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Recent Advances in the Management of Pink Bollworm in Cotton Ecosystems: A Comprehensive Review of Invasion Biology and Integrated Pest Management Approaches

Qazi Pandhi Khan Hajano
Department of Entomology, Sindh Agricultural University Tandojam, Pakistan.
Email: hajano648@gmail.com

Qais Ali
Department of Soil Science, Sindh Agricultural University Tandojam, Pakistan.

Jahanzaib Khurram
Department of Entomology, Sindh Agricultural University Tandojam, Pakistan.

Komal Mithal Jiskani
Department of Plant Pathology, Sindh Agricultural University Tandojam, Pakistan.

Aneesa Zainab
Department of Entomology, SZABAC Campus Dokri, Sindh Agricultural University, Tandojam, Pakistan

Shakira Mushatque
Director of the Dhamrah School, Sindh Education Foundation, Government of Sindh, Pakistan.

Bilawal Magsi
Department of Entomology, Sindh Agricultural University Tandojam, Pakistan.

Ayaz Ali Hajano
Department of Plant Pathology, Sindh Agricultural University Tandojam, Pakistan.

Mehran Ali Keerio
Department of Plant Pathology, Sindh Agricultural University Tandojam, Pakistan.

Waquas Rathore
Department of Plant Pathology, Sindh Agricultural University Tandojam, Pakistan.

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Corresponding Author:
hajano648@gmail.com

ABSTRACT

Pink bollworm (Pectinophora gossypiella) remains one of the most economically damaging pests of cotton worldwide, with particularly severe impacts in Pakistan, India, the United States and China. This review synthesizes current knowledge on the pest's biology, invasion history, and management, highlighting how temperature and other climatic factors regulate its development, survival, and seasonal population dynamics. While Bt cotton dramatically reduce resilience on chemical insecticides following its introduction, the emergence of resistance linked to mutation in cadherin and ABC transporter genes has undermined control in several regions even as areas like the southwestern United States achieved near-eradication through integrated approaches. Field data from Punjab and other cotton belts show rising infestation trends tied to seasonal and climatic patterns, underscoring the need for region-specific monitoring. This review examines a broad-spectrum management tool, including cultural practices such as early sowing, season shortening, stalk destruction and deep ploughing; Pheromone-based tactics including mating disruption and mass trapping; biological control agents such as Trichogramma parasitoid and entomopathogenic fungi; and chemical options including newer selective insecticides and rotational spray programs. Findings across studies consistently indicate that no single tactic provides adequate suppression and that combining cultural, biological, pheromone-based and chemical strategies within an integrated pest management framework offers the most sustainable and economically viable path forward for cotton-growing regions facing continued pink bollworm pressure.

Introduction

Cotton is an essential cash crop across worldwide serving as foundation of global textile industry and sustains rural economies with advances in production technologies contributing to higher production and economic growth. in Pakistan, cotton is a key agricultural crop that significantly supports national economy through exports and employment generation. Despite this importance, its production increasingly affected by biological pressure, changing climate conditions and economic challenges however, to ensure its long-term sustainability to strengthen the productivity of cotton it is essential to take the adaptive measures, improve scientific research and strong policy support to secure the future of this crop (Ali et al., 2019; Rehman et al., 2020; Ashraf et al., 2024). The pink bollworm, Pectinophora gossypiella Saunders (Lepidoptera: Gelechiidae), is considered as most threatening insect pest of cotton crop worldwide affecting yield production contributing sufficient economic losses and challenges to sustainable agriculture. Because of its strong dispersal ability and damaging feeding on cotton bolls, PBW has been a major target of pest management studies in many cotton growing countries particularly in the southwestern united states, India and China. The biology and population behavior of this pest are greatly affected by environmental factors particularly temperature, it plays a critical role in the development and survival as well as reproductive ability of PBW which in turn influences its spread and the intensity of crop infestation (Nagaraju et al., 2024). Early approaches to pest management were largely dependent on chemical insecticides, however, increasing costs, environmental risks, and emergence of resistance have shifted attention toward integrated pest management (IPM). Modern ecologically based strategies now combine pest monitoring, biological control, cultural practices and resistance crop varieties to design localized pest control systems (Henneberry and Naranjo., 1998). The widespread adoption of bt cotton toxins from becillus thuringienesis significantly improved pink bollworm control and decreased dependency on chemical pesticides, reducing environmental hazardous risks, however, the emergence of resistance in P. gossypiella against bt toxins like Cry1ac and Cry2ab has become a growing concern in different cotton-growing regions (Lu & Li., 2024). While the advances in molecular studies have revealed that at the basis of resistance mechanism that mutations in cadherin (PgCad1) and ATP binding cassette transporter (PgABCA2) genes disrupt the interaction between the bt toxins and insect targets, thereby conferring resistance leading to control failures china remains largely effective with only initial resistance indications, and the united states has successfully managed to suppress or eliminate P. gossypiella through integrated approaches that compliment bt cotton additional control measures (Carriere et al., 2001; Tabashnik et al.,2005; Fabrick et al., 2023). Current advancements in pest management emphasize combined use of novel and conventional techniques against pink bollworm. Green synthesized silver nanoparticles, microbial formulations of bacillus thuringiensis and selected chemical insecticides have demonstrated significant larvicidal activity, providing environmentally safer alternatives for effective controls (Khan et al., 2024). implementing these innovative approaches is crucial to reduce the risk of evolution of resistance, effectively control resistant populations and maintain stable cotton production systems in long term. This review summarizes current knowledge regarding biology, ecology, resistance genetics and integrated management strategies of P. gossypiella, while, also outlining the recent scientific advances and future investigation areas important for sustainable cotton protection.

Origins and Distribution

Pectinophora gossypiella originated from Asia and later dispersed across global cotton-growing areas, including India, Mexico and the southwestern united states (Gutierrez et al., 1977; Naik et al., 2020) genetics research in India reveals pattern of population growth along with diverse haplotypes indicating recent expansion and extensive spread of the species (Naik et al., 2020). Its distribution across arid zones in the United States and Mexico is influenced by adult dispersal through flight as well as key adaptations (Gutierrez et al., 1977; Henneberry and Naranjo., 1998). Development and survival are strongly regulated by temperature, making it important to impacting distribution and population dynamics (Nagaraju et al., 2024)

Biology and ecology

The biology of pink bollworm encompasses through various traits the study findings under the laboratory conditions using artificial diet was investigated to understand its developmental duration, reproductive potential, adult longevity and sex-ratio on cotton seed. The study has proved that environmental factors and host diet have influence on the developmental biology of the pest (Zinzuvadiya et al., 2017). Life cycle of PBW passes through four life stages egg-larva-pupae and adult, have the distinct time interval between the life stages. Lustrous white Eggs are laid by females singly or in small groups on bolls, squares, flowers, and sheltered plant parts (Arif et al., 2024; Rao G., 2022). Caterpillars are small and white in color with dark brown head in early instar. As they reach to 3rd instar onward, the larval body changes the color into pink and then becomes darker in the last larval instar. The growing intensity influenced by the type of food specifically mature cotton seeds. Full grown larvae are 10-12 mm in length and show reddish bands on the body surface with dark-brown head. Larvae can pupate in 10-14 days (cited by Bhute et al., 2023). Pupal stage is non feeding transitional phase which the insect undergoes metamorphosis develop into the adult. During this period the pupae is initially lighter brown in color and gradually changes into dark brown as development progresses. The pupae are oval shaped with a pointed posterior end. Sexually dimorphism is observed at this stage where male pupae is smaller than female pupae. Duration of pupal stage varies with host plants generally ranging from 7.5 to 9.5 days (Shrinivas et al., 2019). The moth is adult stage of pink bollworm life cycle in cotton crops, arising from the pupae located within the infested bolls. Adult female lay eggs within the boll surface newly emerged larvae bore into the bolls and continue development as well as pupate inside the cotton bolls. Because adults are responsible for production and spread (Semmons et al., 2011; Fand et al., 2019)

Climatic influence and agroecosystem interactions on development and survival of PBW

Temperature

Temperatures significantly influence the growth and development of pink bollworm populations. Research indicates that the insect's overall developmental duration decreases as temperatures increase from 20℃ to 40℃ while the highest larval survival rates approximately 80-86% occur at 30℃ and 35℃. moreover, the biological traits, including pupal mass, reproductive success and egg laying capacity, are highest within this optimal temperature range in contrast, extreme temperatures of 20℃ and 40℃ negatively affect egg hatchability, larval survival and adult emergence. Considerably, females demonstrated greater longevity then males across all temperature regimes the influence of temperature on these biological parameters has major implications for population fluctuations and implementations of sustainable pest management practices under the different climatic conditions (Nagaraju et al., 2024)

Infestation on low temperature

Evidence from the field studies in Pakistan and India shows that pink bollworm incidence is generally higher under cooler weather conditions. A decrease in minimum temperatures, along with seasonal cooling trends, is closely related with elevated pest infestations, and greater trap captures, especially during late-season and winter periods (Sabir Hussain et al., 2022; Muneer Abbasi et al., 2022; Rakhesh et al., 2023; DV et al.,2025)

Humidity and rainfall

field evidence shows that larval infestation and boll damage tend to be lower under conditions of higher humidity and rainfall, while extended sunshine exposure is associated with greater larval abundance and a higher abundance and a higher incidence of rosette flowers (KM vora et al., 2024)

Reproduction and Genetics

The reproductive biology of pink bollworm offers important insights for developing effective pest management measures. Genetic transformation through piggyBac-mediated germline transposable elements have enabled stable genetic transformation, paving the way for improved SIT programs and more efficient resistance management practice (Peloquin et al., 2000). While studies on genetic structures of pink bollworm have revealed mechanisms underlying its adaptation to BT cotton. Resistance has been documented against both single toxin and pyramided BT cultivars expressing Cry1ac and Cry2ab. Evidence suggests that the resistance traits are inherited in an autosomal recessive manner (Fabrick et al., 2015). However, the progression of resistance can be mitigated through resistance-management practices such as non-BT cotton refuges and exploiting the fitness costs associated with genotypes (Tabashnik et al., 2005)

Interaction with Host Plants

Host plant characteristics play a crucial role in determining the survival and reproductive success of PBW. Variations among cotton cultivars can impose different levels of antibiosis, thereby affecting the persistence and prevalence of resistance traits within pest populations. While experimental evidence shows little variation in fitness cost between cultivars, theoretical models imply that differences in host plant mediated survival may affect the rate and direction of resistance development (Carriere et al., 2005).

Regional implications and population outbreaks

Field investigations conducted in 17 districts of Punjab between 2012 and 2019 revealed that pest infestation exceeded the economic threshold level, ranging from 0.1% to 35.7%. The highest infestation rate was recorded in Bahawalnagar, Bahawalpur, Faisalabad, Jhang, Mianwali, Multan, Muzaffargarh, Rahim Yar Khan, Lodhran (Sabir Hussain et al.,2022). Intensive monitoring conducted in Faisalabad, Multan and Bahawalpur between 2018 and 2020 revealed that Bahawalpur consistently recorded the highest moth and larval populations. With abundance reaching its maximum during august to November (Shamim Akhter et al., 2026). Rising number of insects recorded in traps during 2018-2020 indicates an upward trend in population abundance (Muneer Abbasi et al., 2022)

Table-1 Regional patterns of Pectinophora Gossypiella in Pakistan.

Aspect	Main findings in Punjab (Pakistan)	References
High-risk districts	Bahawalnagar, Bahawalpur, south & central Punjab belt	(Sabir Hussain et al., 2022; Shamim Akhter et al., 2026)

Peak activity	Aug–Nov (flowers then bolls)	(Syed Asmat Hussain Shah et al.,2021; Muneer abbasi et al., 2022; Shamim Akhter et al., 2026)
Trend	Increasing moth captures over years	(Sabir Hussain et al., 2022; Muneer Abbasi et al., 2022; Shamim Akhter et al., 2026)
Climate link	Often higher at moderate temps, humidity; temp often negative correlation	(Sabir Hussain et al.,2022; Muneer Abbasi et al., 2022; Shamim Akhter et al.,2026)

Integrated pest management approaches

Cultural practices

Sowing dates

Adjusting sowing time is a simple yet highly effective cultural control measure. Cotton planted earlier tends to set and mature bolls before pink bollworm population reaches their peak, resulting in lower infestation levels. Attia et al., (2021) observed that the three planting dates (23 march, April 17, May 6) and mean PBW infestation rates 2.11, 3.5, and 2.33 larvae/boll respectively, results showed that earliest sowing dates were associated with lowest pest infestation level and greatest cotton productivity. Bollworm et al., (2022) conformed that early sowing of fast maturing cotton cultivars is an effective strategy for interfering with pink bollworm diapause and shortening pest susceptible phase of crops. R.S et al., (2023) similarly recognized early planting as a fundamental cultural component of IPM for controlling PBW.

Season shortening

Maintaining cotton fields for an extended period enables PBW to complete more lifecycles, which can increase overwintering larval populations. Tabashnik et al., (2019) reported that the growing prevalence of BT cotton resistance has reinforced the need of IPM programs that focus on the shortening of the cotton season, eliminating crop residues and integrating other non-chemical management practices. Khakwani et aal., (2022) further suggested adopting early maturing verities along with growth regulators and harvest aid treatments to facilitate earlier crop termination and reduce the survival of diapausing larvae. Likewise, sarangi et al., (2024) recognized timely sowing and early crop removal as effective and eco-friendly approach for PBW suppression, particularly because the pest remains protected from man chemical control measures while feeding inside the plant tissues.

Stalk destruction

Post harvest cotton stalks and residual bolls provide suitable shelter for PBW larvae during diapause, enabling the pest to survive between cropping seasons. As a result, removing destroying these residues is considered as an effective integrated pest management tactic. Ahamed et al., (2020) demonstrated the effectiveness of an AMRI developed stalk puller shredder in breaking down cotton residues and reducing habitat favorable for larval survival. Their study further highlighted the role of optimized blade design in enhancing shredding efficiency. Similarly, fransischini et al., (2019) reported that a combination of stalk removal and herbicide application successfully eliminated cotton plants and prevented regrowth within 14days. Surveyed from India revealed widespread farmer adoption of residue management practices, including stalk destruction and deep ploughing, as preventive measures against pink bollworm. Furthermore, findings by Baraiya et al., (2022) showed that many farmers were aware of the value of burning cotton residues after harvest to suppress the overwintering pest populations.

Deep ploughing

Deep tillage during the summer months, reaching depths of 30-40 cm, helps reduce pink bollworm populations by bringing diapausing larvae and pupae to the soil surface, where they are exposed to harsh environmental conditions and natural predators such as birds. Additionally, it buries infested crop residues beyond the depth from which adults can successfully emerge. Katole et al., (2022) mentioned that deep ploughing ranked among the most extensively adopted IPM interventions in Vidarbha cotton districts, with a reported adoption level of 90.33%. its inclusion in standard IPM recommendations is attributed to its effectiveness in reducing pest survival in soil and creating favorable seedbed conditions for the following crop cycle.

Crop rotation

Since pink bollworm depends exclusively on cotton for its development, rotating cotton with non-host crops such as cereals and legumes disrupts its lifecycle by removing a suitable food source. This practice also supports the conservation of natural enemies in agro-ecosystems. Hanif et al., (2025) studies from Pakistan have identified the combined use of suitable crop verities and optimized planting schedule as an important cultural approach for disrupting the life cycle of pink bollworm and reducing pest pressure. Katole et al., (2022) observed that crop rotation is widely recognized as an effective pest management strategy. Findings showed that nearly half (47%) of the farmers in Vidarbha had yet to adopt this practice, underscoring challenges in its implementation. R.S et al., (2023) crop type modification was highlighted as one of three major cultural interventions for reducing pest persistence, together with early planting and elimination of crop residues, rotation practices may be strengthened using short duration cotton verities and plants exhibiting structural traits associated with pest resistance.

Field sanitation

Frequently collection and destructions of infested rosette flowers, damaged bolls and fallen fruiting bodies can effectively suppress pink bollworm populations by eliminating developing larvae and limiting pest multiplication during the growing season. Hanif et al., (2025) emphasized the importance of eliminating the infested plant debris, including remaining bolls, as a key component of cultural control programs. Baraiya et al., (2022) found that 59.5% of farmers surveyed in Gujrat were aware of the importance of the collecting and destroying infested flowers and bolls. The study also showed that post-harvest grazing sheep and goats was the most widely recognized sanitation practices with an awareness level of 72.25%. U.S.S. et al., (2024) emphasized that resistance management can be strengthened through the adoption of timely planting, effective field sanitation, the use of pheromone traps and mating disruption technologies. Birah et al., (2023) demonstrated that the adoption of IPM practices, including effective field sanitation, reduced insecticide applications by 49.74% decline in insecticide use and a 28.49% improvement in cotton yield to standard farming practices.

Water management

Effective water management practices can contribute to pink bollworm suppression by hastening crop maturity and lowering the survival of dormant larvae. Bariola et al., (1981) reported that stopping irrigation earlier in the season substantially reduces the abundance of diapausing larvae remaining after harvesting. The integrated of early irrigation termination with chemical defoliation or crop termination further minimize moth emergence in the following spring. In addition, lower levels of boll infestation and reduced heliothis spp. Oviposition were observed during the late growing season. Henneberry., (2007) also emphasized irrigation management is a historically successful cultural control component of area-wide PBW control strategy.

Host free period

A coordinated host-free season can significantly contribute to pink bollworm suppression by removing cotton plants across a region and thereby limiting the survival of dormant populations. Khakwani et al., (2022) highlighted host-free management as an essential component of comprehensive PBW eradication strategies. According to Henneberry., (2007) because the adult moths can diapause over considerable distances, effective management must be implemented on a large geographical scale and involve all stakeholders in the agriculture sector. Fand et al., (2019) similarly advocated modifications in regional cotton production patterns to improve pest management outcomes. The eradication program carried out in the south-western USA from 2001 to 2005 successfully incorporated these coordinated cultural measures alongside BT cotton and sterile insect release.

Stalk stalking

Preventing the accumulation of the cotton stalks around the fields and households in an important yet frequently neglected pest management strategy. Stacked stacks can harbor dormant PBW larvae, which later developed into moths reinfest cotton crops according to Hanif et al., (2025) avoiding the vertical pilling of infested plant material is essential for disrupting the pink bollworm life cycle. Similarly, Katole et al., (2022) found that 88.33% of farmers in Vidarbha region adopted the practice of not retaining cotton stalks for fuel as part of improved IPM program.

Pheromone Trap for Pink Bollworm Control

The pheromone Gossyplure

Gossyplure (ZZ/ZE-7,11-Hexadecadiene-1-yl acetate), the synthetic sex pheromone of pink bollworm, forms pheromone-based management programs for this pest. Early research by Gaston et al., (1977) demonstrated that maintaining a continuous concentration of gossyplure within cotton fields throughout the growing season disrupted mate finding behavior between male and female moths. This disruption significantly reduced larval infestation and provided level of pest suppression comparable to those achieved with insecticide treatments. Their pioneering work, initiated in the early 1970s, established mating disruption as an environmentally friendly alternative to chemical control and encouraged extensive subsequent research and field adoption in different cotton growing regions worldwide (Lykouressis et al.,2005)

Trap designs and monitoring

The effectiveness of pheromone-based monitoring largely depends on trap design and deployment. Research by Tamhanker et al., (2001) introduced the BARC trap, a modified dry-funnel system that demonstrated substantially higher moth captures than commonly used Delta and omnidirectional traps. In addition, to improved trapping efficiency, the design showed greater durability under field conditions.

The design showed greater durability under field conditions. More recently, Katranas et al., (2024) examined the influence of trap type and installation height in cotton fields and reported superior performance of delta traps compared with funnel traps. Their findings indicated that traps positioned approximately 30cm above the ground collected more moths than those placed at 90cm, helping refine monitoring recommendations. For population suppression through mass trapping, Lakshmi et al., (2023) observed that sleeve traps deployed at densities ranging from 20 to 50 traps per hectare were more effective than funnel and Delta traps, resulting in reduced larval infestation, lower locule damage, and increased seed cotton production in Pakistan, pheromone trap monitoring conducted in the Sindh cotton-growing regions identified the third week of July as the period of highest moth activity, which coincided with peak flowering, highlighting the value of pheromone traps in determining the optimal timing of management interventions (Khoso et al., 2025)

Mating Disruption Using PB rope L Dispensers

PB Rope L dispensers, which consist of ropes impregnated with the synthetic pheromone gossyplure and design for gradual release, have been extensively studied as a matting disruption technique for pink bollworm management. Field evaluation conducted in different cotton-growing regions have consistently demonstrated their effectiveness in suppressing pest populations and reducing crop damage. In Punjab, Pakistan, Husnain et al., (2021) observed a substantial decline in male moth captures throughout the cotton season when dispensers were deployed at a rate of 100 units per acre. This reduction in pest activity was accompanied by lower boll infestation levels and improved seed cotto yield compared with untreated fields. Similarly, outcomes were reported by Babar et al., (2022) in Faisalabad where the application of 240 dispensers per hectare significantly decreased moth abundance, green boll damage, and larval populations over two successive growing seasons. In India, Meena et al., (2021) found that a single deployment of PB rope L Dispenser at 685 units per 10 hectares, approximately 50 days after sowing, provided season-long suppression of pink bollworm populations and effectively limited boll infestation, thereby reducing reliance on repeated insecticide applications. Research conducted in Greece by Lykouressis et al., (2004) also demonstrated the value of PB Rope L technology, showing marked reductions in moth captures and boll injury intreated fields. The study further revealed that gossyplure dispensers remained biologically active for nearly three months under field conditions. Subsequent investigations highlighted those environmental factors, particularly the orientation of cotton rows in relation to prevailing wind direction, can influence the overall effectiveness of matting disruption programs (Lykouressis et al., 2005)

Novel formulation and IPM

Recent developments in pheromone technology have introduced new slow-release formulations for pink bollworm management. Mahalakshmi et al., (2020) reported that SPLAT (Specialized Pheromone and Lure Application Technology) effectively reduced moth populations, larval infestation, and boll damage while improving seed cotton yield in bt cotton. Researchers have also evaluated formulations combining gossyplure with pyrethroids, which attract male moths and expose them to insecticides, enhancing control through both matting disruption and direct mortality (Beasley et al., 1984). Pheromone-based technologies are most effective when incorporated into integrated pest management (IPM) programs. Studies by Rajashekhar et al., (2022), Narayanamma et al., (2023) and Rao et al., (2024) showed that IPM modules containing pheromone traps, biopesticides, and selective insecticides provided better pest suppression, higher yields, and greater economic returns than conventional farmer practices. These findings highlighted the importance of integrating pheromone tools with other management strategies for sustainable pink bollworm control.

Biological control of pink bollworm

Parasitoids: egg parasitoids, particularly species of Trichogramma and trichogrammatoidea, are among the most important biological control agents used against pink bollworms. According to Ali et al., (2025), these parasitoids can achieve high levels of egg parasitism and substantially reduce boll damage when integrated with cultural management practices. In Pakistan, Lodhi et al., (2025) demonstrated that field releases of Trichogramma chilonis significantly lowered flowers and boll infestations, highlighted its potential as an environmentally sustainable control option. Among the evaluated species, Trichogrammatoidea bactrae has shown particularly strong performance. Kumar et al., (2022) reported higher egg parasitism rates for Tr.bactrae than for several other trichogrammatids species under laboratory, cage, and field conditions, repeated field releases improved cotton yield without relying on chemical insecticides. Similarly, results were reported by Mahalakshmi et al., (2020) who observed reductions in larval populations and boll damage flowering releases of Tr. Bactrae. Padma Shree et al., (2023) further noted that its effectiveness was comparable to neem-based treatments while posing less risk to beneficial organisms than broad-spectrum insecticides. Studies from Egypt also support the value of egg parasitoids in pink bollworm management. Abd El Hafeez et al., (2004) found that early -season release of Trichogramma evanescens provided greater suppression of boll infestation than delayed releases or programs combining parasitoids with insecticides. Likewise, Darwish et al., (2017) reported that parasitoids release reduces boll infestation levels, although mass trapping generally produced the highest level of control. Overall, these findings indicate that egg parasitoids are valuable components of integrated pest management programs, particularly when released at the appropriate time and combined with other compatible control measures.

Use of Entomopathogenic Fungi and Botanical biopesticides

Entomopathogenic fungi are important biological agents that can complement parasitoids in the management of pink bollworm. Laboratory investigations conducted by Farooq et al., (2020) demonstrated that the fungal species Beauveria bassiana, Metarhizium anisopliae and verticillium lecanii were effective against second-instar PBW larvae. The highest level of larval mortality, along with significant reduction in population and adult emergence, was achieved when all three fungal species were applied together at elevated conidial concentrations and combined with azadirachta indica (neem) extract. These findings suggest that combining EPFs with botanical products can enhance their insecticidal activity through synergist effects. Reviewed by Da Fabrice et al., (2020) highlighted the value of Beauveria bassiana as a component of integrated cotton pest management program. The author emphasized its effectiveness against several lepidopteran pests, including PBW, while noting that field performance depends largely on factors such as formulation quality and environmental conditions. Similarly, Rind et al., (2025) reported that botanical pesticides provide a promising eco-friendly option for PBW suppression. Including neem seed kernel extract (NSKE), neem oil, and azadirachtin-based formulations, have shown considerable effectiveness against PBW larvae while preserving beneficial natural enemies. The review also identified other plant-based extracts, such as tobacco, datura, chili, and artemisia annua, as potential control options, particularly when used alongside biological control agents. The authors concluded that integrating botanical pesticides with pheromone-based monitoring systems and biological control measures can contribute significantly to sustainable PBW management within an integrated pest management (IPM) framework.

Table-2 Performance of natural enemies in pink bollworm suppression

Natural Enemy	Type	Mode of Action	Efficacy	References
Trichogramma chilonis	Parasitoid	Egg parasitization	High (70-90%)	(Kumar et al., 2022; Sharm & Verma., 2021; Desai et al., 2021),
Telenomus remus	Parasitoid	Egg parasitization	Medium (40-60%)	(Chen et al., 2023; Anderson et al., 2023)
Bracon hebetor	Parasitoid	Larval parasitization	Medium (30-50%)	(Sharm & Verma., 2021; Martinez et al., 2022)
Campoletis chlorideae	Parasitoid	Larval parasitization	High (60-75%)	(Kumar et al., 2022; Desai et al., 202; Gupta et al., 2022)
Metarhizium anisopliae	Entomopathogen	Fungal infection	Medium (40-55%)	(Chen et al., 2023; Oliveria et al., 2021; White et al., 2023),
Beauveria bassiana	Entomopathogen	Fungal infection	Medium (35-50%)	(Martinez et al 2022; Hassan et al., 2022)
Coccinella septempunctata	Predator	Direct predation of eggs/larvae	Low-Medium (15-35%)	(Sharma & Verma., 2021; Anderson et al., 2023)
Chrysoperla carnea	Predator	Larval predation	Low-Medium (10-30%)	(Desai et al., 2022; Robinson et al., 2021)
Bacillus thuringiensis	Biopesticide	Larval pathogen	High (75-85%)	(Gupta et al., 2022; White et al., 2023; Ferreira et al., 2023)

Chemical control

Efficacy of synthetic insecticides: Although concerns regarding environmental contaminations, resistance development and non-target effects have encouraged the adoption of integrated pest management approaches, chemical insecticides continue to play an important role in suppressing pink bollworm populations when infestation surpasses economic threshold levels. Recent studies have highlighted the effectiveness of several modern insecticides against this pest. Shree et al., (2024) reported that emamectin benzoate 5SG provided the greatest reduction in boll damage, decreasing infestation by 89.25% and producing the highest seed cotton yield (1,955kg ha^{-1}). Other highly effective treatments included chlorantraniliprole 18.5 SC, Spinosad 45 SC, and flubendiamide 39.5 SC. In comparison, botanical products exhibited moderate efficacy, within 5% neem seed kernel extract (NSKE) reducing boll damage by 58.06% and a 5% neem-based formulation (1,500 ppm) achieving a 50.54% reduction, indicating their values as supplementary control measures. Similarly, Hnialum et al., (2023) identified Spinosad 45SC and emamectin benzoate 5SG as the most effective insecticidal treatments, recording larval mortality of 76.2% and 70.54% respectively, while cypermethrin 25EC also demonstrated satisfactory performance. Under rainfed conditions, Naik et al., (2023) found that a combination formulation containing profenofos 40% and cypermethrin 4% EC was superior to individual insecticides. The treatments resulted in the lowest levels of PBW injury. Including reduced exit holes, epicarp mines, larval populations and locule damage (1.7-7.3%), while also producing the highest seed cotton yield (11.6-12.04 q ha-1). However, R.S et al., (2024) further emphasized that benefits of insecticide rotation as a resistance-management strategy. A spray schedule consisting of profenofos 50EC, clorantraniliprole 18.5 SC, emamectin benzoate 5 SG, and bifenthrin 10 EC applied at 65, 80, 95, and 110 days after sowing (DAS), based on economic threshold levels, significantly reduced pink bollworm incidence and generated the highest seed and generated the highest seed cotton yield (18.10 q ha-1), within a benefit-cost ratio of 1.55. likewise, of 1.55. likewise, Kumar et al., (2025) evaluated 21 insecticides recommended by the central insecticide board (CIB) and identified emamectin benzoate 5SG, spinetoram 11.7 SC, indoxacarb 15 SC, and profenofos 50 EC as the most effective options, consistently producing more than 70% larval mortality and significantly lowering boll and locule damage at harvest. Collectively, these findings demonstrate that collectively, these findings demonstrate that selective and rotational use of effective insecticides remains an essential component of integrated PBW management programs particularly when combined with biological and cultural control tactics.

Conclusion

The evidence assembled in this review makes clear that pink bollworm cannot be managed through any single control tactic in isolation. Its resilience stems from a combination of favorable temperature-driven population dynamics, its concealed feeding habit within bolls that shields larvae from many interventions, and its demonstrated capacity to evolve resistance to Bt toxins. Regions such as the United States have shown that sustained suppression, and even localized eradication, is achievable when transgenic cotton is deployed alongside coordinated cultural practices, host-free periods, and sterile insect releases. In contrast, areas like Punjab, Pakistan continues to report rising infestation trends, pointing to gaps in the adoption and integration of available tools at the farmer level. Cultural practices, including early sowing, stalk destruction, deep ploughing and crop rotation, remain foundational and low-cost interventions, while pheromone-based mating disruption and mass trapping have proven effective as environmentally safer complements to chemical control. Biological control agents, particularly Trichogramma species and entomopathogenic fungi, further reduce dependence on synthetic insecticides when timed and applied correctly and selective, rotated insecticide use continue to serve as an important tool where infestation exceeds economic thresholds. Moving forward, sustainable pink bollworm management will depend on wider farmer adoption of integrated pest management packages, continued monitoring of resistance mechanisms, region-specific climatic modeling and coordinated area-wide implementation rather than isolated, farmer-level efforts. strengthening extension outreach and policy support around these integrated strategies will be essential to safeguarding long-term cotton productivity.

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