



Integrated Pest Management for Sustainable Management of Major Insect Pests of Agricultural Crops

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Food security is essential for societal stability and for maintaining mental and physical health. However, food losses continue to pose a major challenge to economic policies and global food security (Ejiohuo *et al.*, 2024). Developing countries are particularly vulnerable to food insecurity because of population growth, rising living standards and increasing food consumption. These factors place considerable pressure on food production resources and may result in food scarcity and increased prices, further straining agricultural, economic and environmental systems (Breisinger *et al.*, 2010).

The growing global population has consequently increased the demand for food production (IFAD and UNICEF, 2021). Increasing food demand places greater pressure on resources such as land and water and creates challenges in producing sufficient food in a sustainable manner. According to the Food and Agriculture Organization (FAO), meeting the food requirements of the global population by 2050 will require annual crop and livestock production to increase by approximately 60% compared with current levels (Muhie, 2022). To meet this increasing demand, several strategies are being adopted, including expansion of cultivated areas, improvement of productivity per unit area, development of improved crop varieties, optimization of agricultural inputs and refinement of agricultural practices such as precision farming, pest and disease management, irrigation, nutrition and pruning (Anastasiou *et al.*, 2023).

Insect Pests and Agricultural Production

Since the beginning of agriculture, human societies have faced substantial crop losses caused by insect pests and have utilized naturally occurring materials and botanical extracts as deterrents and pest-management measures. These early practices, based on biodiversity and local ecological knowledge, anticipated some of the fundamental principles of Integrated Pest Management (IPM), which emphasizes ecological balance rather than dependence on a single pest-control method (Rathee and Dalal, 2018).

Insect pests remain an important constraint to agricultural production. On average, they are estimated to cause 15–20% yield losses in major food and cash crops. Sucking insect pests and defoliators, including mirid bugs, mealybugs, whiteflies, aphids, planthoppers, shoot flies, tobacco caterpillars, leaf miners and leaf folders such as *Cnaphalocrocis medinalis* (Guenee), have emerged as major pests (Chakrabarty, 2015).

Several important insect pests have become increasingly severe in different agricultural crops. *Helicoverpa armigera* (Hübner) is an important pest of vegetables and pulses, while *Spodoptera litura* (F.) has become a major pest of vegetables, cotton and oilseeds. *Pieris brassicae* (L.) is an important pest of cruciferous crops, *Liriomyza trifolii* Burgess affects vegetables, and *Atherigona* spp. are important pests of spring maize.

An increasing incidence of aphid complexes comprising *Sitobion avenae* (F.), *Rhopalosiphum maidis* (Fitch) and *Schizaphis graminum* (Rondani) has been recorded on wheat, barley and oat. Similarly, the green mirid bug, *Creontiades biseratense*, has emerged as a pest of cotton in Karnataka, Tamil Nadu, Maharashtra and Andhra Pradesh (Udikeri *et al.*, 2012).

Mites belonging to the families Eriophyidae and Tetranychidae have also emerged as major pests of bean, brinjal, cotton, cucurbits, okra, apple, ber, citrus and mango in northern India. *Maruca vitrata* (Geyer) has emerged as a predominant pest in pigeon pea and cowpea growing areas, causing up to 42% damage in cowpea in Andhra Pradesh.

Changing Pest Status and Emergence of New Pests

The pest status of agricultural insects is changing due to altered cropping patterns, indiscriminate pesticide use, climate change and high-yielding varieties, leading to shifts in pest distribution, abundance and importance. Global trade further facilitates the introduction and establishment of invasive pests, which may cause severe damage in new regions because of limited natural enemies. Important examples include papaya mealybug, cotton mealybug, tomato leaf miner, coconut mite and serpentine leaf miner. Economic impacts highlight the seriousness of these emerging pests. Bagde and Pashte (2014) reported 64.2–89.4% nut infestation by the invasive coconut eriophyid mite *A. gurreronis* in Maharashtra. Dhawan *et al.* (2007) reported 30–40% cotton losses from mealybugs, while Punjab cotton growers incurred approximately Rs. 159 crores in losses. During 2015–16, *Bemisia tabaci* caused severe cotton damage, with losses estimated at Rs. 4200 crores despite Rs. 150 crores spent on pesticides, highlighting limitations of chemical-dependent pest management.

Chemical Pest Management and Its Limitations

Global pest-control practices underwent a major transformation during the mid-twentieth century with the chemical revolution and the widespread adoption of synthetic insecticides such as DDT following the Second World War (Clarke and Lean, 2022). Synthetic pesticides provided effective and rapid solutions for controlling many economically important insect pests. However, their intensive and repeated use also resulted in several ecological and evolutionary consequences. The limitations associated with intensive chemical pest management include ecological disruption, effects on pollinators, bioaccumulation and development of insecticide resistance (Nath *et al.*, 2023). Repeated pesticide application can also alter natural enemy populations and disrupt ecological interactions within agricultural ecosystems. These consequences highlight the biological, ecological and evolutionary limitations of depending exclusively on chemical pest control. The changing pest status of agricultural insects, combined with increasing concerns regarding pesticide resistance and environmental impacts, has therefore created a need for more sustainable pest-management approaches.

Emergence and Importance of Integrated Pest Management

Integrated Pest Management (IPM) is a systems-based framework that combines biological control, host-plant resistance, cultural practices and threshold-guided chemical management to reduce dependence on insecticides. Sustainable IPM addresses environmental degradation while supporting agricultural productivity (Pirlot *et al.*, 2025). Practices such as crop rotation, habitat diversification and biological control reduce pesticide use while conserving biodiversity and protecting soil and water health. Conservation of pollinators, natural enemies and other beneficial organisms further supports ecological balance and stable agroecosystem functions. Economically, IPM can reduce pesticide costs, improve resource-use efficiency, stabilize yields and facilitate access to markets demanding residue-free or environmentally certified produce (Sharma, 2023). Recent advances in digital diagnostics, artificial intelligence and precision agriculture are transforming IPM into data-driven decision-support systems, enabling real-time pest forecasting, detection and targeted interventions for more efficient and sustainable pest management.

IPM as an Approach for Sustainable Crop Production

Increasing food demand, pesticide resistance and environmental concerns necessitate sustainable IPM, integrating ecological, cultural, biological and chemical tactics. Wheat in India's North-Western Plains is affected by aphids, termites, pink stem borer and brown wheat mite. Four major aphid species cause 3–21% grain yield losses, while termites and pink stem borer damage young crops (Singh, 2012). Wheat IPM therefore emphasizes preventive, cultural, biological and need-based chemical measures rather than routine insecticide application.

Components of IPM	IPM module	Farmer's practice
Seed treatment	Seed treatment with combination of reduced dose of Vitavax 75 WP @ 2 g + biogenic fungus <i>Trichoderma viride</i> @ 4 g/kg seed to avoid incidence of diseases like loose smut of wheat. Seed treatment with thiamethoxam 70 FS @ 1 g/kg of seed to avoid incidence of termite or aphids up to 45 days after sowing.	Seed treatment with tebuconazole @ 1 g/kg seed
Soil treatment	For termite or pink stem borer control, need-based broadcasting of fipronil 0.3 G (Regent) @ 17 kg/ha mixed with 50 kg sand at the time of infestation in moist wheat fields before or after first irrigation.	Blanket application of insecticides viz. chlorpyrifos @ 2 L/ha or fipronil 0.3 G/ha at the time of sowing
Cultural control	Installation of yellow sticky traps @ 12 to 15/ha for monitoring aphid incidence.	No trap
Economic threshold level-based chemical control	Border rows spraying of thiamethoxam 25 WG @ 50 g/ha or 5% neem seed kernel powder considering the pest/aphids economic injury level as 5 aphids/earhead.	Blanket spray of thiamethoxam 70 WS @ 20 g a.i./ha at flag leaf stage
Biological control	One spray of either 5% neem seed kernel powder or <i>Metarhizium anisopliae</i> 1.15% WP @ 1 kg/ha in water followed by thiamethoxam 25 WG @ 50 g/ha (if required) at an interval of 15 days, after the notice of infestation for the control of wheat aphid.	No bio control

India ranks among the largest producers and consumers of cotton globally. However, cotton cultivation in India is highly input-intensive, especially in terms of pesticide usage, making it one of the crops most vulnerable to pest-induced yield losses. In the current scenario, key pests affecting cotton include jassids (*Amrasca biguttula biguttula* Ishida), whiteflies (*Bemisia tabaci* Gen), thrips (*Thrips tabaci* Lindeman), mealybugs, and the resurgence of pink bollworm (*Pectinophora gossypiella* Saunder) (Nagrare et al., 2019). These challenges underscore the urgent need for the development and implementation of ecologically sustainable and integrated pest management (IPM) strategies targeting major cotton pests.

IPM Component	Practices Implemented
Cultural practices	Timely sowing in June along with refugia to avoid peak pest infestation. Use of pest-tolerant <i>Bt</i> cotton hybrids; deep summer ploughing to expose pupae. Removal and destruction of crop residues and infested bolls. Crop termination by last week of December followed by destruction of all residues.
Mechanical and physical control	Installation of pheromone traps @ 2/acre for bollworm monitoring and yellow sticky traps @ 10/acre for whitefly monitoring. Collection and destruction of fallen squares/flowers/bolls during early pink bollworm infestation. Application of SPLAT (Gossypure 4% RTU) @ 125 g/acre, applied four times (Aug–Nov); dollops placed at 400–500 spots/acre (3 m apart, zigzag) for mating disruption.
Biological control	Border cropping with sorghum/bajra/maize and cowpea intercropping for conservation of predators (ladybird beetles, spiders, green lacewings). Two sprays of neem oil (Azadirachtin 1500 ppm) @ 5 mL/L for sucking pests and pink bollworm.
Chemical control	Selective insecticides applied only when pest levels exceeded ETL. Need-based use of flonicamid 50 WG @ 200 g/ha for sucking pests. Need-based use of spinetoram 11.7 SC @ 0.8 mL/L or emamectin benzoate 5 SG @ 0.5 g/L for

Tomato pests such as *Tuta absoluta*, aphids, serpentine leaf miner and fruit borer can cause substantial losses. Walia et al. (2024) evaluated IPM modules in Himachal Pradesh using botanicals, microbial agents, biocultural inputs, sticky traps and selective insecticides. Among treatments, T4 (lambda-cyhalothrin + indoxacarb + rynaxypyr + novaluron) recorded the lowest pest populations and improved flowering, fruit production, healthy fruits and seed yield. The study demonstrated that integrated pest-management measures can effectively suppress pests while improving tomato seed yield and quality.

Bt soybean as an IPM strategy for sustainable pest management

Bt soybean adoption in Brazil increased substantially, reaching approximately 94% by 2023/2024, contributing to lepidopteran pest suppression and reduced insecticide use. However, documented Cry1Ac resistance highlights the importance of refuge compliance, monitoring and complementary tactics. Thus, Bt soybean should remain an IPM component rather than replace other sustainable pest-management practices.

Integrated pest management strategy in Bt cotton (*Gossypium hirsutum*) under farmers participatory mode in central India

A field-validated Bt cotton IPM strategy integrated refugia, timely sowing, sanitation, border cropping, cowpea intercropping, pheromone monitoring, natural-enemy conservation, neem treatments and ETL-based selective insecticides. It reduced insecticide use by 46.55%, increased seed cotton yield by 25.38% and net profit by 56.18%, while conserving beneficial predators under farmers' conditions.

Future Directions and Innovations in IPM

Future IPM programmes will increasingly integrate ecological approaches with biotechnology, precision agriculture and digital technologies. Genomics, CRISPR-Cas and RNAi may support targeted pest suppression and resistant crops, although RNAi requires further field validation. AI, IoT sensors, remote sensing and drones can enable real-time monitoring, early detection and site-specific biopesticide application, reducing chemical use and drift. Future programmes should prioritize affordable, accessible technologies for smallholders, alongside appropriate regulation, data privacy and digital infrastructure. Integrating biological control with emerging technologies can improve IPM accuracy, scalability and sustainability.

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