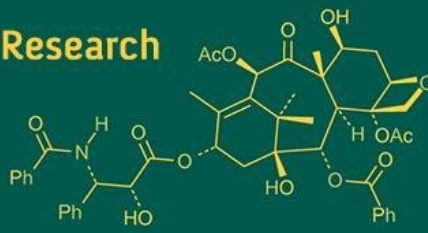
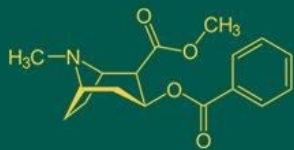


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Adaptive strategies of managing insect pests in rice under climate stress

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Abstract

Rice (*Oryza sativa* L.) plays a vital role in global food security, providing a staple food diet for more than 60% of the world's population, particularly in Asia. Despite its importance, rice production is increasingly threatened by pest outbreaks intensified by climate change. Across India, more than 100 insect species have been reported to attack rice, with approximately 20 considered economically significant such as stem borers, leaf folders, and planthoppers leading to considerable yield reductions. Climate driven factors like rising temperatures, irregular rainfall, and elevated atmospheric CO₂ have altered pest biology, leading to increased survival rates, faster development, overlapping generations, and reduced effectiveness of natural plant defenses. This review examines both the direct and indirect consequences of climate change on pest populations in rice ecosystems and presents sustainable and adaptive pest management options. The focus is on integrated approaches that include cultural modifications, mechanical and biological interventions, and strategic use of chemical pesticides. Practical methods like adjusting sowing dates, managing water and crop residues, deploying parasitoids such as *Trichogramma* spp., and conserving beneficial insects are highlighted. In addition, the integration of climate smart tools such as pest monitoring through light traps and predictive forecasting systems are emphasized. Strengthening community based Integrated Pest Management (IPM) and minimizing dependence on chemical inputs are crucial steps toward enhancing the resilience and sustainability of rice farming under changing climatic conditions.

Keywords: Climate change, direct and indirect effects, pest management, rice pest and *Trichogramma*

Introduction

Rice (*Oryza sativa* Linnaeus.) is one of the significant ancient grain crops, structuring the staple eating food for more than 60% of the world population including all of East and Southern Asia making it one most crucial agricultural commodity of the worlds (Yu *et al.*, 2020) [61]. It has been cultivated in all continents, especially in Asian countries for thousands of years; hence, it is called as "Global food Grain". Rice is cultivated in more than 100 countries in almost all the tropical, subtropical and temperate countries of the world. Globally, rice is cultivated in an area of 22.3 million hectares with a production of 543.6 million tones and productivity 5.83 tones per hectares. India is the second largest producer and consumer of rice in the world next to China with cultivating area under rice cultivation is 48.86 million hectares, production of 136.42 million tones (*Kharif* rice-120.67 million tones and *Rabi* rice 15.75 million tons) with productivity of 2792 kg/ha during 2024-25 (Annual report, 2024-25). In Haryana, rice is cultivated on 1.67 million hectares with production of 119.93 million tones (MT) 2024-25 and productivity of 4200 kilograms per hectare (Paddy outlook, 2024). Yamunanagar, Kurukshetra, Karnal, Kaithal, Jind, Panipat, Sonapat, Rohtak, Sirsa and Fatehabad are major rice growing districts in Haryana.

Rice crop is attacked by more than 100 species of insects-pest, out of these 20 are of major economic concern in India (Krishanaiah *et al.*, 2008) [24] such as leaf folder, stem borers, plant hoppers, gundhi bug, gall midge, whorl maggot, caseworm, rice hispa, armyworm and thrips. These pests cause damage to all plant parts and growth stages of rice from seedling to maturity etc. with an overall yield decline. Among these, rice stem borers viz. yellow stem borer, *Scirpophaga incertulas* (Walker); white stem borer, *S. innotata* (Walker), pink stem

borer, *Sesamia inferens* (Walker), leaf folder, *Cnaphalocrocis medinalis* (Guenee) and plant hoppers (BPH/WBPH) are of utmost importance in Haryana causing huge yield reduction with the introduction of high yielding varieties, adoption of new agronomic practices, indiscriminate use of pesticides and monoculture over large area along with the humid environment favor the proliferation of insect-pests (Kraker *et al.*, 2000) [23]. The larval feeding of all three-borer species resulted in “dead hearts” during vegetative stage and sterile panicles or “white ears” during reproductive stage. Leaf folder larvae fasten the edges of leaves together, fold them longitudinally and feed on green matter from inside the fold, leaving behind the whitish membranes. Planthopper (BPH/WBPH) because hopper burn in rice field and also helps in virus transmission. White-Backed Planthopper (WBPH) transmits Southern Rice Black Streak Dwarf Virus (SRBSDV). Minor pest rice gundhi bug cause chaffy grains and repugnant smell in the field.

Several agronomic practices such as year-round cultivation, highyielding varieties and hybrids, monoculture, excessive nitrogen fertilizer uses, crop residue burning reducing natural enemy reservoirs, global trade and pest introductions, particular weather patterns, poor pesticide

rotation practices, and indiscriminate pesticide use have aggravated pest problems in rice cultivation. These factors disrupt ecological balance, promote resistance development, and increase pest resurgence (Atwal & Dhaliwal, 2013) [6]. Climate change significantly influences insect populations, affecting their distribution, abundance, and lifecycle dynamics. Among the various climatic elements, temperature is a key factor that directly impacts insect biology, including their reproductive output (eg. eggs laid per female), developmental duration (such as the time spent in larval stages), and overall survival (both mortality rates and lifespan). Insect responses to environmental changes are species-specific and often depend on the type of host crop or habitat they are associated with. In the face of unpredictable climate conditions, pest management strategies that were effective in the past may no longer be reliable. As such, these approaches need to be reassessed and validated in the context of current and future climate projections, particularly when evaluating potential population outbreaks. Furthermore, rising temperatures, increased levels of carbon dioxide (CO₂), and altered rainfall patterns can have significant impacts not only on insect populations but also on the broader ecosystems they inhabit, including both plant and animal life.

Economic threshold level for major pests of Rice

Crop stage	Leaf folder	Stem borers	Planthoppers
Planting to pre tillering	one damaged leaf/hill	5% dead hearts or 1 egg mass/m ²	5-10 insects/hill
Mid tillering stage	1-2 freshly damaged leaves/hill	5% dead hearts	5-10 insects/hill
Panicle initiation to booting:	1-2 damaged leaves/hill	1 moth/m ²	5-10 insects/hill
Flowering and after	1-2 damaged leaves/hill	1 moth/m ²	5-10 insects/hill

Climate change and its direct impact on insect pests in rice

Temperature variability

Research by Morya and Kumar (2020) [31] in Eastern Uttar Pradesh indicated that a 0.7-1 °C rise in average temperature, along with decreased rainfall, has markedly shifted the incidence and distribution of key rice pests like stem borers and leaf folders. Elevated minimum winter temperatures correlate strongly with increased overwintering survival of pests such as rice hispa and stem borers, resulting in earlier spring outbreaks. Rani & Prasad (2020) [41] reported comparable patterns, noting that higher night temperatures boost developmental speeds and survival of early-season rice pests. Long-term studies by Horgan (2018) [17] highlighted that minimum temperatures more profoundly affect planthopper migration and establishment especially for *Nilaparvata lugens* than maximum temperatures, owing to their sensitivity to nighttime conditions.

Population Growth and Generation Overlap

A field investigation in Chhattisgarh during 2024 revealed a strong positive correlation between higher temperatures and multiple overlapping generations of brown planthopper and rice leaf folder, resulting in intense crop damage (Harika *et al.*, 2024) [15]. The results are in close proximity with the study of Morya and Kumar (2020) [31]. IPPC indicates that elevated temperatures significantly accelerate pest development rates in aphids and lepidopterans, increasing voltinism and pest pressure (Rao *et al.*, 2025) [43].

Altered Interspecific Interactions

Regional studies note that *Myzus persicae* populations have surged during milder winter seasons in northern India, whereas *Lipaphis erysimi* dominance declines—a clear case of climate-driven species shifts (Rao and Singh, 2024) [42]. The interactive effects of elevated CO₂ and temperature were demonstrated in experiments at ICAR CRIDA during 2025 showing enhanced performance and population indices of aphids and lepidopterans under warming conditions (Rao *et al.*, 2025; Morya and Kumar, 2020) [43, 31].

Expansion of pest generations

Warmer temperatures accelerate the development of *S. furcifera*, shortening the time between generations and enabling up to five generations per season in regions where fewer were previously possible. This increased voltinism leads to rapidly growing populations and supports their establishment in higher latitudes and cooler uplands, where earlier life cycles were too long to complete successfully. For example, the White-backed Planthopper now overwinters and migrates more successfully from tropical lowlands to regions in southern China such as Yunnan and further into formerly inhospitable areas (Hu *et al.*, 2015) [18]. The research confirms that warmer cold-quarter and winter temperatures are key drivers for expanding their overwintering zones and subsequent generations in these regions.

Change in migrating behavior

Climate change significantly alters the migration behavior of key rice pests by affecting wind patterns, temperature

cues, and seasonal rainfall. These changes can disrupt the timing, distance, and direction of insect migrations leading to earlier arrival, longer presence, or even permanent settlement in formerly migratory zones. Climate change has caused a northward shift of leafhopper in its migratory range, reaching areas like northern China and South Korea, where it was rarely seen before (Sheng *et al.*, 2023) ^[51]. In some years, delayed monsoon caused accidental over summering, trapping them in regions unsuitable for growth and development as ecological trap (NRI, 2025) ^[34].

Indirect Effects via Host Plants in rice

Elevated CO₂ Effects

Rising atmospheric CO₂ profoundly modifies rice plant physiology, promoting up to 20% greater biomass, denser canopies, and higher tillering while elevating leaf C:N ratios by 5-16%, which fosters habitats for pests such as the brown planthopper (*Nilaparvata lugens*, BPH) and drives increased feeding, honeydew production, and fecundity (up to 30%) despite lower nymph survival and prolonged development. Open Top Chamber trials at ~550-725 ppm, including ICAR-CRIDA and PJTSAU efforts document boosted peroxidase activity (up to 11%) amid falling superoxide dismutase under combined CO₂ and ~3 °C warming, intensifying hopper burn by 31% and reducing yields ~10% through fewer reproductive tillers. This necessitates updated strategies like nitrogen-efficient resistant varieties, vigilant monitoring, and ecological practices such as inter-seasonal functional crops in fallow rice fields to sustain natural enemies against looming outbreak surges. Elevated CO₂ also increases C:N ratio in leaves, forcing phloem feeders such as BPH to feed more, resulting in higher honeydew excretion and faster population growth (Sengottayan and Nathan, 2021) ^[48].

Breakdown of host resistance

High temperatures, particularly above 35 °C, can severely impair rice plants' natural defense systems, making them more vulnerable to insect pests. Heat stress affects photosynthesis, membrane stability, and antioxidant enzyme function, weakening the plant's capacity to resist pest attacks such as those by stem borers and planthoppers (Singh *et al.*, 2024) ^[52]. Temperature-sensitive resistance genes, particularly those linked to salicylic acid (SA) and jasmonic acid (JA) pathways, are downregulated under elevated temperatures. This reduces both antibiosis and antixenosis effects, allowing pests like the brown planthopper (*N. lugens*) to thrive on previously resistant cultivars (Anand *et al.*, 2023) ^[3]. Additionally, pests directly benefit from heat-stressed host plants. For example, under simulated warming conditions, yellow stem borer (*S. incertulas*) populations

increased significantly, with faster development and higher survival rates. Similarly, metabolic changes in heat-stressed rice seedlings such as higher sugar and reduced phenolic levels have been associated with increased pest fitness (Tanwar *et al.*, 2024) ^[58].

Pest management strategies of rice under changing climate

Cultural Practices

For centuries, people have used traditional pest management practices to maintain healthy crops and reduce pest populations, often without relying on synthetic chemicals (Rathore *et al.*, 2021) ^[44]. These methods are sustainable and environmentally friendly, making them valuable components of IPM systems.

Altering crop spacing and sowing dates

Altering crop spacing and sowing dates significantly influences pest incidence in rice by disrupting pest life cycles or escaping peak infestation periods. Wider crop spacing enhances air circulation within the canopy, reducing humidity that favors pests like the brown planthopper (*Nilaparvata lugens*) (Savary *et al.*, 2012) ^[47]. Adjusting sowing dates helps avoid peak infestations from pests such as stem borers (*Scirpophaga incertulas*) and gall midges (*Orseolia oryzae*) (IRRI, 2010) ^[19]. Optimized crop spacing and timely sowing also contribute to better pest management under climate change by minimizing pest survival and reproduction rates (Pegalepo *et al.*, 2025) ^[36].

Water management through alternate wetting and drying (AWD)

Alternate wetting and drying (AWD) is a water-saving irrigation technique that involves intermittent drying of rice fields instead of continuous flooding. This practice has shown effectiveness in disrupting the breeding habitats of water-dependent pests like the rice water weevil (*Lissorhoptrus oryzophilus*) and planthoppers (IRRI, 2013) ^[20]. It also improves root growth, reduces methane emissions, and enhances nitrogen uptake efficiency, making plants more resilient to both pests and heat stress (Norton *et al.*, 2009) ^[33].

Crop Rotation

This method disrupts the life cycles of pests reducing their populations over time. Evidence of its efficacy was demonstrated in rice, where crop rotation had improved soil health, crop yield, and pest control. In the context of rice production in several countries have demonstrated the value of this practice in pest control.

Crop Rotation

Country	Crop	Intercropped	Effects	References
Nigeria	Rice	cowpeas	reduced stem borers population	Lella & Jagadeesh, 2023 ^[27]
Tanzania	Rice	maize	effectively managed rice leafhoppers	Esuyawka, 2025 ^[25]
Uganda	Rice	groundnuts	control the incidence of rice yellow mottle virus	Esuyawka, 2025 ^[24]
Kenya	Rice	soybeans	incidence of rice gall midge	Hajjar <i>et al.</i> , 2023 ^[14]
Ghana	Rice	cassava	managing rice hispa infestations	Hajjar <i>et al.</i> , 2023 ^[14]
China	Rice	<i>Pontederiacordata</i>	Control rice diseases and pests, results in higher overall productivity and total income, and improves grain quality.	Xiang <i>et al.</i> , 2021 ^[59]
India	Castor	Cowpea, cluster bean, black gram, groundnut	Reduced A. janata and C. punctiferalis pests; higher natural enemies	Srinivasa <i>et al.</i> , 2012 ^[57]
India	Rice	<i>Pontederia cordata</i>	22-46% reduction in sheath blight and leaf folders; LER 1.09	Singh <i>et al.</i> , 2023 ^[55]

Field bund trimming and post-harvest residue crushing

Field bunds often harbor alternate hosts and overwintering stages of rice pests. Regular trimming of bunds helps to eliminate shelter and breeding grounds for insects such as stem borers and rodents. Similarly, crushing and ploughing of rice stubble and other residues after harvest can destroy pest eggs and larvae, minimizing the carryover population to the next season (Baruah *et al.*, 2015) ^[7].

Use of nutrient supplements under heat stress

Under changing climate conditions, particularly during heat stress, rice plants often become physiologically weak, making them more vulnerable to pest attacks. The use of micronutrients and silicon has been found effective in enhancing plant tolerance and resistance. Silicon strengthens plant cell walls, making it more difficult for chewing insects like the leaf folder and stem borers to penetrate (Ma, 2004) ^[29]. Supplementation with zinc, potassium, and boron supports enzymatic activities and stress-related metabolic functions, indirectly reducing susceptibility to pests like planthoppers (Chandramani *et al.*, 2020) ^[8].

Mechanical and physical measures for rice pest management

Mechanical and physical methods are essential components of Integrated Pest Management (IPM), especially in the context of sustainable and climate-resilient agriculture. These approaches aim to reduce pest populations directly through manual or mechanical means, without relying on chemical pesticides.

Light traps for insect monitoring

Light traps attract night-flying pests like stem borers (*S. incertulas*), leaf folders (*C. medinalis*), and planthoppers using UV or fluorescent light. They help monitor pest populations for timely control, especially important as climate change alters pest life cycles (Ramasamy & Jeyaprakash, 2021) ^[39]. Long-term trap-capture studies show that climate warming has advanced pest migration and altered population peaks, further increasing the relevance of trap-based surveillance in adaptive pest management (Yuan *et al.*, 2019) ^[62]. In addition to monitoring tools, mechanical suppression tactics such as stubble destruction, deep ploughing, and residue incorporation effectively reduce overwintering stages of stem borers and leaf feeders, contributing to lower early-season pest pressure (Sithanantham *et al.*, 2013) ^[5]. These approaches align with ecological engineering frameworks that emphasize minimizing chemical inputs while enhancing system resilience and natural enemy activity under changing climates (Horgan, 2018) ^[17]. Together, these mechanical and physical interventions strengthen sustainable rice pest management by directly reducing pest populations and improving the accuracy of decision-making in climate-vulnerable rice environments.

Clipping of nursery leaves to reduce stem borer eggs

Clipping about one-third of rice seedling leaves before transplanting physically removes many stem borer egg masses, thereby reducing early infestations. This simple, low-cost practice is especially useful in organic and low-input systems and remains effective when combined with

clean nursery management (Litsinger *et al.*, 2006) ^[28].

Destruction of diseased plants to curb virus spread

Uprooting and burning virus-infected rice plants effectively curbs the spread of rice tungro virus (RTV) by eliminating primary infection sources and reducing transmission by vectors like the green leafhopper (*Nephotettix virescens*). This cultural practice disrupts the virus lifecycle, preventing secondary spread in fields, especially under climate-driven vector surges (Amelia *et al.*, 2025) ^[12].

Biological control for rice pest management

Four releases of *T. japonicum* at density of 50,000 wasps/ha/release at weekly interval, begun on the 32nd DAT, followed sequentially by 39th, 46th and 53rd DAT (2nd schedule of release) had positive results on the reduction of dead heart symptom by 54.7% and white ear by 66.1% (Murali-Baskaran *et al.*, 2021) ^[32]. Combined strategy of pheromones traps 20/ha and 3-5 release of *T. chilonus* (100000 wasp/ha) record significantly lesser stem borer and leaf folder damage resulting in significant increase 38%-45% in grain yield over to traditional farming methods (Gururaj *et al.*, 2001) ^[13]. YSB was parasitized by *T. japonicum* at 7.1%-23.1% rates in Tiruchirappalli's reported by Sharmistha *et al.* (2020) ^[50].

Different doses of *T. chilonis*, viz., 50,000, 75,000, 100,000, 125,000 and 150,000 parasitized eggs per hectare were tried by Chhavi *et al.*, (2019) ^[9] and reported maximum control when 150,000 parasitized eggs per hectare were released. Egg releases of *Trichogramma* sp. @ 100000 and 1250000 per hectare significantly reduced leaf folder infestation (Sagheer *et al.*, 2008) ^[46]. The efficiency of *T. japonicum* and *T. chilonis* reported by Kumar and Khan (2005) ^[25] on tiller damage and folded leaves varied from 78.1 % to 81.6 % from 72.6 to 81.8 %, respectively, where egg parasitoids were released @ 1,00,000/ha in rice ecosystem.

Conservation of Parasitoids and Predators

Biological control relies on conserving natural enemies of pests, such as parasitoids and predators, to naturally suppress pest populations. Important parasitoids like *Apanteles* spp. and *Pediobius* spp. attack stem borers by laying eggs inside their larvae, reducing pest outbreaks. Similarly, predators such as the mirid bug *Cyrtorhinus lividipennis* prey on planthopper eggs and nymphs, providing effective biological control (Heong and Hardy, 2009) ^[16]. Maintaining or enhancing habitats that support these beneficial insects is crucial, especially under climate change scenarios where pest pressures may intensify. Conservation biological control reduces reliance on chemical pesticides and supports sustainable rice production (Gurr *et al.*, 2016) ^[12].

Biodiversity enhancement to improve pest resilience

Enhancing agro-biodiversity by integrating flowering plants, hedgerows, and maintaining non-crop vegetation boosts populations of natural enemies and overall ecosystem resilience. Diverse ecosystems help regulate pest populations by providing alternative prey and refuges for beneficial insects (Altieri, 1999) ^[1]. Biodiversity-friendly practices improve ecological balance, reduce pest outbreaks, and help rice fields adapt to the stresses of changing climate.

Biodiversity enhancement to improve pest resilience

Target Pest(s)	Chemical Recommendation	Reference(s)
Stem borers and leaf folders	Flubendiamide 20WG @ 25 g a.i./ha Chlorantraniliprole 7.5 Kg Cartaphydrochloride 4G 4 Kg Ferterra 0.4%G mix with 10 Kg sand	Jaglan & Chaudhary (2022) ^[21] Kumar <i>et al.</i> (2021) ^[5] Annonymus, 2021 ^[26]
Planthoppers	Buprofezin 25SC + Acephate/Buprofezin 15% + Acephate mix	Choudhary & Singh (2018) ^[10] ; Rajesh <i>et al.</i> (2020) ^[38]
Planthoppers	Dinotefuran 20SG @ 200 g a.i./ha 120 g Pymetrozine 50WP/acre 80 g Dinotefuran 20SG	Ratnakar <i>et al.</i> (2020) ^[45] ; Matsumura & Yoshioka (2019) ^[30] , Annonymous, 2021 ^[26]
Multiple pests	Thiamethoxam 25WG 20-50 g a.i./ha	Khan <i>et al.</i> (2020) ^[22] ; Singh <i>et al.</i> (2022) ^[53]
Multiple pests	Chlorantraniliprole + Thiamethoxam mix 125-150 g/ha	Poonam <i>et al.</i> (2025) ^[37]

Chemical control (judicious use)
Climate mitigation and future recommendations for rice pest management

Reduce fossil fuel-based inputs and greenhouse gas emissions

Reducing fossil-fuel based inputs such as synthetic fertilizers, pesticides, and diesel reduces CO₂ and N₂O emissions in rice systems. Precision farming, integrated nutrient management (INM), and climate-smart practices like reduced tillage, slow-release fertilizers, and alternate wetting and drying (AWD) improve input efficiency, lower greenhouse gases, and support natural enemies for pest control (Zheng *et al.*, 2024) ^[62]. These strategies enhance both climate resilience and sustainable pest management. Implement residue-based nutrient recycling to reduce nitrogen use by up to 25%

Recycling crop residues as organic matter can reduce the need for synthetic nitrogen fertilizers by up to 25%, improving soil fertility, nutrient-use efficiency, and crop yields. Long-term field experiments in rice-wheat systems have shown that retaining and incorporating crop residues allows reduced N fertilizer rates while maintaining productivity (Singh *et al.*, 2018) ^[54]. Integrated Nutrient Management (INM) approaches combining crop residues, green manure, and reduced mineral fertilizers enhance soil microbial activity, soil organic carbon, and nutrient cycling, further reducing dependence on synthetic N. Additionally, residue incorporation improves plant vigor, indirectly reducing susceptibility to pests, while lowering nitrogen runoff and greenhouse-gas emissions (Ramesh *et al.*, 2025) ^[40]. These findings support residue-based nutrient recycling as a sustainable, climate-smart strategy for rice production.

Encourage climate-resilient agro-technologies and farmer advisories based on real-time pest monitoring

Deploying climate-smart technologies such as remote sensing, mobile applications, and light-trap or IoT-based pest monitoring systems enables real-time tracking of pest populations and environmental conditions, helping farmers take timely and precise management decisions (Xiong *et al.*, 2024) ^[60]. IoT-based pest management systems integrating light traps and sensors have been shown to reduce pesticide use while effectively controlling insect populations. Similarly, UAV and hyperspectral imaging tools provide early detection and mapping of pest infestations, allowing spatially targeted interventions instead of blanket pesticide application. Meta-analyses and recent reviews confirm that precision farming technologies, automated pest surveillance, and decision-support tools improve Integrated Pest Management (IPM) efficiency, reduce environmental

impact, and enhance climate resilience in rice agroecosystems (Sharma *et al.*, 2024) ^[49].

Promote community-level IPM strategies integrated with weather-based forecasting tools

Community-based Integrated Pest Management (IPM) combined with weather forecasting allows coordinated pest control activities that are more effective and environmentally sustainable. Weather data help predict pest outbreaks, enabling preventive actions at the community scale and improving resilience to climate variability (Gurr *et al.*, 2016) ^[12]

Conclusion
Threat posed by insect pests to rice cultivation is intensifying as climate change continues to disrupt pest behavior and reduce the reliability of traditional control methods. This calls for a transition toward climate-resilient pest management approaches. implementing a holistic strategy that integrates ecological methods, timely pest monitoring, careful pesticide application, and biodiversity preservation is vital for maintaining crop yields. Adopting adaptive cultural practices, enhancing the use of natural enemies, and aligning pest control measures with climatic trends can improve the crop’s ability to withstand pest attacks. Modern tools such as satellite imaging and climate-based pest prediction models can help farmers act proactively. moreover, practices that lower emissions such as efficient input use and recycling of crop residues can connect pest control efforts with environmental sustainability. To ensure long-term success, greater emphasis must be placed on supportive policies, training programs for farmers, and locally coordinated IPM initiatives. Ultimately, the resilience and productivity of rice systems under climate stress will depend on blending ecological knowledge with forward looking agricultural innovations.

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Conflict of Interest
The authors declare no conflict of interest.

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