Volume 4, Issue 1
January I 2026
Agri Roots
e- Magazine
www.agrirootsmagazine.in
ISSN: 2583-9071

Bt Cotton in India: Success or Failure? A Genetic Perspective

ARTICLE ID: 0321

Shivendu Kumar Sinha[1], Naveen Kumar[2], Srinivasa Rao Meesala[3]

[1]Graduate Student, B.Sc. (Hons.) Agriculture, School of Agriculture, K. K. University, Biharsharif, Nalanda, Bihar – 803115, India

[2]Research Scholar (Ph.D. Agronomy), School of Agricultural Sciences, K. K. University, Biharsharif, Nalanda, Bihar – 803115, India

[3]Professor & Dean, School of Agricultural Sciences, K. K. University, Biharsharif, Nalanda, Bihar – 803115, India

Since its commercial adoption in 2002, Bt cotton has reshaped cotton cultivation in India. Engineered to express Cry1Ac and later pyramided Cry2Ab toxins from *Bacillus thuringiensis*, Bt cotton promised reduced pesticide use, increased yields, and improved farmer incomes. However, over time, genetic resistance in insect pests—particularly the pink bollworm (*Pectinophora gossypiella*)—has emerged as a major challenge. This review examines the genetic basis of Bt cotton, mechanisms of pest resistance, and evidence of field-evolved resistance in India. It critically evaluates whether Bt cotton remains a viable technology and provides recommendations emphasizing integrated pest management (IPM), refuge strategies, and advanced breeding approaches to mitigate resistance-related failures.

Bt cotton, genetically engineered to express *Bacillus thuringiensis* (Bt) toxin genes, was introduced to Indian farmers in 2002 and rapidly gained popularity due to its effectiveness against key lepidopteran pests. First-generation Bt cotton expressed the Cry1Ac toxin, while second-generation hybrids were later developed to co-express Cry1Ac and Cry2Ab (pyramided toxins) to delay resistance evolution.

Despite initial success, increasing reports over the past decade indicate the development of resistance in major cotton pests, particularly the pink bollworm (PBW). Genetics plays a central role in this resistance—encompassing the structure and inheritance of Bt genes in cotton, pest adaptation mechanisms, and the effectiveness of resistance management strategies. Therefore, evaluating Bt cotton from a genetic perspective is critical for assessing its long-term sustainability.

Genetic Basis of Bt Cotton and Resistance

Bt Genes in Cotton

Most Bt cotton hybrids commercialized in India contain the Cry1Ac gene or a combination of Cry1Ac + Cry2Ab. These toxins act by binding to specific receptors in the insect midgut, causing cell lysis and larval death. The "high-dose–refuge" strategy, which requires planting non-Bt cotton alongside Bt cotton to delay resistance, remains a cornerstone of resistance management but is poorly implemented in practice.

Additionally, genetic segregation in hybrid cotton contributes to resistance development. Although Bt cotton hybrids are F_1 plants, the seeds formed in the bolls segregate genetically, resulting in variable toxin expression. This variability can allow partially resistant larvae to survive, thereby accelerating resistance evolution.

Mechanisms of Resistance in Pest Populations

Resistance in pink bollworm populations has been well documented. Molecular studies have identified mutations in the *PgABCA2* gene, an ATP-binding cassette transporter involved in Cry2Ab toxicity. Disruptions in this gene reduce toxin binding and confer resistance. Similarly, Cry1Ac resistance has been linked to reduced toxin binding to midgut receptors, as demonstrated in brush-border membrane vesicle (BBMV) assays.

These molecular adaptations reflect intense selection pressure imposed by widespread Bt cotton cultivation in the absence of effective refuge compliance.

Field-Evolved Resistance: Evidence from India

Pink Bollworm Resistance

Large-scale monitoring studies conducted between 2010 and 2017 across 38 cotton-growing districts in India reported clear field-evolved resistance in pink bollworm populations to both Cry1Ac and Cry2Ab. The median lethal concentration (LC_{50}) values increased dramatically—from approximately 0.33 µg/mL to 6.938 µg/mL for Cry1Ac and from 0.014 µg/mL to 12.51 µg/mL for Cry2Ab—representing resistance ratios in the thousands.

A 2023 F_2-screen study from Andhra Pradesh estimated resistance allele frequencies of 0.082 for Cry1Ac and 0.054 for Cry2Ab, with detection probabilities exceeding 97%. A subsequent study in 2025 reported a combined Cry1Ac + Cry2Ab resistance allele frequency of approximately 0.059 across South Indian populations, confirming the widespread nature of resistance.

Cotton Bollworm (*Helicoverpa armigera*)

In addition to pink bollworm, *H. armigera* populations are showing increasing tolerance to Bt toxins. Screening studies from Telangana (2021) estimated Cry1Ac resistance allele frequencies ranging from 0.05 to 0.056, indicating early warning signs of resistance development.

Impacts and Agronomic Realities

Yield, Agronomic Performance, and Farmer Benefits

Initially, Bt cotton significantly reduced pesticide usage, improved pest control, and increased yields, resulting in economic benefits for farmers. However, the increasing prevalence of resistant pest populations threatens these gains. Rising pink bollworm infestations may force farmers to resume intensive pesticide use or suffer yield losses.

Why Has Resistance Evolved?

Key factors contributing to resistance evolution include:

1. **Poor Refuge Compliance:** Limited adoption of non-Bt refuges reduces dilution of resistance alleles.
2. **Segregation of Bt Genes in Hybrids:** Variable toxin expression facilitates survival of partially resistant insects.
3. **High Selection Pressure and Genetic Diversity:** Multiple independent resistance mutations (over 60 *PgABCA2* variants) have been documented.
4. **Regulatory and Management Gaps:** Weak stewardship, insufficient monitoring, and limited farmer awareness accelerate resistance development.

Discussion

From a genetic standpoint, resistance in cotton pests—especially pink bollworm—poses a serious threat to the sustainability of Bt cotton in India. Molecular evidence demonstrates that resistance is deeply embedded within pest populations through heritable genetic changes. While Bt cotton delivered short-term benefits, inadequate resistance management and the genetic limitations of hybrid systems have hastened resistance evolution.

Future Directions and Recommendations

1. **Improved Insect Resistance Management**

- Strict enforcement of refuge planting
- Farmer education and policy incentives

2. **Advanced Breeding and Biotechnology**

- Development of high-dose Bt events
- Exploration of next-generation pyramids and genome-editing tools (with caution)

3. **Integrated Pest Management (IPM)**

- Crop rotation, biological control, pheromone traps, and cultural practices
- Regular resistance allele monitoring

4. **Surveillance and Genetic Monitoring**

- Sentinel monitoring networks
- Transparent data sharing

5. **Seed Quality and Stewardship**

- Certification to prevent substandard Bt seed
- Awareness of hybrid segregation risks

Conclusion

Bt cotton has been transformative for Indian agriculture; however, its long-term sustainability is increasingly threatened by genetically driven pest resistance, particularly in pink bollworm populations. Resistance is measurable, widespread, and growing. Without rigorous resistance management, the benefits achieved over the past two decades may be lost.

Sustaining Bt cotton requires a holistic approach that integrates genetic innovation, strict refuge compliance, integrated pest management, and robust surveillance systems. Only through coordinated scientific, regulatory, and farmer-driven efforts can Bt cotton remain a viable component of India's cotton production system.

References

1. Annepu, A. A., Naik, V. C. B., Rao, G. M. V. P., et al. Frequency of Cry1Ac and Cry2Ab resistance alleles in pink bollworm from Andhra Pradesh, India. *Phytoparasitica*, 2023.
2. Balasubramani, G., Kari, B., Thakur, P., Jagannathan, A., & Prasad, Y. G. Segregation of Bt genes in cotton and development of pink bollworm resistance. *Journal of Cotton Science*, 2025.
3. Fabrick, J. A., et al. Molecular genetic basis of laboratory- and field-selected Bt resistance in pink bollworm. *Insects*, 2023.
4. Tabashnik, B. E., et al. Field-evolved resistance of pink bollworm to Cry1Ac and Cry2Ab Bt cotton in India. *Journal of Economic Entomology*.