Physical Education, Health and Social Sciences

https://journal-of-social-education.org

E-ISSN: 2958-5996

P-ISSN: 2958-5988

Cotton Genetic Improvement for Insect Resistance; Integrating Plant Breeding and Entomological Approaches for Sustainable Pest Management

Shay Chirag[1], Hafsa Sarfraz[2], Jameel Akram[3], Muhammad Salman[4], Muhammad Awais[5], Shafay Mehmood[6], Khatir Ali[7], Ch. Muhammad Rizwan Khurshid[8], Dr. Sajid-ur-Rahman[9], Dr. Javed Ahmad[10], Dr. Naveed Akhtar[11], Dr. Qurban Ali[12]

[1] Department of Entomology, University of Agriculture Faisalabad.
Corresponding Author: shay33chirag44@gmail.com
[2] Department of Plant Breeding and Genetics, University of Agriculture Faisalabad.
2019ag7689@uaf.edu.pk
[3] Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad.
jameelakram66@gmail.com
[4] Department of Entomology, University of Agriculture Faisalabad. salmanmm360@gmail.com
[5] Texas Tech University. M.Awais@ttu.edu
[6] Department of Entomology, Sindh Agriculture University, Tandojam. shafaym261@gmail.com
[7] Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad.
khatirali34521@gmail.com
[8] FC Section, Agronomic Research Institute, AARI, Faisalabad, Pakistan. rizwanaari@gmail.com
[9] Research Wing, AARI, Govt of the Punjab, Agriculture Department. dgaraari@yahoo.com
[10] Wheat Research Institute, AARI, Faisalabad, Pakistan. wrifsd@yahoo.com
[11] Agronomic Research Institute, AARI, Faisalabad, Pakistan. darifsd84@gmail.com
[12] Ayub Agricultural Research Institute, Faisalabad, Pakistan. info@aari.punjab.gov.pk

https://doi.org/10.63163/jpehss.v3i4.964

Abstract

Cotton is a major fiber and cash crop globally; the productivity of the crop is halting by insect pests which result in huge yield and economic losses. The conventional use of chemical insecticides has also given concern to the issue of resistance development, environmental risks and production expense which has carried out the awful need of alternative methods that are sustainable. The present paper discusses the genetic enhancement of cotton to insect resistance with a particular focus on the combination of plant breeding and entomological strategies as the means of sustainable pest control. The traditional breeding techniques, such as hybridization, recurrent selection and utilization of the wild relatives have high genetic diversity in terms of host plant resistance. The contemporary molecular methods include the Marker Assisted Selection, Gene Pyramiding and RNA interference technology that has been utilized to improve accuracy of breeding programs, transgenic Bt cotton known worldwide to alleviate pesticide pressure and reduce pest. Moreover, with the introduction of CRISPR-Cas genome editing previously unattainable opportunities to selectively modify the genes related to resistance are presented. Entomological knowledge especially under the concept of Integrated Pest Management enhances them by harmonizing ecological activities with the genetic technologies. The future opportunities are to create multi resistant and climate tolerant cotton strains, biotechnological and ecological approaches and support the transition to biotechnology by favorable policies towards farmers. The

integration of the progress in genetics, biotechnology and entomology can assurance the sustainability of cotton in the long track increase in productivity and environmental safety.

Keywords: Insect resistance, Genetic engineering, Bt cotton, Marker assisted selection, RNA interference, Integrated pest management, CRISPR-Cas genome editing, Sustainable agriculture

1. Introduction

Cotton (Gossypium spp.) is a worldwide important fiber crop, providing natural fiber for the textile industry as well as cottonseed for oil and animal feed which are critical to rural livelihoods and national economies (Zafar *et al*., 2020). Despite its importance, insect pests continue to damage cotton yield, threatening cultivation's viability. Lepidopteran pests, particularly bollworms like *Helicoverpa zea* and *Pectinophora gossypiella as* well as sap sucking insects like whiteflies and aphids are among the most devastating (Jurat *et al*., 2021). Reliance on chemical insecticides while historically effective has resulted in serious repercussions such as resistance, environmental damage and disturbance of beneficial insect populations emphasizing the necessity for integrated management approaches (Xiao *et al*., 2024). For example, field evolved resistance in *H. zea* and pink bollworm populations has significantly reduced Bt trait efficacy (Zafar *et al*., 2020). To overcome these experts suggested using organized refuge tactics and pyramiding toxins containing Vip3A proteins to limit resistance evolution (Wang *et al*., 2020). Cry1, Cry2 and Vip3A, in particular has been successful for more than a decade and BG3 cotton which expresses Vip3A has both fatal and sublethal impacts on major pest species highlighting its importance in resistance management (Abbas, 2024). Plant breeding, both conventional and modern plays an important role in increasing pest resistance. Glandless cotton with gossypol free seeds and preserved defensive gossypol in vegetative tissues improves seed quality while maintaining insect protection (Zhang and Wedegaertner, 2021). Furthermore, the development of CRISPR Cas9 and other gene editing technologies has allowed for precise changes to resistance related genes however worries about off-target effects remain (Zafar *et al*., 2020). Entomology supplements these efforts by providing insights into pest behavior, ecology and resistance routes (Tabashnik *et al*., 2021). A case in point is the successful eradication of pink bollworm in the United States which was accomplished through a synergistic approach combining Bt cotton, sterile insect releases and refuge strategies resulting in an 80% reduction in insecticide use and significant environmental and economic benefits (Hussain *et al*., 2019).When paired with Bt traits in pyramiding techniques, RNAi improves durability by targeting critical insect genes and experimental pyramided constructs outperformed Bt alone in delaying resistance (Huang *et al*. 2019).

These findings highlight the importance of a multidisciplinary strategy to cotton pest management that combines plant genetics, biotechnology, and entomology to promote long-term insect resistance (Pujar *et al*., 2024). Modern techniques such as CRISPR and RNAi broaden this integrated toolkit highlighting the importance of integrated pest management (IPM) in improving cotton resistance and productivity (Nagaraj *et al*., 2024).

Objectives

- Highlight the global importance of cotton and the challenges posed by insect pests.
- Examine the contributions of plant breeding and modern genomics to insect resistance in cotton.
- Explore entomological perspectives on pest resistance evolution and ecological interactions.
- Propose an integrated framework combining breeding, biotechnology, and entomology for sustainable cotton pest resilience.

2. Major Insect Pests of Cotton

Cotton is attacked by a diverse variety of insect pests, the importance of which varies by region. Sap sucking insects and the boll weevil (*Anthonomus grandis*) are still the most economically important of the lepidopteran boll feeders (Trapero *et al*., 2023). Pest complexes must be continuously monitored since shifts in dominance frequently occur in response to changes in crop protection techniques notably under Bt cotton production and pesticide regimes (Sgro *et al*., 2020). Despite the success in controlling the bollworm, secondary pests such as whiteflies, aphids and jassids have become more prevalent, causing considerable changes in the pest complex (Wilson *et al*., 2020). The modifications emphasize the necessity of breeding strategies that combine genetic resistance and entomological knowledge to develop cotton varieties that can withstand pest diversity, allowing for long-term and sustainable pest management (Figure 2.1).

2.1 Lepidopteran Pests

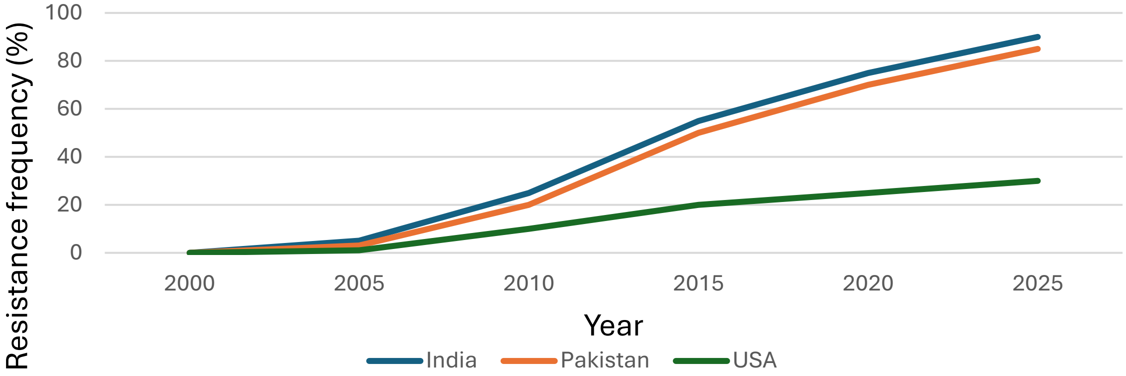
2.1.1 Cotton bollworm (*Helicoverpa Armigera)*

Helicoverpa armigera is one of the world's most damaging cotton pests, due to its polyphagy, fertility and migratory capacity. Resistance is frequently polygenic, encompassing both recessive and non-recessive features complicating management efforts (Yang *et al*., 2021). Cross resistance to Cry and Vip proteins has also been demonstrated raising questions about the stability of present pyramids (Qi *et al*., 2021). Reports from China and India demonstrate that *H. armigera* populations are relocating after protracted Bt exposure emphasizing the significance of resistance monitoring and refuge compliance (Gassmann *et al*., 2023).

2.1.2 Pink bollworm (*Pectinophora gossypiella)*

Pink bollworm larvae feed inside bolls resulting in direct lint and seed loss. Although Bt cotton greatly reduced its impact resistance has quickly arisen in areas where single toxin cultivars predominated (Fabrick *et al*., 2023). In India, field specific resistance has resulted in revival and yield losses (Madhu *et al*., 2025). Similarly, coordinated management combining pyramided Bt cotton structured refuges and area wide programs has eliminated or suppressed pink bollworm in portions of the United States (Gassmann *et al*., 2023). Pink bollworm (*Pectinophora gossypiella*) resistance has become a major issue for the long-term viability of Bt cotton. Field evidence from India, Pakistan and the United States shows that despite initial success pink bollworm populations have developed tolerant of Bt toxins over time reducing their potency. This tendency emphasizes the importance of diversifying the approach to resistance management through a pyramid of gene

Graph 2.1. 2 Resistance Evolution in Pink Bollworm to Bt Cotton (India, Pakistan and USA)



diversification, the use of refuges and the implementation of host plant resistance in order to slow the accumulation of resistance and maintain pest control on a long-term basis (Graph 2.1. 2).

2.1.3 Spodoptera spp.

Armyworms, particularly *Spodoptera litura* and *S. frugiperda* are becoming more prevalent in Bt cotton systems as most Cry toxins are less effective against them. Their epidemics have been related to ecological imbalances caused by excessive pesticide usage or a focus on narrow spectrum pests. Current surveys have indicated that Spodoptera species are among the new pests in Bt cotton fields in Asia and South America (Marques *et al*., 2023).

2.2 Sap sucking insects

2.2.1 Whitefly (*Bemisia tabaci*)

Bemisia tabaci is a cryptic taxonomic complex that causes direct harm to cotton by sap feeding and indirectly through the transfer of viruses such as cotton leaf curl disease in South Asia (Li *et al*., 2023). A cotton germplasm assessment can also demonstrate that varietal resistance features have the ability to reduce whitefly performance while providing host plant resistance prospects (Rizwan *et al*., 2021). Whiteflies are a severe restriction in India and Pakistan regardless of how widespread Bt cotton has become (Subramanian *et al*., 2023).

2.2.2 Cotton aphid (*Aphis gossypii*)

Cotton aphids can cause stunted deposition of honeydew and virus infection. Their attacks typically occur when natural predators are disturbed. According to recent RNAi research gene silencing techniques that inhibit *A. gossypii* could complement host resistance and biological management strategies (Zhan *et al*., 2025). It is well known that germplasm screening has found varietal tolerance which can be used to produce resistant plants (Dinesh Kumar *et al*., 2025).

2.2.3 Cotton jassid (*Amrasca devastans*)

Cotton jassids damage crops in South Asia by feeding on leaf sap, causing hopper burn and yield loss. They are now resistant to most insecticides, and their management is primarily dependent on host plant resistance due to trichome density and biochemical deterrents (Aherkar *et al*., 2023).

2.3 Boll weevil (*Anthonomus grandis*)

The historical boll weevil was the most damaging cotton pest in the Americas. The larvae thrive within floral buds and bolls resulting in substantial yield losses. In the United States and Mexico, the pest has been nearly eradicated in many areas because to area wide eradication methods using pheromone trapping and the use of insecticides (Gassmann *et al*., 2023). Nonetheless, it exists in South America particularly in areas where it is tough to regulate because to gaps in surveillance. It is no longer a major threat in most parts of the world, but the prospect of re-employment is underscored by the fact that it must be monitored (Nagaraj *et al*., 2024).

2.4 Regional variation in pest complexes

The relative importance of pests at cotton production sites South Asia. The resurgence of pink bollworms, along with persistent pressure from whiteflies and jassids, results in excessive insecticide use and economic loss (Kumar et al., 2025). Bt cotton has long been used successfully in China to eradicate bollworms but H. armigera is showing signs of early resistance and whiteflies remain a concern (Gassmann et al., 2023). In Brazil, pyramided Bt cultivars have emerged.

Cotton is attacked by a vast range of insect pests each with unique eating habits, potential harm and location. *Helicoverpa armigera* and *Pectinophora gossypiella* are lepidopteran pests that feed directly on bolls and reproductive structures while sap sucking insects such as *Bemisia tabaci* and *Aphis gossypii* reduce plant vigor and increase viral infections. These pests demonstrate why the world has to implement coordinated resistance strategies to protect cotton productivity (Table 2.1).

Table 2. 1 Major Insect Pests of Cotton and Their Impact

Pest Specie	Types	Damage Symptoms	Global Distribution	Citations
Helicoverpa armigera	Lepidopteran	Boll/leaf feeding	Asia, Africa, Australia	Yang *et al*., 2021
Pectinophora gossypiella	Lepidopteran	Pink bollworm damage	India, Pakistan, USA, China	Fabrick *et al*., 2023
Bemisia tabaci	Sap-sucker	Sap loss, virus transmission	Asia and Africa	Li *et al*., 2023
Aphis gossypii	Sap-sucker	Stunting, honeydew, virus	Global	Zhan *et al*., 2025
Anthonomus grandis	Boll weevil	Bud/boll destruction	Americas	Joga *et al*., 2023

3.1 Breeding Methods of Cotton for Insect Resistance

The pink bollworm (*Pectinophora gossypiella*) and cotton bollworm (*Helicoverpa armigera*) cause significant yield losses in cotton (*Gossypium* spp.) (Nagaraj *et al*., 2021). Reliance on chemical control has raised concerns over resistance and environmental safety (Razzaq *et al*., 2023). Thus, breeding insect-resistant cultivars remains a vital strategy, with host plant resistance proving effective in reducing pest damage (Arora *et al*., 2023).

Resistance traits such as glandular trichomes, boll hardness, delayed fruiting, and early boll opening reduce pest infestation (Dinesh *et al*., 2025; Saleem *et al*., 2022). For instance, resistance traits from *G. arboreum* have been introgressed into *G. hirsutum* to enhance bollworm resistance (Messmer *et al*., 2019). Breeding programs also exploit hybrid vigor to strengthen resistance and yields (Shahzad *et al*., 2022). The success of Bt cotton highlights the effectiveness of combining natural resistance and biotechnology (Shuli *et al*., 2021). However, the durability of resistance depends on genetic diversity, accurate selection, and continuous monitoring of evolving pest populations (Shuli *et al*., 2021).

3.1 Insect Tolerance through Hybridization and Selection

Hybridization between resistant and high-yielding lines enables the transfer of resistance traits into agronomically superior cultivars (Razzaq *et al*., 2023). Interspecific crosses, such as *G. hirsutum* × G. barbadense, have produced hybrids with improved bollworm resistance while maintaining fiber quality (Saleem *et al*., 2022). Subsequent selection stabilizes resistance and yield across diverse environments (Kumar *et al*., 2024). Hybrid vigor further enhances yield under pest pressure (Basal and Turgut, 2003). Despite challenges like parental incompatibility and high seed costs, hybridization remains a practical approach to balancing resistance, yield, and fiber quality (Shahzad *et al*., 2022).

3.2 Marker-Assisted Selection (MAS) for Resistance Genes

Molecular markers accelerate resistance breeding by enabling early detection of resistance traits, reducing reliance on lengthy phenotypic screening (Kumar *et al*., 2024). For example, the Cry1Ac gene has been tracked in Bt cotton using markers (Cordo and DeLoach, 2020). MAS facilitates precise selection, shortens breeding cycles, and supports gene pyramiding for broad and durable resistance (Salimi *et al*., 2021). Advances like GWAS and high-throughput sequencing further enhance resistance gene identification (Wilson *et al*., 2020). MAS is now integral to insect-resistant cotton breeding, complementing conventional and transgenic methods (Cordo and DeLoach, 2020).

3.3 Transgenic Approaches

Genetic engineering has introduced insecticidal proteins, particularly Bt Cry toxins, into cotton, significantly reducing bollworm damage (Khan *et al*., 2023). Stacked Bt varieties (e.g., Cry1Ac + Cry2Ab, Cry1F) provide broader and more durable resistance (Briefs, 2023). However, resistance evolution in pests like H. armigera and P. gossypiella necessitates continuous innovation (Sripathy *et al*., 2024). Concerns regarding non-target organisms, gene flow, and environmental effects persist (Kumar *et al*., 2024). Emerging tools such as RNA interference (RNAi) and CRISPR-based genome editing offer promising alternatives (Khan *et al*., 2023).

3.4 Integrated Pest Management (IPM) and Entomology

Understanding pest ecology, biology, and resistance dynamics is essential for effective IPM in cotton (Razzaq *et al*., 2023; Sripathy *et al*., 2024). IPM integrates biological control (parasitoids, predators), cultural practices (rotation, intercropping), and judicious pesticide use to delay resistance and conserve natural enemies (Shahzad *et al*., 2024). Its success depends on collaboration among entomologists, breeders, agronomists, and farmers (Sgro *et al*., 2020). However, limited farmer awareness and institutional support hinder adoption in some regions (Arshad *et al*., 2019). Despite challenges, IPM remains central to sustainable pest management, complementing genetic and biotechnological approaches (Shahzad *et al*., 2024).

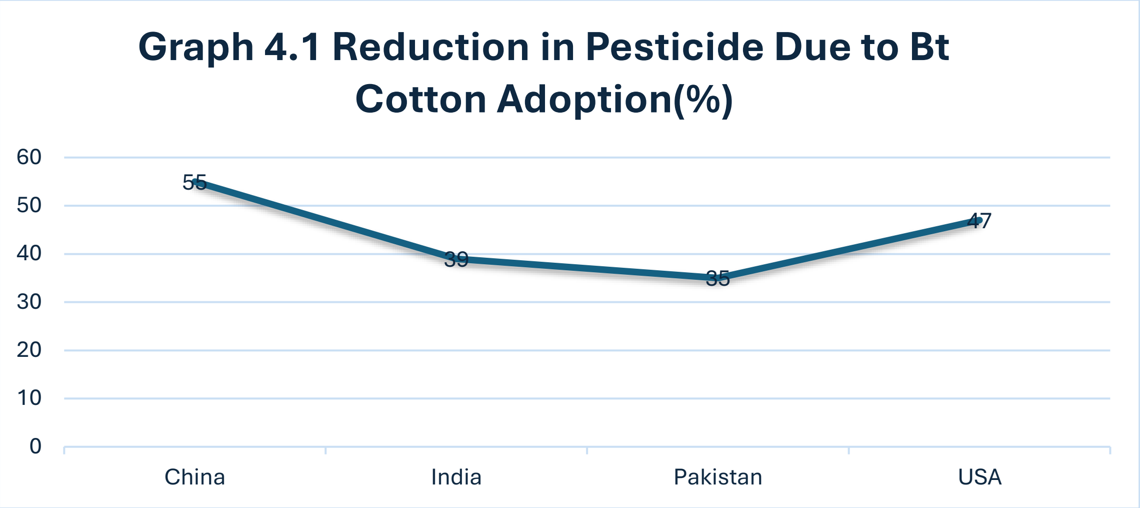
4. Advances in Molecular and Biotechnology

Cotton enhancement had taken on a new dimension with the development of molecular and biotechnological technologies that provide precise and effective methods of generating insect resistance. Conventional breeding has historically been ineffective in keeping up with shifting pest pressures but new opportunities are emerging through the use of transgenic Bt cotton, gene pyramiding, RNA interference (RNAi) and CRISPR/Cas genome editing (Shahzad *et al*., 2022). Such advances not only improve pest resistance, but also reduce reliance on chemical insecticides, contributing to environmental sustainability and the benefits of cotton productivity (Zafar *et al*., 2020).

4.1 Transgenic Bt Cotton and Pest Dynamics

The introduction of Bt cotton revolutionized pest management, reducing reliance on broad-spectrum insecticides and lowering environmental risks (Shahzad *et al*., 2024). Early Bt cultivars expressing Cry1Ac provided effective control of *Helicoverpa armigera* and Pectinophora gossypiella, resulting in significant yield gains (Zafar *et al*., 2020). Adoption of Bt cotton reduced bollworm populations, pesticide sprays, and health risks, particularly in India, China, and the U.S. In China, pesticide use declined by about 70% following widespread Bt adoption (Khan *et al*., 2023).

However, repeated pest exposure has led to resistance, notably in pink bollworm populations in India (Leko *et al*., 2021). To address this, pyramided Bt cotton with stacked toxins (Cry1Ac + Cry2Ab, Cry1F) was developed, offering broader resistance and delaying resistance evolution (Khan *et al*., 2023). Long-term studies in Australia and the U.S. confirmed their effectiveness (Jin *et al*., 2025). Yet, secondary pests such as whiteflies and mealybugs have emerged due to reduced insecticide applications (Sgro *et al*., 2020). Current research focuses on next-generation Bt proteins, RNAi-based designs, and CRISPR editing to sustain effectiveness (Cordo and DeLoach, 2020). Pesticide use has dropped by 55% in China, 47% in the U.S., 39% in India, and 35% in Pakistan, demonstrating Bt cotton's role in lowering chemical dependence, production costs, and environmental hazards.



4.2 Gene Pyramiding for Durable Resistance

Gene pyramiding, which integrates multiple resistance genes into one genotype, is a proven strategy to extend resistance durability (Gupta *et al*., 2022). Two-gene Bt cotton (Cry1Ac + Cry2Ab or Cry1F) provides wider control of lepidopteran pests and reduces the likelihood of resistance compared to single-gene events (Tabashnik and Carriere, 2019). In Australia, pyramided Bt delayed resistance development in H. armigera, while studies in the U.S. showed prolonged efficacy against *H. zea* (Downes *et al*., 2020).

Pyramiding reduces cross-resistance risk, especially when toxins bind to different insect receptors (Bravo *et al*., 2020). Success, however, depends on refuge strategies that preserve susceptible pest populations. Non-compliance, as in India, has accelerated resistance in pyramided Bt lines (Kranthi and Stone, 2020). Modeling studies confirm that combining non-redundant resistance genes with refuge practices can significantly delay resistance (Tabashnik *et al*., 2023). Increasingly, pyramiding strategies now combine Bt proteins with RNAi for multi-layered control (Nim *et al*., 2020).

4.3 RNAi Technologies to Insect Pests

RNA interference (RNAi) is a precise gene-silencing tool that disrupts essential insect functions by degrading targeted mRNA (Zhang *et al*., 2024). It has shown efficacy against major cotton pests, including *H. armigera*, whiteflies and aphids (Mamta and Rajam, 2025). Silencing of digestion, reproduction, and detoxification genes reduces survival while minimizing risks to non-target organisms (Cooper *et al*., 2019).

Host-induced gene silencing (HIGS) in transgenic cotton provides durable resistance, while spray-induced gene silencing (SIGS) offers a non-transgenic alternative (Xuh *et al*., 2021). However, efficiency varies among insect taxa due to differences in dsRNA stability and uptake (Christiaens *et al*., 2020). Delivery challenges remain, but nanoparticle carriers are being developed to improve dsRNA stability and absorption (Yan *et al*., 2020). Integrating RNAi with Bt technologies could provide synergistic control and delay resistance (Nim *et al*., 2020). Overall, RNAi offers strong potential but requires solutions for delivery and field stability before commercial adoption (Joga *et al*., 2021).

4.4 CRISPR- Cas Based Cotton Genome Editing

CRISPR-Cas has emerged as a precise genome-editing platform for enhancing insect resistance and agronomic traits in cotton (Chen *et al*., 2019). It enables targeted mutagenesis, knockouts, and insertions in resistance-related genes (Linoj *et al*., 2021). CRISPR has been used to modify pathways regulating gossypol and terpenoid biosynthesis, improving natural defenses (Mahrang *et al*., 2020). Unlike conventional transgenics, CRISPR does not require foreign DNA insertion, enhancing regulatory acceptance (Sedeek *et al*., 2020).

Recent studies show CRISPR can silence susceptibility genes, reducing pest damage, while multiplex editing enables simultaneous modifications at multiple loci for pyramided resistance (Wang *et al*., 2020). Integration with omics tools enhances the identification of key target genes (Mahrang *et al*., 2020). CRISPR is thus projected to be transformative in pest-resistant cotton breeding, complementing RNAi and gene pyramiding (Chen *et al*., 2019). Alongside ecological approaches such as refuges, IPM, and biological control, genome editing highlights the importance of multidisciplinary strategies for long-term cotton pest management (Linoj *et al*., 2021). These techniques underline the importance of combining several disciplines in order to achieve sustainable, long-term control of risk insects in cotton production systems (Table 4.1).

Table 4.1 Breeding, biotechnological and ecological strategies for insect resistance in cotton

Strategy	Genes / Approaches	Advantages	Limitations	Citations
Conventional Breeding	Trichome density, boll toughness	Non-GMO, eco-friendly	Slow progress, limited diversity	Arora *et al*., 2023
Hybridization Combines	G. hirsutum × G. barbadense	resistance + quality	Costly seed production	Shahzad *et al*., 2024
Marker-Assisted Selection (MAS)	Cry1Ac markers	Precise, faster breeding	Requires robust markers	Trapero *et al*., 2021
Transgenic Bt Cotton	Cry1Ac, Cry2Ab, Vip3A	High efficacy vs bollworms	Resistance evolution	Khan *et al*., 2023
Integrated Pest Management (IPM)	Biological control, crop rotation, refuges, intercropping	Reduces pesticide use, supports ecological balance	Requires farmer training and adoption	Shahzad *et al*., 2024

5. Insect views in Cotton pest management

Understanding insect behavior, resistance mechanisms, evolutionary dynamics, and the employment of natural enemies helps breeders, entomologists, and agronomists better balance pest management measures (Zhang *et al*., 2023).

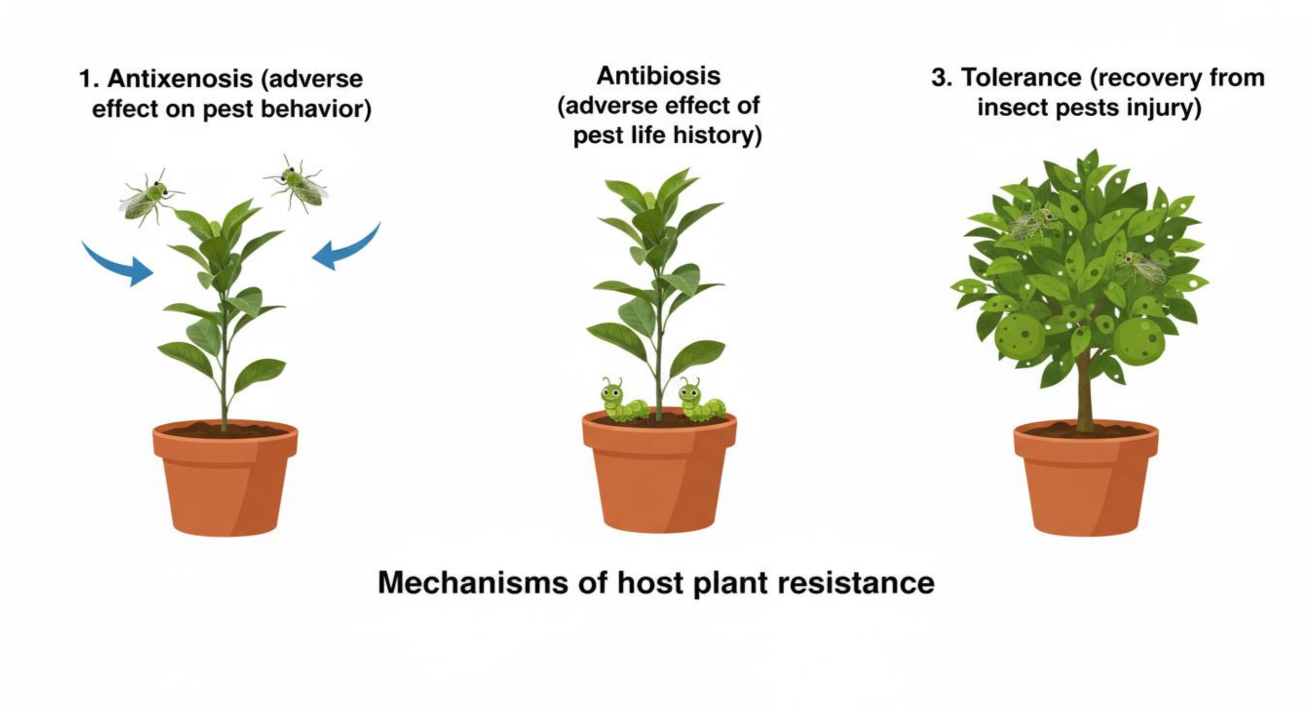
5.1 Insects Behavior and Host Plants.

Host plant traits such as volatiles, surface morphology, and biochemical signals strongly influence insect colonization (Zhou *et al*., 2023). Cotton plants release herbivore-induced volatiles, with methyl jasmonate reducing oviposition and feeding of Helicoverpa armigera and Spodoptera frugiperda (Zhang *et al*., 2023). Canopy features, including leaf angle and trichome density, affect Bemisia tabaci settlement, with pubescent cultivars showing 40% fewer infestations than glabrous ones (Chen *et al*., 2022). Trichomes also serve as dual physical and chemical barriers against whiteflies (Singh and Verma, 2021). Biochemical cues such as flavonoids, phenolic acids, and terpenoids deter sap-sucking pests and shape host choice (Abro *et al*., 2021). For boll weevils (Anthonomus grandis), oviposition is influenced by boll size and pericarp toughness (Silva *et al*., 2020). Climate-driven volatiles further affect distributions; Aphis gossypii prefers fragile cultivars under high temperatures, showing adaptive avoidance (Kumar *et al*., 2022).

5.2 Mechanisms of Resistance

Cotton resistance operates through antixenosis, antibiosis, and tolerance. Antixenosis involves avoidance where flavonoid- and ferulic acid–rich lines reduce infestation by *A. gossypii* and *B. tabaci*. Antibiosis causes direct harm, with *Pectinophora gossypiella* showing delayed development and 70% mortality on Bt + RNAi lines (Souza *et al*., 2024). High gossypol cultivars also reduce lepidopteran pupal weight (Das *et al*., 2020). Tolerance is seen in cultivars maintaining boll survival despite jassid damage (Johnson *et al*., 2020) and sustaining photosynthesis and yield recovery under aphid and whitefly stress (Iqbal *et al*., 2021). Combining these mechanisms provides broader, sustainable resistance (Sheri *et al*., 2025).

Figure 4.1 Mechanism of Host Plant Resistance



5.3 Insect Development of resistance to Controlling measures.

Despite resistant varieties, pests adapt. H. armigera in Pakistan developed SNP-based Cry1Ac resistance via cadherin gene mutations (Khan *et al*., 2023). Metabolic resistance has emerged in *Amrasca devastans* with increased esterase and P450 activity against pyrethroids and neonicotinoids (Pandey *et al*., 2022). Behavioral avoidance was observed in *S. litura* which avoided Vip3A tissues (Liang and Zhou, 2024). Pink bollworm developed resistance to Cry2Ab2 and Vip3Aa19 in India (Madhu *et al*., 2025). Bt-resistant populations also showed tolerance to flonicamid and pyriproxyfen (Hameed *et al*., 2021). These examples illustrate diverse resistance pathways genetic, metabolic and behavioral driven by strong selection pressures.

5.4 Role of Natural Enemies and Biological Control

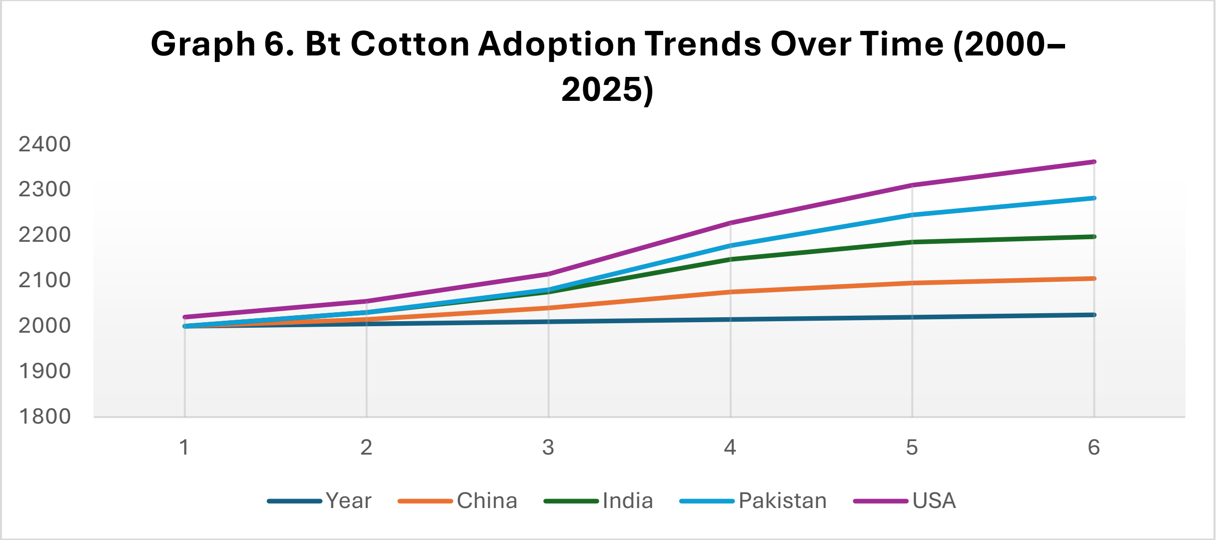
Biological control strengthens cotton resilience while reducing insecticide dependence. Predators like *Chrysoperla externa* and *Coccinella septempunctata* suppressed aphids in Bt cotton where reduced pesticide use supported natural enemies (Smith *et al*., 2021). Parasitoid releases of *Trichogramma* spp. cut pink bollworm infestations by ~60% (Kumar and Rao, 2019). Entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*) reduced larval survival and improved seedling vigor (Patel and Desai, 2022). Microbial seed treatments enhanced rhizosphere interactions, indirectly lowering pest colonization (Razaq *et al*., 2021). Landscape-level tactics such as intercropping with nectar plants increased parasitoid abundance and suppressed H. armigera and whiteflies (Kiran *et al*., 2022).

5.5 Synthesis and Implications for IPM

Cotton pest management requires diverse, integrated approaches. Plant traits (morphological, biochemical) deter colonization (Zhang *et al*., 2022). Resistance mechanisms antixenosis, antibiosis, tolerance—limit pest survival (Souza *et al*., 2024). Yet, rapid resistance evolution demands gene pyramiding, refuges, and resistance cycles (Liang and Zhou, 2024). Integrating behavioral, physiological and ecological insights within IPM ensures sustainable cotton production, balancing yield security with reduced environmental impact.

6. Integration to Sustainable Pest Management

The latter foundation is entomology and the incorporation of PBG to enable sustainable cotton pest management. The key to their survival in IPM systems is ecological knowledge of insect behavior, ecology and resistance evolution, even when genetic innovations such as resistant



cultivars, Bt characteristics and CRISPR based innovations are utilized to provide crop resistance. This kind of cooperation makes it possible to produce environmentally friendly and genetically strong cotton that is resistant to pests (Carriere *et al*., 2019). As Graph. 6 shows. By 2025, usage had surpassed 90% in China and India, demonstrating their exponential expansion. In contrast to the United States, which embraced the technology early but eventually stabilized at around 80%, Pakistan showed a slower but stable growth over time. The broad use of Bt cotton as a method to reduce insect pressure and increase output is reproduced in these trends.

6.1 Genetics and Entomology Synergies in IPM

For instance, entomological surveillance has been utilized to detect changes in *Helicoverpa armigera* populations, Bt and RNAi stacking has been used to breed pest resistance (Arora *et al*., 2020). Although MAS has consistently made it possible for whitefly and aphid resistance alleles to be introduced, they have not been effectively used without ecological studies on how insects interact with their host plants, which can lead to the breakdown of resistance (Rahman *et al*., 2022). These illustrations show how entomology and genetics work together to increase resistant lifetime in a way that neither discipline could do alone (Sun *et al*., 2021).

6.2 Combined Methods of Breeding and Ecological Pest Control

Cotton breeding today is primarily focused on integrating ecological compatibility and resistance genes. The traits of high gossypol concentrations, trichome density and nectar less lines that have been entomologically confirmed to repel bollworms, aphids and whiteflies have been included into traditional breeding (Mei *et al*., 2019). Nowadays, targeted editing of the genes of susceptibility and the development of cultivars with the necessary antixenosis features are made possible by advancements in CRISPR-Cas9 (Zhou *et al*., 2023). For example, the intercropping of marigold with cotton aided in the development of jassid-resistant cotton, increasing predators and reducing jassid populations (Kiran *et al*., 2022). Similarly, cotton lines resistant to conservation tillage maintained natural enemy numbers and soil health increasing the biological control of bollworms. These tactics demonstrate how PBG driven resistance is resistant to deployment in environmentally favorable settings (Wang *et al*., 2020).

6.3 Success Case Studies of Integrated Approaches

A Numerous case studies exemplify how well entomology and genetics work together in IPM. When hybrid Bt cotton was introduced in China, large scale biological control programs resulted in steady yields and a 70% decrease in pesticide levels (Liu *et al*., 2021). The successful delay of resistance in *Pectinophora gossypiella* populations in India through the use of both Bt cotton and non-Bt seed mixtures is an example of how genetic strategies require entomological counseling on resistance development (Kranthi and Stone, 2020). Similarly, when used in the United States, RNAi-mediated resistance to Spodoptera frugiperda combined with predator conservation efforts remained effective for five years (Tabashnik *et al*., 2021). When considered collectively, these success stories highlight the idea that combining entomology and genetics is not only feasible but also essential for global cotton production to be sustainable (Mwangi *et al*., 2022).

7. Challenges and Limitations

Many challenges in establishing a connection between PBG and entomology continue to exist currently. The sustainability of genetic treatments is still threatened by the high rate of resistance development of important pests as whiteflies and pink bollworm (Carriere *et al*., 2019). Furthermore, it is difficult to propagate generally resistant cultivars in agroecological diversity, and regional pest variances are commonly observed in entomology research (Fand *et al*., 2021).

Additionally, there are issues with ecological integration, intercropping, and the potential for minimal pesticide usage to not always be determined by farmers' commercial objectives, which leads to unequal application (Sharma *et al*., 2020). CRISPR-Cas based genetic solutions generate biosafety and regulatory concerns, especially in developing nations with weaker policymaking institutions (Kumar *et al*., 2023).

8. Future Prospects and Research Opportunities

8.1 Multi Resistant Cotton

Developing cotton cultivars resistant to multiple pest complexes is vital for future sustainability (Gupta *et al*., 2022). Combining antixenosis, antibiosis, and tolerance within elite germplasm increases survival and lowers resistance risk (Sheri *et al*., 2025). Gene pyramiding, proven in extending Bt efficacy, can integrate metabolic traits, RNAi, and Bt to provide broader protection (Huang *et al*., 2019). Such cultivars will reduce pesticide dependence and enhance resilience against fluctuating pest pressures (Tabashnik and Carriere, 2019).

8.2 Integration of Biotechnological and Ecological Methods

Future cotton improvement requires merging biotechnology with ecological practices (Carriere *et al*., 2019). Tools such as MAS, Bt, RNAi, and CRISPR can be combined with crop rotation, intercropping, and biological control for stronger resistance (Kiran *et al*., 2022). Companion planting with nectar-rich crops supports predators and parasitoids, complementing resistant cultivars (Smith *et al*., 2021). Conservation agriculture and soil health further sustain natural enemies and amplify cultivar effectiveness (Wang *et al*., 2020).

8.3 Pest Resistance Breeding and the Climate Change

Climate change will significantly affect host–pest dynamics and resistance breeding outcomes (Sgro *et al*., 2020). Rising temperatures and irregular rainfall expand pest ranges and accelerate infestations (Rodrigues and Beldade, 2020). Heat-stressed cotton may alter pest interactions and weaken resistance (Zhang and Li, 2023). Breeding must incorporate traits like drought tolerance, heat resistance and insect resistance (Shuli *et al*., 2021). Modeling suggests gene pyramiding and ecological IPM remain effective under changing climates (Tabashnik *et al*., 2023). Combining climate-smart breeding with pest surveillance is essential for long-term resilience (Chakraborty *et al*., 2022).

8.4 Perspectives of Policy and Farmer Adoption

The success of resistance technologies depends on farmer adoption and supportive policy (Sharma *et al*., 2020). Training and awareness programs ensure compliance with resistance management practices (Kranthi & Stone, 2020). Farmer participation in breeding programs increases adoption of resistant cultivars (Mwangi *et al*., 2022). Policy support for habitat management and biological control further enhances deployment (Rahman *et al*., 2022). Transparent regulation of gene-edited crops like CRISPR cotton is also crucial for commercialization (Kumar *et al*., 2023). Ultimately, coordinated efforts between research, policy, and farmers will ensure sustainable and productive cotton systems (Carriere *et al*., 2025).

9. Conclusion

Cotton is the world’s leading fiber crop, yet insect pests continue to threaten yield and quality. Improvement strategies range from conventional breeding and hybridization with wild relatives to advanced molecular tools such as gene pyramiding, RNA interference, and CRISPR genome editing. Integrating insect biology with plant breeding has proven essential for developing durable resistance. Combining genetic resistance with ecological practices, biological control, and IPM reduces pesticide dependence and promotes sustainability. Future progress lies in developing climate-resilient, multi-resistant cultivars, supported by farmer adoption and enabling policies. Collaboration between scientists, policymakers, and farmers will ensure cotton remains productive, sustainable, and capable of meeting global fiber demand while protecting ecosystems and livelihoods.

Acknowledgment

We would like to express my deepest gratitude to my parents for their unconditional love, constant encouragement, and unwavering support throughout my academic journey. Their guidance and prayers have always been a source of strength and motivation for me. We are also sincerely thankful to my teachers, whose dedication, knowledge, and mentorship have shaped my learning and inspired me to strive for excellence. Their continuous support and valuable guidance played an essential role in the completion of this work.

References:

Abbas, M. S. T. (2024). Genetically engineered crops BT (*Bacillus thuringiensis* crops) and the world controversy on their safety. Egyptian Journal of Biological Pest Control, 28(1), 1-12.

Abro, G. H., Syed, T. S., & Awan, M. S. (2021). Biochemical resistance mechanisms in cotton against sap-sucking insect pests. Crop Protection, 144, 105594.

Aherkar, S. S., Ingole, A. V., Bhale, U. N., & Kale, V. S. (2023). Morpho-physiological and biochemical basis of tolerance in cotton genotypes against sucking pests. Agriculture, 13(7), 1315.

Arora, R., Kataria, S. K., & Singh, P. (2023). Breeding for insect resistance in cotton: advances and future perspectives. In Breeding insect resistant crops for sustainable agriculture (pp. 265-288). Singapore: Springer Singapore.

Arora, R., Kaur, P., & Singh, R. (2020). Bt and RNAi stacking in cotton: Advances, prospects and entomological considerations. Frontiers in Plant Science, 11, 543892.

Bates, S. L., Zhao, J. Z., Roush, R. T., & Shelton, A. M. (2025). Insect resistance management in GM crops: Past, present and future. Nature Biotechnology, 23(1), 57-62.

Bravo, A., Likitvivatanavong, S., Gill, S. S., & Soberón, M. (2020). Bacillus thuringiensis: A story of a successful bioinsecticide. Insect Biochemistry and Molecular Biology, 41(7), 423-431.

Briefs, I. S. A. (2023). Global status of commercialized biotech/GM crops in 2022: Biotech crop adoption surges as economic benefits accumulate in 22 years. ISAAA brief, 53, 25-26.

Carriere, Y., Crickmore, N., & Tabashnik, B. E. (2025). Optimizing pyramided transgenic Bt crops for sustainable pest management. Nature Biotechnology, 33(2), 161-168.

Carriere, Y., Fabrick, J. A., & Tabashnik, B. E. (2019). Can pyramids and seed mixtures delay resistance to Bt crops? Philosophical Transactions of the Royal Society B, 374(1773), 20180290.

Chakraborty, S., Newton, A. C., & Alakonya, A. (2022). Climate change, plant disease and pest interactions in agriculture. Current Opinion in Plant Biology, 70, 102243.

Chen, K., Wang, Y., Zhang, R., Zhang, H., & Gao, C. (2019). CRISPR-Cas genome editing and precision plant breeding in agriculture. National Science Review, 6(2), 84-94.

Chen, L., Wang, H., & Zhao, J. (2022). Leaf morphology influences whitefly settlement: Effects of trichome density and leaf angle in cotton. Entomologia Experimentalis et Applicata, 170(3), 290-299.

Christiaens, O., Whyard, S., Vélez, A. M., & Smagghe, G. (2020). Double-stranded RNA technology to control insect pests: Current status and challenges. Annual Review of Entomology, 65, 273-292.

Cooper, A. M. W., Silver, K., Zhang, J., Park, Y., & Zhu, K. Y. (2019). Molecular mechanisms influencing efficiency of RNA interference in insects. Pest Management Science, 75(1), 18-28.

Cordo, H. A., & DeLoach, C. J. (2020). Host specificity of Sameodes albiguttalis in Argentina, a biological control agent for waterhyacinth. Environmental Entomology, 7(2), 322-328.

Das, S., Bhattacharya, R., & Ghosh, A. (2020). Impact of gossypol content on pink bollworm development in cotton genotypes. Arthropod-Plant Interactions, 14(2), 112-120.

Dinesh Kumar, G., Shukla, R., & Ponnusamy, S. (2025). Guarding cotton fields against sucking pests through host plant resistance: Traits, strategies and future prospects. Journal of Cotton Research, 8, 22.

Dinesh, G., Manikanda Boopathi, N., Geethanjali, S., Subramanian, A., Somasundaram, S., Kannan, M., ... & Ravikesavan, R. (2025). Guarding the cotton fields by refining the resilience against sucking pests: use of cutting-edge breeding and other techniques. Journal of Cotton Research, 8(1), 24.

Downes, S., Parker, T., & Mahon, R. (2020). Incipient resistance of Helicoverpa punctigera to the Cry2Ab Bt toxin in Bollgard II cotton. Pest Management Science, 72(4), 558-567.

Fabrick, J. A., Unnithan, G. C., Masson, L., & Tabashnik, B. E. (2023). Field-selected resistance to Bt toxins in pink bollworm (Pectinophora gossypiella): Lessons for sustainable management. PNAS Nexus, 2(4), pgad123.

Fand, B. B., Sul, N. T., & Nagrare, V. (2021). Regional variations in cotton insect pests and their management challenges. Crop Protection, 143, 105468.

Gassmann, A. J., & Reisig, D. D. (2023). Management of insect pests with Bt crops in the United States: Lessons for sustainable agriculture. Annual Review of Entomology, 68, 393-414.

Gupta, P., Raghuvanshi, S., & Singh, P. K. (2022). Gene pyramiding: An overview and its applications in plant breeding. Journal of Genetics, 96(5), 1253-1264.

Hameed, A., Saeed, Q., & Saleem, M. (2021). Emerging resistance in *Bemisia tabaci* against novel insecticides in Pakistan's cotton system. Crop Protection, 147, 105716.

Huang, R., Teng, W., Zhang, X., Hu, M., Ren, M., & Yang, D. (2019). Next-generation transgenic cotton: pyramiding RNAi and Bt counters insect resistance. Plant Biotechnology Journal, 15(9), 1204-1213.

Hussain, F., Unnithan, G. C., Dong, S., UlAbdin, Z., Gu, S., ... & Li, X. (2019). A long non-coding RNA regulates cadherin transcription and susceptibility to Bt toxin Cry1Ac in pink bollworm, Pectinophora gossypiella. Pesticide biochemistry and physiology, 158, 54-60.

Iqbal, M., Ashraf, W., & Rehman, A. (2021). Tolerance mechanisms in cotton germplasm against multiple sap-sucking insect pests under field conditions. Journal of Cotton Research, 4, 33.

Jan, A., Adil, S., Ali, T., Ahmed, B., Ahmed, Z., & Hussain, Z. (2025). Desert and medicinal plants as novel sources of antimicrobial agents for crop protection. Planta Animalia, 4(3), 197-218.

Jan, A., Adil, S., Ali, T., Ahmed, B., Ahmed, Z., & Hussain, Z. (2025). Desert and medicinal plants as novel sources of antimicrobial agents for crop protection. Planta Animalia, 4(3), 197-218.

Jan, A., Ali, T., Chirag, S., Ahmed, S., Ali, M., Wali, S., ... & Ullah, K. (2025). Eco-Friendly Management of Insect Pests and Plant Diseases Using Botanical Extracts. Global Research Journal of Natural Science and Technology.

Jan, A., Ali, T., Chirag, S., Ahmed, S., Ali, M., Wali, S., ... & Ullah, K. (2025). Eco-Friendly Management of Insect Pests and Plant Diseases Using Botanical Extracts. Global Research Journal of Natural Science and Technology.

Jan, A., Hussain, Z., Ullah, A., Ahmed, Z., Bakhsh, B. P., Latif, A., ... & Ahmed, M. (2025). Sugarcane Whip Smut: A Comprehensive Review of Pathogen Biology, Epidemiology, and Control Measures. Annual Methodological Archive Research Review, 3(5), 211-232.

Jan, A., Hussain, Z., Ullah, A., Ahmed, Z., Bakhsh, B. P., Latif, A., ... & Ahmed, M. (2025). Sugarcane Whip Smut: A Comprehensive Review of Pathogen Biology, Epidemiology, and Control Measures. Annual Methodological Archive Research Review, 3(5), 211-232.

Jan, A., Razzaq, F., Umair, M., Ullah, I., Shamsullah, S., Uzair, M., Ikram, M., Ayyaz, M., & Ali, T. (2025). Cotton Leaf Curl Disease: Pathogen Diversity, Whitefly Ecology, and Integrated Management Approaches. Planta Animalia, 4(4), 363-371.

Jan, A., Razzaq, F., Umair, M., Ullah, I., Shamsullah, S., Uzair, M., Ikram, M., Ayyaz, M., & Ali, T. (2025). Cotton Leaf Curl Disease: Pathogen Diversity, Whitefly Ecology, and Integrated Management Approaches. Planta Animalia, 4(4), 363-371.

Jan, A., Shaikh, G. Y., Ullah, S., Saddam, S., Ali, T., u Rehman, A., ... & Ahmed, M. (2025). In-vitro antifungal activity of medicinal plant extracts against Fusarium oxysporum causing wilt in okra. Indus Journal of Bioscience Research, 3(8), 406-414.

Jan, A., Shaikh, G. Y., Ullah, S., Saddam, S., Ali, T., u Rehman, A., ... & Ahmed, M. (2025). In-vitro antifungal activity of medicinal plant extracts against Fusarium oxysporum causing wilt in okra. Indus Journal of Bioscience Research, 3(8), 406-414.

Jin, L., Zhang, H., Lu, Y., Yang, Y., Wu, K., Tabashnik, B. E., & Wu, Y. (2025). Large-scale test of the natural refuge strategy for delaying insect resistance to transgenic Bt crops. Nature biotechnology, 33(2), 169-174.

Joga, M. R., Zotti, M. J., Smagghe, G., & Christiaens, O. (2021). RNAi efficiency, systemic properties, and novel delivery methods for pest insect control: What we know so far. Frontiers in Physiology, 7, 553.

Johnson, A., Martinez, S., & Roberts, C. (2020). Tolerance traits in modern cotton cultivars under leafhopper pressure: Root-shoot compensation effects on yield. Field Crops Research, 250, 107774.

Jurat, J. L., Karumbaiah, L., Jakka, S. R. K., Ning, C., Liu, C., Wu, K., ... & Adang, M. (2021). Reduced levels of membrane-bound alkaline phosphatase are common to lepidopteran strains resistant to Cry toxins from Bacillus thuringiensis. PLoS One, 6(3), e17606.

Khan, R. A., Ghayas, M., Khalid, M. N., & Amjad, I. (2023). Transgenic strategies for enhancing cotton disease resistance: current status and future directions.

Khan, R., Ahmed, M., & Mustafa, S. (2023). SNP variation in midgut cadherin correlates with early Cry resistance in Helicoverpa armigera. Pest Management Science, 79(4), 1234-1242.

Kiran, K., Rani, R., & Subramanian, A. (2022). Habitat manipulation through intercropping enhances parasitoid abundance and suppresses cotton pests. Biological Control, 168, 104835.

Kranthi, K. R., & Stone, G. D. (2020). Long-term impacts of Bt cotton in India. Nature Plants, 6(3), 188-196.

Kumar, G., Manikanda Boopathi, N., Geethanjali, S., Subramanian, A., Somasundaram, S., Kannan, M., & Ravikesavan, R. (2024). Guarding the cotton fields by refining the resilience against sucking pests: use of cutting-edge breeding and other techniques. Journal of Cotton Research, 7(2), 26.

Kumar, P., Gupta, R., & Singh, A. (2023). Gene-editing regulations and CRISPR applications in cotton pest resistance breeding. Plant Biotechnology Journal, 21(2), 209-220.

Kumar, R., Sharma, P., & Kranthi, K. R. (2025). Resistance development in pink bollworm (Pectinophora gossypiella) against Bt cotton in India. Scientific Reports, 15, 8214.

Kumar, S., & Rao, V. (2019). Augmentative Trichogramma chilonis releases against pink bollworm in cotton: Field efficacy under unsprayed conditions. Biological Control, 135, 87-95.

Kumar, V., Sharma, P., & Ali, S. (2022). Influence of climatic factors on cotton aphid and whitefly infestation dynamics. Environmental Entomology, 51(4), 765-774.

Leko, V., Adrianse, R. L., Loe, T., Foss, E. J., Dalrymple, E., ... & Bedalov, A. (2021). Screen for reactivation of MeCP2 on the inactive X chromosome identifies the BMP-TGF-β superfamily as a regulator of XIST expression. Proceedings of the National Academy of Sciences, 214(8), 1618-1327.

Li, D., Zhou, L., Wang, H., & Zhang, J. (2023). Plant resistance against whitefly (*Bemisia tabaci*) and prospects for resistance engineering. Horticulture Research, 10, uhad012.

Liang, G., & Zhou, X. (2024). Behavioral avoidance of Vip3A-expressing tissues by Spodoptera litura: Implications for resistance management. Journal of Insect Behavior, 37(1), 32-40.

Linoj, J., Manghwar, H., Sun, L., Wang, P., Wang, G., Sheng, H., Zhang, J., & Jin, S. (2021). CRISPR/Cas: A powerful tool for crop genome editing. The Crop Journal, 9(1), 1-15.

Liu, Y., Wu, K., & Guo, Y. (2021). Bt cotton in China: Reductions in insecticide use and gains in biological control. Science of the Total Environment, 781, 146780.

Madhu, T. N., Gupta, S., & Nagrare, V. S. (2025). Distribution and characterization of multiple-toxin resistance in pink bollworm across Indian Bt cotton-growing regions. Crop Protection, 176,

Mahrang, X., Zhang, Q., Zhu, Q., Liu, W., Chen, Y., Qiu, R., Wang, B., Yang, Z., Li, H., & Lin, Y. (2020). A robust CRISPR-Cas9 system for convenient, high-efficiency multiplex genome editing in monocot and dicot plants. Molecular Plant, 13(9), 1264-1274.

Mamta, B., & Rajam, M. V. (2025). RNAi technology: A new platform for crop pest control. Physiology and Molecular Biology of Plants, 23(3), 487-501.

Marques, L. H., Oliveira, W. S., Ribeiro, L. M., & Fatoretto, J. (2023). Efficacy of cotton plants expressing Cry1Ac, Cry1F and Vip3Aa19 against key lepidopteran pests. Frontiers in Bioengineering and Biotechnology, 11, 112233.

Mei, Y., Sun, D., & Li, H. (2019). Breeding cotton for pest resistance: Morphological and biochemical strategies. Euphotic, 215(9), 145.

Messmer, M. M., Boller, T., Shrivas, Y., Patil, S. S., & Riar, A. (2019). Extent of bollworm and sucking pest damage on modern and traditional cotton species and potential for breeding in organic cotton. Sustainability, 11(22), 6353.

Mwangi, E., Ochieng, P., & Ogada, M. (2022). Farmer participatory breeding and push–pull strategies in African cotton systems: A sustainable pest management model. Agriculture, Ecosystems & Environment, 333, 107975.

Nagaraj, S. (2024). Strengthening Integrated Pest Management in Transgenic Cotton through Genetic Resistance. Journal of Cotton Research, 7, 15.

Nagaraj, S., R., Palaniappan, J., Rangasamy, S., Narayanasamy, C., & Narayanan, M. B. (2021). Emerging technological developments to address pest resistance in Bt cotton. Journal of Cotton Research, 8(2), 20.

Nagaraj, S., Rajasekaran, R., Palaniappan, J., Rangasamy, S., Narayanasamy, C., & Narayanan, M. B. (2024). Host Resistance Integration for Resilient IPM in Transgenic Cotton. Journal of Cotton Research, 7(1), 30.

Nim., Ma, W., Wang, X., Gao, M., Dai, Y., Wei, X., ... & Chu, C. (2020). Next-generation transgenic cotton: Pyramiding RNAi and Bt for durable pest resistance. Trends in Biotechnology, 35(6), 598-601.

Noor, R. N., Atiq, M., Usman, M., Jan, A., Nawaz, A., Iqbal, S., ... & Rajput, N. A. (2025). Physiology, Epidemiology and Fungicidal Subdual Strategies for whip smut of sugarcane Caused by Sporisoriums Scitamineum.

Noor, R. N., Atiq, M., Usman, M., Jan, A., Nawaz, A., Iqbal, S., ... & Rajput, N. A. (2025). Physiology, Epidemiology and Fungicidal Subdual Strategies for whip smut of sugarcane Caused by Sporisoriums Scitamineum.

Noor, S., Nawaz, A., Ahmed, M., Akhtar, H., Ahmed, K., Irshad, M. S., ... & Jan, A. (2025). Beneficial Fungi and Bacteria as Biocontrol Agents against Fungal and Bacterial Plant Pathogens. Global Research Journal of Natural Science and Technology, 3(1).

Noor, S., Nawaz, A., Ahmed, M., Akhtar, H., Ahmed, K., Irshad, M. S., ... & Jan, A. (2025). Beneficial Fungi and Bacteria as Biocontrol Agents against Fungal and Bacterial Plant Pathogens. Global Research Journal of Natural Science and Technology, 3(1).

Pandey, D., & Rao, S. (2022). Metabolic resistance evolution in Amrasca devastans: Increased esterase and P450 activity in field populations. Journal of Economic Entomology, 115(6), 2167-2174.

Patel, V., & Desai, M. (2022). Seed treatment with Beauveria bassiana reduces early-season bollworm damage in cotton seedlings. Biocontrol Science and Technology, 32(8), 801-812.

Pujar, K., Pagire, K. S., R., A. B., Purushotham, P., Chakrabarty, S., Muwel, K., Saikia, R., & Kumar, A. (2024). A Comprehensive Review on Genomic Approaches for Insect Pest Management. Journal of Agriculture and Ecology Research International, 25(3), 146-164.

Qi, L., Wang, Y., Xu, H., & Wu, K. (2021). Evaluating cross-resistance and synergism between Cry and Vip toxins in Helicoverpa armigera. Toxins, 13(5), 326.

Rahman, M., Zafar, Y., & Mansoor, S. (2022). Marker-assisted breeding for insect resistance in cotton: Integrating genetics and entomology. Molecular Breeding, 42(7), 49.

Razaq, M., Nawaz, M., & Riaz, A. (2021). Synergistic effects of microbial seed treatments on cotton seedling vigor and pest resistance. Applied Entomology and Zoology, 56(2), 167-178.

Razzaq, A., Abbas, T., & Naeem, M. (2023). Insect-pest resistance management for improvement and development of Bt cotton. Plants, 12(3), 567.

Razzaq, A., Zafar, M. M., Ali, A., Li, P., Qadir, F., Zahra, L. T., ... & Gong, W. (2023). Biotechnology and solutions: Insect-pest-resistance management for improvement and development of Bt cotton (Gossypium hirsutum L.). Plants, 12(23), 4071.

Rizwan, M., Naeem, M., Abbas, T., & Saleem, M. (2021). Evaluation of cotton germplasm for resistance against whitefly and jassid under field conditions. Journal of Cotton Research, 4, 32.

Rodrigues, Y. K., & Beldade, P. (2020). Thermal plasticity in insects' response to climate change and to multifactorial environments. Frontiers in Ecology and Evolution, 8, 271.

Roonjha, M. A., Roonjho, R., Ali, M., Anas, M., Khalid, H., & Jan, A. (2025). Aphid-Transmitted Plant Viruses: Epidemiology and Integrated Vector Management. International Journal of Agriculture Innovations and Cutting-Edge Research (HEC Recognised), 3(3), 109-126.

Roonjha, M. A., Roonjho, R., Ali, M., Anas, M., Khalid, H., & Jan, A. (2025). Aphid-Transmitted Plant Viruses: Epidemiology and Integrated Vector Management. International Journal of Agriculture Innovations and Cutting-Edge Research (HEC Recognised), 3(3), 109-126.

Saleem, M. A., Binyameen, M., & Shad, S. A. (2022). Response of Mid and Short Season Promising Genotypes of Cotton Crop to Earias vittella (Fab.) Infestation in Punjab, Pakistan. Pakistan Journal of Zoology, 54(4).

Salimi, S., Almuktar, S. A., & Scholz, M. (2021). Impact of climate change on wetland ecosystems: A critical review of experimental wetlands. Journal of Environmental Management, 286, 112160.

Sedeek, K. E. M., Rao, G. S., Khan, M. Z., Amin, I., Kamel, R., Mukhtar, Z., Zafar, M., Mansoor, S., & Mahfouz, M. M. (2020). Genome editing technologies for crop improvement: Progress and prospects. Plant Biotechnology Journal, 18(9), 1656-1679.

Sgro, C. M., Terblanche, J. S., & Hoffmann, A. A. (2020). plasticity contributes to insect responses to climate change. Annual review of entomology, 61(1), 433-451.

Shahzad, K., Mubeen, I., Zhang, M., Zhang, X., Wu, J., & Xing, C. (2022). Progress and perspective on cotton breeding in Pakistan. Journal of Cotton Research, 5(1), 29.

Shahzad, R., Jamil, S., Chaudhry, U. F., Rahman, S. U., & Iqbal, M. Z. (2024). In-depth analysis of Bt cotton adoption: farmers' opinions, genetic landscape, and varied perspectives, a case study from Pakistan. Journal of Cotton Research, 7(1), 31.

Sharma, D., Singh, P., & Singh, S. (2020). Adoption barriers for ecological pest management practices in cotton. Agricultural Systems, 185, 102937.

Sheri, V., Kiran, K., & Rani, R. (2025). Advances in CRISPR-Cas genome editing for insect resistance in cotton: Current progress and future prospects. Journal of Cotton Research, 8, 45.

Shuli, F., Jarwar, A. H., Wang, X., Wang, L., & Ma, Q. (2021). Overview of the cotton in Pakistan and its future prospects. Pakistan Journal of Agricultural Research, 31(4), 396.

Silva, R. S., Oliveira, W. L., & Marques, L. H. (2020). Oviposition behavior of the boll weevil in relation to boll size and pericarp thickness in cotton. Journal of Applied Entomology, 144(8),

Singh, A., & Verma, P. (2021). Ferulic acid and flavonoid-induced aphid antixenosis in cotton: Biochemical basis and varietal differences. Crop Science, 61(2), 880-889.

Smith, T., Nguyen, K., & Williams, D. (2021). Role of predators in aphid suppression under reduced pesticide regimes in Bt cotton. Agricultural and Forest Entomology, 23(4), 459-468.

Souza, L. R., de Almeida, F. S., & Silva, V. R. (2024). Efficacy of Bt + RNAi stacked cotton against pink bollworm: Mortality and developmental delay. Transgenic Research, 33(1), 45-58.

Sripathy, S., Leko, V., Adrianse, R. L., Loe, T., Foss, E. J., Dalrymple, E., & Bedalov, A. (2024). Screen for reactivation of MeCP2 on the inactive X chromosome identifies the BMP-TGF-β superfamily as a regulator of XIST expression. Proceedings of the National Academy of Sciences, 114(7), 1619-1624.

Subramanian, A., Venugopalan, R., & Ramasundaram, P. (2023). Revisiting Bt cotton: Insights from pink bollworm resurgence in southern India. Sustainability, 15(6), 5123.

Sun, Y., Zhang, H., & Zhou, Y. (2021). Pyramiding volatile-linked resistance genes for whitefly management in cotton. Plant Biotechnology Reports, 15(6), 643-653.

Tabashnik, B. E., & Carriere, Y. (2019). Global patterns of resistance to Bt crops highlighting pink bollworm in the United States, China, and India. Journal of Economic Entomology, 112(6), 2513-2523.

Tabashnik, B. E., Brevault, T., & Carriere, Y. (2021). Insect resistance to Bt crops: Lessons from the first billion acres. Nature Biotechnology, 39(2), 144-155.

Tabashnik, B. E., Brevault, T., & Carriere, Y. (2021). Transgenic cotton and sterile insect releases synergize to eradicate pink bollworm. Proceedings of the National Academy of Sciences, 118(9), e2019115118.

Taning, C. N. T., Arpaia, S., Christiaens, O., Dietz-Pfeil Stetter, A., Jones, H., Mezzetti, B., & Smagghe, G. (2020). RNA-based biocontrol compounds: Current status and perspectives to reach the market. Crop Protection, 136, 105213.

Trapero, C., Stiller, W. N., & Wilson, L. J. (2023). Enhancing integrated pest management in GM cotton systems using host plant resistance. Frontiers in Plant Science, 8, 510.

Trapero, C., Wilson, I. W., Stiller, W. N., & Wilson, L. J. (2021). Augmenting Integrated Pest Management in GM Cotton through Host Resistance Traits. Frontiers in Plant Science, 7, 500.

Wang, J., Zuo, Y. Y., Li, L. L., Wang, H., Liu, S. Y., Yang, Y. H., & Wu, Y. D. (2020). Knockout of three aminopeptidase N genes does not affect susceptibility of *Helicoverpa armigera* larvae to Bacillus thuringiensis Cry1A and Cry2A toxins. Insect science, 27(3), 440-448.

Wang, X., Li, F., & Yang, X. (2020). Conservation tillage enhances natural enemy communities and pest suppression in cotton. Agriculture, Ecosystems & Environment, 297, 106926.

Wilson, I. W., Stiller, W. N., & Wilson, L. J. (2020). Enhancing integrated pest management in GM cotton systems using host plant resistance. Frontiers in Plant Science, 7, 500.

Wuk. M., Guo, Y. Y., & Lv, N. (2024). The evolution of resistance in cotton bollworm to Bt cotton in China. Crop Protection, 110, 123-130.

Xiao, Y., Zhang, T., Liu, C., Heckel, D. G., Li, X., Tabashnik, B. E., & Wu, K. (2024). Mis-splicing of the ABCC2 gene linked with Bt toxin resistance in Helicoverpa armigera. Scientific reports, 4(1), 6184.

Xuh. J., Chen, T., Ma, X. F., Xue, J., Pan, P. L., Zhang, X. C., ... & Zhang, C. X. (2021). Genome-wide analysis of RNA interference efficiency reveals variable insect responses. Journal of Economic Entomology, 114(1), 1-11.

Yang, F., Li, Y., & Wu, K. (2021). Evolution of non-recessive resistance to Bt proteins in cotton bollworm (Helicoverpa armigera): Implications for IRM. Crop Protection, 143, 105492.

Zafar, M. M., Razzaq, A., Farooq, M. A., Rehman, A., Firdous, H., Shakeel, A., ... & Ren, M. (2020). Insect resistance management in Bacillus thuringiensis cotton by MGPS (multiple genes pyramiding and silencing). Journal of Cotton Research, 3(1), 33.

Zhan, C., Liu, J., & Wang, Q. (2025). Topical RNA interference induces mortality in cotton aphid (Aphis gossypii): Towards RNAi-based pest management. Insects, 16(2), 145.

Zhang, H., Yin, W., Zhao, J., Jin, L., Yang, Y., Wu, S., & Wu, Y. (2024). Early warning of cotton bollworm resistance associated with intensive planting of Bt cotton in China. Plos One, 6(8), 22-874.

Zhang, J., & Wedegaertner, T. (2021). Genetics and breeding for glandless upland cotton with improved yield potential and disease resistance: A review. Frontiers in Plant Science, 12, 753426.

Zhang, Y., & Li, X. (2023). Role of methyl jasmonate mediated volatile emissions in deterring lepidopteran larvae in Gossypium hirsutum. Journal of Chemical Ecology. 49(5), 412-423.

Zhou, J., Zhao, L., & Zhang, W. (2023). CRISPR-Cas9 mediated editing of susceptibility genes in cotton for improved pest resistance. Plant Cell Reports. 42(3), 389-402.