



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(1): 389-401
Received: 25-11-2025
Accepted: 27-12-2025

Lalita
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Meenu
Krishi Vigyan Kendra, (CSSHU),
Bhiwani, Haryana, India

Sumit Saini
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Parvesh Kumar
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Vishal Gandhi
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Mahaveer Singh
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Ashish Jain
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Rakesh Kumar
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Charan Singh
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Amit Kumar
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Sukham Madaan
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

OP Chaudhary
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Corresponding Author:
Lalita
Rice Research Station, Chaudhary Charan
Singh Haryana Agricultural University,
Kaul (Kaithal), Haryana, India

Integrated and sustainable strategies for the management of rice leaf folder, *Cnaphalocrocis medinalis* (Guenee): Recent developments, challenges and prospects

**Lalita, Meenu, Sumit Saini, Parvesh Kumar, Vishal Gandhi, Mahaveer
Singh, Ashish Jain, Rakesh Kumar, Charan Singh, Amit Kumar, Sukham
Madaan and OP Chaudhary**

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i1Se.4777>

Abstract

Rice leaf folder (RLF), *Cnaphalocrocis medinalis* (Guenee) (Lepidoptera: Crambidae), is a major migratory pest of rice that cause severe chlorophyll loss, reduced photosynthesis and significant yield decline through leaf folding, scraping and defoliation, particularly when populations surpass economic thresholds. To mitigate leaf folder, wide array of insecticides is available at commercial level however overreliance on chemical insecticides has resulted in resistance development, pest resurgence and destruction of natural enemy communities, creating ecological imbalance. Effective and long-term control of *C. medinalis* demands an integrated framework combining ecological regulation, cultural and behavioral interventions, biological control and judicious, need-based pesticide use. Strategies such as habitat manipulation, ecological engineering and biodiversity enhancement strengthen natural pest regulation, while improved agronomic practices, including balanced nutrient application, proper water management and deployment of tolerant varieties, which reduce crop susceptibility. Additionally, behavioral tools like pheromone traps enhance monitoring, facilitate early detection and support mating disruption, whereas biological agents, including *Trichogramma* spp., entomopathogenic fungi like *Beauveria bassiana*, *Pseudomonas fluorescens* and a diverse range of predators, provide environmentally safe and effective suppression of the pest.

Keywords: *Cnaphalocrocis medinalis*, sustainable management, ecological regulation, biological control, rice protection

Introduction

Rice (*Oryza sativa* L.) is among the most vital food crops worldwide, serving as the primary staple food for nearly half of the global population, particularly in Asia and contributing significantly to global food and nutritional security. Global rice production in 2024-25, reached a record 540.93 million metric tonnes, largely due to increased cultivation area and improved yields, with India and China contributing 28% and 27% of the total production, respectively (USDA 2025)^[77]. India ranked first with a production of 150 million tonnes and a productivity of 4.35 tonnes per hectare (USDA 2025)^[77]. In Haryana, rice was cultivated on 1.84 million hectares, producing 7.14 million tonnes with a productivity of 3.88 t/ha in 2024-25 (DAFWH 2025). Despite its immense importance, rice production consistently faces threats from numerous insect pests and diseases throughout the crop cycle; although over 120 insect species are known to infest rice, only 15-20 are considered economically significant. Among these, the rice leaf folder (RLF), *Cnaphalocrocis medinalis* (Guenee), has become a major limiting factor in rice productivity. RLF was first reported in 1981 named as *Marasmia patnalis*, later it described as *C. medinalis* and now it is widely distributed across major rice-growing regions (figure. 1) including Asia, Oceania, Australia, American Samoa, Cook Islands, Fiji, New Caledonia, Papua New Guinea, and parts of Africa. Severe outbreaks have also been reported from China, India, Pakistan, Japan, Korea, Malaysia, Sri Lanka, Thailand, the Philippines, and Vietnam.



Fig 1: Map representing the geographical distribution of *Cnaphalocrocis medinalis* (Guenée) worldwide

Economic importance

Until late 1980s, this pest was considered as minor threat, but it has since escalated to major pest status across many rice-growing countries. Its larvae cause damage by folding and feeding on rice leaves, leading to substantial chlorophyll loss (Yang *et al.* 2015)^[83] and creating distinct longitudinal, white, transparent streaks that eventually lead to leaf drying. A single larva can injure multiple leaves, reduce photosynthesis and weaken plant growth, ultimately resulting in economic yield losses. In India, severe infestation has been reported to cause yield reductions of 63-80% (Shaki *et al.* 2020)^[66], in high yielding varieties and hybrid cultivars and 30-80% reductions during epidemic conditions (Gangwar 2015)^[22]. From several years, the management strategies of *C. medinalis* have relied heavily on chemical insecticides, but excessive and indiscriminate pesticide use has led to environmental contamination, pest resurgence, secondary pest outbreaks, insecticides resistance, residues in food and soil and adverse effects on non-target organisms, along with risks to human health. These challenges underscore the urgent need for ecologically sustainable alternatives, particularly the strategic use of biological control agents through systematic and sustained releases for long-term pest suppression. In alignment with growing emphasis on green agriculture, the Government of India has been actively promoting eco- friendly management approaches for the RLF, guided by the national plant protection principle of “prevention first and integrated management”.

A wide range of strategies including integrated pest management (IPM), biopesticides, host plant resistance and cultural practices are now being promoted to manage this pest more sustainably. The national initiative on “reducing chemical pesticide use” further strengthens the shift toward non-chemical and environmentally sound pest management in rice cultivation. In recent years, both research and field implementation of such eco-friendly practices have increase substantially in India. To manage *C. medinalis* with three complementary levels: (i) fundamental ecological measures, which focus on ecological regulation, improved agronomic practices and healthy crop cultivation to enhance ecosystem resilience and plant tolerance or resistance; (ii) conventional green control techniques,

including behavioral manipulation such as pheromone-based tools and biological control measures targeting adult or larval suppression; and (iii) advanced green control approaches, involving the judicious use of biopesticides, reduced and need-based insecticide applications and integrated IPM components to prevent economic damage while maintaining ecological balance. Together, these strategies allow farmers to effectively manage RLF populations, keep them below economic threshold levels, reduce dependence on harmful chemicals and support a stable, sustainable rice production system.

Biology and nature of damage

Adult is a yellowish-brown moth known for its damaging effects on rice crops (Fig. 2). Each female lays around 300 discs-shaped, ovoid eggs singly or in pairs on the underside of tender leaf blades, mostly during night (Gangwar 2015)^[22]. The eggs hatch within 4-7 days. The newly emerged larvae are pale yellow and gradually turn yellowish green with brown heads as they mature, attaining lengths of 12-25 mm. Larvae create protective folds by rolling rice leaves and fastening the margins with silk threads. Within these folded leaves, larvae scrape the green mesophyll tissue, significantly reducing the photosynthetic area (Adhikari *et al.* 2022)^[1]. This feeding behavior results in narrow, horizontal white streaks on the leaves, which may later develop into transparent membranous patches. Under severe infestation, leaves become yellow, curled or stunted, and heavily affected fields often appear scorched. Generally, each larva folds and feeds on 2-4 leaves (Gangwar 2015)^[22]. After feeding for about 15-20 days, the larva pupates inside the folded leaf. The pupa, greenish-brown and 9-12 mm long, remains in this stage for 6-8 days before emerging as an adult moth. The complete life cycle lasts approximately 25-35 days (Gangwar 2015)^[22]. Infestation triggers various physiological and biochemical changes in rice plants. These include declines in chlorophyll and carbohydrate levels, along with the activation of defense mechanisms such as the jasmonic acid signaling pathway and silicon application (Adhikari *et al.* 2022)^[1]. Silicon application has been reported to lower larval survival and extend developmental duration, thereby reducing overall pest damage.



Fig 2: Life cycle of rice leaf folder (*Cnaphalocrocis medinalis* Guenee). a) Eggs; b) Larvae; c) Pupa; d) Adult

Principles and applications of ecological regulation in rice ecosystem

Ecological regulation represents a holistic, system-based paradigm for sustainable pest management, emphasizing the maintenance of pest populations below the economic threshold by leveraging natural ecological processes alongside targeted interventions (Fig. 3). The approach integrates at wide array of regulatory tools, including modern biotechnological innovations, cultural and agronomic practices, genetic and behavioral manipulation, biological control, physical and chemical attractants and judicious insecticides use under principle of “prevention first, ecology as the priority, integrated management and precise implementation” (Ge 2020) [26]. At its core, ecological regulation promotes self-regulation of

agroecosystems through environmental enhancement and improved ecological functioning (Liu *et al.* 2024) [49]. Ecological engineering mimics the ecological principles and natural production processes. In agricultural systems, ecological engineering manifests through landscapes redesign, habitat manipulation and diversification strategies that create pest-suppressive environments while promoting the abundance, activity and stability of beneficial organisms. By enhancing multitrophic interactions, strengthening natural enemy guilds and fostering ecosystems services such as predation, parasitism and pollination, ecological regulation and ecological together form a cornerstone of modern sustainable pest management (Selvam *et al.* 2020) [64].

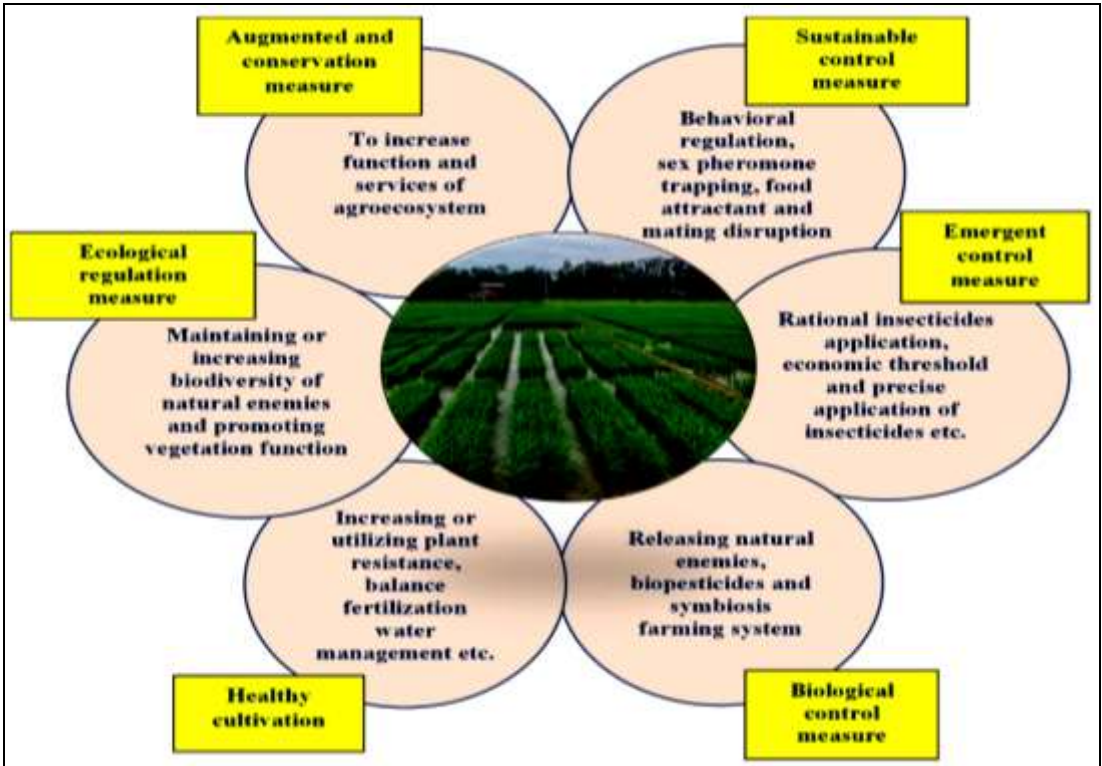


Fig 3: Schematic diagram of sustainable management strategies for *Cnaphalocrocis medinalis*

In rice ecosystems, ecological engineering forms a key component of green pest management technologies. It focuses on landscape-level planning and ecosystem design to balance biodiversity needs and enhance ecosystem services related to natural pest suppression (Zhu *et al.* 2022) ^[97]. Ecological engineering for rice insect pest management encompasses a comprehensive set of strategies that operate at both foundational and supportive levels to strengthen natural pest suppression within agroecosystems. The core ecological engineering techniques include intercropping, establishing nectar-rich flowering strips, manipulating habitats to enhance natural enemy activity and cultivating resistant rice varieties, all of which directly modify the cropping environment to create pest-suppressive conditions. Several supporting techniques such as augmentative release of natural enemies, targeted application of biopesticides, optimized fertilizer, water management, use of monitoring and forecasting tools; although not purely ecological, these practices significantly reinforce the impact and stability of core interventions (Zhu *et al.* 2022; Horgan *et al.* 2022) ^[97, 35]. Together, these components form an integrated ecological framework that enhances biodiversity, promotes ecosystem services and reduces reliance on chemical pesticides. Demonstrating the practical value of this approach, several successful models have emerged, notably the pioneering banker plant systems developed in China by Lv *et al.* (2015) ^[52], where alternate grasses are cultivated to sustain parasitoids such as *Anagrus* spp., enabling continuous biological control and effective suppression of planthopper populations.

In India, planting flowering crops such as marigold and sesame on paddy bunds increases natural enemy abundance and sustainably reduces brown planthopper infestations (Chandrasekar *et al.* 2017) ^[10]. Similarly, establishing flowering strips of pigeon pea and cowpea along rice field borders enhances populations of predators such as *Micraspis crocea* (Chowdhury *et al.* 2023) ^[14], *Ophionea indica* and spiders including *Lycosa pseudoannulata*, *Oxyopes germanicus*, *O. salticus*, *Tetragnatha maxillosa* and *T. mandibulata* (Yaligar *et al.* 2021; Prabhu 2015) ^[82, 58]. These interventions also support natural enemies such as coccinellids, ground beetles and parasitoids (*Anagrus* spp., *Bracon* spp.) (Chandrashekar *et al.* 2017; Sreelatha and Rajan 2018) ^[10, 71], subsequently lowered RLF infestation and improved yields. Habitat manipulation within ecological regulation enhances resources for natural enemies by providing pollen nectar alternative prey, physical refugia alternative hosts and lekking sites. As a result, agroecosystem resilience increases, fostering higher natural enemy abundance and suppress RLF. Ecological engineering approaches have been widely promoted by the Ministry of Agriculture and Farmers' Welfare (MoAFW, India) and are now globally recognized as essential tools for sustainable rice pest management. By facilitating self-regulation and enhancing ecosystem services, ecological regulation remains a cornerstone strategy for maintaining low pest densities and promoting ecologically balanced rice production systems.

Natural enemies' conservation and biodiversity management in rice field

Natural enemies, including predators, parasitoids and spiders constitute a vital component of rice field ecosystems. Their diversity not only reflects the ecological stability of the production system but also indicates their capacity to suppress pest populations. In rice ecosystems, natural enemies play a significant role in regulating *C. medinalis* populations. Parasitoids associated with the RLF are widely distributed across different rice production environments, with occurrence rates of 9-13% in dryland systems, 5-61% in rainfed wetlands and 7-33% in irrigated wetlands. Enhancing biodiversity in paddy fields provides substantial benefits for the natural suppression of RLF populations. A diverse assemblage of parasitoids contributes to biological control of *C. medinalis* across various developmental stages. Egg parasitoids such as *Trichogramma* spp. (including *T. chilonis* and *T. japonicum*) effectively parasitize RLF eggs, thereby reduced successful larval emergence. Several larval parasitoids, *Cardiochiles philippinensis* Ashm., *Apanteles* sp., *Itopectis* sp., *Goniozus* sp., *Copidosomopsis nacoieiae*, *Trichomma cnaphalocrocis*, *Macrocentrus philippinensis*, *Cotesia angustibasis* and *Goniozus* spp. play key roles in suppressing larval populations. Additionally, the pupal parasitoid *Xanthopimpla flavolineata* Cameron and the larval-pupal parasitoid *Brachymeria* sp. also contribute to natural regulation of the RLF (Rautaray 2019) ^[63]. The presence and conservation of such diverse natural enemy communities are integral to maintaining ecological balance in rice fields and can significantly enhance sustainable suppression of *C. medinalis*.

Role of semi-natural habitats in enhancing biological control agents

The rational utilization of non-paddy field habitats such as field ridges, irrigation ditches, bunds and mechanized road margins plays a crucial role in conserving natural enemy communities and strengthening ecological resilience within rice agroecosystems. These semi-natural habitats function as key refugia and alternative resource that support the persistence, reproduction and seasonal stability of beneficial arthropods (as summarized in Table 1). Predator movement indicate strong ecological connectivity between these habitats and paddy fields, with 1.1-2.7 folds more predators migrating from non-paddy areas into paddy fields than in the reverse direction underscoring their importance as continuous sources of natural enemies. Additionally, arthropod communities overwintering in ridge and field-weed habitats maintain relatively stable populations with higher species diversity and evenness, demonstrating the value of these habitats in sustaining functional biodiversity. By conserving, diversifying, and appropriately managing these non-paddy habitats, farmers can reinforce the ecological infrastructure essential for maintaining robust natural enemy populations, thereby enhancing biological control services and promoting more sustainable rice pest management.

Table 1: Contribution of non-paddy crop with rice for the management of leaf folder in rice fields

Sr. No.	Main crop	Another crop	Methods	Effects	Reference
1	Paddy	Soybean and sesame	Planting on ridges	Increased natural enemy abundance and reduces pest incidence	Zhou <i>et al.</i> (2011) [95]
2	Paddy	Sesame	Along rice fields	Increased abundance of natural enemy	Zhu <i>et al.</i> (2015) [96]
3	Paddy	Nectar plants	Along rice fields	Reduce the rice leaf folder population and increasing the function of the natural enemies.	Raju and Srinivas (2016) [61]
4	Paddy	Weed environments	Around the paddy fields	Increased spider population	Hegazy <i>et al.</i> (2021) [32]
5	Paddy	Soybean and maize	Ridge	Increased egg and larval parasitism rates increasing by 2.1% and 5.7%, respectively	Ge <i>et al.</i> (2013) [27]
6	Paddy	Annual wild rice (<i>Zizania aquatica</i>)	Adjacent to rice fields	shelter for spiders such as <i>Pirata subpiraticus</i> increase the number of spiders by approximately 30%, and density in <i>Z. aquatica</i> fields is 4-40 times	Zheng <i>et al.</i> (2002) [91]
7	Paddy	Marigold, sunflower, sesame, cowpea, Mustard, Ekdandi, Sunflower, Cosmos, Cock's comb, and Zinnia	Bund cropping	Increased natural enemy abundance and reduces pest incidence	ICAR-NCIPM (2020) [38]
8	Paddy	Flowering plants	Bund cropping	Reduced the incidence of leaf folder enhance the abundance and diversity of natural enemies	Rajendran (2013) [60]

Strengthening biological control through winter planting and habitat management in rice

Planting functional plants in winter fallow rice fields is an effective ecological strategy to conserve natural enemies by mitigating the drastic habitat and resource loss after rice harvesting. By introducing flowering or structurally diverse plants during the off-season, farmers can provide essential food sources, shelter and alternative prey or hosts that sustain predators and parasitoids until the next cropping cycle. In the Indian rice ecosystem, winter cultivation of mustard (*Brassica* spp.), marigold (*Tagetes* spp.) and sunflower (*Helianthus annuus*) has been shown to significantly enhance the survival and reproductive success of beneficial insects (Raju and Srinivas 2016) [61]. Natural enemies, including spiders, dragonflies and numerous insect parasitoids serve as major regulators of pest populations in rice and adjacent cropping systems such as cotton (Chaitanya *et al.* 2024) [9]. Landscape configuration also influences these interactions; for example, spider diversity tends to increase in fallow and varied landscapes but decreases in regions dominated by construction (Zhong 2022) [92]. Similarly, fields planted with Italian ryegrass (*Lolium multiflorum*) or naturally occurring winter weeds support higher densities of beneficial insects, especially parasitic wasps, compared with bare fallow land, thereby improving biological control in the subsequent rice season. Additional winter cover crops, such as Chinese milkvetch (*Astragalus sinicus*) and oilseed rape (*Brassica campestris*), also enhance natural enemy abundance without contributing to pest buildup (Luo 2016).

Winter legumes, such as lentil, chickpea, lathyrus and mustard play a pivotal role in rice-fallow rotations by enhancing system productivity, improving soil moisture use efficiency and fostering ecosystem services that indirectly sustain natural enemy biodiversity (Kumar *et al.* 2019) [44]. Winter vegetable cultivation similarly enriches biodiversity and ecological stability within rice landscapes. During the rice-growing season, in-season interventions further contribute to natural pest suppression. For example, intercropping rice with water spinach (*Ipomoea aquatica*) has been shown to substantially reduce RLF incidence (5.1-58.2%) while simultaneously enhancing crop nutrition and yield. Additionally, relay cropping rice with lathyrus combined with maintaining taller rice stubble (30 cm), improve soil moisture conservation, increase lathyrus productivity and create favorable microhabitats that support

beneficial arthropods under conservation agriculture practices (Chauhan *et al.* 2016) [11]. Together, these winter and in-season ecological interventions reinforce the habitat continuity and resource availability necessary to maintain robust natural enemy communities during the off-season, thereby strengthening the ecological foundation for sustainable, biologically driven rice pest management.

Deploying resistant rice varieties for environmentally sustainable control of rice leaf folder

The deployment of pest-resistant rice varieties remains one of the most effective and environmentally sustainable approaches for managing *C. medinalis*. Resistance is governed by a combination of morphological and biochemical traits that influence the host plant's suitability for RLF feeding and development. Morphologically, taller plants and longer leaves are associated with reduced RLF damage, whereas wider leaves tend to favor infestation. Leaf color and texture play additional roles, with dark green, soft and broad leaves are more susceptible, while lighter-colored, tougher leaves with higher silica content hinder larval feeding and reduce suitability. Biochemical factors are equally important in determining resistance. Higher concentrations of sugars and proteins generally promote susceptibility, whereas increased levels of phenolic compounds and antioxidative enzymes enhance plant defense. Resistant genotypes respond to RLF infestation by accumulating phenolics and activating antioxidative defense pathways, which act as deterrents and protective agents (Nayak *et al.* 2023) [55]. Cultivars with elevated free amino acids tend to experience greater damage, whereas those with higher soluble protein contents show reduced infestation. Overall, the integration of morphological and biochemical traits provides a robust basis for identifying, breeding, and deploying rice genotypes with enhanced resistance to the RLF, contributing to long-term sustainable pest management.

Impact of early sowing and transplanting on rice leaf folder management

Early sowing or transplanting is widely recognized as one of the most effective cultural practices for minimizing RLF incidence, while ensuring higher grain yields. Several studies have consistently reported significantly lower pest infestation and enhanced productivity in early-transplanted rice systems (Yadav

2018; Kumari and Prasad 2021) [98, 99]. By advancing crop establishment, rice plants are able to escape the peak period of RLF activity, thereby minimizing larval feeding pressure during vulnerable growth stages. This temporal avoidance not only decreases the severity of pest damage but also enhances plant vigour, tillering and ultimately yield performance, making early transplanting a cornerstone cultural practice in integrated RLF management.

Role of water-regime manipulation for managing RLF in rice ecosystem

Water management plays a pivotal role in regulating the microclimatic conditions that influence the growth, development, and population dynamics of RLF. Low humidity reduces egg weight, cause shriveling, delay embryonic development, and increase egg mortality, thereby suppressing population buildup, whereas high relative humidity shortens incubation time and enhances hatchability, creating conditions favorable for rapid pest proliferation. Elevated microclimatic humidity is associated with higher RLF incidence in field. Consequently, strategic water-regime manipulation offers an effective cultural tool for RLF management. Recommended practices include drying fields during the egg incubation period to lower humidity and inhibit development and maintaining deep water for 2-3 days during pupation to reduce pupal survival. Interestingly, in some agroecosystems, increased rainfall and prolonged moisture can also suppress RLF populations by interfering with adult behavior, larval establishment and overall survival (Supawan and Chongrattanamateeku 2017). Collectively, these insights highlight the importance of microclimate-oriented water management as an integral component of ecological and cultural pest management strategies for RLF.

Optimizing fertilization strategies to enhance rice resilience against RLF

Balanced fertilization is fundamental not only for sustaining rice productivity but also for minimizing vulnerability to RLF infestations. While excessive nitrogen (N) promotes vigorous vegetative growth, it can inadvertently make rice plants more attractive and susceptible to RLF damage. Although India-specific evidence directly linking high N to RLF outbreaks is limited, extensive nutrient management underscores the importance of balanced nutrient supply for enhancing plant robustness and reducing pest incidence. Applying nitrogen judiciously, alongside adequate phosphorus (P), potassium (K) and essential micronutrients, improves plant vigor, strengthens physiological resilience and optimizes nutrient-use efficiency. Technologies such as slow-release fertilizers, split N applications and urease or nitrification inhibitor-based formulations further help mitigate the risks associated with excessive nitrogen use. Previously, Indian fertilizer recommendations followed the generalized 4:2:1 (N: P: K) ratio, however, recent evidence indicates widespread application of P and K, reinforcing the need for soil and location specific nutrient strategies rather than uniform prescriptions (NITI Aayog 2021). In eastern India, soil-test-based fertilizer recommendations (STFR) and integrated nutrient management (INM), which combine chemical fertilizers with organic amendments have significantly enhanced nutrient uptake and yield performance compared with blanket recommendations. Similarly, in Assam's wet direct-seeded rice (Wet-DSR) systems, fertilizer deep placement (FDP) of 80-120% of recommended N, applied with

full P and K at 7-10 cm depth, increased nitrogen-use efficiency, raised yields and reduced N₂O emissions relative to surface broadcasting. In Kerala's rice-rice-fallow cropping sequence, integrating NPK with zinc sulphate (ZnSO₄) achieved the highest rice equivalent yield, superior economic returns and the most favorable sustainability index among tested nutrient regimes (Bindhu *et al.* 2023) [5].

Harnessing plant compensation and preserving natural enemies through reduced early insecticide use

Avoiding insecticide applications during the early growth stages of rice is a key ecological strategy that capitalizes on the plant's inherent ability to tolerate and compensate for herbivory by the RLF. Rice possesses modular growth and strong compensatory mechanisms that allow it to recover from substantial leaf injury. Indian studies indicate that up to 50% leaf damage during the tillering stage can be sustained without significant yield loss, as yield reduction is influenced more by crop stage, plant vigor and prevailing environmental conditions than by the absolute level of leaf injury (Padmavathi *et al.* 2013) [57]. A major benefit of refraining from early-season chemical sprays is the preservation of natural enemy communities. Predators such as *Lycosa pseudoannulata* (spiders) and *Cyrtorhinus lividipennis* (mirid bug), along with egg parasitoids like *T. japonicum*, contribute to control RLF and planthopper populations. In Punjab, early use of insecticide helps maintain robust predator and parasitoid assemblages, thereby enhancing natural biological regulation of major rice pests (Kaur and Brar 2018) [41]. Alternatives strategies such as botanical extracts from neem (*Azadirachta indica*), lantana (*Lantana camara*), bael (*Aegle marmelos*), garlic (*Allium sativum*) and lemon (*Citrus limon*) successfully managed RLF and yellow stem borer infestations in Odisha during 2022-2023. Neem-based extracts achieving higher yields comparable to acephate (4.68 t/ha vs. 4.66 t/ha), while supporting higher populations of beneficial arthropods (Sethy *et al.* 2024) [65]. These insights underscore that minimizing insecticides at early crop stages not only harnesses rice's natural compensatory capabilities but also conserves predator-parasitoid complexes, fosters ecological resilience and promotes safer botanical-based pest management options.

Behavioural manipulation through sex pheromone traps

Sex pheromones, species-specific chemical signals released by females to attract males have become essential tools for behaviour based RLF management in rice systems. While the chemical structure of *C. medinalis* pheromones has been well elucidated in China and other Asian countries. In India, the primary focus to optimize their field deployment within IPM frameworks rather than on chemical characterization. Experience from closely related rice pests, particularly the yellow stem borer, demonstrates that pheromone-based monitoring, mating disruption, and population suppression can be effectively integrated into Indian rice IPM programs. In India, trap performance depends greatly on factors such as trap design, lure longevity and trap placement, with positioning at or slightly above the crop canopy consistently improving male capture rates (ICAR 2023). Although large-scale mass-trapping trials against *C. medinalis* in India are still limited. The pheromone mass trapping can reduce larval populations by up to 51% and safeguard nearly 80% of foliage. Despite the inherent limitation that pheromone traps mainly attract males, sustained male removal disrupts mating success, reduces egg deposition, lowers

larval pressure and diminishes reliance on chemical insecticides. Moreover, reduced insecticide use enhances natural enemy survival, making pheromone-based approaches an ecologically compatible and integral component of sustainable rice IPM.

Food based attractant systems as emerging behavioural strategies in rice IPM

Complementing pheromone systems, food-attractant traps based on plant volatiles, fermenting substrates or other odor cues are emerging as promising behavioral tools for suppressing *C. medinalis*. These traps are easy to deploy, highly sensitive and particularly valuable because they attract both sexes, especially reproductive females (Gao *et al.* 2023a)^[23]. Food attractants can capture females at over twice the rate of males, achieve unmated female ratios as high as 96.15%, and provide stronger larval suppression and leaf protection than pheromone traps (Zeng *et al.* 2021)^[87]. While India currently lacks targeted field evaluations of food attractants for *C. medinalis*, their proven use against other rice pests such as stem borers and planthoppers using molasses, jaggery or fermented fruit baits suggests strong potential for widespread applicability across diverse agroclimatic zones. The ability to target females makes food attractants especially powerful for population reduction and with systematic optimization they may outperform pheromones in certain scenarios. India is urgently needed to refine lure formulations, trap densities, placement strategies, seasonal windows and comparative performance against established monitoring methods like light traps and sweep nets. In the meantime, exploratory use of generalist attractant blends by researchers and progressive farmers can provide preliminary insights. With dedicated testing and standardization by ICAR institutes and State Agricultural Universities, food-attractant traps can become a robust complement to pheromone and light traps, integrating seamlessly with biological, cultural and mechanical tools to form a holistic, eco-friendly IPM package for sustainable rice protection in India.

Augmentative release of biological control agents for sustainable pest management

Augmentative biological control through mass releases of *Trichogramma* spp. is one of the most widely adopted strategies for lepidopteran pest suppression globally. The genus comprises over 200 species, with at least nine routinely mass-reared and released across more than 30 countries in crops such as rice, maize, cotton, sugarcane and horticultural systems. In South and Southeast Asia, extensive field evaluations confirm the effectiveness of *Trichogramma* in rice ecosystems, while in India, releases of *T. japonicum* for yellow stem borer and *T. chilonis* for RLF at ~100,000 parasitoids/ha reduced stem borer damage by 12-91% and LF incidence by up to 98.6%, while improving yields by 26-45%; cost-benefit ratios consistently favored biological control over chemical insecticides. Large-scale regional programs in the Greater Mekong Subregion demonstrated community-based mass rearing and release of *T. chilonis* and *T. japonicum*, resulting in 2-10% yield gains, conservation of natural enemies and reduced insecticide use by 1-2 sprays per season (Mochiah *et al.* 2020)^[53]. In China, *T. chilonis*, *T. dendrolimi* and *T. pretiosum* produce parasitism rates of 11-87.5%, with *T. dendrolimi* particularly effective against scale-covered or hair-covered egg masses (Zhou *et al.* 2022)^[94]. Species performance is temperature-dependent, in which *T. dendrolimi* performs optimally at 18-26 °C, whereas *T. japonicum* shows higher activity at 30-34°C (Wu *et al.* 2020)^[80]. Globally, *T. pretiosum* and *T. atopovirilia* provide strong

suppression of *Spodoptera frugiperda* in Latin America, achieving ~80% parasitism and ~700 kg/ha yield gains (Garcia *et al.* 2023)^[25]. Technological advances, including drone-assisted distribution, pheromone-guided release and improved mass-rearing protocols have enhanced release efficiency (Zhang *et al.* 2023)^[89]. Selective breeding has produced pesticide-tolerant strains, such as *T. japonicum* exhibiting 17.8-fold higher imidacloprid tolerance (Tang *et al.* 2022)^[75]. Despite these advances, natural parasitism in intensive rice systems often remains low, requiring repeated inundate releases (Khan *et al.* 2021)^[42]. Therefore, species/strain selection must be tailored to climatic and ecological conditions, especially where protected egg clusters favor specific species such as *T. dendrolimi*.

Sustainable management of pest using microbial and botanical biopesticides

Biopesticides derived from microorganisms, botanical extracts and other natural sources offer environmentally compatible alternatives to synthetic insecticides for managing RLF. Microbial agents, including *Bacillus thuringiensis* (Bt), entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* and viral pathogens like nucleopolyhedroviruses (NPV) are well validated for lepidopteran suppression (Kumar *et al.* 2019; Shylesha *et al.* 2021)^[44, 68]. Bt formulations typically achieve 90-100% reduction in RLF populations within 7-15 days of application (Guo *et al.* 2021). Viral agents such as *Mamestra brassicae* NPV (2×10^9 PIB/mL) display high infectivity and rapid larval suppression (Sun *et al.* 2016)^[74]. Combined Bt + *C. medinalis* granulovirus exhibit synergism, enhancing larval mortality and prolonging residual control (Arneodo *et al.* 2015)^[4]. Entomopathogenic fungi are well suited to humid rice environments, although excessive heat and UV degrade their (Wang *et al.* 2016)^[78]. Antibiotic-derived biopesticides such as abamectin and emamectin benzoate are effective but harmful to beneficial arthropods including *Cyrtorhinus lividipennis* and spiders, requiring cautious use within IPM (Chen *et al.* 2022)^[13]. Overall, microbial and botanical biopesticides offer potent, selective and eco-friendly control options, but their field success depends heavily on humidity, sunlight and temperature, necessitating carefully timed and integrated application.

Symbiotic farming systems for natural control of rice leaf folder

Symbiotic or integrated rice-animal farming systems, including rice-duck, rice-fish, rice-frog, and rice-turtle co-cultures represent ecologically functional production models that naturally suppress pests while improving soil fertility and system resilience. Rice-duck farming, widely practiced in China, is among the most successful traditional models. Ducks feed on pests (including RLF larvae), weeds, and golden apple snails, while their movement aerates soil and their manure enriches nutrient availability. These systems reduce planthopper populations by up to 98.5%, leafhoppers by up to 100%, improve soil health, enhance biodiversity and increase farmer income (Li *et al.* 2019; Hu *et al.* 2020)^[45, 36]. Rice-fish and rice-fish-duck systems recognized by FAO as GIAHS models provide complementary pest suppression, nutrient cycling and diversified production. They increase rice yields by 4-7%, reduce pest incidence by 46%, suppress weeds by ~80%, improve soil structure (7% reduction in bulk density) and lower greenhouse gas emissions (Cui *et al.* 2023; FAO 2018a; Chen *et al.* 2022)^[16, 19, 13]. In Bangladesh and China, such systems increase net income by up to 50% while reducing chemical

inputs and methane emissions (Ahmed and Garnett 2011) [3]. Emerging systems such as rice-turtle farming (*Chinemys reevesii*) align with the rice principles, reduce inputs, increase diversity, coexist with nature and support ecology, promoting biodiversity-friendly rice production (Feng *et al.* 2021; Zhou *et al.* 2019) [21, 93]. Rice-frog systems add further benefits through generalist predation on RLF larvae and other pests, contributing to ecological stability and enhanced soil microbial activity (Yi 2023) [85]. These integrated systems embody sustainable intensification, providing natural pest suppression, improved soil health, increased biodiversity and enhanced climate resilience.

Sustainable and strategic insecticide use for pest management programme

Rational insecticide uses for managing the RLF must follow IPM principles, as emphasized by FAO, which promote economic thresholds, ecological sustainability and reduced chemical dependence (FAO 2018b) [20]. Monitoring-based and threshold-guided decisions are strongly preferred over traditional calendar spraying, which historically caused natural enemy disruption and recurrent pest outbreaks. Proper timing is essential: insecticide applications are most effective during the booting stage, when severe leaf folding can sharply reduce photosynthesis and yield. Although infestations may appear as early as tillering, plants generally compensate for early leaf injury (Cai *et al.* 2018) [7]. Selective and safer insecticides, macrolides such as spinetoram, spinosad, abamectin, emamectin benzoate as well as microbial products like *B. thuringiensis* (Bt) are recommended. Broad-spectrum or banned pesticides should be avoided to reduce ecological risks (Gao *et al.* 2023a) [23]. However, insecticide resistance has become a growing concern. In China, RLF populations have developed low to moderate resistance to several selective insecticides, with alarmingly high (~113-fold) resistance to chlorantraniliprole linked to ryanodine receptor (RyR) mutations such as I4712M and Y4621D (Sun *et al.* 2023; Wang *et al.* 2024) [73, 79]. Similar patterns have been reported for *Chilo suppressalis*, where RyR mutations and increased cytochrome P450 activity contribute to resistance (Li *et al.* 2024) [47]. In India, high resistance levels to chlorantraniliprole (10-80%) and even greater resistance to chlorpyrifos and cartap have been documented (Rani *et al.* 2017). To delay resistance, rotation of insecticides with distinct modes of action, reduced dependence on chlorantraniliprole and avoidance of pyrethroids known to negatively affect natural enemies are essential (Wu *et al.* 2021; IRAC 2023) [81, 40]. Integrating chemicals with cultural measures such as resistant varieties, synchronized planting, and strict field sanitation further enhances sustainability (Horgan *et al.* 2018) [34]. All applications must comply with national guidelines to ensure environmental safety, minimal residues, and limited impact on beneficial organisms (CABI 2022) [6].

Economic thresholds driven application strategy for LF management

Economic threshold-based decision-making is central to sustainable RLF management. Rice plants can recover from moderate leaf injury during early growth, especially at the tillering stage, meaning that light infestations at this phase rarely justify chemical control (Yang *et al.* 2015) [83]. Therefore, thresholds are set higher at tillering and become stricter during booting and reproductive phases, when damage more directly affects yield. According to national guidelines, the control interventions should be applied when the population reaches 150 larvae or fresh leaf folds per 100 hills during tillering stage,

while at booting stage, control interventions is recommended at 60 larvae or fresh folds per 100 hills. Intervention is most effective shortly after egg hatch and during early larval stages, when larvae are still exposed and before severe folding occurs. Early vegetative injury seldom results in yield loss because plants compensate through new leaves and tillers (Cai *et al.* 2018; Sharma and Rao 2014) [7, 67]. Conversely, infestations at booting and heading stages reduce photosynthetic leaf area and can significantly reduce yield (FAO 2018) [19]. Threshold-driven spraying also helps conserve beneficial arthropods, reducing the risk of pest resurgence and secondary pest outbreaks.

Harmonised insecticide management for major rice pests

RLF management must be aligned with strategies for other major pests, particularly planthoppers and stem borers to avoid excessive chemical use and ecological disruption. Widely used insecticides like abamectin and emamectin benzoate, although effective against leaf folders, are highly detrimental to natural enemies such as spiders, *Cyrtorhinus lividipennis*, *Cyrtopeltis tenuis* and *Trichogramma japonicum* (Yuan *et al.* 2019) [86]. Their usage can unintentionally trigger brown planthopper (*Nilaparvata lugens*) outbreaks by: (i) Stimulating ovarian development and fecundity, increasing reproductive potential; (ii) Suppressing natural enemies, weakening biological control (He *et al.* 2024) [31]. Abamectin exposure similarly accelerates population growth of *Sogatella furcifera* (Cao *et al.* 2014) [8]. Such disruption is widely documented across Asian rice systems, where indiscriminate insecticide use destabilizes predator-prey dynamics and leads to pest resurgence. Since RLF injury often peaks during later crop stages, abamectin and emamectin benzoate should be avoided during early vegetative growth to protect parasitoids and predators. This strategy helps prevent secondary pest outbreaks and reduces planthopper incidence during reproductive and ripening stages (Horgan *et al.* 2018) [34]. Coordinated management considering combined thresholds for RLF, planthoppers and stem borers reduces chemical inputs without compromising yield. Integrated approaches have been successful in China and Vietnam, where ecological engineering practices that enhance natural enemy habitats reduced insecticide reliance and ensured sustainable suppression of multiple pests. Similar successes have been reported from West African rice ecosystems (Kouassi *et al.* 2019) [43].

Advancing spraying technologies with UAV precision for pest Management

Pesticide application efficiency in rice depends on sprayer design, application method, physicochemical properties of the pesticide, canopy structure, and prevailing environmental conditions. Precision spraying technologies, particularly unmanned aerial vehicles (UAVs) have significantly improved the efficiency and sustainability of RLF management. In India, UAV-based precision spraying using a hexacopter ("ANGRAU-Pushpak-01") achieved uniform flubendiamide deposition at an optimal flight height of 0.6 m above the canopy. A 75% reduced dose delivered via UAV provided control equivalent to the full recommended dose applied by backpack sprayers, while increasing grain yield and reducing pesticide use (Raghavaiah *et al.* 2023) [59]. Similar success has been reported for weed control in direct-seeded rice, where UAVs using only 30 L/ha achieved results comparable to >500 L/ha applied by knapsack sprayers (Gao *et al.* 2023b) [24] and spray adjuvants further enhance UAV performance. Products such as "Wonderful Rosin" and "Tiandun" reduce surface tension, improve droplet uniformity,

reduce drift, and increase deposition, resulting in up to 35% higher control efficiency (Lu *et al.* 2019; Sun *et al.* 2019) ^[45, 100]. In Japan, the commercial adjuvant Kao A-200® improved droplet distribution and consistently enhanced leaf folder suppression across multi-year trials. Beyond insect control, UAV-based multitarget spraying demonstrates additional benefits. Tank-mixed insecticide-fungicide applications in India achieved 77.4% control of sheath blight and 78.1% reduction in grain discoloration, with yield increases of 7,995 kg/ha and strong cost-benefit ratios. Emerging UAV applications include hyperspectral imaging integrated with machine-learning models such as XGBoost, enabling rapid, non-destructive detection of RLF infestations with >86% accuracy. Combining precision spraying with ecological approaches, natural enemy conservation, behavioral manipulation tools and reduced chemical reliance aligns with global goals for sustainable rice pest management (Zeng *et al.* 2021; Wang *et al.* 2025) ^[87, 101].

Integrated pest management strategies for sustainable control of RLF

Modern green plant protection emphasizes strengthening the ecological resilience of rice ecosystems rather than relying excessively on chemical pesticides. Integrated strategies prioritize ecological regulation, physical trapping and biological control, with insecticides applied only when economically justified. Habitat manipulation forms the foundation of this approach. Ecological engineering interventions such as bund vegetation, flowering strips and banker plant systems have been widely validated across Asia for enhancing parasitoid activity and providing more sustainable pest suppression compared with chemically intensive systems (Lu *et al.* 2019; Zhang 2021) ^[50, 90]. These vegetational enhancements support diverse predator-parasitoid complexes, stabilize trophic interactions and improve natural regulation of RLF populations (Horgan *et al.* 2021) ^[33]. Biological tools complement these ecological strategies. Microbial consortia involving *P. fluorescens* and *B. bassiana* have demonstrated dual suppression of RLF and sheath blight while simultaneously enhancing plant defense enzymes and improving yield. Silicon amendments further strengthen rice resistance through both mechanical and biochemical pathways by delaying larval development, reducing survival, and suppressing feeding efficiency of *C. medinalis* larvae (Han *et al.* 2016) ^[30]. These tactics align with global IPM principles that advocate a holistic combination of cultural, ecological and biological methods, supplemented with minimal pesticide inputs (FAO 2018b) ^[20].

Monitoring and early warning improvements

Robust monitoring and early warning systems are essential for sustainable RLF management. Effective surveillance should integrate measurements of pest population density, biological traits and crop damage, enabling timely and accurate intervention decisions (Huang *et al.* 2023) ^[37]. Rapid advances in remote sensing have significantly improved detection precision. UAV-based hyperspectral imaging combined with machine learning models such as XGBoost has achieved >86% accuracy in detecting *C. medinalis* damage using vegetation indices including red-edge NDVI, SIPI and EVI (Guo *et al.* 2023) ^[28]. UAV multispectral data have also been used to develop canopy-level SPAD inversion models using ridge and lasso regression methods, with coefficients of determination around 0.78 (Zhang *et al.* 2023) ^[89]. Vegetation index-based approaches further strengthen monitoring reliability. Indices such as GNDVI, Careen and red-edge chlorophyll index (CIred-edge) have shown

strong predictive power for SPAD estimation across rice growth stages, with multivariate and PLS regression models offering robust inversion accuracy (Chen *et al.* 2023) ^[12]. Similarly, UAV hyperspectral data integrated with enhanced modeling techniques provide reliable estimates of leaf area index (LAI) and leaf chlorophyll content (LCC), supporting assessments of crop nutrition and growth (Tian *et al.* 2020; Adhikari *et al.* 2023) ^[76, 21]. Integration of remote sensing with AI and GIS decision-support platforms has proven particularly promising. For example, a field-based system in Andhra Pradesh, India, used remote sensing and AI-driven analytics to deliver early warnings of pest and disease outbreaks, enabling timely interventions and reducing chemical use (CropIn 2023) ^[15]. These advances highlight the growing potential of UAV imaging and machine intelligence for early detection and precision decision-making in rice pest management.

Future directions and recent advances for pest management in rice

Recent advancements in RLF management demonstrate a clear shift toward ecologically sustainable and technologically advanced approaches, integrating natural enemy conservation, habitat manipulation and augmentative biological control such as *Trichogramma* spp. to enhance ecological resilience while reducing chemical dependence (Horgan *et al.* 2022; Lu *et al.* 2023; Sivapragasam *et al.* 2024) ^[35, 51, 70]. Multi-omics research has accelerated the identification of resistant germplasm exemplified by cultivar P213 with elevated salicylic acid, flavonoids, silicon deposition and dense trichomes and broader evaluations show that resistance is largely governed by heritable traits rather than environmental variability (Nayak *et al.* 2023; Sinha *et al.* 2023; Subramanian *et al.* 2023) ^[55, 69, 72]. Advanced biotechnologies including Bt rice (currently uncommercialized), CRISPR/Cas genome editing for precise modification of native resistance genes, and nucleic acid-based pesticides such as dsRNA are emerging as promising, environmentally benign interventions (Li *et al.* 2024; Niu *et al.* 2022) ^[47, 56]. Complementing these genetic and molecular innovations, nano-pesticide formulations are improving insecticidal performance through controlled release, enhanced adhesion, and higher bioavailability, enabling effective RLF suppression at reduced doses Liu *et al.* 2023; Ding *et al.* 2024) ^[48, 18]. Collectively, these developments indicate that the future of sustainable RLF management will be driven by the integration of ecological, genetic, molecular and precision technological innovations to build resilient, low-input rice production systems.

Concept for systems-based framework for sustainable RLF control

Sustainable management of the RLF requires a fundamental shift from conventional pesticide-dependent, pest-eradication approaches toward an ecologically grounded, systems-based framework that prioritizes ecosystem health, crop safety and plant vitality. Historically, rice diseases and insect pests were treated separately and controlled largely through frequent, indiscriminate pesticide applications, which led to rapid resistance development, destruction of natural enemy communities, weakened ecological resilience and disruption of ecosystem services. Because pests and beneficial organisms' function as interconnected components of the rice agroecosystem, non-selective chemical use destabilizes food webs and often triggers pest resurgence through natural enemy collapse. In contrast, modern sustainable management views the rice field as a dynamic, self-regulating ecological system where

the goal is not complete pest elimination but the maintenance of pest populations below economic injury thresholds. By embedding holistic principles such as natural enemy conservation, ecological engineering, precision monitoring and judicious input use, rice production systems can achieve more effective, stable and long-lasting suppression of the RLF while enhancing overall agroecosystem resilience.

Future prospects

Green development is becoming increasingly central to the future of Indian agriculture, with environmentally friendly pest management technologies gaining rapid momentum. Under the guiding philosophy of “green plant protection,” sustainable strategies for managing the RLF are advancing through both scientific innovation and practical field adoption. Eco-friendly tools such as ecological engineering, biological control, UAV-based precision spraying, attractant-based trapping, resistant varieties and emerging molecular technologies are being integrated into rice production systems with encouraging results. These approaches enhance rice productivity and quality while maintaining ecological balance, reducing pesticide residues, and minimizing environmental risks. Concurrently, ongoing research on rice-insect interactions, pest behavior, host plant resistance mechanisms and intelligent monitoring platforms is strengthening the scientific foundation for sustainable pest management. As these technologies continue to mature and become more accessible, their broad-scale adoption will be critical for establishing resilient, environmentally sound and climate-adaptive rice production systems in India.

Conclusion

IPM approaches combining biological control agents, cultural practices and judicious use of insecticides are essential for effective long-term management of RLF populations. These strategies help reduce dependence on chemical pesticides and preserve natural enemies. Newer control methods including ecological engineering with floral resources, use of botanicals and silicon fertilizers show promise in enhancing pest suppression while being environmentally sustainable. Challenges remain in developing resistant rice varieties, managing insecticide resistance and adapting pest management approaches to changing climate conditions and rice cropping systems. Continuous monitoring of pest populations and natural enemy dynamics, along with locally adapted IPM programs informed by research, are critical to facing outbreaks and minimizing crop losses from this pest.

Acknowledgment

The authors wish to extend their heartfelt thanks to the CCS Haryana Agricultural University Rice Research Station, Kaul for their invaluable support and assistance for writing this review article.

Author's contributions

The concept of this study conceived by Lalita and Meenu. The initial draft of manuscript prepared by Lalita, SS, PK, and VG. MS, AJ, RK, CS, AK, SM and OPC read and edited the manuscript. The final draft was read and approved by all the authors

Data availability statement

The data availability statement is not applicable.

Declaration of competing interest

The authors have no relevant competing financial or non-financial interests to disclose.

Disclosure statement

No potential conflict of interest was reported by the authors

Funding

No funding was received to assist with the preparation of this manuscript.

References

1. Adhikari B, Mohapatra LN, Mohapatra SD, Senapati R, Singh R, Satapathy SN. The effect of differential pest load of leaf folder, *Cnaphalocrocis medinalis*, on extent of leaf damage and alteration in leaf biochemical composition in rice. *Int J Plant Soil Sci.* 2022;34(22):1360-1368.
2. Adhikari R, Sharma RC, Ojha RB, Poudel PB. Hyperspectral remote sensing feature selection for predicting rice leaf folder (*Cnaphalocrocis medinalis*) damage. *Comput Electron Agric.* 2023;210:107924.
3. Ahmed N, Garnett ST. Integrated rice-fish farming in Bangladesh: meeting the challenges of food security. *Food Secur.* 2011;3(1):81-92.
4. Arneodo JD, Zanelli ML, Sciocco-Cap A. Interactions between entomopathogenic viruses and other control agents in pest management. *Virol Sin.* 2015;30(1):26-33.
5. Bindhu JS, Hemand J, Jacob J, Meera AV. Enhancing productivity of rice (*Oryza sativa*)-rice-fallow system through balanced fertilization: a farmer participatory approach in Kerala's southern coastal plains. *Indian J Agric Sci.* 2023;95(3):298-303.
6. CABI. PlantwisePlus knowledge bank: rice leaf folder (*Cnaphalocrocis medinalis*). Wallingford (UK): CAB International; 2022.
7. Cai Y, Cheng J, Zhang B. Advances in integrated pest management of rice insect pests in China. *Annu Rev Entomol.* 2018;63:241-261.
8. Cao GC, Zhang HH, Wang ZH, Lu ZX. Sublethal effects of abamectin on the reproduction and offspring development of white-backed planthopper (*Sogatella furcifera*). *Crop Prot.* 2014;55:40-45.
9. Chaitanya M, Pavan JS, Vireesha P, Nekkanti A. Natural enemies as guardians of crop ecosystem with special emphasis on rice and cotton. *Int J Exp Agric.* 2024;46(9):600-612.
10. Chandrasekar K, Muthukrishnan N, Soundararajan RP. Ecological engineering cropping methods for enhancing predator *Cyrtorhinus lividipennis* (Reuter) and suppression of planthopper *Nilaparvata lugens* (Stål) in rice: effect of border cropping systems. *Int J Curr Microbiol Appl Sci.* 2017;6(12):330-338.
11. Chauhan RC, Sharma SK, Mandal KG, Sahu RK. Effect of rice stubble height on productivity and resource use efficiency in rice-lathyrus relay cropping system under conservation agriculture in Vertisols of Central India. *Indian J Agric Sci.* 2016;86(10):1272-1276.
12. Chen L, Liu X, Wu Y, Yang Z. Rice leaf folder damage detection using convolutional neural networks and rotation region methods. *Plant Phenomics.* 2023;2023:845621.
13. Chen X, Xu H, Guo J. Non-target impacts of insecticides on beneficial arthropods in rice fields. *Ecotoxicology.* 2022;31(6):843-856.
14. Chowdhury SBT, Chatterjee H, Chakraborty A. Effect of

- ecological engineering through border cropping for enhancing population of *Micraspis crocea* toward suppression of rice leaf folder (*Cnaphalocrocis medinalis*). *Pharma Innov J*. 2023;12(4):2139-2144.
15. CropIn. Pest and disease early warning for crop loss mitigation. Bangalore: CropIn Technology Solutions; 2023. Available from: <https://www.cropin.com>
 16. Cui Y, Wu Y, Zhang Z, Li F. Synergistic effects of rice-fish-duck integrated systems on soil fertility and greenhouse gas mitigation. *Sustainability*. 2023;15(6):5321.
 17. DAFS Haryana. Department of Agriculture and Farmers Welfare, Haryana. Haryana (India); 2025. Available from: <https://agriharyana.gov.in/>
 18. Ding Y, Zhang J, Chen X, Li Y, Wu Y. Development of chlorantraniliprole nanosuspension with enhanced insecticidal activity against *Cnaphalocrocis medinalis*. *Pest Manag Sci*. 2024;80(2):765-774.
 19. FAO. Globally Important Agricultural Heritage Systems (GIAHS). Rome: Food and Agriculture Organization of the United Nations; 2018.
 20. FAO. Integrated Pest Management in rice: FAO guidelines. Rome: Food and Agriculture Organization of the United Nations; 2018.
 21. Feng J, Li X, Tang H, Wang L. Rice-turtle farming: an innovative ecological agriculture model for sustainability. *Sustainability*. 2021;13(2):567.
 22. Gangwar RK. Life cycle and abundance of rice leaf folder, *Cnaphalocrocis medinalis*: a review. *J Nat Sci Res*. 2015;15(5):103-105.
 23. Gao Y, Shi X, Wu J. Biopesticides for lepidopteran pests: progress and prospects in rice systems. *Pest Manag Sci*. 2023;79(4):1587-1599.
 24. Gao Y, Xu Y, Wu J, Wang L. UAV-based herbicide application for efficient weed management in direct-seeded rice. *Front Agron*. 2023;5:1491842.
 25. Garcia MP, Ali MP, Yao J, Gurr GM, Huang D. Landscape structure influences natural pest suppression in rice agroecosystems. *Sci Rep*. 2023;13:41786.
 26. Ge F. The ecological regulation and management of pests. *Chin J Appl Entomol*. 2020;57(1):10-19.
 27. Ge LQ, Xia T, Huang B, Song QS, Wu JC. Effects of amino acids and proteins in rice varieties on the population parameters of the rice leaf folder (*Cnaphalocrocis medinalis*). *J Insect Sci*. 2013;13:148.
 28. Guo J, Xu X, Chen Z, Wang P. Monitoring rice pests using UAV hyperspectral imagery and machine learning approaches. *Remote Sens*. 2023;15(11):2660.
 29. Guo Y, Wang H, Liu C. Evaluation of spinosad and microbial agents for rice leaf folder control. *Crop Prot*. 2021;144:105605.
 30. Han Y, Li P, Gong S, Yang L, Wen L. Silicon amendment reduces feeding and performance in the rice leaf folder, *Cnaphalocrocis medinalis*. *Entomol Exp Appl*. 2016;158(3):250-260.
 31. He X, Zhang C, Liu Y, Zhao Y, Chen G. Non-target impacts of abamectin and emamectin benzoate on brown planthopper resurgence and its natural enemies in rice fields. *Crop Prot*. 2024;174:106118.
 32. Hegazy FE, Hendawy E, Mesbah I, Salem F. The insect pests, the associated predatory insects and prevailing spiders in rice fields. *J Plant Prot Pathol*. 2021;12(5):365-371.
 33. Horgan FG, Ramal AF, Bernal CC, Villegas JM, Stuart AM, Almazan MLP, et al. Ecological engineering with floral resources enhances parasitism of rice leaf folders (*Cnaphalocrocis medinalis*) and suppresses planthopper populations in the Philippines. *Pest Manag Sci*. 2021;77(1):147-158.
 34. Horgan FG, Srinivasan TS, Naik BS, Ramal AF. Ecological engineering and IPM for rice insect pests. *Crop Prot*. 2018;110:1-9.
 35. Horgan FG, Tamo C, Lu Z, Kenmore PE, Heong KL. Restoration of rice ecosystem services: ecological engineering and related practices in the Mekong Delta. *Agronomy*. 2022;12(5):1042.
 36. Hu L, Zhang J, Ren W, Guo L, Cheng Y, Li X. Rice-duck farming: an ecological approach to reduce agrochemicals and improve soil fertility. *Agron Sustain Dev*. 2020;40(5):37.
 37. Huang J, Zhang F, Li Y. Monitoring and early warning of rice pests: current progress and perspectives. *J Integr Agric*. 2023;22(5):1185-1198.
 38. ICAR-NCIPM. Integrated Pest Management Package for Rice. New Delhi: National Centre for Integrated Pest Management; 2020.
 39. Indian Council of Agricultural Research. Integrated Pest Management Package for Rice. Cuttack (Odisha): National Rice Research Institute; 2023.
 40. IRAC. Insecticide Resistance Management Guidelines. Brussels: Insecticide Resistance Action Committee; 2023.
 41. Kaur R, Brar BS. Effect of organic and inorganic nutrient sources on yield and nutrient uptake by rice under temperate conditions. *Arch Agron Soil Sci*. 2018;64(4):542-555.
 42. Khan ZR, James DG, Midega CAO, Pickett JA. Constraints and prospects for *Trichogramma* in intensive rice systems. *Crop Prot*. 2021;146:105671.
 43. Kouassi KN, Nwilene FE, Togola A, Kiepe P, Ekeleme F. Rice insect pest management in Africa: status and perspectives. *Outlook Agric*. 2019;48(4):267-274.
 44. Kumar V, Kaur J, Singh J. Role of biopesticides in sustainable agriculture: a review. *J Entomol Zool Stud*. 2019;7(3):1345-1350.
 45. Li X, Zhang J, Chen F, Hu L. Rice-duck farming system in China: a review. *Agron Sustain Dev*. 2019;39(3):45.
 46. Li X, Zhang Y, Chen J, Wang S. CRISPR/Cas-mediated genome editing for improving stress resilience and pest resistance in rice. *Plant Biotechnol J*. 2024;22(3):421-436.
 47. Li Y, Sun L, Zhang C. Cytochrome P450-mediated resistance to chlorantraniliprole in *Chilo suppressalis*. *Pestic Biochem Physiol*. 2024;195:105326.
 48. Liu Q, Zhao Y, Xu W, Zhou G. High drug-loaded phosphate-modified cellulose/chitosan microspheres for controlled delivery of emamectin benzoate in rice soils. *J Agric Food Chem*. 2023;71(15):4876-4887.
 49. Liu XT, Liu MX, Zhao DH. Control of ecological networks: abundance control or ecological regulation? *Chaos*. 2024;34(7):073115.
 50. Lu Z, Heong KL, Gurr GM. Ecological engineering for rice pest management: principles and practices. In: Horowitz AR, Ishaaya I, editors. *Advances in Insect Control and Resistance Management*. Cham: Springer; 2019. p. 209-227.
 51. Lu Z, Xu H, Chen L. Advances in ecological engineering for rice insect pest management in Asia. *Agric Ecosyst Environ*. 2023;349:108463.
 52. Lv N, Lu Z, Heong KL. Ecological engineering for pest management in rice ecosystems. *Chin J Appl Entomol*. 2015;52(1):8-15.
 53. Mochiah MB, Asamoah EK, Oppong SK. Biological control interventions reduce pest abundance and crop damage while

- maintaining natural enemies in sub-Saharan Africa: a meta-analysis. *Biol Control*. 2020;160:104677.
54. National Agricultural Technology Extension Service Center (NATESC). Guidelines for the green prevention and control of major rice pests and diseases. Beijing: NATESC; 2018.
 55. Nayak AK, Golive P, Sasmal A, Adak T, Kumar G. Morpho-biochemical responses of rice genotypes against leaf folder *Cnaphalocrocis medinalis* Guenée. *J Biotechnol Bioprocess*. 2023;4(4):1-9.
 56. Niu J, Yang W, Li C. RNAi-based pest control in rice: mechanisms, applications, and challenges. *Front Plant Sci*. 2022;13:934516.
 57. Padmavathi GH, Singh R, Singh VP. Impact of silicon nutrition on growth, yield and nutrient uptake in rice (*Oryza sativa* L.) under saline conditions. *J Plant Nutr*. 2013;36(14):2216-2228.
 58. Prabhu MJ. A new concept called ecological engineering to reduce pests. *The Hindu*. 2015 May 7.
 59. Raghavaiah CV, Rao AS, Prasad MS. Development and evaluation of a UAV for pesticide application against rice leaf folder (*Cnaphalocrocis medinalis*). *J Entomol Zool Stud*. 2023;11(2):45-52.
 60. Rajendran R. Role of bund cropping in conservation of natural enemies in rice fields. *J Biopestic*. 2013;6(2):174-177.
 61. Raju MV, Srinivas A. Field level validation of ecological engineering approaches for pest management in rice. *Pest Manag Horticult Ecosyst*. 2016;22(1):69-74.
 62. Rani PU, Rajasekar B, Chinniah C. Monitoring insecticide resistance in rice leaf folder *Cnaphalocrocis medinalis* in Tamil Nadu, India. *J Entomol Zool Stud*. 2017;5(4):566-572.
 63. Rautaray BK, Bhattacharya S, Panigrahi D, Dash SR. Species diversity of rice leaf folder and their natural enemies in North Eastern coastal plains of Odisha. *Int J Curr Microbiol Appl Sci*. 2019;8(10):634-645.
 64. Selvam K, Nagendran S, Manikandan P. Ecological engineering: a sustainable tool for insect pest management. In: Raju SVS, Sharma KR, editors. Recent trends in insect pest management. Vol 2. New Delhi: AkiNik Publications; 2020. p. 23-53.
 65. Sethy A, Patra PS, Das SR. Enhancing aromatic rice production through agronomic and nutrient management practices. *Sci Rep*. 2024;14:65476.
 66. Shaki AA, Prasad YG, Babu VR, Rao MRK. Feeding potential of rice leaf folder *Cnaphalocrocis medinalis* Guenée and its impact on rice crop. *Indian J Entomol*. 2020;82:28-33.
 67. Sharma HC, Rao GR. Plant compensation for insect herbivory in crop pest management. *Crop Prot*. 2014;55:74-79.
 68. Shylesha AN, Jalali SK, Rabindra RJ. Biological control of insect pests in rice ecosystems. *Indian J Entomol*. 2021;83(SI):1-15.
 69. Sinha AK, Sharma P, Roy D. Stability of leaf folder resistance across rice landraces under diverse environments. *Euphytica*. 2023;219:12.
 70. Sivapragasam A, Chen Y, Heong KL. Ecological regulation for sustainable rice pest management: global lessons and future directions. *Agronomy*. 2024;14:45.
 71. Sreelatha E, Rajan SJ. Ecological engineering for sustainable agriculture: simple concept with greater impact. *Int J Sci Res Publ*. 2018;8:123-125.
 72. Subramanian N, Ramesh R, Singh SP. Biochemical basis of resistance in rice germplasm against rice leaf folder. *Physiol Mol Biol Plants*. 2023;29:1105-1116.
 73. Sun X, Chen J, Zhao S. Mutations in RyR confer resistance to chlorantraniliprole in *Cnaphalocrocis medinalis*. *Pestic Biochem Physiol*. 2023;192:105150.
 74. Sun X, Chen X, Zhang Z. Application of insect viruses in pest management in China. *Virol Sin*. 2016;31:3-10.
 75. Tang R, Xie LC, Li XY, Li P, Zhang R, Hu CX. Selection for insecticide resistance in *Trichogramma japonicum*. *Pest Manag Sci*. 2022;78:4561-4571.
 76. Tian Y, Guo B, Zhang Z. Mapping rice leaf folder damage using UAV multispectral images. *Int J Remote Sens*. 2020;41:2541-2556.
 77. USDA. Foreign Agricultural Service, U.S. Department of Agriculture. Washington (DC); 2025.
 78. Wang D, Qiu J, Yu H. Photodegradation and environmental fate of spinosad in water and soil. *Bull Environ Contam Toxicol*. 2016;97:105-110.
 79. Wang L, Zhang H, Li Q. Inheritance of chlorantraniliprole resistance in *Cnaphalocrocis medinalis*. *Insects*. 2024;15:134.
 80. Wu K, Li Y, Zhang J, Liu Q, Liu Y, Wang F. Climate adaptability of *Trichogramma japonicum*. *J Appl Entomol*. 2020;144:325-334.
 81. Wu S, Gao C, Xu J. Strategies for delaying insecticide resistance in rice pests. *Pest Manag Sci*. 2021;77:4567-4576.
 82. Yaligar R, Shivanna BK, Sreenivas AG, Jaylaxmi NH, Sharanabasappa. Influence of ecological engineering on major lepidopteran pests and natural enemies of paddy in Tungabhadra project area. *Biol Forum Int J*. 2021;13(3a):683-690.
 83. Yang Y, Li C, Liu X. Threshold-based integrated management of rice leaf folder in China. *J Integr Agric*. 2015;14:89-98.
 84. Yang YJ, Xu HX, Zheng XS, *et al*. Progress in management technology of rice leaf folders in China. *J Plant Prot*. 2015;42:691-701.
 85. Yi ZF. Frogs as biological control agents in Asian rice ecosystems: implications for agroecological intensification. *Ecol Indic*. 2023;146:109799.
 86. Yuan Y, Zhao X, Guo J. Effects of emamectin benzoate on rice pests and their natural enemies in paddy ecosystems. *Plant Prot*. 2019;45:110-116.
 87. Zeng W, Liu Q, Ma Y. Efficacy of UAV-based low-dose pesticide applications against major rice pests. *Pest Manag Sci*. 2021;77:5068-5077.
 88. Zhang H, Li X, Wang Y, Chen J. Innovations in augmentative biological control with *Trichogramma*. *Sustainability*. 2023;15:4499.
 89. Zhang L, Liu H, Sun K, Wang L. Intelligent monitoring networks for rice leaf folder detection and management. *Sensors*. 2023;23:1789.
 90. Zhang W. Ecological approaches to sustainable pest management in rice-based systems. *J Integr Agric*. 2021;20:987-1002.
 91. Zheng XS, Yu XP, Lu ZX, *et al*. The diversity and structure of spider community in *Zizania caduciflora* field. *Nat Enem*. 2002;2:53-59.
 92. Zhong HN. The effect of farmland landscape pattern on diversity and density of overwintering spiders and carabids [thesis]. Nanchang: Jiangxi Agricultural University; 2022.
 93. Zhou W, Huang J, Hu R. Ecological and economic benefits of rice-turtle integrated farming systems in China. *Ecol*

- Econ. 2019;159:11-20.
94. Zhou Y, Zhang M, Wang C, Zhao J, Liu Q. Comparative parasitism potential of *Trichogramma* spp. against fall armyworm in China. J Pest Sci. 2022;95:1341-1354.
 95. Zhou ZY, Huang XC, Meng L. Arthropod diversity on plants at field margins of organic farming paddy rice. Chin J Ecol. 2011;30:1347-1353.
 96. Zhu PY, Wang GW, Zheng XS, *et al.* Selective enhancement of parasitoids of rice Lepidoptera pests by sesame (*Sesamum indicum*) flowers. BioControl. 2015;60:157-167.
 97. Zhu ZR, Zheng XS, Horgan FG, Lu ZX, Heong KL. Ecological engineering for rice pest suppression in China: a review. Agron Sustain Dev. 2022;42:75.
 98. Yadav D, Park WG, Fogel EL, Li L, Chari ST, Feng Z, Fisher WE, Forsmark CE, Jeon CY, Habtezion A, Hart PA. PROSpective evaluation of chronic pancreatitis for EpidEmiologic and translational StuDies: Rationale and study design for PROCEED from the consortium for the study of chronic pancreatitis, diabetes, and pancreatic cancer. Pancreas. 2018 Nov 1;47(10):1229-38.
 99. Prasad D, Parween S, Kumari K, Singh N, Kumari KD. Prevalence, etiology, and associated symptoms of vaginal discharge during pregnancy in women seen in a tertiary care Hospital in Bihar. Cureus. 2021 Jan 14;13(1).
 100. Sun J, Dai X, Wang Q, Van Loosdrecht MC, Ni BJ. Microplastics in wastewater treatment plants: Detection, occurrence and removal. Water research. 2019 Apr 1;152:21-37.
 101. Chen Z, Wang J, Liu K, Gong J, Sun L, Wu Z, Timofte R, Zhang Y, Zhang J, Wu J, Wang J. NTIRE 2025 challenge on real-world face restoration: Methods and results. In Proceedings of the Computer Vision and Pattern Recognition Conference 2025 (pp. 1536-1547).