Sustainable Insect Pest Management in Cotton Cultivation: A Review of Challenges and Integrated Approaches for Maharashtra, India

Ashish B Gulwe

School of Technology, Department of Bioinformatics, SRTM University Sub Campus, Ausa Road Latur- 413512, India

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Abstract— *Cotton (Gossypium spp.) is a vital commercial crop in Maharashtra, contributing substantially to the agricultural economy and rural livelihoods. However, chronic insect pest infestations, particularly by bollworm complexes and sucking pests, threaten productivity. Overreliance on chemical pesticides has led to resistance development, ecological imbalances, and environmental and health hazards. This review synthesizes current knowledge on sustainable pest management strategies for cotton in Maharashtra, with emphasis on Integrated Pest Management (IPM). We examine the status of major pests, limitations of conventional practices, and evidence-based sustainable alternatives. Key findings highlight that while Bt cotton initially reduced bollworm pressure, field-evolved resistance in pink bollworm (Pectinophora gossypiella) has diminished its efficacy. IPM approaches integrating cultural, biological, botanical, and judicious chemical methods show promise in reducing pesticide dependence while maintaining yields. However, adoption barriers persist, including knowledge gaps and infrastructural constraints. The review concludes that farmer education, participatory extension, and supportive policies are crucial for scaling sustainable pest management in Maharashtra's cotton belt.*

Keywords— Cotton, Integrated Pest Management, Bt resistance, Pink bollworm, Maharashtra, Sustainable agriculture.

I. INTRODUCTION

Cotton, often termed 'white gold,' is a cornerstone of agriculture in Maharashtra, particularly in the Vidarbha and Marathwada regions. The state accounts for approximately one-third of India's total cotton cultivation area (National and state agriculture department cotton status paper, 2015). Despite its economic significance, cotton production faces severe challenges from insect pests, leading to substantial yield losses estimated at 20-50% annually in the absence of effective management (ICAR-CICR, 2019).

The pest complex in Maharashtra includes lepidopteran bollworms (American bollworm: *Helicoverpa armigera*; pink bollworm: *Pectinophora gossypiella*; spotted bollworm: *Earias vittella*) and sucking pests (jassids: *Amrasca biguttula biguttula*; aphids: *Aphis gossypii*; whiteflies: *Bemisia tabaci*; mealybugs: *Phenacoccus solenopsis*) (Dhawan, 2019). The introduction of Bt cotton expressing Cry toxins initially provided effective control of bollworms, but field-evolved resistance in pink bollworm has become a major concern in recent years (Naik et al., 2018; Dhurua & Gujar, 2011).

Excessive dependence on synthetic pesticides has led to multiple adverse consequences: development of resistance in target pests (Naveen et al., 2017), resurgence of secondary pests (Kumar et al., 2024), destruction of natural enemies, environmental contamination, and health hazards for farmers (Peshin et al., 2014). This scenario necessitates a paradigm shift toward sustainable, eco-friendly pest management strategies.

This review aims to: (1) analyze the current pest scenario in Maharashtra's cotton ecosystem; (2) evaluate the limitations of conventional pest management practices; (3) synthesize evidence-based sustainable alternatives with emphasis on IPM; and (4) identify adoption barriers and policy recommendations for scaling sustainable practices.

II. METHODOLOGY

This narrative review employed a systematic approach to literature identification and synthesis. Electronic databases (ScienceDirect, Google Scholar, JSTOR) were searched using combinations of keywords: "cotton pest management

Maharashtra," "Bt cotton resistance India," "Integrated Pest Management cotton," "pink bollworm resistance," "sustainable agriculture cotton." The search covered publications from 2000 to 2024, with emphasis on recent developments. Inclusion criteria prioritized peer-reviewed articles, institutional reports from ICAR-CICR and state agricultural universities, and relevant book chapters. Government reports and extension bulletins from Maharashtra were also consulted. The literature was thematically analyzed to address the review objectives, with particular attention to Maharashtra-specific context and evidence.

III. MAJOR INSECT PESTS AND CURRENT STATUS IN MAHARASHTRA

3.1 Bollworm Complex:

The bollworm complex remains the most destructive pest group in Maharashtra. Pink bollworm has emerged as particularly devastating, with confirmed field-evolved resistance to Cry1Ac and Cry2Ab toxins in Bt cotton across major cotton-growing districts (Naik et al., 2018). Population expansion studies indicate increased genetic diversity and adaptation in pink bollworm populations (Naik et al., 2020). American bollworm (*H. armigera*) continues to pose threats despite Bt cotton, requiring supplemental management (Jalali et al., 2006).

3.2 Sucking Pests:

Sucking pests have gained prominence with changes in cropping patterns and pesticide usage. Whitefly (*B. tabaci*) outbreaks have recurred, with genetic groups Asia-I and Asia-II-7 showing high levels of insecticide resistance (Naveen et al., 2017; Kumar et al., 2024). Mealybug (*P. solenopsis*) infestations have increased, particularly in water-stressed regions of Marathwada (ICAR-CICR, 2019).

3.3 Secondary Pest Resurgence:

Reduced-spectrum pesticide use in Bt cotton fields initially decreased broad-spectrum insecticide applications, but this has led to resurgence of previously minor pests like mirid bugs and spider mites, creating new management challenges (Peshin et al., 2014).

TABLE 1
MAJOR INSECT PESTS OF COTTON IN MAHARASHTRA: DAMAGE AND STATUS

Pest Category	Common Name	Scientific Name	Primary Damage	Key Management Challenge in Maharashtra	Reference(s)
Bollworms	Pink Bollworm	*Pectinophora gossypiella*	Larvae bore into bolls and flowers.	Field-evolved resistance to Cry1Ac & Cry2Ab toxins in Bt cotton.	Naik et al. (2018); Dhurua & Gujar (2011)
	American Bollworm	*Helicoverpa armigera*	Feeds on squares, flowers, and bolls.	Continues to cause damage; requires supplemental management.	Jalali et al. (2006)
Sucking Pests	Whitefly	*Bemisia tabaci*	Sucks sap, transmits viruses, causes sooty mold.	High insecticide resistance in Asia-I & Asia-II-7 genetic groups.	Naveen et al. (2017); Kumar et al. (2024)
	Mealybug	*Phenacoccus solenopsis*	Sucks sap, stunts plant growth.	Increasing infestation in water-stressed regions.	ICAR-CICR (2019)

IV. LIMITATIONS OF CONVENTIONAL PEST MANAGEMENT

4.1 Chemical Pesticide Overreliance:

Farmers in Maharashtra predominantly rely on calendar-based pesticide applications rather than need-based interventions. This practice has accelerated resistance development, with pink bollworm showing resistance ratios exceeding 100-fold to Cry1Ac toxin (Dhurua & Gujar, 2011). Whitefly populations exhibit resistance to neonicotinoids and pyrethroids (Naveen et al., 2017).

4.2 Bt Cotton Resistance Management Failures:

The "high dose/refuge" strategy for Bt resistance management has been poorly implemented in Maharashtra. Non-compliance with refuge planting requirements, coupled with the continuous cultivation of Bt cotton across seasons, has exerted intense selection pressure on pest populations (Tabashnik et al., 2013). Pink bollworm resistance to Bt cotton has followed patterns observed globally but at an accelerated pace in Maharashtra (Fabrick et al., 2023).

4.3 Ecological and Health Impacts:

Indiscriminate pesticide use has disrupted natural enemy complexes. Studies show significantly lower parasitism rates in intensive pesticide-use areas compared to IPM-adopted fields (Liu et al., 2016). Health surveys in cotton-growing districts of Vidarbha indicate higher incidence of respiratory and dermal conditions among farmers engaged in frequent pesticide handling (Peshin et al., 2014).

V. PRINCIPLES AND COMPONENTS OF SUSTAINABLE PEST MANAGEMENT

5.1 Monitoring and Decision Support:

Regular pest surveillance using pheromone traps (for bollworms) and yellow sticky traps (for sucking pests) provides early warning. Economic threshold levels (ETLs) established by ICAR-CICR should guide intervention timing rather than calendar-based spraying (Carrière et al., 2017). Digital tools for pest monitoring are emerging but require scaling (ICAR-NCIPM, 2018).

5.2 Cultural and Agronomic Practices:

Crop rotation with non-host plants (e.g., legumes, cereals) breaks pest cycles. Intercropping cotton with pigeon pea, soybean, or cowpea enhances natural enemy abundance and reduces pest colonization (Liu et al., 2016). Timely sowing (before mid-June) escapes peak bollworm incidence. Destruction of crop residues and deep summer ploughing reduce overwintering pest populations (NIPHM, 2014).

5.3 Host Plant Resistance:

Bt cotton stewardship requires adherence to refuge planting (20% non-Bt cotton or alternative host plants). New-generation Bt cotton hybrids with multiple genes (Cry + Vip) are under evaluation. Non-Bt varieties with morphological (okra leaf, hairy leaves) and biochemical (high gossypol) traits offer partial resistance to sucking pests (ICAR-CICR, 2019).

5.4 Biological Control:

Conservation of natural enemies through habitat manipulation (flower strips, hedgerows) enhances parasitism and predation. Augmentative releases of *Trichogramma chilonis* (egg parasitoid) against bollworms have shown 40-60% parasitism in field trials (Jalali et al., 2006). Microbial agents like *Bacillus thuringiensis* (Bt formulations), *Beauveria bassiana*, and Nuclear Polyhedrosis Viruses (NPVs) provide eco-friendly alternatives (Chakraborty et al., 2023).

5.5 Botanical and Biopesticides:

Neem-based formulations (azadirachtin) disrupt insect growth and feeding. Research indicates 60-70% reduction in sucking pest populations with neem application (Thakore & Srivastava, 2017). Other botanicals (karanj, custard apple seed extract) show promise but require standardization and registration.

5.6 Judicious Chemical Use:

When pesticide application is necessary (pest populations exceed ETLs), selective insecticides (e.g., flonicamid, spiromesifen) with minimal impact on natural enemies should be prioritized. Insecticide rotation based on different mode-of-action groups delays resistance (Pesticide Resistance Action Committee, 2025).

TABLE 2
COMPARISON OF CONVENTIONAL VS. SUSTAINABLE (IPM) PEST MANAGEMENT PRACTICES

Parameter	Conventional Chemical-Intensive Approach	Sustainable Integrated Pest Management (IPM) Approach
Primary Strategy	Calendar-based, prophylactic pesticide sprays.	Intervention based on Economic Threshold Levels (ETLs).
Key Components	Synthetic insecticides (often broad-spectrum).	Cultural controls, biological control, botanicals, **judicious** chemical use.
Impact on Pest	High immediate kill; rapid resistance development.	Suppresses pests below ETLs; aims to delay resistance.
Impact on Natural Enemies	Severe harm; destroys parasitoids and predators.	Conservation and augmentation are central goals.
Economic Cost	High recurring input cost.	Lower input cost; may have higher knowledge/labor cost.
Long-term Sustainability	Low (leads to pest resurgence, resistance).	High (maintains ecological balance).

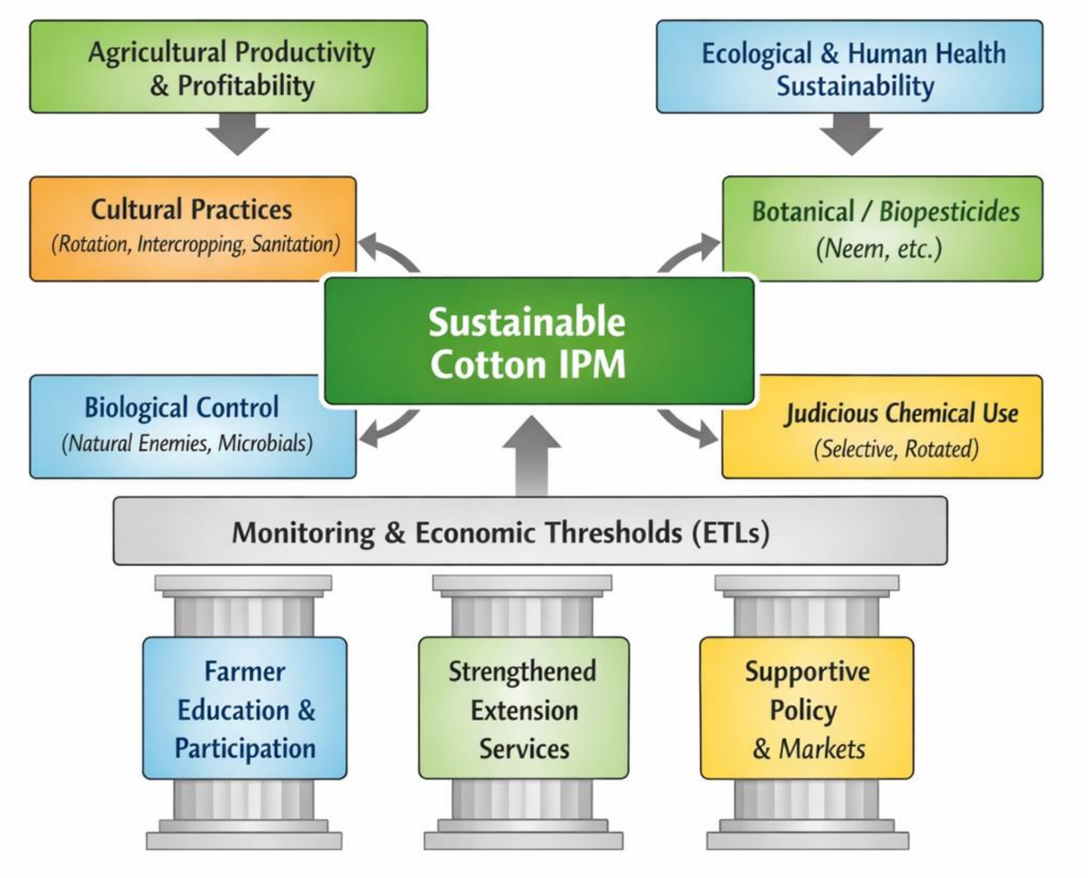

FIGURE 1: A Conceptual Framework for Sustainable IPM in Cotton

VI. CASE STUDIES AND FARMER PARTICIPATION IN MAHARASHTRA

6.1 IPM Validation Trials:

ICAR-NCIPM coordinated IPM validation trials in Jalna district (2017-19) integrating pheromone traps, neem application, and *Trichogramma* releases. Results showed 42% reduction in pesticide applications with yield parity to conventional plots (ICAR-NCIPM, 2018). Similarly, demonstrations by VNMKV, Parbhani in Marathwada region recorded 35% cost reduction in pest management through IPM adoption (Alagar et al., 2020).

6.2 Farmer Field Schools (FFS):

FAO-supported FFS programs in Yavatmal and Wardha districts (2009-12) trained farmer groups in pest scouting, natural enemy identification, and decision-making. Follow-up studies indicated 30% higher IPM adoption among FFS graduates compared to non-participants, with significant reduction in pesticide expenditure (FAO, 2009).

6.3 Community-Based Approaches:

The "Pest Management Committee" model in Amravati district, where farmers collectively monitor pests, procure biocontrol agents, and implement area-wide management, has shown success in reducing pink bollworm incidence through synchronized crop residue destruction (Better Cotton Initiative, 2019).

TABLE 3
SUMMARY OF IPM CASE STUDIES/VALIDATION TRIALS IN MAHARASHTRA

Location (District)	Key IPM Components Tested	Duration	Key Outcome	Source / Reference
Jalna	Pheromone traps, neem, *Trichogramma* releases.	2017-2019	42% reduction in pesticide sprays; yield parity maintained.	ICAR-NCIPM (2018)
Yavatmal/Wardha	Farmer Field Schools (FFS) for scouting & decision-making.	2009-2012	30% higher IPM adoption among FFS graduates.	FAO (2009)
Parbhani Region	Integrated module with cultural, biological, botanical methods.	Not Specified	35% reduction in pest management costs.	Alagar et al. (2020)

VII. CHALLENGES AND FUTURE PROSPECTS

7.1 Adoption Barriers:

Limited farmer knowledge of pest biology and IPM components, coupled with strong influence of pesticide retailers, hinders adoption. Availability and quality of biocontrol agents remain inconsistent. Smallholder farmers (dominant in Maharashtra) perceive IPM as knowledge- and labor-intensive (Peshin et al., 2014).

7.2 Research and Extension Gaps:

Location-specific IPM packages for diverse agro-ecological zones of Maharashtra are lacking. Extension services suffer from capacity constraints and inadequate farmer participatory approaches (Dhawan, 2019). Digital advisory systems are emerging but require integration with existing extension networks.

7.3 Policy and Institutional Support:

Subsidies on chemical pesticides distort economic incentives against sustainable alternatives. Biopesticide registration processes need streamlining. Convergence between agriculture, environment, and health departments is essential for holistic policy support (Chakraborty et al., 2023).

7.4 Future Directions:

Research should prioritize: (1) developing region-specific IPM modules, (2) enhancing biological control through native natural enemy conservation, (3) leveraging digital technologies for pest surveillance and decision support, and (4) socio-economic studies on adoption drivers. Policy initiatives must include: (1) redirecting subsidies toward sustainable inputs, (2) strengthening farmer-producer organizations for collective action, and (3) integrating pest management into climate resilience strategies.

VIII. CONCLUSION

Sustainable insect pest management in Maharashtra's cotton sector is imperative for ecological security, farmer health, and long-term productivity. The review demonstrates that while technological components of IPM are available, their integration and adoption require systemic changes. The resurgence of pink bollworm resistance underscores the limitations of singular technological solutions like Bt cotton. Successful transition to sustainable pest management requires: (1) context-adaptive IPM packages, (2) robust farmer participatory research and extension, (3) market mechanisms for quality biocontrol agents, and (4) conducive policies that incentivize ecological practices. Multidisciplinary efforts involving entomologists, economists, extension specialists, and farmers can transform Maharashtra's cotton cultivation toward sustainability, ensuring the viability of this crucial crop for future generations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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