DOI: https://doi.org/10.70749/ijbr.v3i8.2205

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://ijbr.com.pk
ISSN: 2960-2793/ 2960-2807

Biological Control Strategies for the Pink Bollworm (*Pectinophora gossypiella*) in Cotton (Gossypium spp.)

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ARTICLE INFO

Keywords: Natural Enemies, Parasitoids, Predation, Parasitism, Trichogramma, CRISPR, Beauveria Bassiana, Integrated Pest Management (IPM).

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Declaration
Authors' Contribution
All authors equally contributed to the study and approved the final manuscript

Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History
Received: 26-06-2025 Revised: 14-08-2025
Accepted: 20-08-2025 Published: 30-08-2025

ABSTRACT

The pink bollworm (*Pectinophora gossypiella*) is a destructive global pest of cotton capable of causing up to 90% yield loss and severe fiber quality degradation, resulting in major economic impacts. Heavy reliance on chemical insecticides and transgenic Bt cotton has initially suppressed infestations, but resistance evolution, particularly in India, has renewed concerns about sustainable management. This review synthesizes the role of biological control within Integrated Pest Management (IPM) frameworks as an ecofriendly and long-term solution. Biological control involves harnessing natural enemies' predators (lacewings, lady beetles, and assassin bugs), parasitoids (Trichogramma spp., Bracon hebetor), pathogens (Beauveria bassiana, Metarhizium anisopliae), and entomopathogenic nematodes (Steinernema riobrave, Heterorhabditis indica) to suppress pest populations. These agents can be deployed through conservation, augmentation, or mass release, and combined with sterile insect techniques (SIT) for area-wide suppression. Field studies report up to 80% egg parasitism by Trichogramma and 60% reduction in boll damage when natural enemies are integrated with cultural practices. However, environmental factors, predator-prey dynamics, and farmer compliance with refuge strategies influence success. Future directions include genetic enhancement of cotton (CRISPR-mediated resistance), RNA interference to disrupt pest gene function, and improved pheromone-based mating disruption. Novel strains of biocontrol agents and advanced mass-rearing technologies can further boost efficiency. By integrating diverse biological tactics with cultural, mechanical, and selective chemical controls, IPM offers a sustainable pathway to manage pink bollworm, reduce chemical inputs, delay resistance development, and maintain ecological balance in cotton agroecosystems.

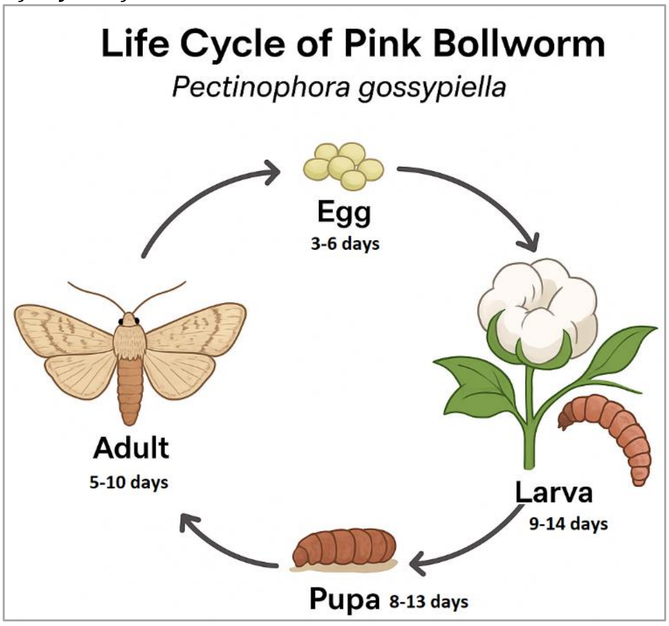
INTRODUCTION

The Pink Bollworm (*Pectinophora gossypiella*) is one of several serious insect pests, this pest species can cause yield losses of up to 90% prior to the widespread application of broad-spectrum insecticides and the advent of transgenic cotton (Patil, 2003). Cotton is in one of the most valuable fiber crops worldwide, cultivated in the tropical and subtropical parts of over 70 countries including India (Shaheen et al., 2012; Chakravarthy et al., 2014). It is the primary fiber crop cultivated in India and dominates the agricultural and industrial markets. It is responsible for 70% of overall fiber usage in the textile industry and 38% of Indian exports, fetching more than Rupees 42 000 crores (Mageshwaran et al., 2019). *Pectinophora gossypiella* (Saunders) is one of the most classic examples of damaging cotton pests all over the world. Larva consumes the seed of the flower and damages the cotton fibers, decreasing crop quantity and quality. Most affected crops are okra, jute, castor bean, and cotton completing 6 generations annually. *P. gossypiella* is among the most oligophagous pest species (Kumar et al., 2025). Pink bollworm is a major challenge to cotton crop production the world over. It presents a chipping threat to the cotton production as it has the ability to infest and destroy cotton bolts causing massive economic losses. This pest has been controlled by means of numerous control methods where one of them is the utilization of transgenic cotton that produces *Bacillus thuringensis* (Bt) toxins (Tabashnik et al., 2020). Nevertheless, flexibility and resistance development of pink bollworm to Bt cotton has been cause of concern and has necessitated integration of pest control (Carriere et al., 2001; Tabashnik et al., 2005). An eradication program was structured in the United States especially in Arizona which involved planting of Bt cotton and mass release of sterile pink bollworm moths (Tabashnik et al., 2012; Wu and Guo, 2005). This multi-tactic strategy did not just eliminate the pest in such cotton producing areas but also saved the government a lot of money economically. Between 2014 and 2019, such attempts preserved $192 million by the U.S. farmers and led to an enormous decrease in insecticides consumption, which is both cost-effective and environmentally friendly (Tabashnik et al., 2020).

The Pink Bollworm (*Pectinophora gossypiella*) is a cotton-destroying pest that originated in Asia and now infests tropical and subtropical areas around the globe, including leading cotton-producing nations like India, China, Pakistan, the United States of America, Brazil, Egypt, and Sudan (Iqbal et al., 2025). The larvae infest cotton bolls and consume seeds and lint, leading to reduced fiber quality and early boll drop. They can cause up to 90% yield loss during heavy infestations, considerably affecting farmers' revenue and world cotton production (Madhu et al., 2025). This pest is very invasive and has been identified in major cotton producers around the world like the United States, India, and China, the three nations that are encountering different challenges attached to pink bollworm infestation and the measures designed to contain it (Gassmann et al., 2006; Quan and Wu, 2023). The pink bollworm is a major problem to the cotton production in India since it appears in large numbers in the Bt cotton fields. The resistance in the pest to Bt cotton is prevalent owing to the limited number of the non-Bt cotton refuges. Genetic findings showcase that there is a demographic increase in the pink bollworm population in the cotton areas of India (Naik et al., 2020; Tabashnik and Carriere, 2019). China has taken another strategy in which a combination of Bt and non-Bt cotton, in combination with a natural strategy manages the pink bollworm resistance. Such an approach has paid off to prevent real-world opposition and the failure of Bt cotton in the nation (Quan and Wu, 2023).

Biological control makes use of natural enemies, predators, parasitoids, and pathogens to control pest numbers, minimizing their impact on crops. For the pink bollworm (*Pectinophora gossypiella*), it includes the introduction or promotion of organisms, parasitic wasps (*Trichogramma* species), predators (lacewings, lady beetles), pathogens (*Bacillus thuringiensis* or *entomopathogenic* fungi) that infect its eggs, larvae, or adults (Abd-ElAzeem et al., 2020). Techniques involve releasing these agents into fields (augmentative control), maintaining their natural populations by managing habitats, or applying sterile insect techniques (SIT) to suppress reproduction (Kumar et al., 2025). The importance of biological control in the Integrated Pest Management (IPM) of pink bollworm (*Pectinophora gossypiella*) is because of issues like emergence of resistance to *Bacillus thuringiensis* (Bt) crops as well as advances that call upon the use of sustainable lifecycle friendly strategies to manage pests. It is still somewhat difficult to detect the origin of the disease (Fabrick et al., 2023; Tabashnik et al., 2012). The use of biological control in IPM programs on pink bollworm is essential because this control type supports other control measures and adds to the efficacy and sustainability of the strategies applied to manage these pests. Such strategies have minimized the use of chemical insecticide and, therefore, biological control is a significant element of sustainable pest management systems in pink bollworm (Henneberry, 2017). Biological control offers the benefits of chemosynthetic control in the management of the Pink Bollworm in terms of economic costs, sustainability of the environment, decreasing the likelihood of resistance, and favoring ecological wellbeing. These advantages render biological control an attractive alternative in the context of pest control management within integrated pest management-based systems in order to secure the sustainable nature of the pest control measure in the long-term (Kolkert et al., 2019; Simmons et al., 2011).

Figure 1.1
Life Cycle of Pink Bollworm



Natural Enemies of Pink Bollworm
Predators of Pink Bollworm

Pink bollworm (*Pectinophora gossypiella*) is one of the most important agricultural pests known as a highly damaging cotton pest that is under natural control against its eggs, larvae, or adults by the many insects, mites, spiders, and bird's species that prey on bollworm and whose inclusion in biological control is critical in Integrated Pest Management (IPM) (Sarwar et al., 2017). Predatory insects, lacewings (*Chrysoperla carnea*), lady beetles (*Hippodamia convergens*), and assassin bugs (*Zelus renardii*) prey on eggs and young larvae (Rakhesh et al., 2025; Boopathi et al.,2024). Other parasites are less important as they sometimes devour the pink bollworm eggs in cotton fields, including predatory phytoseid mites. Adult moths and larvae are both captured in webs by spiders and through active hunting by spiders such as orb-weavers (*Araneidae*) and wolf spiders (*Lycosidae)*, all of which help suppress the pests (Attia et al., 2021). Insectivorous birds, like sparrows (*Passer species*), and other insectivorous species like blackbirds, eat exposed larvae and adult moths when fieldwork such as boll disturbing is in motion. These biological controls kill pink bollworms and in aggregate kill pink bollworms, provide the benefit of having an environmentally friendly alternative to chemical controls and promoting sustainable production of cotton (Younis et al., 2010). The pink bollworm falls prey to birds especially to the synanthropic insectivorous bat *Pipistrellus kuhlii*. These bats have been known to exploit irruptions of pink bollworm through opportunistic feeding, and thus it makes these bats a significant natural enemy in conservation biological control of the cotton pests. Research done in the Mediterranean agroecosystem revealed that pink bollworm constituted a crucial source of food in the faecal samples of the bat, found in 31 percent of cases (Cohen et al., 2020).

Table 2.1.

Natural enemies of pink bollworm (Pectinophora gossypiella) and their reported efficacy in field conditions

Natural Enemy Type	Species Name	Life Stage Targeted	Mode of Action	Average Field Efficacy (%)	Reference
Predator	*Chrysoperla carnea* (Green lacewing)	Egg, Neonate larva	Predation – consumes eggs and early instars	30–40	Younis et al., 2010; Sarwar, 2017
Predator	*Hippodamia convergens* (Lady beetle)	Egg, Larva	Predation – feeds on eggs and young larvae	28–35	Sarwar, 2017
Predator	*Zelus renardii* (Assassin bug)	Egg, Larva	Piercing-sucking predation	25–32	Rakhesh et al., 2025
Parasitoid (Egg)	*Trichogramma chilonis*	Egg	Oviposition inside host egg, preventing hatching	50–80	Moirangthem et al., 2022; Babu et al., 2023
Parasitoid (Egg-Larval)	*Chelonus blackburni*	Egg → Larva	Lays eggs inside bollworm eggs; larva develops within host larva	20–40	Hentz et al., 1997
Parasitoid (Larval)	*Bracon hebetor*	Larva	Paralyzes host larva before oviposition	20–40	Babu et al., 2023
Parasitoid (Pupal)	*Brachymeria ovata*	Pupa	Oviposition inside pupa, killing it	5–15	Nagaraju et al., 2024
Pathogen (Fungus)	*Beauveria bassiana*	Egg, Larva, Pupa	Contact infection – penetrates cuticle, causes mycosis	85–91	Omar et al., 2021
Pathogen (Fungus)	*Metarhizium anisopliae*	Egg, Larva, Pupa	Contact infection – cuticle penetration, systemic colonization	90–94	Iqbal et al., 2025
Bacterium (Bt)	*Bacillus thuringiensis* (Cry1Ac, Cry2Ab)	Larva	Ingestion – gut paralysis and septicemia	80–95	Tabashnik et al., 2020
Nematode	*Steinernema riobrave*	Larva, Pupa	Penetrates natural openings, releases symbiotic bacteria	60–70	Gassmann et al., 2006
Nematode	*Heterorhabditis indica*	Larva, Pupa	Penetrates host, symbiotic bacterial infection	65–72	Thube et al., 2023

Parasitoids of Pink Bollworm

There are many parasitoids that prey on the pink boll worm at various stages in its development thus curbing the population in cadres of cotton. Egg parasitoids of interest include *Trichogramma* species, *T. pretiosum* and *T. chilonis* being the most commonly used in augmentative releases, especially in India, to parasitize pink bollworm eggs by laying their own eggs within the eggs so they never hatch (Sarwar, 2017). Pink bollworm (*Pectinophora gossypiella*) has numerous parasitoids against its different development stages, which helps yield natural biological control in cotton. The most common egg parasitoids belong to the family *Trichogrammatidae*, *Trichogramma evanescens*, *Trichogramma chilonis*, *Trichogramma brasiliensis*, *Trichogrammatoidea bactrae* which lay eggs within the eggs of the hosts and destroy them (Kumara et al., 2022). Egg-larval parasitoids like *Chelonus blackburni* and *Chelonus* sp feed on the eggs and finish development within the larval host but the parasitoid emerges as a pupa after host larva has spun its cocoon (Hentz et al., 1997). The larval parasitoids include *Braconidae*. *Bracon lefroyi*, *Bracon hebetor*, *Bracon greeni*, *Bracon brevicornis*, and *Bracon kirkpatricki* and *Bracon gelechiae*, *Apanteles angaleti*, *Apanteles oenone*, *Rogas* sp., and *Camptothlipsis* sp., *Bethylidae*, *Goniozus pakmanus*, *Goniozus legneri*, and *Perisierola emigrata*, and *Elasmidae*. *Elasmus* The pupal parasitoids are mostly *chalcidids* and *Pteromalidae*, *Brachymeria ovata*, *Brachymeria* sp, *Dibrachys cavus*, *Habrocytus* sp, *Dirhinnus* sp, and *Chalcis obscurata* and are pupal stage specific in their oviposition and development (Naranjo et al., 2002). Among the larval parasitoids are the *Bracon hebetor* and *Apanteles angaleti* that penetrate the larvae in cotton bolls where the *Bracon* species paralyze the larvae then lay eggs resulting in their death. Other parasitoid larva, *Chelonus blackburni* are also occasion, and lay their eggs in the larva which then kill the host as they grow. Parasitoids of the pupal stage are less used but include species such as Ichneumon spp. that attack pink bollworm pupae in the soil, or in debris, and parasitize to derail the life cycle of the pest. These parasitoids, especially when combined with other IPM methods (Rakhesh, et al., 2023).

Predation and parasitism rates of Pink Bollworm in field studies

The ability of predation and parasitism, as evidence in field studies in cotton growing areas, like India, United States and Australia indicates, are essential towards ensuring that there is a reduction of the pink bollworm population. Egg consumption by predators such as lacewings (*Chrysoperla carnea*), lady beetles (*Hippodamia convergens*), assassin bugs (*Zelus renardii*) and others were enhanced in the field where predator populations were conserved, with as much as 30-40 percent of eggs being consumed in predator-protected fields in India (Younis et al., 2010; Sarwar, 2017). Adult moths and exposed larvae are also preyed upon by spiders, most notably orb-weavers (*Araneidae*) and wolf spiders

(*Lycosidae*), and make up to 10-20 percent of the life cycle in certain US field trials. They are further affected by parasitoids, which in Indian cotton fields can parasitize 50-80 percent of pink bollworm eggs when released in augmentation way (Babu et al., 2023). Examples of larval parasitoids include *Bracon hebetor* and *Chelonus blackburni*, which have 20-40% parasitism in larva inside the bolls as was reported in Pakistani and Egyptian projects. Lower (but significant) impacts are found in pupal parasitoids (*Ichneumon* spp.) with 5 and up to 15 percent of soil pupae parasitized in Australian croplands (Nagaraju et al., 2024). Habitat manipulation or augmentative releases of these natural enemies decrease damage to pink bollworm by as much as 60 per cent in some experiments, complementing the protection of Bt cotton, and limiting the use of chemical pesticides, although effectiveness is affected by environmental conditions and by density of target pests (Birah et al., 2023).

Factors influencing natural enemy populations against Pink Bollworm

Various abiotic and biotic factors can act to affect the population of the natural control agents of the Pink Bollworm (*Pectinophora gossypiella*) in cotton fields: predators, parasitoids, and pathogens. These influence their fitness and distribution, and their application in biological control in the Integrated Pest management (IPM) schemes (Gutierrez et al., 2006). Some of the factors affecting the population dynamics of the natural enemies that include *Trichogramma* parasitoids, lacewings, lady beetles, spiders and entomopathogenic pathogens, that prey on or parasite pink bollworm (Somaa et al., 2016). The heavy application of broad-spectrum insecticides that are used in agricultural practices can cause a sharp fall in the natural predators since the beneficial insect death occurs because these non-target insects are keenly focused on. Research findings in India have reported up to 70 percent drop in predator and parasitoid density after spraying. The effects of habitat management on populations: A variety of field margins with nectar rich plants or refuge crops can be used to increase survival of *Trichogramma* and lacewings, providing a food source and shelter increasing parasitism rates by 20-30% in certain studies in the US and India (Ali et al., 2016). Growing conditions, including temperatures, humidity, influence the activity of natural enemies; *Trichogramma* parasitism is maximum between 25-30^{o}C, but decreases at higher temperature levels, as in cotton fields in Pakistan. The level of pests also affects the population level of natural enemies as the higher the density of pink bollworm eggs or larvae the more the presence of parasitoids and predators increases the reproduction levels just like it was observed during Egyptian wild studies where the level of *Bracon hebetor* level increased with the outbreak of pests (Abbas et al., 2022).

Research indicated that development and survivability of pink bollworm is affected by temperature with higher larval survival being implicated when temperature is between 30 ^{0}C and 35 ^{0}C (Nagaraju et al., 2024). The insectivorous bats in the passive form of control, Kuhl pipistrelle, have also been mentioned. Such bats potentially play the role of biological control agents, eating a large number of pink bollworms in particular during pest outbreaks (Cohen et al., 2020). These strategies not only cut the dependence on conventional insecticides thus reducing the risks carried by these organizational practices to the environment they also have an influence on the whole food webs dynamics, which could interfere with the natural populations of natural enemies (Carriere et al., 2003). Climate conditions (temperature), synanthropic insectivorous bats, and pest control means such as transgenic crops and sterile insect release naturally control population levels of enemies against pink bollworm. All these factors have the effect of regulating the prey-predator relationships, as well as the availability and efficacy of the natural enemies in agricultural systems. (Ahmad et al., 2024; Jiang et al., 2019).

Pathogens Affecting Pink Bollworm

Effectiveness of entomopathogenic fungi against Pink Bollworm

Entomopathogenic fungi (EPF) have been found to particularly be effective against the pink bollworm (*Pectinophora gossypiella*), a key cotton pest and these include the *Beauveria bassiana and Metarhizium anisopliae* fungi, whose effectiveness has correlated with strain as well as with fungal concentration, application route and life subject (Omar et al., 2021). These fungi have the potential to cause high mortality rates in eggs, larvae, and pupae as field and laboratory experiments in Egypt and India have indicated. In a 2021 Egyptian study, *B. bassiana* proved more potent than *M. anisopliae* with median lethal concentrations (LC50) of 4.971011 spores/ml of eggs, 8.25108 neonates, 2.52108 4th instar larvae and 6.79108 pupae in comparison to the larger values of LC50 of *M. anisopliae* (6.031012 against. In one central Indian study published in 2025 on strain TMBMA1 of *M. anisopliae*, it was found that it caused 100 per cent larvae mortality in higher doses (1x109 1x1010 spores/ml), with an LC50 of 7.1x105 spores/ml and compatibility with an insecticide such as cypermethrin, improving its field suitability (Iqbal et al.,2025). Egypt against closely related bollworms revealed *M. anisopliae* causing a decrease in infestations of 90-94 percent and *B. bassiana* 85-91 percent following three sprays during field trials. Environmental factors such as temperature (ideal range is 25-30 ^{o}C) and humidity and application rates and integration with IPM approaches also affect efficiency and therefore EPF is an imminent ecofriendly alternative to the use of pesticide in controlling pink bollworm (Farooq et al., 2020). *Beauveria* and *Metarhizium* fungi have mechanisms of action as they infect the insect by contact and penetrate the exoskeleton and ultimately lead to the death of the host by a combination of mechanical destruction and physiological disturbance (Quesada-Moraga et al., 2022). Their potentiality to form an endophytic association with plants also increases their efficacy because it covers and secures crops both directly and indirectly through healthier plants (Bamisile et al., 2018; Panwar and Szczepaniec, 2024). Molecular biology allows genetic modification of these fungi so that they can enhance their biocontrol activities. This is so as to increase pathogenic properties and make them effective even in various environmental conditions (St Leger and Wang, 2009).

Mechanism of *Bacillus thuringiensis* (Bt) in controlling Pink Bollworm larvae

Bacillus thuringiensis (Bt) is a bacterium that contains insecticidal proteins, which have been introduced into transgenic crops, like cotton to regulate insect pests, like pink bollworm larvae (*Pectinophora gossypiella*) (Tabashnik et al., 2022; Tabashnik et al., 2000). *Bacillus thuringiensis* (Bt) destroys pink bollworm (*Pectinophora gossypiella*) larvae in a particular mechanism that includes the generation of insecticidal proteins (referred to as Cry toxins) (Naik et al., 2018). Bt toxins become active in the alkaline midgut of the pink bollworm larvae when they consume either transgenic Bt cotton, Bt toxins applied to the plants as an aerosol formulation. The Cry proteins, active factors often composed of Cry1Ac or Cry2Ab found in Bt cotton, are pro-toxins that are cut into action by midgut protease into their active forms. These produced toxins attach to certain receptors, cadherin or aminopeptidase N on the midgut epithelial cells, creating holes in the cell membrane (Fabrick et al., 2023). The formation of this pore upset the osmotic balance leading to cell lysis, midgut paralysis and feeding termination in general terms, happening within few hours. The destruction permits the intrusion of the intestinal microorganisms into the hemocoel causing septicemia that finally kills the larvae in the 1-3 days basis setting the toxin dosage and larval stage of its growth development. This is quite specific to some insects such as lepidopteran larvae including the pink bollworm which makes Bt an effective and environmentally secure mode of control. However, resistance in a minority of Indian populations may reduce its performance in the long run (Rajput et al., 2019). Bt toxins may be subjected to resistance in the pink bollworms by such different mechanisms. Another important process is alteration of the cadherin proteins in the midgut, which is critical in binding of Cry toxin variation in amino acid sequence of midgut cadherin protein (PgCad1) binding Cry1Ac has been associated with resistance to Cry1Ac. Reduced transcription of PgCad1 gene and cadherin protein with often a reduced amount of cadherin protein occurs in resistant strains thus making the toxin less effective (Fabrick et al., 2019; Wang et al., 2019). Resistance development is determined by genetic factors and their inheritance traits. An example is the Bt toxin such as Cry1Ac where resistance shows recessive inheritance making it more probable to occur due to the resistant genes in both of the parental insect lines (Liu et al., 2001). In spite of emergence of resistance, intercrossing of various Cry toxins in cotton, either Cry1Ac or Cry2Ab, assists in curbing this, by allowing a multitoxin approach that is harder to develop resistance to (Tabashnik et al., 2002).

Use of nematodes for Pink Bollworm control

To help control the pink bollworm (*Pectinophora gossypiella*), with nematodes have been applied in biological control. The main control agent with a lot of potential in controlling this pest has been nematodes especially the entomopathogenic nematodes. *Steinernema riobrave* and *Heterorhabditis indica* are two species of nematode that have been researched on their musicality in combating the pink bollworm (Mengal et al., 2024). *Steinernema riobrave* is known that this nematode enhances the cost of resistance to the Bt toxin Cry1Ac in pink bollworms. Its application resulted in the tremendous increase in the mortality levels of Bt-resistant pink bollworm strains between the fourth instar larval stage and the adult eclosion stage upon exposure to juvenile nematodes. It implies that *Steinernema riobrave* may provide an option of being used in integrated resistance management plans, to either postpone or preclude pest adaptations against Bt toxins (Gassmann et al., 2006). *Heterorhabditis indica* nematodes has proven highly virulent and reproductive to various larval stages of the pink boll worm specifically strain CICR-HI-CL strain CICR-HI-MN. The bioassays revealed that strain CICR-HI-CL was more effective than CICR-HI-MN, inducing high rates of larvae and pupae mortality and demonstrated promising ability to multiply on the pest (Thube et al., 2023). These nematodes of entomopathogenic-nature can be potentially used as good biological control agents to supplement the above required chemical control measures, as well as the currently available transgenic crops in order to control the pink bollworm holistically in a more sustainable manner. (De Brida et al., 2017).

Implementation of Biological Control

Habitat management methods to enhance Pink Bollworm natural enemies.

Habitat management can be of significance in increasing the effectiveness of natural enemies on pink bollworm (*Pectinophora gossypiella*) in cotton agroecosystems. Intercropping cotton with legumes, flowering plants high in nectar such as coriander and fennel, constitutes diversified cropping systems, which can serve as an additional source of food and alternative host to parasitoids like, *Trichogramma* spp. and *Bracon hebetor* thus boosting their survival and reproductive rates (Hassan et al., 2016). Perennial flowering plants (usually Sesbania or marigold) along field borders planted in conservation strips provide support and more food to predators like lacewings and spiders that helps control pink bollworm (Kausarkha et al 2021). Properly strategically planted non-Bt cotton refuges work to keep vulnerable pink bollworm populations in place, maintaining the availability of host populations, particularly parasitoids, *Tetrastichus howardi*, and serves to postpone the onset of resistance in Bt cotton systems (Khakwani et al., 2022). Tillage reduction conserves natural enemies of crops, of which soil-incorporated pupal parasitoids (*Brachymeria* spp., predatory beetles) are valuable because overwintering hosts are preserved and reduced disturbance of habitat. As well, irrigation and mulching moderately create the best microclimates to the ground-going predators such as ants and spiders (Babu et al., 2023).

Planting non-crop vegetation as well as intercropping can offer a necessary source of resources to natural enemies and increase abundance as well as diversity. Variety of flora would increase the complexity of the habitat as it provides nectar, pollen and secondary prey, which are very essential to the growth and survival of natural enemies (Fiedler and Landis, 2007; Gonzalez-Chang et al., 2019). It can increase floristic diversity by planting resource plants that have floral covers of large areas and long-bloom season to attract and maintain greater numbers of natural enemies. These plants also give out the needed resources which are nectar and pollen;

these are important to several predatory and parasitic species (Fiedler and Landis, 2007). Field margin vegetation with strategic plantings has been demonstrated to be repositories of diverse natural enemies which migrate to their neighboring fields as sources of biological control. These vegetative borders act as shelters and reservoirs of different useful species which are capable of ensuring the proliferation of the population of the pests (Mkenda et al., 2019). Complementarity among Natural Enemies Different guilds of natural enemies may find it quite useful to be complementary to each other in the suppression of pests. Different guilds of natural enemies may attack the pest at different life stages or occupy different spatial niches. Such complementarity enhances the general productivity of the biological control (Dainese et al., 2017). Organic and reduced-tillage farming encourage the maintenance and enrichment of local natural enemy communities by the application of reduced amounts of pesticides, and by introducing habitat that promotes biodiversity. Those have proved to increase the number of natural enemies consequently enhancing their effectiveness in pest control (Chen, 2016; Porcel et al., 2018). Plant defenses may be induced by the use of some chemicals (like methyl salicylate) to enhance the lure and performance of the natural enemies (so that parasitism levels increase and the efficiency of predators in their foraging activities (Ahmad et al., 2025). Such habitat management measures can result in a high level of impact by natural enemies against the Pink Bollworm and other pests to augment the sustainable integrated pest management systems (NamdeoAiwale et al., 2025).

Mass-rearing and release techniques for Pink Bollworm biological control agents

The use of mass-reared and augmentatively released biological control agents against pink bollworm (*Pectinophora gossypiella*) has helped integrated management programs pest-wide. Egg parasitoids (*Trichogramma* spp.) and entomopathogenic nematodes (*Steinernema* and *Heterorhabditis* spp.) have been widely mass-produced and released as the most popular (Naik et al., 2019; Thube et al., 2023) *T. chilonis* and *T. pretiosum* are produced on an artificial diet against *Corcyra cephalonica* eggs, with factories in India, China and Egypt: 50,000 to 100,000 wasps per hectare released each week when adult moth numbers are high. Such releases attain 50-80 percent egg parasitism provided the releases take place at the correct time of the oviposition cycles of the pink bollworm (Moirangthem et al., 2022; El-Bassouiny et al., 2025). Entomopathogenic nematodes (*Steinernema riobrave*, *S. carpocapsae*) are currently mass propagated in liquid fermentation systems but may be field applied in the form of a soil drench (1150-5 billion infective juveniles/ha), with efficacy of 60-70% larval/pupal mortality demonstrated in field trials. Sterile insect technique (SIT), or gamma-irradiated moths, has been woven into biological control on extensive area-wide programs where the USDA-APHIS eradication effort was successful (Shairra et al., 2016). The Quality control issues are representated in the genetic diversity required to maintain, the need to eliminate inbreeding in parasitoid colonies, and finally the ability to persist in the field in different soil conditions of nematodes. Combining these releases with habitat manipulation and selective insecticides, successful large-scale cotton program has shown population suppression of 30-60 percent (Gassmann et al., 2009). Mass production and introduction of biological control agents against Pink Bollworm predominantly using SIT is an important measure in terms of controlling and eliminating the menace of this pest. The SIT uses sterile insects in big quantities to be released into the atmosphere so as to reduce the population through sterile breeding. The strategy has been utilized to good effect against the pink bollworm (*Pectinophora gossypiella*), one of the major cotton pests (Simmons et al., 2011). The Pink Bollworm control case demonstrates how genetic engineering can be used in solving an agricultural pest problem along with classical types of control measures (Fabrick et al., 2023).

Figure 4.1.

Relative contribution of different control methods in IPM for Pink Bollworm (Pectinophora gossypiella).

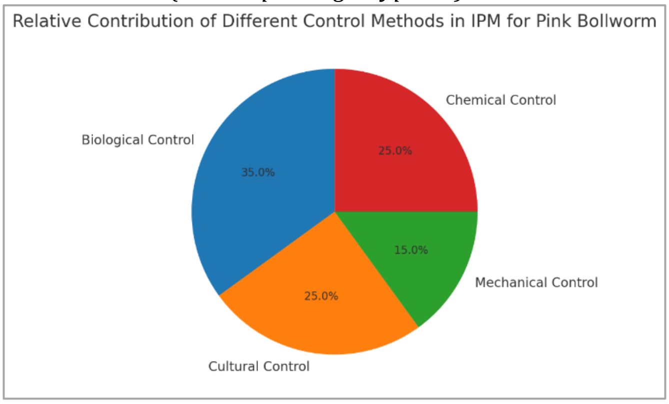


Figure 4.1. This pie chart illustrates the proportional role of various control tactics in integrated pest management (IPM) programs targeting the pink bollworm, based on literature-informed estimates from cotton agroecosystems. Biological control accounts for the largest share (35%), reflecting the extensive use of natural enemies, parasitoids (Trichogramma chilonis, Bracon hebetor), predators (lacewings, lady beetles), entomopathogenic fungi (Beauveria bassiana, Metarhizium anisopliae), and nematodes (Steinernema riobrave, Heterorhabditis indica). Cultural control (25%) includes practices, crop rotation, intercropping, timely sowing and harvesting, and maintenance of non-Bt refuges to delay resistance development. Chemical control (25%) still plays a supplementary role in outbreak situations, employing selective insecticides or biopesticides to minimize impact on beneficial organisms. Mechanical control (15%), pheromone traps for monitoring and mating disruption, and destruction of infested plant residues complements other strategies by directly reducing pest populations. The balanced integration of these methods reduces reliance on chemicals, delays resistance evolution, and sustains ecological stability in cotton production systems (Henneberry, 2017; Tabashnik et al., 2020; Babu et al., 2023).

Challenges and Future Prospects

Environmental and resistance issues limiting Pink Bollworm biological control.

There are several environmental and resistance challenges that may arise to the biological control of the Pink Bollworm (PBW). Such environmental conditions as variable temperatures, moisture levels, humidity and soil wetness can greatly influence whether natural predators or parasitoids employed in a biological control scheme will work (Tabashnik et al., 2002). All this could influence the existence, breeding, and functioning of useful organisms. Evolutionary pressure may also allow resistance in the Pink Bollworm to biocontrol organisms, parasitoids or microbial pathogens and therefore decrease the efficacy of the biocontrol organism (Sarwar et al., 2017). Furthermore, there is chance of justifying the development of resistance based on genetic diversity of the pest's population. Pesticide resistance may also be caused by the use of chemical control methods, sometimes in conjunction with biological controls, which make integrated pest management practice difficult (Ayaz et al., 2020). Moreover, habitat destruction, monoculture and insufficient availability of prey or suitable host may also be introduced as obstacles to the establishment and overall success of biological control agent. These are some of the environmental and resistance factors that have to be closely maintained so as to ensure that the use of the biological control in controlling the Pink Bollworm is maximized (Rao et al., 2021).

There are various environmental challenges and resistance that are addressed towards biological control of the pink boll worm (*Pectinophora gossypiella*). A major case is the resistance of the pink bollworm to transgenic crops that produce *Bacillus thuringiensis* (Bt) toxins. The effectiveness of Bt crops can be reduced by evolution of resistance in pink bollworm. Empirical resistance to pyramided Bt cotton that expresses the cry1Ac and cry2Ab toxins has been witnessed in India and the need to use other means to manage such pests arose like reducing cotton season size and burning crop debris (Fabrick et al., 2023; Tabashnik and Carriere, 2019). A variable rate of farmer compliance as a strategy of deploying refuges or allowing non-Bt host plants to slow development of resistance has constrained the possible use of the strategy in certain areas. Mass releases of sterile pink bollworm moths have complemented low refuge abundance as a part of an integrated pest management and eradication program in the U.S (Tabashnik et al., 2010, 2012).

Figure 4.1

Pink Bollworm Infestation from 2005 to 2023 in India, USA, China and Pakistan

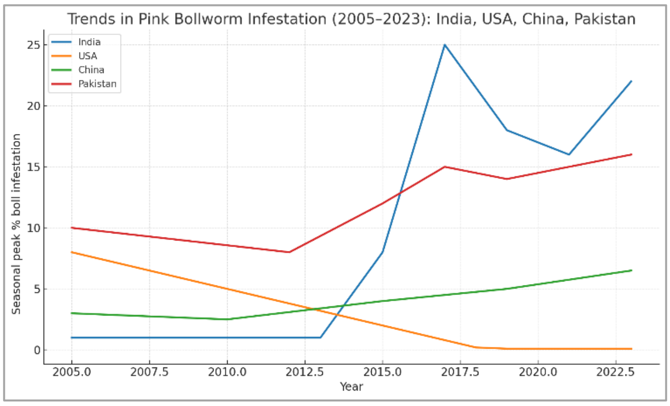


Figure 4.1. Long-term trends in pink bollworm (*Pectinophora gossypiella*) infestation from 2005–2023 across India, USA, China, and Pakistan. Values represent seasonal peak percent boll infestation derived from country-specific field reports and milestones: India shows a resurgence after 2014 with peaks around 2017; the USA reaches near-zero following eradication in 2018; China remains low under refuge/IRM with slight increases; Pakistan exhibits moderate, fluctuating levels consistent with district-level surveys (Kumar et al., 2025; Tabashnik et al., 2021;) Quan et al 2023).

Integration of biological control with chemical, cultural, and mechanical methods

Organic control in tandem with chemical, cultural, mechanical management of the Pink Bollworm (PBW) considers the removal of chemical characteristics, and the development of sustainable use as the hallmark of integrated pests management (IPM) (Rajashekhar et al., 2024). They can be integrated with chemical control in two ways through the use of specific reduced-risk pesticides that cause much less harm to natural predators and parasitoids, including the utilization of biopesticides, such as *Bacillus thuringiensis* (Bt) or neem oil (Ayaz et al., 2020). They may be used as complement or alternative of the chemical methods because they provide a more selective method of pest management. Culturally, the rotational crop cultivation, intercropping, and resistant form of cotton can contribute to PBW reduce their populations by halting the lifecycle of the insect and offering them unfavorable conditions in which to survive (Jahnavi et al., 2019). Organic control could be coupled with mechanical control like pheromone traps to keep tab of the population of PBW and suppress the pest pressure by either mating disruption or physical elimination of infested plants. Also, destruction of cotton waste after the harvest or application of cotton traps in conjunction with organic sprays can avoid the presence of PBW larvae (Narayan et al.,2024) The other feature is the use of organic insecticides with mechanical means such as the boll weevil trap to kill the insects in their particular stages of development in order to minimize the use of chemicals as a whole. Moreover, there is the use of natural predators and parasitoids and pests including *Trichogramma* species as well as cultural controls that will keep a balance in the control of pests, such as proper timing of planting and harvesting of crops (DEVANAND, 2019). The use of this mixture of strategies limits dependence on one approach, improves pests' control and creates environmental sustainability by still carrying the natural pest-controlling organisms and efficient control of PBW populating. The combination of these strategies would enable further sustainably-oriented and efficient management system within farming practice not only preserve the yield but also the ecosystem (Alugoju et al., 2022).

Future research opportunities (genetic improvement, novel pathogens) for improving Pink Bollworm control

Future developments on control of the Pink Bollworm (PBW) might be laying down emphasis on genetic enhancements, newer pathogens and newer technologies. Instead, genetic modifications of cotton crops can lessen dependency on pesticides and produce genetically modified cotton types with better resistance to PBW, Bt crops. CRISPR gene-editing could be selective to crops and pests (Patel et al., 2024). To remain in compliance with the biosafety regulations, the application of novel pathogens, such as more potent forms of *Bacillus thuringiensis* or fungal pathogens, open up some interesting biological control solutions. They could silence key PBW genes with RNA interference (RNAi), to minimize their numbers (Lu and li, 2024). Also, a more effective management can be achieved by improving biocontrol agents like *Trichogramma* parasitoids, and by increasing pheromone-based mating disruption. A combination of these methods would encourage the use of environmentally friendly sustainable solutions to PBW control (Khakwani et al., 2022). Genetically engineered strain that is able to carry a heritable fluorescent marker has been made to enhance the discrimination of sterile and wild moths in monitoring traps. This innovation also makes management an easy task by making sure that the sterile insects that will be utilized in the Sterile Insect Technique (SIT) will be monitored and counted correctly which can ultimately aid in the control of the population in the field (Simmons et al., 2011).

Acknowledgment

I sincerely thanks to Prof. Dr. Mumtaz Baloch, Vice Chancellor of the University of Makran, Panjgur, for his invaluable guidance and encouragement in this Study. His expertise, constructive feedback, and dedication to sustainable agriculture inspired and shaped this work. I am deeply grateful for his mentorship, which made this project possible.

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