AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 02 (February, 2026)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

Climate-Smart Pest Management Approaches for Adaptation and Mitigation of Emerging Pest Problems Under the Global Scenario of Climate Change

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Climate change is increasingly reshaping natural ecosystems across the globe. Extreme weather events like severe cyclones, droughts, floods are occurring more often. In agriculture, the impact of climate change is felt as it is responsible for fluctuations in average temperatures and precipitation regimes. These changes are directly affecting different levels of the food chain in crop ecosystems, including insects, affecting their development, survival, and dispersal patterns (Deutsch *et al.*,2018). Changes in temperature cause changes in insect pest voltinism, favouring them to shorten their lifecycles and complete additional life cycles within a single growing season, leading to drastic increase in their number, causing severe crop losses (Bebber *et al.*,2013). These variations in climatic factors also disrupt the dynamics of natural enemies, as they often fail to coincide with the susceptible developmental stages of pests (Thomson *et al.*,2010). This leads to overdependence on chemical pesticides to reduce the pest load, leading to the development of resistance and/or the resurgence of minor pests. Extended periods of drought or irregular rainfall compromise the natural resilience of plants, increasing their vulnerability to pest infestation. Recently, emphasis has been given to management approaches that are environment-conscious and responsive to changes in climate. Climate-Smart Integrated Pest Management (CS-IPM) has emerged as a promising framework to address these evolving challenges caused by climate change (Heeb *et al*., 2019).

Climate-Smart Integrated Pest Management (CS-IPM)

Climate-Smart Integrated Pest Management (CS-IPM) extends the traditional IPM framework, which mainly focuses on systematic use of cultural, biological, and chemical controls (Kogan, 1998), by explicitly incorporating climate considerations into pest management decision-making. This approach aligns closely with Climate-Smart Agriculture, which aims to improve productivity while enhancing resilience with minimal ecological disturbance (Lipper *et al.*,2014). Pest control decisions are made by observing pest population dynamics in relation to variable climate regimes (Tonnang *et al.*,2025). CS-IPM also reduces the excess dependence on chemical pesticides and encourages the use of target specific, low-toxic pesticides which are safe to environment and reduce greenhouse gas emissions (Popp *et al.*,2013).

Climatic Impacts on Pest Population Dynamics

Climatic factors such as temperature and rainfall play a pivotal role in modifying pest physiology, development rates, fecundity, survival and dispersal rates which are key factors for population development and pest outbreaks (Bale *et al.*,2002). These changes may also alter microclimates and crop microbimes (Chakraborty *et al.*,2011). Even though extreme weather events like floods and prolonged droughts initially suppress pest populations but can trigger rapid rebounds upon arrival of optimal conditions(Cammell & Knight, 1992).

Regulatory issues such as spread of invasive species into entirely new regions is also facilitated by climate change as in the case of rapid global expansion of fall armyworm (Early *et al.*,2018) pose severe threat to food security of a country, where the introduced pest can cause severe crop damage with minimum natural control. CS-IPM address these challenges by embedding climate risk assessment within pest surveillance systems (FAO, 2017).

Monitoring and Forecasting Tools

Timely and precise pest monitoring and forecasting form a cornerstone of climate-smart integrated pest management (CS-IPM), strengthened by weather-driven prediction models (Trnka *et al.*,2007). Climate-resilient approaches, including early warning systems that integrate long-term pest records, real-time meteorological data, and predictive modeling, enable proactive monitoring of pest populations and reduce the risk of outbreaks (Tonnang *et al.*,2017). Such systems are particularly effective in managing climate-sensitive and migratory pests like locusts and armyworms. Furthermore, advances in remote sensing technologies facilitate large-scale detection of crop stress and identification of pest-prone zones (Zhang *et al.*,2019). Complementing these tools, mobile advisory platforms provide rapid dissemination of pest and climate information to farmers, thereby enhancing response times and decision-making (Aker, 2011).

Sustainable Agronomic and Cultural Measures

Cultural practices such as crop rotation disrupt pest multiplication and prevent the buildup of pest populations in cropping systems. These methods constitute a fundamental pillar of climate-smart integrated pest management (CS-IPM), as they modify farm environments to suppress pests while enhancing resilience (Liebman & Dyck, 1993). Techniques like intercropping and diversification increase habitat complexity, thereby reducing crop vulnerability to pest colonization and simultaneously supporting beneficial organisms (Letourneau *et al.*,2011). Adjusting sowing dates enables crops to escape peak pest pressure, which often shifts under changing climatic conditions (Pathak, 2023). Similarly, improving soil health through organic matter inputs strengthens plant vigor and tolerance to pest damage (Altieri *et al.*,2015). These practices also bolster resilience against climate stresses such as heat and water scarcity (Lin, 2011). In addition, CS-IPM promotes the adoption of pest-resistant and climate-adapted crop varieties to mitigate risks under uncertain conditions (Ceccarelli *et al.*,2010). Collectively, these low-input strategies provide durable, sustainable, and environmentally sound solutions for pest management.

Biological Control

Harnessing natural enemies for sustainable pest regulation is a vital component of climate-smart integrated pest management (CS-IPM). Predators, parasitoids, and microbial agents play a crucial role in suppressing pest populations within well-functioning ecosystems (van Lenteren, 2012). Although climate change may disrupt the life cycles of natural enemies and their interactions with hosts, diversification in cropping systems can buffer against such disturbances (Altieri *et al.*,2015). Greater emphasis on conservation biological control enhances the proliferation of native natural enemies and strengthens system stability under shifting climatic regimes (Landis *et al.*,2000). CS- PM therefore advocates the strategic integration of biological control with climate-adaptive practices to sustain ecological balance and minimize pest outbreaks.

Sustainable use of Pesticides under CS-IPM

In CS-IPM, even though priority is given to non-chemical measures of pest management, chemical pesticides remain necessary in certain situations when pest populations reaches over damaging threshold where they no longer be controlled by cultural and biological control measures (Popp *et al.*,2013). Use of threshold-based pesticide application by giving preference to selective and low-toxicity product with minimal effects on non-target organisms is essential (Pretty & Bharucha, 2015). In CS-IPM, the use of chemical pesticides becomes more efficient, targeted, and environmentally responsible.

Socioeconomic and policy considerations

The successful adoption of CS-IPM depends heavily on farmer awareness, access to extension services, and availability of reliable climate information strongly influence uptake (Feder *et al.*, 2004). Conducting farmer field schools have proven effective in building IPM knowledge and adaptive decision-making capacity in small and marginal farmers who often prone to lack of knowledge and accessibility to extension resources (FAO, 2017). Incentive/ award based farmer supportive service is essential for implementing sustainable practices and investment in climate advisory services, are essential for scaling CS-IPM (Lipper *et al.*,2014).

Climate Mitigation Benefits

CS-IPM contributes indirectly to climate change mitigation by reducing reliance on synthetic pesticides, thereby lowering energy consumption and greenhouse gas emissions (Popp *et al.*,2013). It also enhances soil health and strengthens ecosystem services (Lal, 2004). Moreover, by minimizing yield losses, CS-IPM improves resource-use efficiency, which in turn reduces the overall carbon footprint of food production systems. These multiple co-benefits position CS-IPM within broader sustainability frameworks, supporting biodiversity conservation and pollution reduction (Altieri *et al.*,2015).

Conclusions and Future Directions

Climate-Smart Integrated Pest Management (CS-IPM) advances crop protection in the face of climate change by combining climate science, ecological insights, and adaptive practices to strengthen resilience and sustainability. Refining pest–climate models and tailoring solutions to local contexts remain key research priorities (Tonnang *et al.*,2025). Effective adoption will depend on robust extension services, digital innovations, and enabling policy frameworks (FAO, 2017). As climate risks escalate, CS-IPM offers a practical, science-based pathway to safeguard crops, livelihoods, and ecosystems for the future.

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