INSECTICIDE RESISTANCE MANAGEMENT IN COTTON TO ENHANCE PRODUCTIVITY

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Abstract

Over the past five decades, insect pest management in cotton has been the most challenging aspect of applied entomology. Insecticide use has been causing undesirable ecological and economic consequences for cotton cultivators and administrators in many countries. Individual insecticide molecules when first introduced have always been impressive in their rapid efficacy in controlling target insect pests but invariably had inadvertent adverse effects on naturally occurring beneficial insects. As long the target pests were effectively controlled with the pesticide, cultivators would not care for the naturally occurring predators and parasites in their ecosystems. But, usually phytophagous target pests develop resistance much faster than entomophages, thereby causing pest populations to survive the pesticide, increase in numbers in the absence of natural control to cause outbreaks. Cotton crop has been subjected to maximum pesticide exposure than any other crop, in all cotton growing countries of the world. Intense insecticide use resulted in insect resistance to insecticides, pesticide residues, and resurgence of minor pests and caused immense problems to cultivators. With the most reliable tools turning redundant, pest management experts started exploring the utility of naturally occurring pest control components as alternatives to replace the chemical insecticides. Thus, Integrated Pest Management (IPM) programmes began to take shape as ‘intelligent selection and use of pest management tactics that results in favorable ecological, sociological and environmental consequences’ as defined by Rabb, (1972). Insecticide Resistance Management strategies have strengthened pest management systems by identifying appropriate insecticides so as to delay resistance, ensure effective control of target pests, and conserve naturally occurring biological control for enhanced sustainability of ecosystems. With the recent introduction of Bt-cotton, novel eco-friendly pesticides and IRM strategies coupled with the trends in technology dissemination through area-wide farmer participatory approaches and Farmer field schools, IPM programmes all over the world have become successful and sustainable.

Key words: IPM, IRM, Bt-cotton, Helicoverpa armigera, Insecticide Resistance

Introduction

It is estimated that cotton cultivation consumes at least 10% of all insecticides used globally. Pesticides worth US $ 600 M are used annually in India for pest management, of which, nearly 50% of the total insecticides used are applied on cotton crop alone, which occupies only 5% of the total cropping area in the country (Ghosh, 2001). Cotton pest management has always been an immensely challenging task for entomologists all over the world. About 1326 species of insects have been reported on
cotton worldwide (Matthews and Tunstall, 1994). World over, cotton crop suffers severe economic damage from several insect pests, most importantly the bollworms, *Helicoverpa armigera*, *Heliothis virescens*, *Helicoverpa zea*, *Pectinophora gossypiella*, *Earias vittella*, *Earias insulana*, *Diparopsis* sp, the leaf feeding lepidopteran species, *Spodoptera*, *Bucculatrix thurberiella*, *Alabama argillacea*, *Sylepta derogata*, *Anomis flava*, Hemipterous bugs, *Lygus* sp, *Dysdercus* sp, mirids and pentatomid bugs and sucking pests such as jassids, whiteflies, thrips and aphids. Several species apart from these, particularly weevils, rootworms, stem borers, termites, cut worms etc. are also known to cause significant damage in many countries. Conventional insect pest control strategies rely heavily on insecticides. Over the past two decades, the perplexities in pest management intensified with more and more insect species developing resistance to insecticides. Cotton pest management was particularly affected due to insecticide resistance, which was a consequence of excessive use of insecticides on the crop. Insecticide resistance rendered insecticides ineffective, thus increasing the need for repeated applications, wastage of resources and consequent environmental pollution. Several efforts were made all over the world to devise region specific integrated pest management (IPM) systems. However, poor efficacy of insecticides due to insecticide resistance in insects, and performance inconsistencies of biopesticides and biological control have been making IPM unsustainable. The introduction of insect resistant GM (genetically modified) cotton, especially Bt-cotton represents the latest of the various methods being constantly deployed to fight the insect pest menace in cotton.

**Historical Perspective of Cotton IPM**

Cotton being a commercial crop was always subjected to intense human interventions so as to ensure maximum profitability. Over the past five decades cotton cultivators had to rely on the conventional groups of insecticides such as organochlorines (DDT, BHC), cyclodienes (aldrin, dieldrin, endosulfan), organophosphates (monocrotophos, quinalphos, chlorpyriphos, profenofos, dimethoate, phosalone, metasystox, acephate, phorate, methyl parathion etc.), carbamates (carbosulfan, carbaryl, thiodicarb, methomyl) pyrethroids (cypermethrin, deltamethrin, fenvalerate, λ-cyhalothrin, etc.) and formamidines (chlorpyrifos and amitraz). All these insecticides disrupt naturally occurring beneficial insect populations to variable extents. History shows that excessive and indiscriminate insecticide use representing ‘exploitation phase’ was invariably followed by ‘crisis’ and ‘disaster’ phases in cotton, thereby leading to problems of insecticide resistance, pest resurgence, accumulation of harmful residues and toxicity to non-target organisms. Subsequently non-insecticidal alternative methods of eco-friendly pest management are developed. Thus cotton IPM programmes were built around cultural control, biological control and biopesticide interventions in many parts of the world. The pest spectrum on cotton before 1980 comprised mainly of the pink bollworm, spotted bollworm and *Spodoptera litura* as the major insect pests. The American bollworm *Helicoverpa armigera* was mentioned as ‘not a regular or a serious pest’ of cotton in India (Nair, 1981). Standard recommendations for sucking pest control included carbofuran granules, dimethoate and metasystox. Bollworms and other lepidopteran insects were controlled with methyl parathion dust, quinalphos and...
chlorpyriphos. During the late 1970s, *Spodoptera litura* was found to exhibit resistance to several conventional insecticides recommended for its control (Ramakrishnan *et al*., 1984). The synthetic pyrethroids were introduced into India and several other countries in 1980 to control the major pests of cotton, especially the leafworm, *Spodoptera litura*. During 1980-85, synthetic pyrethroids, which were found to be highly effective on a wide range of insect pests at low dose application per unit area, occupied center stage. But their utility started diminishing by 1986-87 when insecticide resistance was recognised as a major contributory factor to pest control difficulties or failures especially in 1987 in India in the coastal belt of Andhra pradesh. It is not known if the introduction of synthetic pyrethroids was the main cause, but within the subsequent 2-3 years, *H. armigera* and the whitefly, *Bemisia tabaci* (Gemm.) emerged as the major pests in place of the earlier species. The American bollworm *Helicoverpa armigera* was found to survive and cause extensive damage to cotton crop despite repeated applications of insecticides of even up to 30 sprays. The pest later continued to cause heavy economic losses to other crops such as chickpea and pigeonpea and was found to withstand a sustained insecticide pressure. High levels of resistance to synthetic pyrethroids were subsequently confirmed by Dhingra *et al*. (1988) and McCaffery *et al*. (1989) as a major cause of control failures. Cotton crop worth US $ 100 M was lost to this insect pest in Andhra pradesh alone, which led to a severe crisis in the state.

The decade 1990-2000 was most difficult for cotton pest management. Excessive use of insecticides, especially synthetic pyrethroids, led to problems of insecticide resistance in *Helicoverpa armigera* and *Spodoptera litura*, which further necessitated the repeated application of insecticides. The first few reports related to high levels of *H. armigera* resistance to pyrethroids and DDT. Mehrotra and Phokela 1992; Armes *et al*. 1992, 1996; Sekhar *et al*. 1996 reported high levels of pyrethroid resistance in several cotton and pulse growing regions of the country. Subsequent studies (Armes *et al*., 1992, 1996; Kranthi *et al*., 2001a, 2001b, 2002a and 2002b) showed that resistance to pyrethroids was ubiquitous and resistance in *H. armigera* to conventional insecticides such as methomyl, endosulfan and quinalphos was increasing in India. Due to unsatisfactory insect control on account of insecticide resistance, farmers were forced to spray repeatedly, most often with mixtures. By 1992, *H. armigera* resistance to insecticides had emerged as a great challenge to cotton pest management in Asia and Australia. Subsequently, a number of IPM programmes, based on a combination of cultural control methods, pheromones and calender applications of biopesticides/bioagents interspersed with need based application of insecticides, were initiated all over the world in all cotton growing countries to ensure effective bollworm management. However, due to the non-availability of good quality biopesticides and biological control organisms, coupled with sub-optimal efficacy under field conditions, cotton cultivators had to depend on insecticides. Since, insect resistance to insecticides had emerged as a major threat to pest control programmes, thereby rendering insect pest control ineffective, inefficient and unsustainable, IPM packages were refined to include IRM (Insecticide Resistance Management) as a major component. IRM was more relevant to the management of crisis caused by insect resistance to insecticides. Therefore specific IRM programmes were designed for regions affected by severe resistance problem. Clearly IPM was seen as a proactive method with emphasis on biopesticide and biological control
interventions, whereas IRM was meant to overcome the existing ‘resistance’ crisis through specific strategies to ensure efficient pest control and mitigate the problem of resistance. Governments, especially in India, wholeheartedly supported the IPM/IRM initiatives. By the late nineties insect resistant GM (genetically modified) Bt-cotton was introduced for bollworm control in major cotton growing countries such as the USA, Australia, China. Bt-cotton was introduced in India in 2002. The technology was so potent that within 3-4 years of its introduction, the area under Bt-cotton increased to more than 50% in almost all the countries. Thereafter there were changes in the cropping patterns, ecosystems comprising pest spectrum and the associated parasite, predator complex, thus altering IPM perspectives significantly.

Cotton pest management underwent a radical change after 2000 all over the world. With the introduction of novel eco-friendly insecticides that were highly effective on bollworms, Helicoverpa armigera and other bollworms were no longer being perceived as intractable problems. Apart from the introduction of Cry toxins in the form of transgenic Bt-cotton technology, chemicals such as spinosad, indoxacarb, emamectin benzoate, novaluron and lufenuron ensured effective control of H. armigera while being less toxic to beneficial insects in the cotton ecosystem. Interestingly, H. armigera infestation ceased significantly in cotton ecosystems since 2000, to the point of non-existence in some parts of India. It is not clear whether it was the introduction of Bt-cotton or the change in insecticide use pattern in Asia, notably the decrease in pyrethroids, coupled with increase in the new chemistries which impose fitness problems in residual surviving populations, which caused the change, but H. armigera populations rarely exceeded economic threshold levels in Asia, particularly in majority of the cotton growing regions of India. Additionally, the chloronicotinyls (imidacloprid, acetamiprid and thiomethoxam) and the insect growth regulator diafenthiuron, which are selectively more effective on the sucking pests and less toxic to beneficial insects as compared to all the conventional insecticides added to sustainable pest management. However, it must be remembered that overuse of any of these molecules with scant regard for the principles of insecticide resistance management can lead to the development of pest resistance to the insecticides. The chloronicotinyl insecticides have been used to treat seeds ever since 1998, thus preventing sucking pest damage on seedlings up to 50-60 days after sowing. However, recent observations during the 2004-06 cropping seasons showed that the benefit of seed treatment was short lived and rarely extended beyond 20-30 days after sowing. In some cases sucking pests such as jassids continued their damage despite seed treatment. After the introduction of Bt-cotton, due to the reduction of insecticide sprays, especially during flowering and boll formation phase, some minor pests (Spodoptera litura, mealy bugs, mirid bugs, thrips, jassids, weevils etc), which are not susceptible to Cry1Ac showed resurgence in many parts of the world. Resistance management strategies have been revised from time to time in light of the introduction of Bt cotton and new insecticides. Primarily the resistance management principles involved in the strategies have been based on use of a ‘refuge’ area under non-Bt cotton and a rational and sensible sequence of insecticides that are effective on the target species, cause less disturbance to beneficial fauna and minimize selection pressure and rotation of insecticide group based on unrelated resistance mechanisms.
Insecticide Resistance and its Management

Cotton insect pests, exposed to repeated application of toxic insecticides of a number of types over many years, have been amongst the most important pests to develop resistance, which has reduced the efficacy of the sprayed insecticides. Though *H. armigera* resistance to insecticides has been a significant concern for well over two decades since 1985, insecticide resistance in sucking pests of cotton was also found to threaten sustainable pest management.

Insecticide resistance in sucking pests

Resistance to organophosphates in aphids, *Aphis gossypii* was first reported in 1964 itself (Kung *et al.*, 1961). Aphids were reported to be resistant to endosulfan, cypermethrin, deltamethrin and fenvalerate (Villate *et al*., 1998, Wei *et al.* 1988, Zhang *et al*., 1997, Ahmed *et al*., 1999, Herron *et al*., 2001 Delorme *et al*., 1997), monocrotophos and dimethoate (Deguine, 1996, Nibouche *et al*., 2002), and carbamates (Furk *et al*., 1980, Bobert *et al*., 1994). Leaf hopper, *Empoasca devastans* was reported to have developed resistance to endosulfan, monocrotophos, cypermethrin, phosphamidon, dimethoate, methyl demeton and acephate (Santhini and Uthamasamy, 1997, Chalam and Subbaratnam, 1999 and Jeyapradeepa, 2000). By 1985, aphids evolved resistance of 126 fold for deltamethrin and 412 fold for Fenvalerate (Wei *et al*., 1988). High level of resistance was detected in cotton aphids from Xinjiang (766 fold) and Shandong (1835 fold) during 1995-96 (Cheng *et al*., 1997). The aphid population of western Australia displayed extreme resistance leading to control failure experiences with a serious impact on cotton industries reported by Herron *et al*., (2001). A resistance factor of 1350 was observed (Delorme *et al*., 1997) for primicarb in *A. gossypii* populations in southern France. In laboratory toxicity studies aphids revealed resistance to Monocrotophos and dimethoate indicate development of resistance in aphids in Cameroon since 1993, according to Deguine (1996). The resistance ratio in thirteen population of aphids from Hawaii ranged from 96 to 2116 as reported by Bobert *et al*., (1994). Dittrich and Ernest (1983) showed that sudanese field strains of *B. tabaci* were highly resistant to dimethoate and monocrotophos. Cahill *et al*., (1996) reported resistance to monocrotophos and other organophosphate insecticides in *B. tabaci* strains from USA, central America, Europe, Pakistan, Sudan and Israel. Resistance to promising insecticide introduced earlier for control of *B. tabaci* such as buprofezin and imidacloprid had already been detected in localized area (Cahill *et al*., 1996). High resistance levels to monocrotophos during 1992-96 were lowered considerably by 2000 due to less reliance on their insecticides for whitefly control in Pakistan (Ahmed *et al*., 2002). The cotton leafhopper *Amrasca devastans* was found to have developed resistance to the recommended organophosphate insecticides, metasystox, diamethoate and phosphamidon in India (Santhini and Uthamasamy 1997, Chalam and Subbaratnam 1999, Chalam *et al*., 2001, Praveen, 2003). The whitefly *Bemisia tabaci* was found resistant to BHC, Endosulfan, Diamethoate, Phosalone, Acephate, Monocrotophos, Quinalphos and carbaryl (Prasad *et al*., 1993). Field strains of *B. tabaci* collected from 22 cotton growing district across India exhibited high level of resistance to methomyl and monocrotophos and moderate resistance to Cypermethrin (Kranthi *et al*., 2002a).
Insecticide resistance in lepidoptera

Until the late 1980s, resistance to organophosphates was almost negligible with highest resistance factors of 9-fold to quinalphos, and 3-fold to monocrotophos in *H. armigera* in India (McCaffery *et al*., 1989; Armes *et al*., 1992). Later, Armes *et al*., (1996) reported the absence of resistance to monocrotophos, but observed resistance levels of up to 59-fold to quinalphos and >30-fold to methomyl in *H. armigera* field strains in India. Kranthi *et al*., (2001a) reported high levels of *H. armigera* resistance to Monocrotophos (65-fold); Chlorpyrifos (82-fold); Quinalphos (15-fold) and Methomyl (22-fold). In China, *H. armigera* strains which were susceptible to monocrotophos until 1993 (Wu *et al*., 1995) exhibited higher levels of resistance in 1995 (Wu *et al*., 1996). High levels of >300-fold resistance to methomyl and >200-fold to monocrotophos were reported from China (Cheng & Liu, 1996, Ren *et al*, 2002) and 720-fold resistance to monocrotophos in Pakistan (Ahmad *et al*., 1995). Resistance levels to endosulfan have generally varied at moderate levels of 4 to 37-fold in India (Armes *et al*. 1996, McCaffery *et al*. 1989, Kranthi *et al*. 2001a).

*H. armigera* resistance to cypermethrin was first reported in Thailand (McCaffery *et al*., 1988). Subsequent reports include, resistance levels of 25 to 205-fold to five pyrethroids in Pakistan (Ahmad *et al*. 1997), 17-fold to cypermethrin in Turkey (Ernst and Dittrich 1992), 1361-fold to fenvalerate and 56,911-fold to deltamethrin in China (Shen *et al*. 1993; Cheng and Liu 1996), 6-fold to fenvalerate in Australia (Gunning 1993) and 189-fold to deltamethrin in South Africa (Martin *et al*., 2003). In India, reports (Dhingra *et al*. 1988; McCaffery *et al*. 1989) on *H. armigera* development of resistance to pyrethroids, attributed field control failures to resistance. Subsequently, high levels of pyrethroid resistance were reported in several cotton and pulse growing regions of the country (Mehrotra and Phokela 1992; Armes *et al*. 1992, 1996; Sekhar *et al*. 1996). Based on a survey conducted during 1991-95, it was concluded that resistance to pyrethroids was ubiquitous across the Indian sub-continent (Armes *et al*. 1996). A follow up survey (Kranthi *et al*. 2001a, 2001b, 2002a and 2002b) showed that insect resistance to insecticides was indeed a critical problem in several parts of the country.

In general, reports of *P. gossypiella* resistance to insecticides have been rare. For example, Tang *et al*., (1988) could not find any evidence of insecticide resistance in *P. gossypiella* in China. However, resistance to azinphosmethyl and permethrin was reported from strains collected in Arizona and California (Osman *et al*., 1991). Resistance in *E. vittella* was > 70-fold to monocrotophos in Sriganganagar and Sirsa strains of north India (Kranthi *et al*., 2002a). Resistance in *Spodoptera litura* to endosulfan, carbaryl and malathion was reported in field strains from Haryana (Verma *et al*., 1971), West Bengal (Mukherjee & Srivastava, 1970) and Andhra Pradesh (Ramakrishnan *et al*., 1984). Armes *et al*., (1996) reported resistance levels of up to 13-fold to quinalphos, 362-fold to monocrotophos and 19-fold to methomyl, in Indian strains of *S. litura*. 
Resistance management

Globally, all insecticide resistance management (IRM) strategies have been designed with emphasis on efficient use of insecticides to conserve the ecosystem for better pest management. In essence, all IRM strategies aim at optimising the use of insecticides in a manner that maximizes their efficacy, minimizes intensity of selection pressure, and mitigates the adverse effect on ecosystems and the environment. The tactics of enhancing efficacy include transient measures such as either the use of synergists or mixtures; or use of least resisted conventional insecticides or new chemistries; or targeting vulnerable stages of the pest. Strategies to minimize selection pressure include either rotation of insecticide groups over space and or time, or use of alternative options such as bio-pesticides or ecosystem management or biological control or reduce application frequency. Currently, many countries have devised IRM strategies that combine the best of all pragmatic resistant management theories amalgamated with conventional IPM tactics to forge a sustainable method of pest management (Russell, 2004).

The Indian IPM/IRM strategies are designed to reduce the dependence on insecticides and are based on the use of a rational and sensible sequence of insecticides that are effective on the target species, cause least disturbance to beneficial fauna and minimize selection pressure. The strategies include, cultivation of sucking pest tolerant genotypes and chemical seed treatment to help in delaying the first spray, thereby conserving the initial build-up of natural enemies (Kairon and Kranthi 1998). After the introduction of Bt cotton, the strategies were revised to further minimise insecticide spray applications so as to move towards eco-friendly systems of pest management. Avoidance of organophosphate (especially, monocrotophos, methyl demeton, phosphomidan, and acephate) as sprays, Trichogramma releases and Bt spray applications on Bt-cotton. Since chloronicotinyl insecticides are used as seed treatment, any further use either as sprays or through stem application is discouraged, to minimize selection pressure. Sucking pest control is carried out either with neem oil sprays, soil application of acephate or with dimethoate as stem application to control aphids, jassids, thrips, mirid bugs and mealy bugs. Initial infestation of whiteflies, Spodoptera and H.armigera at 60-90 days after sowing (DAS), is managed with either neem oil + neem seed extracts, NPV or endosulfan. If biological pesticides such as Verticillium lecanii or Metarhizium anisopliae, are available these are preferred. Thiodicarb is recommended for bollworm control during 90-120 DAS and pyrethroids are used for pink bollworm management after 120 DAS. Expensive insecticides such as spinosad, emamectin and indoxacarb are recommended for irrigated regions with high input use, wherein bollworm infestations are more severe.

The following resistance management strategies have been revised in light of the recent introduction of Bt cotton and new insecticides. Primarily the resistance management principles involved in the strategies are based on use of a rational and sensible sequence of insecticides that are effective on the target species, cause less disturbance to beneficial fauna and minimize selection pressure and rotation of insecticide group based on unrelated resistance mechanisms. The sequence of
insecticides suggested herein has been developed based on the resistance risk assessment, pest control efficacy, ecological selectivity (based on International organization of biological control, IOBC rating) and environmental risk assessment (based on environmental impact quotient, EIQ rating) (Kranthi et al., unpublished).

**IRM strategies for 2007-08**

**Early sucking pests: NO FOLIAR SPRAY up to 60 DAS**

1. **Cultivation of sucking pest tolerant genotypes (Bt-cotton or non-Bt)** to help in delaying the first spray, thereby conserving the initial build-up of natural enemies. There are several Bt-cotton hybrids, which are highly tolerant to jassids, aphids and other sucking pests.

2. **Inter-cropping with cowpea, soybean and blackgram** to encourage predators of sucking pests in the cotton eco-system.

3. **Avoidance of chloronicotinyl and organophosphate sprays for sucking pest control.** All commercial hybrid seeds available in the market are treated with Gaucho or its equivalent. At the time of introduction, Gaucho seed treatment was found to confer protection against jassids and other sucking pests up to at least 40-45 days after sowing (DAS). Experimental data indicate that now the protections last for 20-25 DAS. Therefore, it is important to avoid the use of Confidor and related chloronicotinyls as foliar sprays so as to prevent further additional selection pressure. Avoid foliar sprays of broad spectrum organophosphates such as Monocrotophos, Methyl demeton, Phosphomidon, Acephate etc. especially as early season sprays as these strongly disrupt the natural enemy populations.

4. **Stem application or soil application** (near the root zone) of dimethoate or acephate at 30-40 DAS and 50-60 DAS for effective eco-friendly control of thrips, mirid bugs, mealy bugs and other sucking pests.

5. **Neem oil 2.5 lit/ha mixed with 0.1% Nirma washing soap powder** can be used for the management of jassids or whitefly or aphids.

6. **Verticillium lecanii** can be used for sucking pest control wherever good formulations are available from reliable manufacturers.

**Window 1: 60-90 DAS: Initial bollworm infestation: Mostly eggs and young larvae: biological and biopesticides window**

7. **Use HaNPV on Bt-cotton at 50% bollworm infested plants (plants having flared squares with entry hole) followed by the application of 5% NSKE a week later.**

8. **Or, use endosulfan** at 50% bollworm infested plants (plants having flared squares with entry hole) or for the management of Spodoptera or whitefly.

9. **Do not spray against minor lepidopteran insects** such as the cotton leaf folder, *Sylepta derogata* and cotton semilooper, *Anomis flava*. The larvae cause negligible damage to cotton but serve as hosts for parasitoids such as *Trichogramma* spp., *Apanteles* spp and *Sysiropa formosa*, that attack *H. armigera*. 
10. *Trichogramma*, if available, can be used on non-Bt genotypes at 70-80 DAS. Avoid *Trichogramma* egg parasitoid releases on Bt-cotton since maximum neonates get killed on Bt-cotton and with *Trichogramma* application becoming superfluous.

11. **Do not spray Bt-formulations on Bt cotton** to avoid further selection pressure.

12. **Use Spinosad or Emamectin benzoate on only non-Bt-cotton** at ETLs of 50% infested plants (plants having flared squares with entry hole). **Avoid these insecticides on Bt-cotton** so that the efficacy of these insecticides can be preserved for bollworm control in non-Bt cotton. Excessive use of these expensive insecticides both on Bt-and non-Bt cotton can hasten the development of bollworm resistance to the chemicals. Spinosad, Emamectin benzoate and Indoxacarb are highly effective on pyrethroid resistant *H. armigera*. Apart from their toxicity to *H. armigera*, Spinosad and Emamectin benzoate are also effective on *E. vittella* and jassids and hence are preferred first over indoxacarb. Both insecticides have a high selective toxicity towards the target pests while being less toxic to many beneficial insects in the cotton ecosystem. These insecticides are ideally suited in eco-sustainable insecticide resistance management programmes.

**Window 2: 90-120 DAS: Peak bollworm infestation**

13. **Use Indoxacarb once only on non-Bt cotton** for bollworm control at ETLs of 90-100 % plants showing flared up squares: Thus far there is no evidence of any resistance against Spinosad, Emamectin benzoate or Indoxacarb. However, if the molecules are overused, there is every likely chance that resistance will render the molecules less useful. The three insecticides are expensive. Emamectin costs about Rs 1900/ha, Indoxacarb at Rs 1650/ha and Spinosad at Rs 1200/ha. Therefore care must be taken to ensure that these recommendations are made only in high input systems (generally irrigated), wherein the yields are high and these pesticides are affordable.

14. **Use organophosphates or carbamates only once either on Bt or non-Bt cotton** as effective larvicides for bollworm control at ETLs of 90-100 % plants showing flared up squares. Resistance levels against certain organophosphate group of insecticides (Quinalphos, Chlorpyriphos & Profenophos) and carbamates (Thiodicarb and methomyl) have been found to be low in most populations tested. These insecticides are very effective for bollworm control but have low ecological selectivity and can be harmful to beneficial insects. The populations of beneficial insects in cotton ecosystem are generally low in later part of this window and hence the application of organophosphates and carbamates is rational.

**Window 3: Pink bollworm: >120 DAS: Pyrethroids**

15. ETL based spray: Eight pink bollworm moths per trap per night for 3 consecutive nights. The application of pyrethroids as late season sprays would be effective for pink bollworm management. Pyrethroid resistance in *H. armigera* is generally high, but pyrethroids are very effective against pink and spotted bollworms and are ideally suited for the late season window.
Mealy bug management strategies

Mealy bug infestation can be menacing, since these are not very amenable for insecticide control. The best options therefore center around cultural and biological control methods. Weeds serve as host plant therefore they should be eradicated regularly. The severely infested plants must be cut and burnt immediately and field should be ploughed to kill immature stages available in the soil. Use of neem oil (1 litre + 100 gm detergent soap powder) has been found to be useful in reducing mealy bug populations significantly. Biological control using the coccinellid predator Cryptolaemus montrouzieri and the parasites Anagyrus kamali and Gyranusoidea indica can be effective to mitigate the problem. At present, 21 parasites and 41 predators are known to attack this pest worldwide. Chemical control is the least preferred option. Insecticides such as profenophos, acephate, chlorpyriphos, imidacloprid and thiomethoxam have been commonly recommended by various researchers, but need to be scrutinized properly through experimentation to ascertain the adverse effects on the ecology that keeps mealy bugs under control.

Basic operations to ensure minimum pest problems in cotton.

1. **Destruction of crop residues** to prevent carry over of pest populations and summer ploughing to destroy resting stage insect populations. Especially useful for pink bollworm management. Immediately after the season allow animal grazing in fields and ensure timely removal and destruction of cotton stubbles, followed by deep ploughing to expose the carry-over population of bollworms. Do not stack cotton stalks near fields.

2. **Avoid growing American cotton in orchards** as it favours whitefly and mealy bug outbreaks. Grow only arboreum cotton or CLCV resistant varieties in CLCV hot-spot areas. Only recommended varieties/hybrids from reliable sources must be procured. Avoid growing tur, moong and bhendi in and around cotton field as these harbour insect pests. Off-season hosts must be discouraged. Weeds such as Sida sp., Abutilon sp and Xanthium sp. must be uprooted to prevent initial build-up of spotted bollworm, whitefly and CLCV.

3. **Hybrids must be grown in medium –deep soils having good drainage.** Apply 5-10 tonnes of well decomposed compost or FYM /ha before sowing. Delint the seed with 100 ml sulphuric acid /kg seed for two minutes, wash with water and soak for two minutes in Calcium carbonate (5g/ltr water). Treat seeds with Ceresan wet or Agallol @ 1 g/ltr water, Captan or carbendazim @ 2g/kg, imidacloprid or thiomethoxam. Early sowing on ridges and furrows, especially in areas with drip facility, could be adopted. Sowing must be completed by the third week of May in North India and mid July for central and south India (except Tamilnadu). Sowing can be done at a row spacing of 67.5 cm with 30 cm plant-plant spacing or preferably wider for varieties and 75cm for hybrids.
4. **Application of weedicide Stomp 30EC or Basalin @45EC 2.5 lt/ha and harrow immediately to prevent degradation. Harrowing must be done twice after pre-monsoon showers and field should be levelled.**

5. **Apply fertilizers considering the crop history**, previous crop and its fertilizer use pattern. Nitrogen rates recommended for G. hirsutum varieties range from 40-60 Kg/ha in rainfed and 60-90 Kg/ha in irrigated cotton. For hybrids, 90 Kg/ha in rainfed and 100-120 Kg/ha in irrigated. P and K doses depend on soil test values or in their absence N:P:K is used at a ratio of 2:1:1.

6. **Foliar spray of Urea 1% 70-80 DAS, followed by DAP 2% at 80-90 DAS and soil drenching with Bavistin 1 % to reduce the problem of wilt.**

7. **Gap filling must be completed within 10 days after sowing.** Thinning should be done within 20 days after sowing. First hoeing can be done 30-40 days after sowing followed by second after 15-20 days.

8. **Spotted bollworm** can cause damage to growing points initially, hence **scouting is necessary** during the first two months and removal of affected parts helps in minimizing future damage.

9. **De-topping at 70-80 DAS** effectively removes bollworm eggs and terminal parts affected by the spotted bollworm.

10. **Handpicking of larvae 2-3 days** after insecticide sprays effectively eliminates any surviving population, which can cause future resistance problems.

11. Always use insecticides as **need based applications as per threshold levels.** Always target younger stages of *Helicoverpa* as younger stages of resistant larvae are known to get killed at normal recommended doses.

**Implementing IRM strategies**

During the five year period from 2002-2007, the IRM project was implemented in a total of 196,000 hectares in 1820 villages in 28 districts of 10 cotton-growing states of India with a funding of approximately 8.0 crores from the Ministry of Agriculture, Government of India under the Technology Mission on Cotton (TMC) Mini-Mission (MM-II) programme. A detailed survey was carried out all through 2002-2007 to evaluate the overall impact of the project in terms of the net financial gains gained by farmers. The total economic benefit was estimated to be Rs. 120 crores, due to Rs. 78 crores from yield increase and Rs 42 crores from savings on pesticides.

**Insect Resistant GM (Genetically Modified) Crops and IPM**

**Genes for pest management**

Several genes coding for insecticidal toxins have been isolated and are being used to develop insect resistant transgenic crops. Currently, four GM crops (cotton,
maize, potato and tomato) incorporating nine Cry (crystal) toxin genes (cry1Ab, cry1Ac, cry1F, cry34Ab, cry35Av cry3A, cry3B, cry2Ab, cry9C) and vip-3A gene isolated from Bacillus thuringiensis and one protease inhibitor gene are under commercial cultivation in 22 countries. In India, eleven crops (cotton, corn, brinjal, cabbage, cauliflower, ground nut, mustard, okra, pigeonpea, rice and tomato) have been genetically transformed for enhanced resistance to insects and viruses and are in various stages of testing. Six Cry (crystal) genes (cry1Aa, cry1Ab, cry1Ac, cry1F, cry1B, cry2Ab) and vip-3A gene from Bacillus thuringiensis were used for insect resistance in nine crops.

Impact of Bt-cotton on pests and non-target beneficial insects

The Cry1Ac based Bt-cotton is mainly toxic to the bollworms (cotton bollworm, pink bollworm and spotted bollworm), semiloopers and hairy caterpillars. Bt-cotton expressing Cry1Ac was reported to be safe to all other non-target organisms such as beneficial insects, birds, fish, animals and human beings. Laboratory and field studies carried out all over the world showed that the Cry1Ac protein deployed in Bt-cotton did not have any direct effect on any of the non-target beneficial insects. Dong et al., (2003) reported only minor effects on some life table parameters in laboratory feeding studies with lacewings and predatory beetles and none with predatory bugs and spiders. There was some evidence of a reduction in numbers of predators and parasitoids which specialise on the Bt controlled bollworms, but also of increases in numbers and diversity of generalist predators such as spiders. Generally the decrease in the parasitoid and predator populations were associated with decrease in the densities of the pest populations on account of Bt-cotton. Unsprayed Bt cotton sustained 4 times more attack of tarnished bugs, 2.4 times more with boll weevil, 2.8 times more with stink bugs and Spodoptera. Due to these changes in pest complex, farmers had to spray 3-5 times on bollgard as compared to 6-8 times on non-Bt cottons. Any effects could be assigned to the decrease in prey quality – for example with stunted Spodoptera litura caterpillars which had fed on Bt cotton. In the field situation, partial life studies broadly confirmed this finding. There was no increase in green vegetable bug numbers, aphid or whitefly numbers on Bt cotton. In general, such adverse effects as have been measured are very small when compared with the side effects of the spraying of conventional insecticides.

Efficacy of Bt-cotton

Bt-cotton varieties recorded significantly lesser boll and locule damage compared to non-Bt and check hybrids, indicating higher tolerance to bollworm damage. Bambawale et al. (2003) reported a 50% overall reduction in the H. armigera larval population in Bt-cotton compared to the non-Bt cotton. Further, the locule damage caused by pink bollworm was found to be 58% lesser in Bt-cotton. Udikeri et al. (2003) also showed that Bt-cotton hybrids were able to reduce larval populations of H. armigera up to 40%, spotted bollworm (Earias vittella) up to 30-40% and pink bollworm (Pectinophora gossypiella) up to 60-80% in south India. Reports (Qaim and Zilbermen., 2003; Barwale et al., 2004; Bennet et al., 2004, Morse et al., 2005) showed that yields increased substantially by adopting Bt-cotton and farmers in India were able to reduce at least 2-3 insecticide applications. However, the benefits of Bt-
cotton were more in other countries where bollworm infestation was high. Insecticide applications on Bt-cotton varieties were reduced up to 14 applications in China (Pray \textit{et al.}, 2002), 7 in South Africa and 5-6 in Indonesia and Australia (James, 2002).

\textbf{A critical appraisal on resistance management strategies for Bt-cotton in India}

Bt-cotton transgenic plants can impose a continuous selection pressure on \textit{H. armigera}, eventually resulting in the development of resistance. Transgenic plants expose insects to toxins continually, even at times when they are not causing economic damage (Mallet and Porter, 1992). Development of insect resistance to a toxin is due to progressive selection and sequential propagation of individuals of a population, surviving the toxicant. Continuous selection pressure with the toxicant eventually leads to an increase in numbers of tolerant/resistant individuals in populations. After the introduction and large scale cultivation of Bt transgenic cotton it is reasonably certain that \textit{H. armigera} will respond to the intense selection pressure through a decline in its susceptibility to Cry1Ac, the gene used frequently against it. Hence it is important to develop strategies to retard the rate of resistance development. Resistance management approaches generally rely on 1. conserving susceptibility by minimizing toxin exposure or 2. Getting rid of resistant RS and RR genotypes by using either high dose of the same toxin or by using other unrelated toxins. In India an area of sprayed 20\% refuge of non-Bt with Bt-cotton has been recommended by the Genetic Engineering Approval Committee (GEAC). A stochastic model ‘Bt-Adapt’ developed at CICR, Nagpur (Kranthi and Kranthi, 2004) showed that the 20\% refuge crop would not offer a significant advantage in delaying resistance development. Using the model it was inferred that one of the most important strategies in Bt resistance management would be to reduce the Bt cotton surviving population of \textit{H. armigera} through any pest management practices. The extent of reduction in the surviving population, which represents resistant genotypes, would determine the longevity of the technology utilization. Therefore the strategies that would enable extending the usefulness of Bt technology would be 1. Use alternate genes such as the Cry2Ab in Bollgard-II, that do not share common resistance mechanisms as that of Cry1Ac, in transgenic plants either in rotation or alternation or mixtures. 2. Use eco-friendly methods such as cultural control or handpicking of surviving bollworms in Bt cotton fields. Biopesticides that are neem based or HaNPV would be useful to manage younger larvae on 60-90 days old crop. Alternatively, conventional insecticides such as endosulfan, thiodicarb, quinalphos and chlorpyriphos, or new molecules such as spinosad, emamectin benzoate, novaluron or Indoxacarb can be used on 90 and 120 days old crop to reduce populations of resistant genotypes. 3. Identify and use attractive synchronous alternate host crops for \textit{H. armigera} which could be used as intercrop or trap crop refuges. A net-working programme, sponsored by ICAR, has recently identified bhendi and pigeonpea as useful crops suited for refugia 4. Avoid use of Bt based biopesticides that may contribute to selection of a broad-spectrum resistance to several useful Bt genes of interest.
Conclusion

For several years IPM has been a continuous struggle all over the world to ensure sustainability of the pest management approaches based on biological control and biopesticides. The main constraints have been the sub-optimal efficacy levels, poor quality and non-availability. Since, over the years a wide range of insecticide groups have been introduced with varying levels of toxicity to target pests and beneficial insects in the cotton ecosystem, sustainable methods were evolved through informed choice of selective pesticides to minimize insecticide use, reduce selection pressure, delay resistance and ensure the safety of naturally occurring biological control while reducing target pest populations. The recent introduction of genetically modified (GM) insect resistant crops such as Bt-cotton (Bacillus thuringiensis based GM cotton) and biologically derived novel pesticides such as spinosad and emamectin benzoate have strengthened eco-friendly approaches of pest management. Now, after many years, cotton pest management appears to be moving more closer to a sustainable domain. With extension strategies having been strengthened through area-wide farmer participatory methods and farmer field school approaches, IPM has become more practical, user friendly and adaptable to variable challenges of small-scale farming systems.

REFERENCES


