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Management Strategies Against Cotton Bollworms in Genetically Modified Crops

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Abstract The widespread adoption of Genetically Modified (GM) crops, particularly Bt cotton, has significantly transformed pest management strategies for controlling cotton bollworms. This study explores the biology, behavior, and management strategies for cotton bollworms, emphasizing the role of Bt cotton in mitigating pest-related crop damage. While Bt technology has reduced pesticide use and increased yields, challenges such as the evolution of pest resistance threaten its long-term efficacy. Through Integrated Pest Management (IPM) approaches, including non-GM refuges, biopesticides, and cultural practices, sustainable solutions are proposed to address resistance development. The study also examines socio-economic impacts, environmental concerns, and global regulatory challenges that influence the adoption of GM crops. Future directions suggest innovations in gene-editing technologies, enhanced pest resistance traits, and improved policy frameworks to sustain agricultural productivity. This research underscores the importance of collaborative efforts among farmers, researchers, and policymakers in ensuring the sustainability of GM crops for cotton production.
Keywords Genetically modified crops; Bt cotton; Cotton bollworms; Integrated pest management (IPM); Resistance management

1 Introduction

Cotton bollworms, particularly *Helicoverpa armiger*a and *Pectinophora gossypiella* (pink bollworm), are some of the most destructive pests affecting cotton crops globally. These pests infest cotton plants by damaging the flower buds and bolls, leading to significant reductions in yield. Traditional pest control methods often rely on chemical insecticides, which pose risks to human health and the environment (Abudulai et al., 2018).

Bollworm infestations can cause severe crop damage, with infestations leading to up to 91.2% damage in green bolls. Such extensive damage not only reduces yield but also significantly impacts the quality of the cotton fibers, often resulting in increased pesticide use and higher production costs (Naik et al., 2021). A resurgence of *Helicoverpa armigera* following reduced Bt cotton cultivation in China resulted in a 2.1-fold increase in crop loss and a 4.4-fold rise in pesticide use, underlining the critical role bollworms play in reducing both yield and fiber quality (Lu et al., 2021).

The introduction of Genetically Modified (GM) crops producing insecticidal proteins from *Bacillus thuringiensis* (Bt) has revolutionized pest management in cotton. Bt cotton, which expresses Cry proteins that are toxic to bollworms, has been adopted in several countries, significantly reducing the need for chemical insecticides. For example, in Ghana, Bt cotton resulted in lower bollworm densities and higher yields, proving to be more cost-effective and environmentally sustainable than conventional practices (Abudulai et al., 2018). However, over time, pest resistance to Bt proteins, particularly in India and China, has threatened the efficacy of GM crops, necessitating new strategies for resistance management (Wan et al., 2017).

This study evaluates the effectiveness of genetically modified cotton, particularly Bt cotton, in controlling bollworm infestations and enhancing cotton yields, while exploring the long-term sustainability of Bt cotton as a pest management tool, with a focus on resistance management strategies. Given the resistance issues to Bt toxins in regions like India and China, this study assesses Integrated Pest Management (IPM) approaches that combine Bt cotton with other agricultural, biological, and chemical control methods, also explores new strategies to address resistance development, such as intercropping Bt and non-Bt cotton or using crop refuges, aiming to deepen the understanding of effectively integrating genetically modified crops into sustainable agricultural practices for long-term productivity and environmental safety.

2 Biology and Behavior of Cotton Bollworms

2.1 Life cycle of cotton bollworms

Cotton bollworms, particularly *Helicoverpa armigera* and *Pectinophora gossypiella* (pink bollworm), undergo a complete metamorphosis, which includes four stages: egg, larva, pupa, and adult. The life cycle duration varies depending on environmental conditions, particularly temperature and food availability. Eggs are laid on the host plants, and larvae hatch within a few days to feed on the plant tissues. The larval stage, lasting two to three weeks, is the most destructive, as the larvae burrow into buds and bolls. The pupal stage is completed in the soil, lasting approximately 7 to 10 days before the adult moth emerges to continue the cycle (Tabashnik and Carrière, 2019).

2.2 Feeding patterns and damage to crops

Bollworms cause significant damage during the larval stage, with larvae feeding on the cotton bolls, squares (flower buds), and leaves. *Helicoverpa armigera* prefers to feed on the reproductive parts of the plant, leading to direct damage to cotton lint and seeds. Infestations can lead to over 50% yield loss if not properly managed. Larvae also create entry points for secondary infections by fungi and bacteria, compounding the damage. Bt cotton varieties expressing Cry proteins have been effective in reducing bollworm feeding, but the development of resistance has become a concern in recent years (Shera and Arora, 2016).

2.3 Reproductive strategies and population dynamics

The reproductive capacity of cotton bollworms is high, with adult females laying several hundred eggs over their short lifespan of approximately one week. This high reproductive rate contributes to rapid population growth, particularly in favorable environmental conditions. Bollworm populations tend to spike during periods of high temperature and humidity, which provide optimal conditions for larval development. In Bt cotton fields, reduced population growth has been observed, but the evolution of resistance to Cry proteins in certain regions has allowed bollworm populations to resurge, particularly in India and China (Naik et al., 2021).

2.4 Adaptations to various environmental conditions

Cotton bollworms exhibit a remarkable ability to adapt to diverse environmental conditions. Their capacity to survive in both arid and humid climates, as well as to develop resistance to chemical insecticides and Bt toxins, has made them a persistent pest across the globe. Larvae can tolerate a range of temperatures and humidity levels, and adult moths are capable of long-distance migration, which allows for rapid spread in favorable conditions. In Bt cotton systems, bollworms have developed genetic resistance mechanisms, such as mutations in the cadherin gene (*PgCad1*), which confers resistance to Cry1Ac in pink bollworms (Fabrick et al., 2023).

3 Genetically Modified Crops for Cotton Bollworm Management

3.1 Bt cotton: Mechanism of action and development

Bt cotton, a genetically modified variety, expresses *Bacillus thuringiensis* (Bt) proteins, specifically Cry proteins, which are toxic to lepidopteran pests like cotton bollworms. These Cry proteins bind to specific receptors in the gut cells of the larvae, causing cell lysis and eventually death (Li, 2024). Bt cotton was first introduced in the mid-1990s, and different varieties have since been developed, such as Bollgard I and Bollgard II, which express different combinations of Cry toxins (Cry1Ac and Cry2Ab). This innovation has revolutionized pest control, significantly reducing the reliance on chemical insecticides and enhancing crop protection (Tabashnik and Carrière, 2019).

3.2 Resistance management in Bt cotton

Despite its effectiveness, Bt cotton faces challenges due to the evolution of resistance in pests like the pink bollworm (*Pectinophora gossypiella*). Resistance management strategies include planting non-Bt refuges, rotating crops, and employing Integrated Pest Management (IPM) approaches to delay resistance. In India, where pink bollworm resistance to Cry1Ac and Cry2Ab in Bollgard II has been documented, IPM practices such as reducing the cotton season and destroying crop residues have become essential to mitigate resistance development (Edpuganti, 2018). Additionally, strategies like hybridizing Bt with non-Bt cotton have shown potential to counter resistance by preserving susceptible insect populations (Wan et al., 2017).

3.3 Benefits of genetically modified crops in reducing pesticide use

The adoption of Bt cotton has led to a substantial reduction in pesticide use. For example, in Ghana, Bt cotton varieties significantly decreased bollworm densities, resulting in lower pesticide application and higher net profits compared to conventional cotton farming (Abudulai et al., 2018). Similarly, in India, Bt cotton reduced pesticide consumption by 28%, while simultaneously increasing productivity by 34% and profitability by 98% (Narayanamoorthy et al., 2020).

3.4 Comparison with conventional control methods

In comparison to conventional methods, such as chemical insecticides, Bt cotton offers a more sustainable and environmentally friendly solution for managing cotton bollworms. While chemical control relies on repeated applications of insecticides that can harm non-target organisms and lead to pest resistance, Bt cotton reduces these risks. For instance, in Mexico, Bt cotton has significantly reduced the application of chemical insecticides, contributing to environmental benefits such as the reduction in primary pest populations and minimal impact on non-target species (Rocha-Munive et al., 2018). However, the need for integrated pest management (IPM) strategies remains critical to ensure the long-term effectiveness of Bt cotton and to manage the risks of resistance.

4 Case Study: Management of Cotton Bollworms in Bt Cotton Fields

4.1 Location and background information

This case study examines cotton bollworm management in the Saurashtra region of Gujarat, India. Bt cotton, particularly Bollgard II® varieties, has been widely adopted in this region since the mid-2000s. However, starting in 2015, farmers reported high levels of pink bollworm (*Pectinophora gossypiella*) infestations, leading to severe crop losses. The return of this pest is attributed to the development of resistance to Cry1Ac and Cry2Ab proteins, which are integral to Bt cotton's insecticidal capabilities (Mohan and Komarlingam, 2017).

4.2 Implementation of Bt cotton in the region

Bt cotton was introduced in Gujarat in the early 2000s, significantly reducing the use of chemical insecticides and increasing cotton yields. The Bollgard II® technology, which produces two Bt proteins (Cry1Ac and Cry2Ab), became the dominant variety in the region. Farmers quickly adopted the technology, relying on its effectiveness in controlling bollworms and other lepidopteran pests. However, by 2015, pink bollworm populations exhibited resistance to these Bt toxins, particularly in the western cotton-growing states of Gujarat, Madhya Pradesh, and Maharashtra (Naik et al., 2018). This led to widespread crop damage and necessitated new management strategies.

4.3 Monitoring and management practices

Following the reemergence of pink bollworm, an area-wide Integrated Pest Management (IPM) approach was implemented. Key strategies included pheromone-based monitoring, which utilized gossyplure-baited traps to track moth populations, and targeted insecticide applications based on trap data. In fields where infestations were detected early, foliar sprays of chemical insecticides were used to supplement Bt cotton’s defenses. This strategy successfully reduced the number of larvae and decreased boll damage rates. The integration of pheromone traps and targeted chemical applications demonstrated improved control over relying solely on Bt cotton (Carrière et al., 2017).

Furthermore, efforts were made to increase compliance with refuge planting-growing non-Bt cotton alongside Bt cotton to slow the evolution of resistance. However, the effectiveness of this approach was limited due to poor adoption of refuges by farmers. To address the resistance issue more effectively, additional management tactics were introduced, such as shorter cotton seasons and destruction of crop residues to prevent pest overwintering (Tabashnik and Carrière, 2019).

4.4 Analysis of results: success and challenges

The implementation of Bt cotton in Gujarat, India, initially brought significant success in controlling pink bollworm populations and reducing reliance on chemical insecticides. The Cry1Ac and Cry2Ab proteins expressed by Bollgard II® cotton were effective in reducing bollworm infestations and increasing yields. However, the success of Bt cotton was challenged by the emergence of resistance in pink bollworm populations, as reported in multiple studies from India. This resistance, particularly to Cry1Ac, posed a major threat to the sustainability of Bt cotton as an effective pest control tool (Naik et al., 2018).

The key challenge identified was the inadequate implementation of resistance management strategies. Non-compliance with refuge planting by farmers was one of the major reasons for the accelerated development of resistance, as refuges are crucial for maintaining populations of susceptible pests. Additionally, poor adoption of Integrated Pest Management (IPM) practices, such as shorter cotton seasons and destruction of crop residues, exacerbated the problem (Tabashnik and Carrière, 2019).

Despite these challenges, the use of pheromone traps and targeted insecticide applications provided some level of control over bollworm populations. Pheromone-based monitoring, when combined with foliar insecticides, successfully reduced bollworm densities and boll damage in several regions (Carrière et al., 2017).

4.5 Lessons learned from the case study

Several important lessons can be drawn from the management of cotton bollworms in Bt cotton fields in Gujarat. While Bt cotton is an effective tool for pest control, its long-term success depends on the rigorous implementation of resistance management strategies. Compliance with refuge planting, shorter cotton seasons, and IPM practices are essential to prevent the rapid development of resistance among pest populations (Mohan and Komarlingam, 2017).

The use of complementary pest management strategies, such as pheromone traps and selective insecticide applications, is crucial in maintaining pest control efficacy (Figure 1) (Tabashnik et al., 2020). Integrating non-chemical methods into pest management strategies, such as the use of pheromone-based mating disruption, can reduce dependence on Bt proteins and extend the life of genetically modified crops (Sreenivasa et al., 2021).

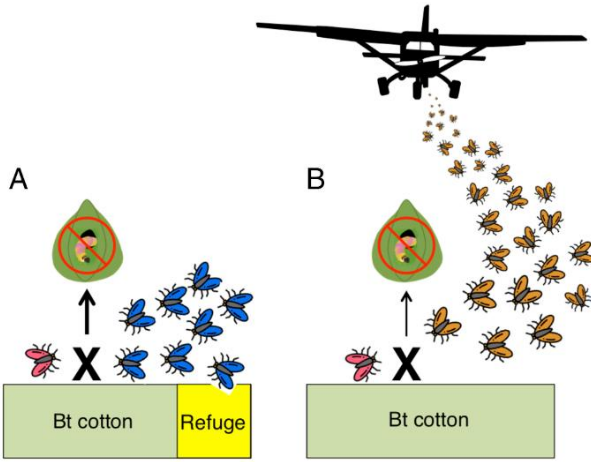

Figure 1 Management strategies (Adopted from Tabashnik et al., 2020)

Image caption: (A) The refuge strategy is the primary approach adopted worldwide to delay the evolution of pest resistance to Bt crops and was used in Arizona from 1996 to 2005. Refuges of non-Bt cotton planted near Bt cotton produce abundant susceptible moths (blue) to mate with the rare resistant moths (red) emerging from Bt cotton. If the inheritance of resistance to Bt cotton is recessive, as in pink bollworm, the heterozygous offspring from matings between resistant and susceptible moths die when they feed on Bt cotton bolls as larvae (24). (B) Bt cotton and sterile moth releases were used together in Arizona from 2006 to 2014 as part of a multitactic program to eradicate the pink bollworm. Susceptible sterile moths (brown) were released from airplanes to mate with the rare resistant moths emerging from Bt cotton. The few progeny produced by such matings (48) are expected to be heterozygous for resistance and to die when they feed on Bt cotton bolls as larvae (Adopted from Tabashnik et al., 2020)

The case highlights the importance of continuous monitoring and early detection of resistance development. Monitoring resistance alleles and ensuring early interventions can help mitigate the risks posed by resistant pest populations (Wang and Lin, 2024), as seen in the management efforts in the United States, where pink bollworm was successfully eradicated through a combination of Bt cotton and sterile moth releases (Tabashnik et al., 2020).

5 Resistance Development in Cotton Bollworms

5.1 Mechanisms of resistance to Bt toxins

The primary mechanism of resistance in pink bollworm (*Pectinophora gossypiella*) to Bt cotton lies in genetic mutations. These mutations often occur in the cadherin gene and ATP-Binding Cassette (ABC) transporters, disrupting the binding of Bt toxins (e.g., Cry1Ac and Cry2Ab) to the insect gut receptors, thereby reducing their efficacy (Wang et al., 2022). Cross-resistance is another issue, as resistance to one Cry protein can sometimes extend to another (Wei et al., 2015).

5.2 Factors contributing to resistance evolution

Several factors drive the evolution of resistance, including continuous exposure to Bt toxins without effective refuges. In regions like India, non-compliance with structured refuge planting has accelerated resistance development, as seen with widespread pink bollworm resistance to Cry1Ac and Cry2Ab toxins (Tabashnik and Carrière, 2019). Additionally, the high reproductive rate of cotton bollworms and their genetic adaptability contribute to the rapid evolution of resistance (Akhtar et al., 2018).

5.3 Monitoring resistance in field populations

Monitoring the prevalence of resistance alleles is crucial for early intervention. In China, DNA-based screening revealed that mutations in the cadherin gene were associated with Cry1Ac resistance in pink bollworm populations (Wang et al., 2020). Similar mutations in the ABC transporter gene (PgABCA2) have been documented in resistant strains from India and Arizona, indicating that resistance mechanisms are consistent across regions (Mathew et al., 2018).

5.4 Strategies to delay resistance development

Implementing strategies to delay resistance development is essential for the sustainability of Bt cotton. One effective approach is the use of "pyramided" Bt crops that express multiple toxins, reducing the likelihood of resistance development to all toxins simultaneously. Additionally, integrating Bt cotton with non-Bt refuges, as practiced in China, has successfully delayed resistance evolution by maintaining susceptible pest populations (Wan et al., 2017). Monitoring resistance at the molecular level, along with adopting shorter cotton-growing seasons, has proven to be effective in managing resistance in other regions (Chen et al., 2017).

6 Integrated Pest Management (IPM) Approaches

6.1 Role of Non-GM crops in IPM for cotton bollworms

Non-GM crops play a crucial role in IPM strategies by serving as refuges that slow the evolution of resistance in bollworm populations. For instance, planting non-Bt cotton alongside Bt cotton allows the survival of susceptible pest populations, reducing the selection pressure for resistance. Research in India emphasizes that compliance with refuge planting has a significant impact on delaying resistance and enhancing the long-term efficacy of Bt cotton (Rakhesh et al., 2023).

6.2 Use of biopesticides in combination with Bt cotton

The integration of biopesticides, such as neem-based formulations and *Bacillus thuringiensis* (Bt) sprays, with genetically modified cotton strengthens pest control strategies. In a study from Telangana, India, combining Azadirachtin sprays with pheromone traps demonstrated reduced pest damage and higher yields (Alugoju et al., 2022). This approach minimizes chemical pesticide use and supports ecological sustainability.

6.3 Cultural and mechanical control strategies

Cultural practices, such as early sowing and crop rotation, are essential components of IPM. For example, removing and destroying plant residues disrupts the pest's lifecycle, reducing overwintering populations. Studies emphasize the effectiveness of combining these practices with mechanical controls, such as pheromone-based mating disruption and targeted handpicking of larvae, to minimize bollworm infestations.

6.4 Future directions in ipm for sustainable cotton production

The future of IPM in cotton production lies in developing more sustainable and innovative pest management strategies. Increased adoption of mating disruption tools and bio-based products, along with greater education and farmer engagement, is essential to improve IPM practices. Furthermore, precision agriculture technologies, such as remote sensing and predictive pest modeling, offer potential to enhance pest monitoring and control efficiency. The integration of new technologies and continued collaboration among stakeholders will ensure the sustainability and resilience of IPM programs (Figure 2) (Anderson et al., 2019).

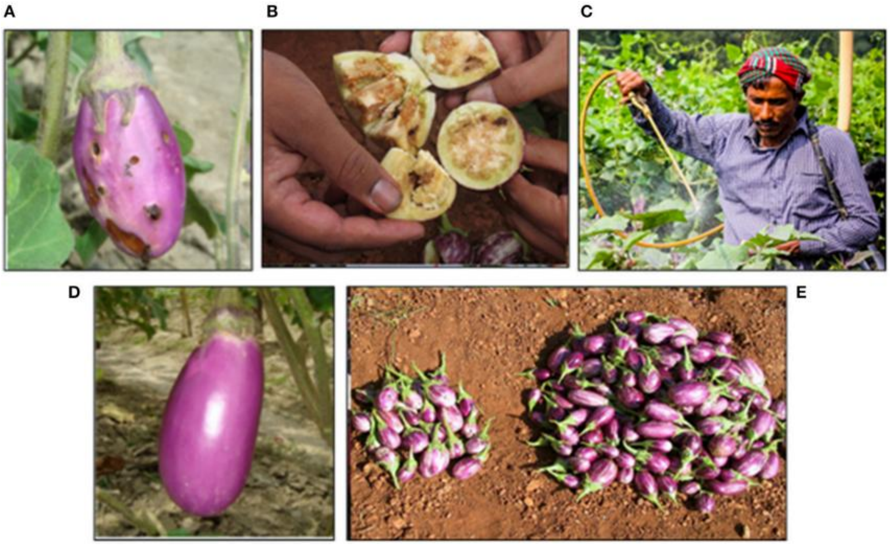

Figure 2 Diagram of eggplant infestation by cotton bollworm and yield increase after farmer intervention (Adopted from Anderson et al., 2019)

7 Future Perspectives and Challenges

7.1 Innovations in genetic modification for pest resistance

Advancements in biotechnology are enabling the development of genetically modified crops with more effective pest resistance. New techniques, such as CRISPR-Cas9 gene editing, RNA interference (RNAi), and gene stacking, allow for precise genetic modifications and enhanced insect resistance, reducing the reliance on chemical pesticides. Future genetically engineered crops may feature multiple pest-resistant traits to counter evolving resistance, and innovations such as drought tolerance and nitrogen-use efficiency are also being integrated into pest management strategies (Ricroch and Hénard-Damave, 2016).

7.2 Environmental and ecological concerns

While Genetically Modified (GM) crops offer environmental benefits, such as reduced pesticide use, their long-term ecological impacts remain under scrutiny. Concerns include unintended gene flow to wild relatives, the development of herbicide-resistant weeds, and effects on non-target organisms, including beneficial insects. Studies also highlight the potential for reduced biodiversity in ecosystems dominated by GM crops. Policymakers emphasize the need for comprehensive risk assessments and environmental monitoring to address these concerns effectively (Tsatsakis et al., 2017).

7.3 Socioeconomic impacts of GM crops in cotton farming

The adoption of GM crops has brought both benefits and challenges for smallholder farmers. Benefits include increased yields, reduced pesticide expenses, and improved occupational health due to fewer chemical applications. However, challenges persist, such as the high cost of GM seeds, limited access to technology, and concerns over market dependency on large agrochemical corporations. Intellectual property rights associated with GM crops can also disadvantage small-scale farmers, particularly in developing countries (Azadi et al., 2015).

7.4 Global policy implications and regulatory challenges

Regulatory frameworks for GM crops vary widely across regions, creating challenges for global trade and technology adoption. Inconsistent regulations, particularly between developed and developing countries, delay the commercialization of new GM traits. Additionally, public skepticism and resistance to GM crops complicate policy decisions. Harmonizing global regulatory standards and fostering public trust through transparent communication are essential to realize the potential of GM technology for food security and sustainability (Huesing et al., 2016).

8 Concluding Remarks

This study highlights the transformative role of Genetically Modified (GM) crops, particularly Bt cotton, in managing cotton bollworm populations and reducing pesticide reliance. Innovations in biotechnology have demonstrated significant economic and environmental benefits by improving crop yields, lowering pest damage, and reducing pesticide use. However, challenges such as pest resistance to Bt toxins have emerged, requiring effective resistance management strategies, including the use of refuges and Integrated Pest Management (IPM) approaches. Non-compliance with IPM strategies, especially in regions like India, has exacerbated the resistance problem, underscoring the importance of regulatory support and farmer education. Moreover, socio-economic challenges, such as seed access and intellectual property concerns, remain significant obstacles for smallholder farmers in adopting GM technologies.

Future research must focus on developing new GM crop varieties with stacked traits, combining multiple insect-resistant and herbicide-tolerant genes to mitigate the risks of resistance. Advances in gene-editing technologies such as CRISPR-Cas9 should be explored for creating more precise and sustainable pest-resistant traits. Additionally, there is a need for more extensive monitoring systems to detect early signs of resistance, supported by molecular diagnostics for tracking resistance alleles in pest populations.

From an implementation perspective, greater emphasis should be placed on IPM practices that incorporate biopesticides, crop rotation, and cultural controls to complement GM crops. Educating farmers on refuge management and fostering public-private partnerships can enhance the sustainable use of GM crops. Harmonizing global regulatory frameworks will also be critical in facilitating trade and the adoption of new technologies, especially in developing countries. Long-term research should further investigate the socio-economic impacts of GM crops, ensuring that smallholder farmers can access and benefit from these innovations equitably.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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