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Insect Pest Dynamics and Integrated Pest Management Strategies in Cotton (Gossypium hirsutum L.) under Changing Agro-Climatic Conditions

Dr. Nadia Jabeen[1], Tauseef Iqbal[2], Talha[3]

1 Department of Agriculture, Hazara University Mansehra KPK. nadia.agri@hu.edu.pk nadia_khan909090@yahoo.com Orcid id : 0000-0001-6617-8301

2 School of Agriculture and Biomanufacturing, Zhengzhou University, Zhengzhou 450001, China tauseefiqbal@gs.zzu.edu.cn

3 University of Makran. talha@uomp.edu.pk

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Abstract

Cotton (Gossypium hirsutum L.), a vital industrial crop supporting a $12 billion global textile industry and 350 million jobs, faces escalating threats from insect pests amid climate change, which alters pest phenology, distribution, and resistance patterns. This review examines the dynamics of key pests (e.g., bollworms, aphids, whiteflies) under shifting agro-climatic conditions rising temperatures, erratic rainfall, and extreme events leading to novel pest complexes and reduced host resistance in genetically narrow cultivars. Integrated Pest Management (IPM) strategies are emphasized, integrating cultural practices (crop rotation, trap cropping), biological controls (parasitoids like Trichogramma, biopesticides from Neem, Bacillus thuringiensis), host-plant resistance (Bt cotton, marker-assisted breeding), and judicious chemical use with resistance monitoring. Climate-driven adaptations include predictive modeling for pest outbreaks, mating disruption via pheromones, and regenerative agriculture to enhance ecosystem resilience. Field studies demonstrate IPM reduces pesticide reliance by 30–50%, boosts yields by 15–25%, and mitigates environmental impacts. The synthesis underscores the need for adaptive, multi-tactic IPM frameworks to sustain cotton productivity in vulnerable regions like North India, ensuring economic viability and ecological balance.

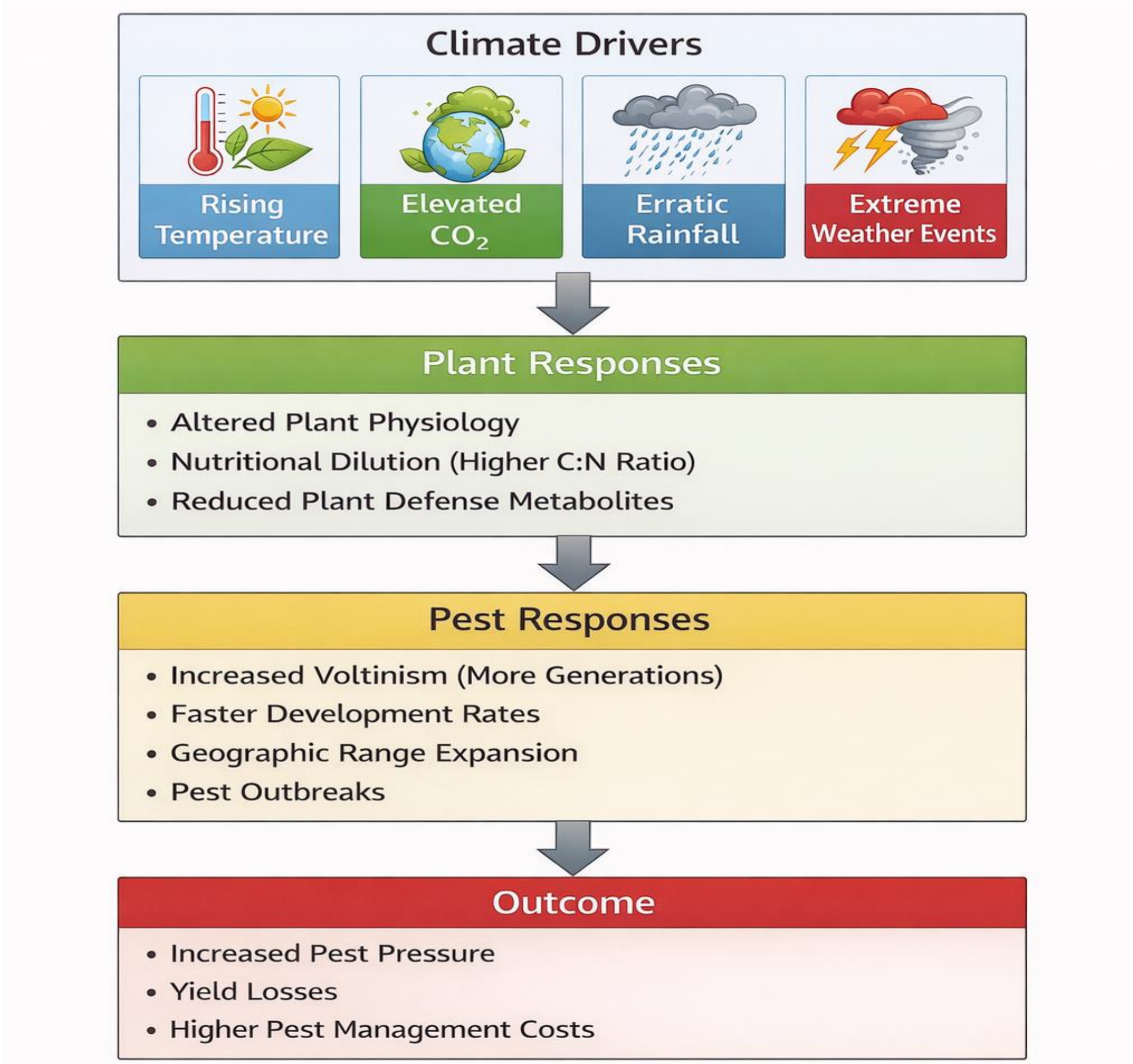
Keywords: Cotton, Insect Pests, Climate Change, Integrated Pest Management, Bollworms, Biological Control, Host Resistance, Bt Cotton, Pest Dynamics, Regenerative Agriculture, Mating Disruption, Predictive Modeling

1. Introduction

Cotton (*Gossypium hirsutum* L.) serves as a critical industrial crop, providing the primary raw material for a global textile industry valued at approximately 12 billion US dollars and supporting nearly 350 million jobs (Purcell & Perlak, 2004). However, as the global population is projected to reach 9.1 billion by 2050, the demand for land, water, and fiber is intensifying amidst an accelerating rate of climate change (Food and Agriculture Organization [FAO], 2022). Environmental stressors including erratic precipitation, escalating temperatures, and extreme weather events not only threaten the physiological health of the cotton plant but also fundamentally alter the ecological landscape by facilitating the emergence of novel pest complexes (Sharma, 2016). Modern cotton production is particularly vulnerable due to a narrow genetic background that limits its inherent resilience to these evolving environmental pressures (Das et al., 2025). Consequently, traditional Integrated Pest Management (IPM) strategies require a fundamental rethinking to address the shifting biological thresholds of insect pests in a warming world (Kariyanna & Sowjanya, 2024). Climate change affects cotton production through complex ecological interactions involving the host plant, insect pests, and environmental variables. Figure 1 presents a conceptual framework illustrating how major climatic drivers influence pest dynamics and crop vulnerability in cotton agroecosystems.

Figure 1: Conceptual Framework: Climate Change Drivers Influencing Cotton Pest Dynamics

2. Mechanisms of Climate Impact on Cotton Agroecosystems



The impact of climate change on cotton pest dynamics is mediated through three primary drivers: rising temperatures, elevated atmospheric carbon dioxide (CO2), and altered precipitation regimes. These variables influence the tri-trophic interactions between the host plant, herbivorous pests, and their natural enemies (Sharma et al., 2010).

2.1. Thermal Fitness and Metabolic Rates

As poikilothermic organisms, insect internal temperatures fluctuate with the environment, making metabolic rates and reproductive success highly sensitive to thermal shifts. Global surface temperatures are projected to rise between 1.1 degrees Celsius and 5.4 degrees Celsius by the next century (Barbosa, 2016). For every 10 degrees Celsius increase, insect metabolism almost doubles, leading to faster development and increased generations per season, a phenomenon known as increased voltinism (Dukes et al., 2009).

2.2. Atmospheric CO2 and Nutritional Dilution

Atmospheric CO2 levels have risen from 280 ppm to over 426 ppm and may double by 2100. In C3 crops like cotton, elevated CO2 boosts biomass but increases the carbon-to-nitrogen ratio in leaf tissues (Arora, 2019). This nitrogen dilution often forces pests to engage in compensatory feeding, consuming up to 57% more tissue to meet nutritional requirements, thereby increasing damage per individual (Bala et al., 2018).

2.3. Precipitation and Extreme Weather Events

Altered precipitation patterns, including intensified droughts and sudden floods, exert direct and indirect effects on pest mortality (Nakatani et al., 2025). Extreme rainfall can physically drown soil-dwelling pupae or wash away eggs, while prolonged drought stresses the cotton plant, weakening its defensive secondary metabolites and making it more susceptible to infestation (Mehla et al., 2026).

Table 1. Summary of Climatic Factors and Biological Outcomes in Cotton Pest Dynamics

Climatic Factor	Mechanism of Impact	Primary Biological Outcome
Temperature Rise	Shorter life cycles and faster metabolism	Increased generations/season (voltinism) (Sharma, 2016)
Elevated CO2	Altered leaf chemistry (higher C:N ratio)	Compensatory feeding and altered host-finding (Sharma et al., 2010)
Extreme Rainfall	Physical mortality and soil saturation	Disruption of soil-dwelling pupae (Sharma, 2016)
Drought Stress	Weakening of plant defense metabolites	Outbreak triggering (e.g., mealybugs) (Sharma, 2016)

3. Dynamics of Lepidopteran Pests in a Warming World

Lepidopteran pests, including the African bollworm (*Helicoverpa armigera*), pink bollworm (*Pectinophora gossypiella*), and fall armyworm (*Spodoptera frugiperda*), represent the most destructive threats to cotton yield (Nature, 2024).

3.1. Phenological Advancement of Bollworms

Thermal adaptation is a defining trait of the pink bollworm (*P. gossypiella*). Research indicates that its developmental period shortens from 42.7 days at 20 degrees Celsius to 26.1 days at 40 degrees Celsius (Hussain et al., 2023). Furthermore, higher soil temperatures in autumn and winter decrease pupal mortality, ensuring a more robust spring population build-up. For *H. armigera*, climate warming has advanced spring emergence by approximately 1.276 days per year. (Nagaraju et al., 2024

3.2. Invasive Potential and Geographic Range Shifts

Climate change facilitates the poleward movement of pests. Species previously confined to tropical regions, such as *H. armigera* and *Maruca vitrata*, are moving into temperate zones in northern Europe and Asia (Nitta et al., 2024). The fall armyworm (*S. frugiperda*) has rapidly spread across sub-Saharan Africa since 2016, thriving in tropical conditions where local varieties lack co-evolved defense mechanisms (Shah et al., 2025).

4. Proliferation of Sucking Pests and Viral Complexes

Changing agro-climatic conditions have facilitated a surge in sucking pests, including whiteflies, aphids, and jassids, which damage crops through sap extraction and viral transmission (Singh & Aggarwal, 2024).

4.1. Whitefly Resurgence and Management Triggers

The whitefly (*Bemisia tabaci*) has become a persistent threat, with major outbreaks in North India recorded in 2015 and 2022. Hot and humid conditions, with temperatures between 20 degrees Celsius and 34 degrees Celsius, favor rapid population growth. Resurgence is often triggered by the overuse of synthetic pyrethroids or sub-lethal doses of insecticides like acephate, which can cause hormoligosis and destroy generalist predators (Kumar et al., 2024).

Table 2. Dynamics of Common Sucking Pests in Cotton

Species	Primary Damage Mechanism	Conducive Climatic Driver
Bemisia tabaci	Sap extraction and virus vector (CLCuV)	Hot and humid conditions (Singh & Aggarwal, 2024)
Aphis gossypii	Leaf curling and honeydew secretion	Warming and altered CO2 levels (Sharma et al., 2010)
Thrips tabaci	Seedling damage and leaf silvering	Seasonality and high humidity (Explainable AI study, 2025)
Amrasca biguttula	"Hopper burn" and yield reduction	Minimum temperature and humidity (Explainable AI study, 2025)

5. Emergence of Secondary Pests in Transgenic Systems

The adoption of Bt (Bacillus thuringiensis) cotton has unintentionally elevated previously minor species to major status due to reduced broad-spectrum insecticide use (Zhang et al., 2015).

5.1. Mirid and Stink Bug Outbreaks

In China, mirid bugs (*Heteroptera: Miridae*) have surged in Bt cotton fields where they were previously suppressed by sprays targeted at bollworms. In the United States, stink bugs (*Pentatomidae*) have replaced bollworms as primary pests (Lu et al., 2010). These mobile, polyphagous pests move from early-season hosts like corn or winter wheat into cotton bolls as they mature (Clemson University, 2024; NC State, 2024).

6. Host Plant Resistance and Genetic Frontiers

Developing resilient genotypes through host plant resistance (HPR) is foundational to IPM (Naranjo, 2011).

6.1. Interspecific Hybridization

Researchers are utilizing wild relatives of cotton, such as *G. anomalum*, to transfer stress-resistance alleles into cultivated varieties. SSR marker analysis has confirmed that these hybrids demonstrate significantly higher growth under strong osmotic stress and enhanced resistance to whiteflies and aphids in natural field conditions (Das et al., 2025).

6.2. Bt Technology and Resistance Management

Bt cotton remains a cornerstone of cotton IPM, contributing to a reduction of over 140 million kilograms of insecticide active ingredient globally. Current technology has evolved toward "stacked" varieties (e.g., TwinLink, Bollgard II) that produce multiple insecticidal proteins to delay resistance (BASF, 2023). Successful Insecticide Resistance Management (IRM) requires structured refuges to maintain susceptible pest populations (Sarangi et al., 2025).

7. Biological Control and Biopesticides

Biological control utilizes natural enemies like ladybugs, spiders, and entomopathogens to suppress pests sustainably (Brazil Cotton, 2024).

7.1. Predators and Parasitoids

In Brazil, the mini wasp *Trichogramma pretiosum* is released via drones to target caterpillar eggs. However, rising temperatures can disrupt these services by altering the diurnal activity of parasitoids and reducing their foraging efficiency (Thilak et al., 2025).

7.2. Microbial and Botanical Biopesticides

Biopesticides such as *Beauveria bassiana*, Nucleopolyhedrovirus (NPV), and neem oil offer environmentally safe alternatives. In South Africa, Bolldex (NPV) has achieved consistent control of *H. armigera*, yielding up to 6,400 kg/ha of seed cotton (O'Malley, 2024). Neem extract acts as both an insecticide and a growth promoter, though it requires dosage optimization and protection from UV degradation (Tijjani et al., 2024).

Table 3. Efficacy and Limitations of Selected Biopesticides in Cotton IPM

Biopesticide Type	Target Pest(s)	Key Advantage	Limitation
Beauveria bassiana	Bollworms, aphids, thrips	Broad spectrum; low residue	Sensitive to heat/low humidity (O'Malley, 2024)
NPV (e.g., Bolldex)	*Helicoverpa armigera*	Highly specific to target	Narrow range; slow action (O'Malley, 2024)
Neem Oil	Sucking pests; bollworms	Multi-modal; growth promoter	Rapid UV degradation (Nagpur Thesis, 2009)

8. Behavioral Control: Pheromones and Mating Disruption

Mating disruption (MD) saturates the environment with synthetic sex pheromones to prevent mate location (Adamič Zamljen et al., 2025).

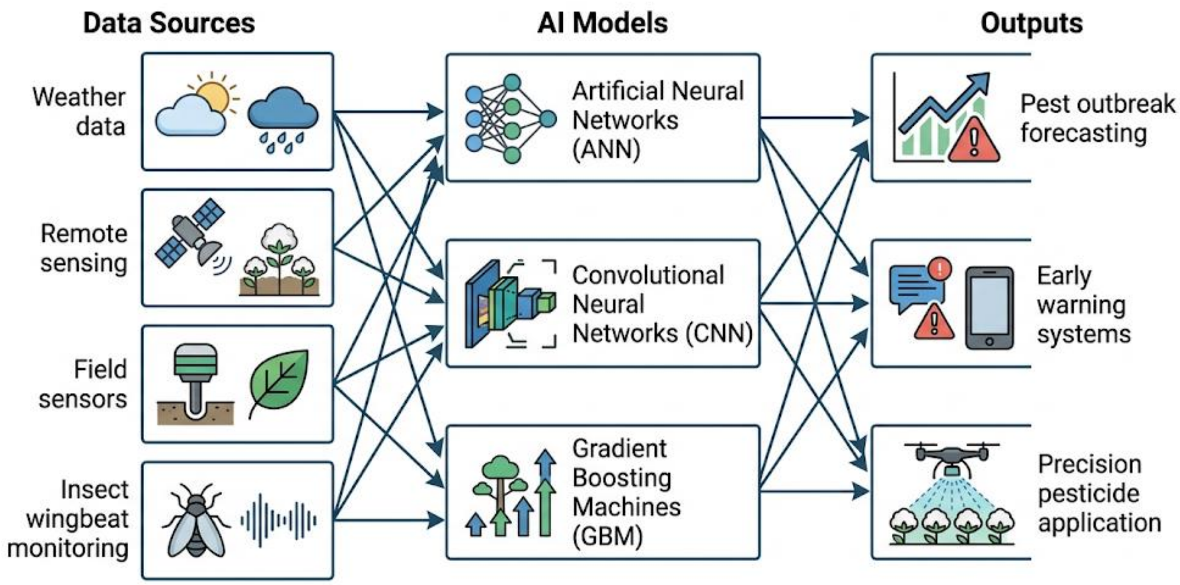
8.1. Technological Advancements

Yeast-derived pheromones have significantly lowered production costs, making MD viable for large-scale field crops. These pheromones, delivered via biodegradable paraffin formulations, can be deployed via Unmanned Aerial Vehicles (UAVs) for uniform coverage (Nature, 2025). In Brazilian trials, pheromone treatment achieved an 82% reduction in male moth trapping and 27% less damage to reproductive structures (Pest Management Science, 2025).

9. Precision Agriculture and Artificial Intelligence (AI)

The integration of AI transforms cotton protection into a proactive science (Kariyanna & Sowjanya, 2024). Digital technologies are transforming pest monitoring and forecasting in modern agriculture. Figure 2 illustrates how artificial intelligence and precision agriculture tools integrate environmental data and pest monitoring systems to improve decision-making in cotton pest management.

Figure 2: Role of Precision Agriculture and Artificial Intelligence in Cotton Pest Monitoring



9.1. Forecasting and Monitoring Systems

Machine learning models, such as Gradient Boosting Machines (GBM) and Artificial Neural Networks (ANN), predict pest outbreaks with up to 93% accuracy (McCorkindale & Ghahramani, 2025). Systems like the FlightSensor identify insects by their unique wingbeats, allowing for precision farming rather than blanket spraying (Kalfas et al., 2021).

Table 4. AI Techniques and Performance in Cotton Pest Management

AI Technique	Primary Application	Performance Metric
Gradient Boosting (GBM)	Outbreak timing prediction	93% Accuracy (McCorkindale & Ghahramani, 2025)
CNN (Deep Learning)	Image classification/pest ID	95% Accuracy (McCorkindale & Ghahramani, 2025)
Stacking Ensemble	Meteorological pest incidence	0.985 AUC Score (Explainable AI study, 2025)
ANN (GFF)	Climate-driven yield forecasting	Reliable 2050 estimates (Smart Agricultural Technology, 2025)

10. Socioeconomic and Institutional Frameworks for Sustainability

Resilient pest management depends on the interaction between ecological, socioeconomic, and institutional domains (Khan et al., 2024).

10.1. Sustainable Cotton Framework

The ecological domain focuses on enhancing biodiversity to absorb shocks, while the socioeconomic domain addresses farmer knowledge and adoption barriers. Institutional support, such as the 2025 Sustainable Cotton Challenge, provides market incentives for farmers transitioning to organic or regenerative practices (Patil et al., 2025).

11. Conclusion

Insect pest dynamics in cotton are profoundly influenced by climate change, necessitating a paradigm shift from chemical-dependent control to holistic IPM strategies that incorporate biological, cultural, and technological innovations. By leveraging host resistance, biopesticides, parasitoids, and predictive tools, IPM not only curbs pest outbreaks but also enhances sustainability, reducing environmental degradation and economic losses. As global warming intensifies pest pressures, adaptive research and policy support for climate-resilient cultivars and ecosystem-based practices will be crucial to safeguard cotton production, support livelihoods, and maintain the industry's role in global food and fiber security.

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