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Ecologically based non-chemical strategies for sustainable management of rice insect-pests

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Abstract

Rice sustains more than half of India's population and is fundamental to national food security, rural livelihoods, and agricultural sustainability. However, rice production is increasingly threatened by frequent and severe insect pest outbreaks, driven by climate variability, intensive cropping systems, and the excessive use of chemical fertilizers and pesticides. Prolonged dependence on chemical pest control has resulted in loss of biodiversity, disruption of natural enemies, pesticide resistance, secondary pest resurgence, environmental pollution, and growing risks to human and ecosystem health. Consequently, there is a strong need to shift toward ecologically sound and sustainable pest management strategies. This review critically examines recent advances and field-based evidence on non-chemical and ecologically based approaches for managing insect pests in Indian rice ecosystems. It highlights cultural, mechanical, biological, genetic, and ecological engineering strategies that reduce initial pest populations and limit population growth, including low-stubble harvesting, tillage and flooding, adjustment of sowing time, optimized crop geometry, synchronous planting, water and nutrient management, grazing, and field sanitation. Particular emphasis is placed on habitat manipulation, semi-natural habitats, nectar provisioning, banker plant systems, and early-season insecticide avoidance to conserve and enhance natural enemies. Progress in host-plant resistance, biological insecticides, *Trichogramma* based biological control, pheromone-mediated technologies, and integrated rice-animal farming systems is also reviewed. In addition, the role of regulatory and policy frameworks in supporting safe pesticide use and promoting Integrated Pest Management is discussed.

Keywords: Rice, non-chemical pest management, ecological and environmental integrity and sustainability

Introduction

In India, rice is the staple food for more than half of the population and plays a pivotal role in national food security and rural livelihoods. Insect pest infestations in rice occur frequently with varying intensities and periodicities, which are increasingly influenced by climate variability, intensified cropping systems, and the widespread cultivation of high-yielding varieties (Savary *et al*., 2019; Pathak *et al*., 2021) [48, 35]. Modern intensive rice cultivation, primarily aimed at maximizing productivity, is often associated with the indiscriminate and excessive use of chemical fertilizers and pesticides. Such practices have resulted in several adverse environmental consequences, including loss of on-farm biodiversity, disruption of natural biological control, contamination of surface and groundwater with pesticide residues, rapid development of insecticide resistance in major rice pests, resurgence of secondary pests, environmental pollution, and ecological imbalance (Heong *et al*., 2020; FAO, 2021) [17, 10]. These negative feedbacks weaken ecosystem resilience, promote frequent pest outbreaks, and necessitate higher pesticide inputs, thereby creating a vicious cycle (Conway and Pretty, 1991). The irrational use of pesticides has thus emerged as a major constraint to sustainable rice production in India and poses serious risks to food safety, environmental health, and human well-being (ICAR, 2022) [22].

In recent years, several new principles, technologies, and strategies for sustainable pest management have been promoted in India. Among these, the concept of green plant protection and ecologically based pest management has gained increasing attention through national programs on Integrated Pest Management (IPM) and agroecological approaches (FAO, 2021; Pathak *et al*., 2021) [10, 35]. Ecological control approaches aimed at minimizing pesticide dependence include cultural, biological, and habitat management practices, with ecological engineering emerging as a key strategy. Ecological engineering in rice ecosystems focuses on enhancing functional biodiversity to conserve and augment natural enemies of insect pests, thereby improving ecosystem services and reducing reliance on chemical control (Heong *et al*., 2020; ICAR, 2022) [17, 22]. This paper reviews recent progress and research advances in the development and adoption of such non-chemical and ecologically sound strategies for rice insect pest management in India.

Low-stubble harvesting, tillage, and pre-sowing flooding

Rice stubbles remaining after harvest serve as important overwintering and carry-over habitats for major rice stem borers in India, particularly the yellow stem borer (*Scirpophaga incertulus*), striped stem borer (*Chilo suppressalis*), and pink stem borer (*Sesamia inferens*). The population levels of these pests in the subsequent cropping season are largely influenced by the survival of immature stages within rice stubbles during the off-season. Mechanized harvesting, especially when combined with reduced stubble height, plays a crucial role in minimizing these overwintering refuges and thereby suppressing early-season pest populations (Singh *et al*., 2016; ICAR-IIRR, 2021) [, 23]. Studies under Indian conditions have shown that lowering rice stubble height to about 5-10 cm can significantly reduce stem borer survival by destroying larval and pupal habitats (Kumar *et al*., 2018). In addition, deep ploughing followed by flooded irrigation before land preparation has been reported to kill a substantial proportion of overwintering larvae and pupae through mechanical injury and anaerobic conditions (Pathak and Khan, 2017; Katti *et al*., 2020) [38, 29, 27]. The integration of low-stubble harvesting with timely tillage and pre-sowing irrigation can therefore effectively reduce the initial population density of rice stem borers and contribute to sustainable pest management in Indian rice-based cropping systems.

Adjustment of sowing time of rice

In rice-growing regions affected by virus diseases transmitted by planthopper vectors, particularly the small brown planthopper (*Laodelphax striatellus*), the timing of rice sowing plays a critical role in determining pest abundance and disease incidence. Early sowing often coincides with peak migration and population build-up of planthoppers, resulting in higher virus infection during the seedling and vegetative stages of the crop (Singh *et al*., 2025) [52]. Delaying sowing allows the most susceptible crop stages to escape periods of high vector pressure, thereby reducing both planthopper density and virus transmission without adversely affecting grain yield (ICAR, 2025) [20]. Recent studies and field advisories have further demonstrated that postponing sowing and transplanting dates can significantly suppress populations and damage caused by stem borers and planthopper vectors in both transplanted and direct-seeded rice systems (FAO, 2025; Kumar *et al*., 2025) [11].

Seed rate use

Seed rate strongly influences plant population and canopy structure, which in turn affect insect pest dynamics in rice. Higher seed rates often produce dense canopies that create humid, shaded microclimates favorable for pests such as brown planthopper (*Nilaparvata lugens*) and white-backed planthopper (*S. furcifera*), leading to increased pest settlement and reproduction (Verma *et al*., 2025[a]) [63]. Dense stands may also impede movement of natural enemies, reducing biological control effectiveness. In contrast, moderate to lower seed rates improve air circulation and light penetration, reducing pest colonization and supporting stronger plant growth that is more resistant to damage (Kumar *et al*., 2024; Singh *et al*., 2024) [30, 56]. Field experiments in eastern and southern India indicate that optimized seed rates matched to cultivar and environment can lower planthopper and stem borer incidences while still achieving target yields (Rao *et al*., 2022) [44].

Plant spacing

Plant spacing significantly alters the physical and biological environment of rice crops, affecting both pests and their natural enemies. Wider spacing (e.g., 20-25 cm rows) increases airflow and sunlight within the canopy, making conditions less favorable for pests and disease vectors while facilitating greater activity of predators and parasitoids (Sharma & Yadav, 2023; Jha *et al*., 2025) [49, 65, 26]. In contrast, narrow spacing or overcrowded hills can create humid microhabitats that enhance reproduction of planthoppers, stem borers, and leaf folders, and can reduce the foraging efficiency of natural enemies (Singh *et al*., 2024) [56]. Recent multilocation trials in the Indo-Gangetic Plains have shown that slightly wider inter-row spacing improves predator abundance (e.g., spiders and predatory bugs) and reduces planthopper pressure without reducing grain yield (ICAR-NRRI, 2024; Tiwari *et al*., 2025) [19, 61].

The positive effects of optimized seed rates and spacing on insect pest suppression are largely mediated through microclimate modification**,** natural enemy conservation, and enhanced plant vigor. Reduced canopy humidity and shade discourage colonization by pests, while improved conditions favor predators, parasitoids, and arthropod biodiversity (Jha *et al*., 2025) [26]. Healthy, vigorous plants resulting from appropriate crop geometry are also more resilient to pest damage. For effective pest management, these crop establishment practices should be integrated within a broader Integrated Pest Management (IPM) framework that includes balanced fertilization, water management, habitat diversification, and biological control (ICAR-NRRI, 2024) [19].

Synchronous planting

Synchronous planting of rice across fields in a region is an effective cultural practice to suppress pest populations, particularly stem borers, planthoppers, and leafhoppers, by limiting the continuous availability of suitable host plants and disrupting pest life cycles. Coordinated planting within a 2-3-week window, combined with rice-free periods, reduces pest survival, movement, and the incidence of vector-transmitted viral diseases (National IPM Package for Rice, 2023) [24]. Studies in Indian rice ecosystems and other rice-growing regions have shown that synchronized crop establishment lowers pest colonization, reduces stem borer damage, and minimizes outbreaks by preventing staggered infestations (Holt *et al*., 2017; Jacob *et al*., 2010) [18, 25].

Water management

Intermittent irrigation, periodic draining, and alternate wetting and drying (AWD) are effective cultural practices in Indian rice fields to reduce populations of major pests such as brown planthopper, white-backed planthopper, and leafhoppers. These practices expose eggs, nymphs, and early instars to unfavorable conditions, disrupting pest life cycles and reducing initial infestations (Singh & Rao, 2023; Integrated Pest Management Package for Rice, 2023) [53, 44,]. Field studies and farmer advisories have shown that draining rice fields for short periods during early crop stages or when pest pressure is detected can significantly suppress pest numbers without affecting yields (TNAU Agritech, 2024). AWD not only improves water use efficiency but also lowers pest and disease incidence compared with continuous flooding (Sahu *et al*., 2023) [47]. Adoption of these water management strategies as part of integrated pest management enhances natural pest suppression, reduces reliance on chemical insecticides, and promotes sustainable rice production in India.

Fertilizers application

Large numbers of insect pest in rice tends to do more damage and increase in numbers with fertilizers particularly nitrogen. Fertilization synchronize pest development and survival. Effects of fertilizer application on pest population is depicted in the table 1.

Table 1: Effects of fertilizer application on pest population

Fertilizer	Effects on pest population
Nitrogen	Increase Thrips, whorl maggots, leaf folder population
Phosphorus	Increase abundance of stem borer
Potassium	Suppress whorl maggot, green leafhoppers, yellow stem borers, leaf folders, thrips and BPH
Silica	Reduces stem borer larval feeding
Zinc	Reduce *Elasmopalpus* damage
Bone meal	Control gall midge

Field sanitation and stubble management

Field sanitation and stubble management are important mechanical practices in rice cultivation for reducing pest populations. Collecting, plowing, or removing rice stubbles and plant residues after harvest destroys overwintering sites for major pests such as stem borers and leaf folders, preventing their survival and reducing infestations in the subsequent crop (Singh & Rao, 2023; Kumar *et al*., 2024; Integrated Pest Management Package for Rice, 2023; Heinrichs, 1994; Pathak & Khan, 1994) [53, 44, 30, 19, 14, 36]. Proper field sanitation, including the removal of weeds and residues, exposes hibernating eggs, larvae, and pupae to unfavorable conditions, further lowering pest carry-over. Regular tillage or mechanical weeding exposes pest eggs and larvae to predators, desiccation, or mechanical injury, reducing pest survival in early crop stages (ICAR-IIRR, 2025) [20]. Studies in Indian rice ecosystems have shown that combining residue management with post-harvest plowing or flooding can significantly suppress pest populations and enhance the effectiveness of integrated pest management strategies.

Shavings of field bunds

Mowing and shaving rice bunds is a common practice for rodents and weed control that affects varying pest population that spent at least a part of their life cycle in soil *viz*., army worm pupate, grasshoppers oviposit and mole crickets' tunnels in rice bunds. Trimmed soil can be thrown into the flood water to drown eggs and pupae. Sides of the bunds can be plastered with fresh mud to trap mole cricket's population in rice field.

Landscape manipulation for natural enemy conservation in rice

Enhancing non-rice habitats and floral resources within rice landscapes strengthens biological control by supporting predators and parasitoids. Planting grasses, nectar-rich border plants, and legume cover crops such as sesbania and dhaincha along field bunds or in adjacent fallow areas provides shelter, alternative hosts, and nectar for natural enemies, improving their overwintering survival and activity. Non-crop refuges and field margins act as reservoirs of beneficial arthropods, allowing them to recolonize rice fields after transplanting. Research in eastern and southern India shows that these habitats increase densities of egg parasitoids (*Anagrus* spp.), predatory spiders, and lacewings, resulting in lower planthopper and stem borer populations compared to fields without refuges (Rai *et al*., 2022; Tiwari *et al*., 2025) [42, 61]. Incorporating flowering plants like marigold (*Tagetes* spp.), cosmos (*Cosmos bipinnatus*), and buckwheat (*Fagopyrum esculentum*) along rice field margins has been shown to improve the survival, foraging, and reproduction of natural enemies, enhancing pest suppression and reducing insecticide dependence (ICAR-NRRI, 2024) [19].

Semi-natural habitats such as bunds with flowering plants, grass strips, hedgerows, and non-crop vegetation surrounding rice fields provide refuges, alternative prey, and nectar resources for natural enemies of major rice pests including brown planthopper (BPH), white-backed planthopper (WBPH), rice stem borers, and leaf folders (Altieri, 1999; Landis *et al*., 2000) [2, 32]. These habitats sustain populations of predators (spiders, lady beetles, predatory bugs) and parasitoids (*Trichogramma* spp., *Anagrus* spp.) during periods of low pest abundance, ensuring timely suppression of pest outbreaks. Flowering plants like sesbania, marigold, cosmos, and buckwheat planted on field margins improve parasitism of planthopper eggs and predation of stem borer larvae. Grass strips and non-crop refuges act as corridors for recolonization of natural enemies, reducing reliance on chemical insecticides (Tiwari *et al*., 2025; ICAR-NRRI, 2024) [61, 19]. Overall, maintaining semi-natural habitats enhances species diversity and functional redundancy among natural enemies, strengthening biological control and supporting sustainable rice production in India (Heong & Hardy, 2009) [16].

Nectar food

Providing nectar resources within rice landscapes can substantially enhance biological control by supporting populations of natural enemies. Nectar availability improves the longevity, fecundity, and foraging efficiency of key predators and parasitoids, thereby increasing their effectiveness against rice pests (Wackers *et al*., 2005; Singh & Rai, 2023) [53, 41]. Recent studies in Indian rice ecosystems emphasize planting flowering crops along field margins and bunds to provide continuous nectar throughout the cropping season, benefiting arthropods such as *Anagrus* spp., *T. chilonis*, and the predatory bug *Cyrtorhinus lividipennis*. In India, nectar-rich plants like sesbania (*Sesbania bispinosa*), marigold (*Tagetes spp.*), mustard (*Brassica juncea*), and cosmos (*Cosmos bipinnatus*) have been evaluated for attracting and sustaining natural enemies. Field and laboratory studies show that nectar from these plants increases adult longevity and parasitism rates of egg parasitoids (*T. chilonis*, *Anagrus* spp.) and enhances predation by *C. lividipennis* on planthopper eggs (ICAR-NRRI, 2024) [19]. Similarly, planting buckwheat (*Fagopyrum esculentum*) and sunflower (*Helianthus annuus*) along rice field margins promotes lacewings and hoverflies, key natural enemies of lepidopteran and sucking pests (Tiwari *et al*., 2025) [61]. Careful selection of nectar plants is essential, as some species may also benefit pest insects. Preference should be given to plants that enhance natural enemy survival without aiding pest populations (Rai *et al*., 2022) [42]. Integrating nectar-producing plants into rice landscapes, together with other ecological engineering approaches, strengthens biological control, reduces pest damage, and decreases reliance on chemical insecticides in Indian rice systems (ICAR-IIRR, 2025; FAO, 2024[b]) [20, 12].

Alternative hosts and early-stage insecticide avoidance

Native natural enemies are vital for controlling rice insect pests, but their populations often lag behind pest outbreaks under conventional management. Supplying alternative hosts and food sources early in the season helps build predator and parasitoid populations, improving biological control before pest numbers peak (ICAR-IIRR, 2025) [20]. The banker plant system comprising banker plants, alternative hosts or prey, and beneficial natural enemies creates an open-field rearing environment that sustains these populations with minimal external inputs (Chandra *et al*., 2024) [5].

In India, similar approaches involve planting graminaceous border vegetation that hosts non-pest planthoppers and leafhoppers, which act as alternative hosts for egg parasitoids such as *Anagrus* spp. and *T. chilonis*. These refuges allow natural enemies to multiply before the arrival of major pests, resulting in consistent suppression of planthoppers and other herbivores. Field trials in eastern and central Indian rice-growing regions show that plots with banker vegetation maintain pest populations below economic thresholds more effectively than control fields without refuges (Tiwari *et al*., 2025; ICAR-NRRI, 2024) [61, 19].

Avoiding insecticide sprays during the early growth stages is equally important. In this period, neutral insects such as *chironomid midges* and other saprophagous arthropods serve as alternative food for predators and parasitoids, helping natural enemies thrive. Early chemical applications can kill these beneficial organisms, weakening natural enemy populations and causing pest outbreaks later. Studies in India indicate that delaying insecticide use for the first 30-40 days after transplanting when pest densities are low does not compromise yield but enhances natural enemy survival and pest suppression in subsequent stages (ICAR-IIRR, 2025) [20].

Reduction of initial population sizes of rice insect-pests:

All major rice insect pests are exogenous in origin, and therefore the size of the initial insect population directly influences the population dynamics of subsequent generations (Demis, 2025) [9]. Consequently, one important strategy in pest management is to *reduce the initial population levels* of overwintering or immigrating pest generations through early-season monitoring, habitat manipulation, and culturally based suppression tactics (Anand, 2025) [3]. Such approaches aim to lower the buildup of pest pressure later in the season and thereby reduce the need for intensive chemical control later in the crop cycle. Recent rice pest ecology studies reinforce the importance of understanding seasonal pest dynamics for effective early interventions in integrated pest management programs (Singh *et al*., 2025) [52].

Rice-animal husbandry integrated systems for pest management

Integrated rice-animal husbandry systems, such as rice-fish, rice-duck, and rice-crab farming, provide ecological benefits beyond productivity by promoting self-regulating pest suppression and enhancing system resilience. In India, rice-fish and rice-duck systems have gained attention as sustainable alternatives to conventional monoculture due to their contributions to nutrient cycling, weed and pest reduction, and increased biodiversity (Singh *et al*., 2018; FAO, 2024) [57, 11].

In rice-duck systems, ducks introduced into paddy fields forage on weed seedlings, insect pests, and rice residues, which helps reduce pest populations and improve plant health. Studies in tropical rice belts of eastern and southern India report chick mortality of major rice pests such as planthoppers and stem borers by up to 50-70% in fields with ducks compared with control fields without ducks (Rai *et al*., 2020) [43]. The foraging activity of ducks also enhances soil aeration, accelerates organic matter decomposition, and promotes nutrient availability-factors that contribute to greater plant vigor and indirectly improve resistance to pests.

Rice-fish integration, especially with carp species, supports natural enemy populations and reduces pest densities through habitat diversification and food web support. Research in eastern India shows that fish in rice fields consume insect larvae and other pest stages, resulting in significantly lower infestation levels of stem borers and defoliators while providing an additional source of protein and income for farmers (Tiwari *et al*., 2021; ICAR-IIRR, 2025) [61, 20]. Additionally, such systems are associated with higher abundances of predatory arthropods like spiders and dragonflies, further contributing to pest suppression. Field trials in India demonstrate that integrated rice-animal systems can reduce the need for chemical insecticides, increase overall farm productivity, and improve ecological balance. Compared with monoculture rice, rice-duck and rice-fish systems have shown enhanced natural enemy densities and lower pest pressure without compromising grain yield (ICAR-NRRI, 2024) [19]. These co-mutualistic systems thus offer sustainable pathways to strengthen rice ecosystem resilience, enhance food security, and support diversified livelihoods in Indian rice landscapes.

Grazing

Grazing livestock such as cattle, buffaloes, sheep and goats in recently harvested rice fields helps suppress stem borer populations by trampling larvae and pupae lingering in rice stubbles, thereby reducing pest carry-over to the subsequent crop (Pathak & Khan, 1994; Heinrichs, 1994) [37, 14]. The effectiveness of this practice is largely dependent on the stocking rate and body size of the animals, as higher trampling pressure leads to greater destruction of overwintering stages of pests (Heinrichs, 1994) [15]. Post-harvest grazing also assists in weed removal and improves field sanitation, indirectly contributing to reduced pest incidence in the following season (Pimentel, 1997). But in some countries like USA and Australia, many cattles were found died due to unknown cause when grazed on rice during an outbreak of fall armyworms. Grazing also helps to remove weeds in the field and destruction of hidden stages of insect-pest.

Clipping rice seedling tips

Clipping the tips of rice seedlings at transplanting or early vegetative stages is an effective cultural practice to reduce early-season pest infestations in Indian rice fields. By removing the tender shoot tips, the seedlings become less attractive for feeding and oviposition by key pests such as BPH, WBPH and rice leaf folder. This leads to a reduction in initial pest colonization and delays population buildup during the critical early growth period. Clipping also improves canopy aeration and sunlight penetration, which suppresses pest-favorable microclimatic conditions and enhances the activity of natural enemies such as spiders, predatory bugs (*Cyrtorhinus lividipennis*), and parasitoids, further contributing to pest population suppression (Kumar *et al*., 2024; Tiwari *et al*., 2025) [30, 61]. Field studies in eastern and central India show that plots with clipped seedlings consistently maintain lower pest densities and reduced damage compared to unclipped controls, supporting its integration as a low-cost, environmentally friendly component of IPM (ICAR-NRRI, 2024; Verma *et al*., 2025^b) [19, 64].

Passing of ropes over paddy fields

Passing ropes or wires over the paddy canopy is a simple mechanical technique used in some parts of India to reduce the infestation of early-season pests such as BPH, WBPH and rice leaf folder. The method involves gently dragging a rope across the crop canopy, which physically dislodges small nymphs and adults from the plants, causing them to fall into the water below where they perish (Singh & Rai, 2023) [58, 41]. This technique helps to reduce the initial pest population, delaying population buildup during the critical early growth stages and thereby reducing crop damage. Field trials in eastern and southern India have shown that plots treated with rope-passing recorded significantly lower pest densities and reduced incidence of hopperburn compared to untreated plots (Tiwari *et al*., 2025) [61].

Escape from virus vectors during rice seedling culture

To manage rice virus diseases transmitted by insect vectors such as planthoppers, physical protection and strategic nursery management during the seedling stage are highly effective. Covering rice seedling beds with insect-proof nets (>20 mesh) or non-woven fabrics (15-20 g m^{-2}) throughout the nursery period can effectively prevent early infestation by virus vectors and reduce virus transmission, thereby minimizing the need for chemical seed treatments (NIPHM, 2024) [34]. In rice-growing regions of India where virus diseases such as Southern rice black-streaked dwarf virus occur regularly, selecting nursery sites away from known virus reservoirs and vector-prone areas allows seedlings to “escape” early infection (TNAU, 2024). Rice nurseries may be raised in upland fields, protected structures, or areas intercropped with non-host crops such as vegetables or fruit plantations, which are less favorable for planthopper buildup (ICAR-IARI, 2025b) [21]. In addition, the adoption of commercial, factory-based intensive rice seedling production systems under protected conditions has emerged as a promising option to reduce vector exposure and ensure healthy seedlings for transplanting (FAO, 2025).

Light trap of overwintering and immigrating insect pests

Light traps are an effective mechanical tool for monitoring and managing overwintering and immigrating populations of major rice insect pests such as stem borers and planthoppers in Indian rice ecosystems. Pest-killing light traps, including solar-powered and frequency-based lamps, are usually installed at a height of 1.3-1.5 m above ground in a grid or checkerboard pattern and operated from dusk to dawn during peak immigration periods to reduce initial pest populations and assess pest influx (NIPHM, 2024; ICAR-IIRR, 2025) [34, 21]. Collected egg masses or larvae can be destroyed (ICAR-NRRI, 2024) [19]. However, indiscriminate or prolonged use of conventional light traps may lead to high mortality of beneficial and non-target insects. To address this concern, improved designs such as suction- or exhaust-fan-assisted light traps have been recommended, as they effectively trap target pests while conserving natural enemies, with survival rates exceeding 60-70% (Katti *et al*., 2024; ICAR, 2025) [28, 21]. In integrated rice-fish farming systems, trapped insects can also be used as supplementary fish feed, enhancing system productivity (FAO, 2024) [11]. Moreover, regular monitoring of light-trap catches provides valuable information on pest population dynamics and migration trends, supporting timely and need-based interventions under Integrated Pest Management (IPM) programs (NIPHM, 2024; ICAR-IIRR, 2025) [34, 21].

Decreasing population growth rates of rice insect pests by enhancing resistance of rice varieties

In agro-ecological systems, pest population growth depends on initial infestation, intrinsic growth rates, and control measures (Cheng *et al*., 2008) [6]. Limiting initial pest recruitment is key to suppressing future generations. Strategies include cultivating genetically resistant rice varieties, enhancing resistance through cultural practices, improving environmental resilience, and deploying natural enemies like *Trichogramma* species to reduce pest pressure and maintain ecosystem balance. Advances in understanding the genetic and biochemical mechanisms of rice resistance to major pests such as planthoppers also highlight the importance of integrating host resistance into pest management programs (Pati *et al*., 2023) [39].

Cultivating pest-resistant rice varieties

Developing rice varieties with enhanced resistance to insect pests is a key component of sustainable pest management. Host-plant resistance limits pest survival and reproduction, reducing reliance on chemical control (Cheng *et al*., 2008)

[6]. In India, breeding programs focus on major rice pests including BPH, WBPH, leaf folder and stem borers. Traditional genetic resistance, improved through recurrent selection and marker-assisted breeding, remains central to national varietal releases (Singh *et al*., 2021; ICAR-NRRI, 2024) [54, 19]. Field screening under Indian conditions has identified rice genotypes with moderate to high resistance to planthoppers, which are being incorporated into breeding pipelines (Tiwari *et al*., 2025) [61]. Cultural practices, such as balanced nutrition and timely sowing, further enhance resistance by improving plant vigor and tolerance to pests (Yadav *et al*., 2023) [65]. Biotechnological approaches, including transgenic and gene-edited varieties, offer additional options. *Bt* genes and anti-insect genes, such as lectins and protease inhibitors, have shown efficacy against lepidopteran pests and planthoppers in Indian trials (Reddy *et al*., 2021) [46]. Marker-assisted selection and gene pyramiding of multiple resistance loci, such as *Bph14* and *Bph15*, have been used to develop lines with broad-spectrum and durable resistance (ICAR-IIRR, 2025) [21]. These resistant varieties help maintain ecological balance, reduce insecticide use, and stabilize yields. Adoption of host-plant resistance, combined with cultural and biotechnological measures, is therefore a critical strategy for sustainable rice pest management in India, supporting both productivity and food security (Brar *et al*., 2023; ICAR-NRRI, 2024) [4, 19].

Enhancing resistance to insect pests through cultivation management

Optimizing fertilizer management is key to reducing pest pressure in rice. Excessive nitrogen fertilization increases plant susceptibility by improving pest survival, development, and reproduction, especially for planthoppers and stem borers. In India, site-specific nitrogen management and balanced N-P-K fertilization enhance plant vigor, reduce pest incidence, and maintain or increase yield (Sharma & Yadav, 2023; ICAR-NRRI, 2024) [50, 65, 19]. Silicon application further improves tolerance to pests and structural defenses against planthoppers and stem borers (Prasad *et al*., 2022; Reddy *et al*., 2025) [40, 45]. Environmental management through ecological engineering, such as planting nectar-rich border crops or flowering strips, supports natural enemies and reduces pest populations (FAO, 2024) [11]. Studies in Indian rice fields have shown that such habitat diversification increases predator and parasitoid density, decreases pest damage, and lowers insecticide use (Rai *et al*., 2023; ICAR-IIRR, 2025) [41, 21]. Integrating optimized fertilization with ecological approaches enhances both plant resistance and ecosystem resilience, contributing to sustainable and productive rice cultivation in India.

Increasing environmental resistance through agro-ecosystem management

Enhancing the resistance of rice cropping systems at the field and landscape scale can significantly reduce pest population sizes and outbreak frequency. Ecological engineering approaches—such as flowering hedgerows, nectar-rich border plants, and push-pull systems—support natural enemies of pests and improve biological control services in Indian rice ecosystems (FAO, 2024) [12]. For instance, studies in eastern and southern India have documented higher densities of predator and parasitoid populations in rice fields surrounded by strips of flowering legumes, resulting in reduced planthopper and stem borer damage and lower insecticide use (Rai *et al*., 2023; ICAR-IIRR, 2025) [41, 21]. Such habitat diversification enhances environmental resistance and contributes to resilient, ecologically based pest management strategies.

Genetic Control

Genetic control uses resistant rice varieties to suppress pest populations and reduce pesticide use. In India, host-plant resistance against brown planthopper (BPH), white-backed planthopper (WBPH), stem borers, and leaf folders has been developed through conventional breeding, molecular marker-assisted selection, and transgenic approaches (ICAR-NRRI, 2024) [19]. BPH-resistant genes like *Bph1, Bph3, Bph14, and Bph17* in high-yielding varieties significantly reduce pest damage (Rai *et al*., 2023) [41]. Bt transgenic rice has been evaluated for controlling Lepidopteran pests with high efficacy and safety for non-target organisms. Genetic resistance, combined with cultural and biological methods, forms a key component of Integrated Pest Management (IPM) in Indian rice systems.

Application of biological control agents: biological insecticides

Environmentally safe biological insecticides are increasingly used in Indian rice production due to rising concerns about food safety, environmental protection, and pesticide resistance. Bacillus thuringiensis (Bt) formulations are widely applied against key lepidopteran pests, including stem borers and rice leaf folder (RLF), demonstrating high efficacy and minimal impact on non-target organisms (Reddy *et al*., 2021) [45]. Entomopathogenic fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae***,** have shown significant activity against rice stem borers and planthoppers under Indian field conditions, offering effective pest suppression while conserving beneficial insects (Singh & Patel, 2022; Reddy *et al*., 2025) [59, 46]. Similarly, spinosad and spinetoram are recommended in India for controlling lepidopteran and sucking pests due to their high efficiency and selectivity (ICAR-NRRI, 2024; Sharma *et al*., 2023) [19,]. Viral bioinsecticides, particularly *Cnaphalocrocis medinalis* granulovirus (CnmeGV), are emerging tools for rice leaf folder management. When combined with Bt, these viral formulations show synergistic effects, faster pest mortality, and prolonged control periods (ICAR-IIRR, 2025) [21]. Additionally, entomopathogenic nematodes (*Steinernema* and *Heterorhabditis* spp.) and other microbial bioagents are being evaluated as part of integrated pest management (IPM) strategies in rice (Tiwari *et al*., 2025) [61]. The adoption of these biological insecticides in IPM programs allows Indian rice farmers to reduce reliance on synthetic chemicals, maintain high yields, and protect environmental and human health.

Release of *trichogramma* parasitoids for rice pest management

The use of *Trichogramma* egg parasitoids has gained renewed interest in India as an effective and eco-friendly approach for suppressing key lepidopteran pests in rice, such as stem borers and rice leaf folder (Singh & Rai, 2023) [58, 41]. Although early studies highlighted challenges with species selection, mass rearing, and field application techniques, recent research and on-farm trials in India have demonstrated that strategic releases of *Trichogramma* can significantly reduce pest pressure and lower reliance on chemical insecticides (ICAR-IIRR, 2025) [21]. In Indian rice ecosystems, *T. chilonis* and *T. japonicum* are the most commonly evaluated species due to their adaptability to local climatic conditions and efficacy against eggs of major rice pests (Rai *et al*., 2022) [42]. Field evaluations indicate that *T. chilonis* performs well under moderate temperatures typical of the coastal and eastern rice belts, whereas *T. japonicum* maintains higher parasitism rates under warmer, inland conditions.

Advances in release methods have improved *Trichogramma* use in rice. These include optimized ground release techniques, timed releases synchronized with peak egg laying, and drones (unmanned aerial vehicles) for uniform distribution across larger fields (Tiwari *et al*., 2025; ICAR-NRRI, 2024) [61, 19]. Supplementation with nectar plants or food sprays at release sites has also been shown to enhance parasitoid survival and efficacy. Demonstration trials conducted under the Indian Council of Agricultural Research (ICAR) network have refined release parameters such as species selection, timing, frequency, density, and deployment height to improve parasitism and pest suppression outcomes (ICAR-IIRR, 2025) [21]. With continued refinement and farmer adoption, *Trichogramma* release is emerging as a scalable and sustainable strategy for rice pest management in India.

Sex pheromone interference and trap planting for rice pest management

Sex pheromone-based mating disruption and trapping have become promising components of integrated pest management (IPM) for rice pests in India, particularly against stem borers and rice leaf folder (RLF). Synthetic sex pheromones for key pests such as rice yellow stem borer and leaf folder are now available and can be deployed effectively in field trapping systems (ICAR-NRRI, 2024) [19]. For optimum efficiency, each trap should contain a single species' pheromone lure, as combining multiple pheromones can reduce attraction. Traps positioned just below the rice canopy (approximately 10-20 cm) have shown higher capture rates of target males under Indian conditions (Kumar *et al*., 2024) [30]. Field demonstrations in rice belts of eastern and southern India have reported that pheromone traps can reduce pest pressure by over 50%, particularly when used in combination with other IPM tactics such as habitat manipulation and biological control (Tiwari *et al*., 2025; ICAR-IIRR, 2025) [61, 21]. Deployment of pheromone traps has also enabled rice producers to reduce insecticide sprays by 1-2 applications without compromising yield or crop health (Singh & Rai, 2023; FAO, 2024) [58, 41, 12].

Mass trapping of overwintering and early immigrant males further suppresses the first-generation pest populations. In large-scale trials, setting high densities of pheromone traps per hectare led to substantial reductions in egg laying and larval damage in both seedling beds and transplanted rice fields (Sharma *et al*., 2023) [50]. Results indicate that the wider the area of pheromone trap deployment, the greater the suppression of stem borer populations and associated crop damage. An additional strategy is the use of trap plants to divert oviposition away from rice. In India, vetiver grass (*Chrysopogon zizanioides*) planted along rice field margins has shown potential as a "pull" crop, attracting stem borer adults to lay eggs on an unsuitable host, thereby reducing pest pressure in the main crop (Prasad *et al*., 2022) [40]. Eggs and early larvae on vetiver can then be destroyed through targeted interventions, further lowering stem borer populations.

Legal control

Legal control in rice pest management in India involves implementing national and state regulations to ensure safe and sustainable pest control practices. The Insecticides Act, 1968 and its amendments govern the manufacture, sale, distribution, and application of chemical insecticides**,** with registered labels and usage guidelines designed to prevent misuse, reduce environmental contamination, and safeguard consumer health (Singh & Rao, 2023; Sharma & Singh, 2022) [44, 51, 59]. Legal frameworks also support the adoption of Integrated Pest Management (IPM) by promoting environment-friendly approaches, including bio-pesticides, microbial agents, and biocontrol technologies, and by restricting or phasing out highly hazardous pesticides (ICAR-NRRI, 2024; Das *et al*., 2020) [19, 8].

At the state level, crop protection and pesticide regulation acts reinforce surveillance systems, seed certification standards, and region-specific advisories to prevent pest invasions and spread of migratory pests such as brown planthopper and rice stem borers (TNAU Agritech, 2024; Reddy & Singh, 2021) [55, 45]. Quarantine rules under the Plant Quarantine (Regulation of Import into India) Order further help block entry of exotic pest species that could threaten rice production (Government of India, 2017; Khan *et al*., 2023) [13, 29]. Compliance with these legal frameworks not only helps maintain ecosystem health and food safety but also promotes adoption of certified seed systems, safer pesticide uses patterns, and sustainable pest management practices across rice landscapes in India (ICAR-IIRR, 2025) [21].

Prospects and challenges in rice pest management

With growing concerns over excessive pesticide use, frequent pest outbreaks, environmental pollution, and pesticide residues in rice grains, integrated approaches are being promoted in India to reduce reliance on chemical insecticides. Non-chemical strategies that emphasize the protection and utilization of indigenous natural enemies, habitat management, and biological trapping of pests are increasingly applied under the principle of maximizing natural pest control. Field trials in India and other countries have shown that simple ecological engineering measures, such as planting nectar-rich flowering plants along field bunds or using trap crops, can enhance biodiversity, improve pest suppression, reduce pesticide usage, and promote sustainable rice production. Multi-year evaluations indicate that ecological engineering can reduce pesticide applications by up to 60-70% without significant yield loss while improving farm profitability. Despite these successes, non-chemical methods alone may not fully control migratory or rapidly reproducing pests, such as stem borers and planthoppers. Therefore, judicious and precise chemical control remains essential under high pest pressure. Integration with automated pest monitoring systems, resistance management, and nutrient regulation can optimize pesticide use, enhance natural enemy effectiveness, and maintain ecosystem functions while ensuring rice quality and food safety. Adoption of such strategies requires consideration of local agro-climatic conditions, pest ecology, and rational selection of pesticide types and doses to achieve the primary goal of reducing chemical inputs while maintaining stable yields and ecological sustainability.

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