can be used to detect major alleles conferring resistance to Bt cotton in the targeted insect (Kennedy et al. 2017a, b).

A stochastic model, Bt Adapt, was developed to simulate the rate of resistance development in *H. armigera*, using genetic and ecological factors in addition to the response of *H. armigera* to Cry toxins expressed in plants (Kranthi and Kranthi 2004). Protocols were designed at CICR for field evaluation based on the concept of "refuge in bag" (Rishi Kumar et al., unpublished). The "refuge in bag" (RIB) concept was approved by the government through its official Gazette S.O. 4215(E) in 2016, with a Bt cotton RIB seed pack (475 g) with a minimum of 90% and a maximum of 95% seeds positive for each transgene. The 475 g RIB seed packet shall hence contain a minimum of 5% and a maximum 10% of non-Bt cotton seeds. The non-Bt seeds provided along with the Bt hybrid as a separate pack or as a refuge in bag shall be of a non-Bt hybrid isogenic version corresponding to the Bt hybrid or a non-Bt hybrid with similar flowering period and fiber traits as that of the Bt hybrid as per label claim. RIB was formulated to ensure the sustainability of the Bt technology to the other target insect pests.

11.7 Development of Window-Based IRM Strategies

In the late 1980s and early 1990s, cotton pest management in India was based mainly on biological control, where emphasis was placed on the multiplication and release of natural enemies (Rajendran et al. 2005) in an environment that still relied on the use of hazardous chemicals for cotton crop protection. A remarkable change was noticed in the approach to cotton pest management since 1997. IPM strategies were implemented in the village Astha, in Marathwada. Farmers were trained in the use of botanicals, NPV, reducing diversity in the varieties being cultivated in the village, with the adoption of farm operations of sowing and spraying in a synchronous manner. The model, however, did not spread after its initial adoption largely due to the non-availability of recommended inputs. Using the data generated in the lab, insecticide resistance management strategies were developed by CICR to combat insecticide resistance, first in bollworms in 1997, mealybugs in 2007, sucking pests in 2008, and whiteflies and pink bollworm in 2013. Strategies were developed based on robust scientific data on insecticide resistance monitoring and mechanisms mediating resistance, generated under various funded projects. Exploitation of host plant resistance in the first 60 days, thereby avoiding use of broad-spectrum organophosphates against sucking pests and withdrawal of pyrethroids against bollworms, was an important feature in this program. The choice of insecticides was based on their ecotoxicological profiles, ensuring minimal disruption of the cotton ecosystem. A "window" concept of pest management was introduced for the first time in the country, where emphasis was on the conservation of natural enemies, through intelligent selection and use of insecticides on the basis of economic threshold levels instead of calendar-based sprayings. Strategies were fine-tuned for compatibility with Bt cotton. A widespread use of neonicotinoid seed-treated Bt hybrids caused an upsurgence in leafhopper populations. Sucking pest management on Bt cotton, with the emergence of resistance in leafhoppers to the commonly used neonicotinoids, was also addressed. Scientific data generated in the lab, for the first time, was directly made relevant to address the issues of cotton pest management at the farmers' level. Bt resistance management strategies must be implemented henceforth on BGII cotton, to sustain the production of seed cotton.

11.8 Dissemination of Insecticide Resistance Management Strategies

The IRM dissemination program was carried out under the Technology Mission on Cotton Mini Mission II, funded by the Ministry of Agriculture and Farmers' Welfare, Government of India, and linked the Central Institute to state agricultural universities. Nine state coordinators, from national institutes or universities, worked along with the state agricultural departments to supervise the program implementation through 28 district coordinators and 56 research fellows.

The program brought about a radical change in the farmers' perception on the insect pests and native natural enemies of cotton, thereby bringing about a change in the pesticide use. The results of this farmer participatory approach were encouraging, and farmer awareness and reduction in the usage of pesticides in all the districts implementing the program were noticed. Staff for resistance monitoring were trained under the project, and they, in turn, helped farmers take guided decisions on the appropriate choice of insecticides.

In 2013–2014, IRM for high density planting system (HDPS) was introduced. HDPS is a method of growing cotton varieties with more number of plants per unit area. This is in contrast to the Bt hybrid technology, where each plant produces a higher number of bolls. HDPS is recommended for marginal soils in rain-fed regions, where the program was launched to enhance the productivity of cotton. Grown at a spacing of 45 cm or 60 cm between rows and 10 cm between plants, the systems support 1.5 lakh plants/ha, as compared with Bt (11,000 plants/ha). Use of early maturing, sucking pest-tolerant varieties such as PKV081, NH615, and Suraj helped popularize the technology in the rain-fed district of Vidarbha. Because the varieties were non-Bt, necessary bollworm protection needed to be accorded. The technology also aims to fit the boll development stage into the window of available moisture in rain-fed regions, to help overcome moisture stress at boll development stage. HDPS was demonstrated on about 2,000 acres (800 ha, 1 ha = 2.5 acres) showing that, with proper pest management and appropriate production practices, cotton yield from recommended varieties could be equal or more than that in Bt, with a dramatic reduction in input costs, especially in rain-fed regions.

During the period 2007–2011, IRM strategies were disseminated to 1,69,268 farmers in 3,33,883 hectares in 2,922 villages of 28 districts from 10 states across India. Implementation of the program resulted in yield increases estimated at a net additional benefit of ca. US $51.87 million (Rs 2593.6 million, US $1 = ca. Indian Rs. 50 at 2011 average conversion rate) and a saving due to reduction in insecticide use accounting for ca. US $15.26 million (Rs 763 million), thus adding up to a total additional benefit of ca. US $67.13 million (Rs 3356.6 million).

From 2012 to 2015, IRM strategies were disseminated to 24,613 farmers in 12,231 hectares in a total of 445 villages of 22 districts from 10 states across India. Implementation of the program resulted in yield increases estimated at a net additional benefit of ca. US $9.94 million (Rs 656 million, US $1 = ca. Indian Rs. 66 at 2015 conversion rate) and a saving due to reduction in insecticide use accounting for ca. \$1.75 million (Rs 115.6 million), thus adding up to a total additional benefit of ca. \$11.69 (Rs 771.6 million).

11.9 Pink Bollworm Management Strategies for Cotton Including BGII Cotton[1]

Pink bollworm management strategies were devised for implementation in the affected districts of India. The causes for pink bollworm outbreak on BGII cotton were determined and strategies devised for its management.

The major reasons for pink bollworm outbreak were (1) cultivation of large number of long-duration hybrids that serve as continuous hosts to the pink bollworm, (2) long-term storage of raw cotton, (3) early sowing and extended duration of the crop with supplemental irrigation, (4) noncompliance of refugia, and (5) lack of adoption of timely interventions for bollworm infestation on BGII cotton. In addition, squares and flowers have less Bt-toxin expression as compared with that in leaves and seeds. Also, the segregating seeds in bolls of F1 hybrid plants accelerate resistance development. India is the only country in the world that cultivates Bt cotton as hybrid F1 plants, harboring the F1 bolls carry seeds that segregate in the ratio of 9:3:3:1 (Cry1Ac + Cry2Ab in 9; Cry2Ab alone in 3; Cry1Ac in 3; and none in 1). Thus a spectrum of non-Bt seeds, seeds with Cry1Ac alone, seeds with Cry2Ab alone, and seeds with Cry1Ac + Cry2Ab is present in a single boll. This situation is ideal for resistance development, due to the selection for resistance to independent toxins. The segregation pattern is further affected by the unauthorized cultivation of BGII hybrids of F2 and F3 generations.

IRM programs consider fine-tuned regular pest surveillance, resistance monitoring, and monitoring of field efficacy in bollworms to ensure that Bt cotton continues to be effective for the longest possible time. Management strategies relying on the following approaches in an area-wide manner are:

(a) Regular monitoring of bollworm resistance to Bt cotton, including Bollgard II.
(b) Use of the parasitoid *Trichogramma bactriae* in Bt cotton fields, for pink bollworm management.
(c) Refugia: recommend planting of *desi* (*G. herbaceum*)/conventional non-Bt *G. hirsutum* cotton and late-planted okra as refugia crop.
(d) Timely termination of the crop latest by December, avoiding ratoon and/or extended crop.
(e) Utilization or destruction of crop residues and cotton stalks immediately after harvest.
(f) Crop rotation strongly recommended to break the pest cycle.
(g) Use of short-duration, single-pick varieties (150 days) that provide high yields in high density and escape the pink bollworm.

[1] See also http://www.cicr.org.in/pdf/Kranthi_art/Pinkbollworm.pdf.

(h) Installation of light traps (timer operated) and pheromone traps in fields during the season and also near load areas, ginning mills, market yards, etc., to trap post-season moths.
(i) Mass trapping and mating disruption using pheromone traps. Use of "pheromone traps" and "green boll dissection" for regular monitoring and initiation of control interventions, based on economic threshold levels of eight moths/trap/night and/or 10% damage in green bolls.
(j) Utilization of insecticides such as quinalphos in early stages and synthetic pyrethroids after October at economic threshold levels of damage.
(k) Strictly avoiding spraying pyrethroids before November, or acephate, fipronil, or any insecticide mixtures at any time to prevent whitefly outbreaks.
(l) Select hybrids/varieties that are tolerant to sucking pests.

The USA recently celebrated successful eradication of the pink bollworm (https://www.usda.gov/sites/default/files/documents/usda-pink-bollworm-proclamation.pdf). Impeccable planning and area-wide implementation of strategies for its management was evidenced during the entire program. The exercise was grower driven, involved extensive surveys, incorporated Bt cotton varieties as a management tool, used pheromones for monitoring, mass trapping, and mating disruption. Sterile moth release along with cultural practices such as mandatory crop termination (closed season), destruction of crop residues, shredding stalks, disking, ploughing, and winter irrigation were followed over phase I, phase II, phase IIIa, phase IIIb, and containment where phases denoted particular mapped areas where the area-wide approach was executed. The United States Department of Agriculture, state departments of agriculture in Arizona, California, New Mexico, and Texas adopted these approaches even before the pink bollworm developed resistance to the Cry toxins. With the pink bollworm having developed resistance to Cry toxins in India, area-wide management approaches ought to be focused and executed even in years of low incidence as an outbreak of resistant pink bollworms would not only impact seed cotton yield and its quality, but would also render a major tool (Bt cotton) useless in the Indian cotton scenario.

11.10 Conclusion

To summarize, cotton crop protection has considerably progressed since the early 1990s in India. The technology/strategies were not only relevant and timely but were also sustainable. Scientific lab experiments directly contributed to the evolution of sustainable strategies and technologies that were evaluated in multiple locations. The most significant achievement was the ability of cotton scientists of the country to work together as a team in funded programs in an effort to contribute to area-wide cotton crop protection, fine tuned to location-specific strategies if necessary, for the welfare of cotton farmers. Unexpected pest control failures, despite technologies and strategies being in place, were due to reasons other than failure of the technology itself.

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