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MODERN TECHNIQUES AND NOVEL APPROACHES IN RICE PEST MANAGEMENT: A REVIEW

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ABSTRACT

Rice is the staple food for the majority of the global population, especially in Asia, where 90% of rice is cultivated and consumed. With the human population projected to reach 9.7 billion by 2050, the demand for increased rice production must be met using ever-decreasing resources. In India, rice is cultivated under diverse agroecological conditions, with cropping intensity varying based on the environment. Fertile deltaic regions with consistent irrigation can support up to three rice-growing seasons annually. However, rice crops face significant stress during growth due to a range of pests, including insects, nematodes, diseases, weeds and rodents. Rice in India faces significant challenges from insect pests, with farmers experiencing average yield losses of 37% annually due to pests and diseases, while over 800 insect species can damage rice, about a dozen are considered major pests in India and Key pests include Brown planthopper (*Nilaparvata lugens* Stal), Yellow stem borer (*Scirpophaga incertulas* Walker), Leaf roller (*Cnaphalocrocis medinalis* Guenée) and Gall midge (*Orseolia oryzae* Wood-Mason). The complexity and prevalence of pests damaging rice crops are on the rise, necessitating innovative solutions. This review discusses recent advancements in pest management and their implications for future rice production, highlighting novelties in host plant resistance, including RNAi, genome editing techniques and the application of nanotechnology.

Key words : Rice, Pest Management, RNA interference (RNAi), Genome editing, Nanotechnology, Host plant resistance, CRISPR-Cas9, Biopesticides, Sustainable agriculture.

Introduction

Rice production is crucial for India's food security and economy, as the country is the world's second-largest producer (FAO). Approximately 65% of India's population depends on rice as a staple food, providing a vital livelihood source for rural communities (Janaiah, 2020). In 2022–2023, India's rice production is estimated to have reached a record high of 1,357.55 lakh tonnes, marking an increase of 62.84 lakh tonnes over the previous year's production of 1,294.71 lakh tonnes (PIB, 2023). However, paddy farmers continue to face substantial economic losses annually due to multiple biotic and abiotic stresses. Several factors, including pests, diseases, soil fertility, rainfall variability, waterlogging and climate conditions, contribute to reduced rice yields. Among these, pest infestations are particularly detrimental, with approximately 100 insect species affecting rice crops; around 20–33 of these cause significant economic damage (Ali *et al.*, 2021; Tripathi and Saxena, 2013; Virmani, 1994). Major pests such as yellow stem borer (*Scirpophaga incertulas* Walker), Leafhoppers (*Nephotettix nigropictus* Stal), Brown plant hopper (*Nilaparvata lugens* Stal), Gall midge (*Orseolia oryzae* Wood-Mason) and defoliators contribute significantly to yield losses, with Asia reporting losses between 20–51% due to pest attacks (Ali *et al.*, 2021; Parasappa *et al.*, 2017). Specific pests like the yellow stem borer (*Scirpophaga incertulas* Walker), leafhoppers, Brown plant hopper (*Nilaparvata lugens* Stal), Gall midge (*Orseolia oryzae* Wood-Mason) result in losses ranging from 25–30%, 10–70% and 15–60%, respectively (Ali *et al*., 2021). Compared to other crops, rice suffers notable losses—estimated at 15–25%—due to pest infestations in South Asia, largely driven by favourable climatic conditions that facilitate pest spread (Dhaliwal *et al*., 2010).

These pressures push farmers to rely extensively on insecticides to manage infestations and maintain yields, highlighting the importance of sustainable pest management practices in rice cultivation. In India, the Central Insecticide Board and Registration Committee (CIBRC) has recommended over 90 pesticides or combination products to tackle various insect-related issues. While the high pesticide usage contributes to direct crop returns, there is growing concern about its effects on non-target organisms, particularly humans. Small pesticide residues may persist in crops, either from direct application or environmental contamination, raising significant health and environmental concerns. Despite their agricultural benefits, less than 1% of pesticides reach target pests, with over 99% affecting non-target areas, thus contaminating air, water and soil and harming non-target organisms (Shreya and Rahul 2022). Runoff and wind dispersion can further spread pesticides, affecting non-point areas and endangering other animals. The need for sustainable pest management drives the development of economically and ecologically viable alternatives. Current technologies in pest management aim to create environmentally friendly strategies that leverage renewable natural resources. The following objectives have been identified, focusing on addressing the economic and social impacts of existing limitations and bottlenecks in applying various pest management techniques like RNAi and CRISPR/Cas approaches for pest management.

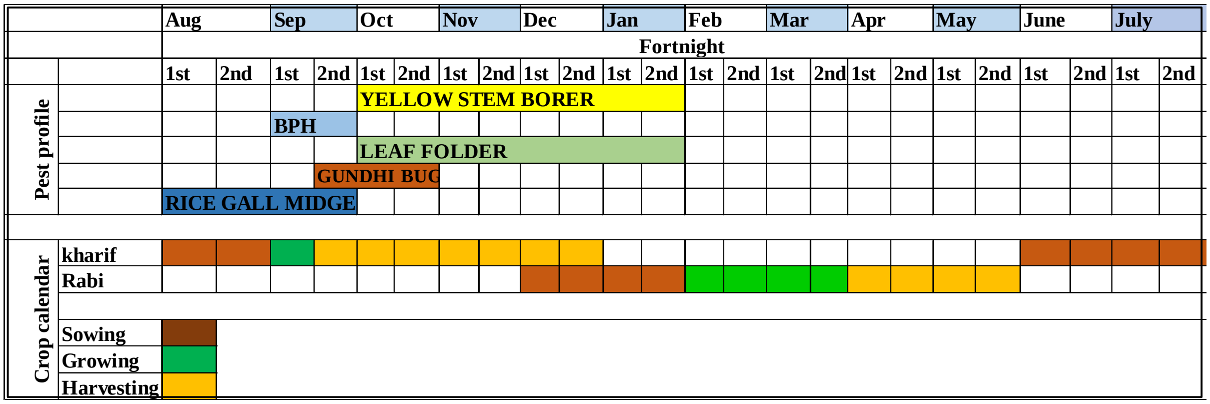
Major insect pests of rice

A. National significance: Yellow stem borer (*Scirpophaga incertulas* Walker), Brown plant hopper (*Nilaparvata lugens* Stal), Leaf folder (*Cnaphalocrocis medinalis* Guenée), Gandhi bug (*Leptocorisa acuta* Thunberg), Gall midge (*Orseolia oryzae* Wood-Mason)

B. Regional significance: Termite (*Odontotermes obesus* Rambur) - In rainfed upland areas, irrigated rice-wheat system, Swarming caterpillar (*Spodoptera mauritia* Boisduval) - Odisha, West Bengal, Jharkhand, Chhattisgarh, and Punjab, Rice Hispa (*Dicladispa armigera* Oliver) - Bihar, West Bengal, Assam, Odisha, Meghalaya, Mizoram, Tripura, Punjab, Himachal Pradesh, Uttar Pradesh and Uttarakhand, Climbing cutworm/Rice Ear Cutting Caterpillar/ Armyworm (*Mythimna separate* Walker) - In coastal rice growing areas, Haryana, Punjab and Uttar Pradesh. Caseworm (*Nymphula depunctalis* Guenée) - In low-lying and water-logged areas in eastern India. Thrips (*Stenchaetothrips biformis* Bagnall) - In upland rice in Odisha, Andhra Pradesh, Madhya Pradesh, Punjab, Haryana, Assam and Tamil Nadu. Mealy bug (*Brevennia rehi* Lindinger) - In upland rice in Uttar Pradesh, Bihar, West Bengal, Odisha, Madhya Pradesh, Tamil Nadu, Kerala, Pondicherry and Karnataka. Panicle mite (*Steneotarsonemus spinki* Smiley)-Andhra Pradesh, Odisha, West Bengal, Gujarat and Western Uttar Pradesh and Leaf mite (*Oligonychus oryzae* Hirst) –Eastern India and Andhra Pradesh, Root weevil (*Echinochemus oryzae* Marshall) - Haryana, Punjab, and Tamil Nadu, White grub (*Holotrichia* spp.) - Hill rice, Black bug (*Scotinophara coaractata* Fabricius) -Andhra Pradesh, Tamil Nadu, and Kerala., Blue beetle (*Leptisma pygmaea* Baly) - Kerala, Maharashtra, and Tamil Nadu. (Source: https://niphm.gov.in/IPMPackages/Rice.pdf)

Crop calendar and Pest profile

Rice insect pests are an important biotic stress component and a significant production restriction globally. Although over 200 insect species have been observed to feed on rice plants, only a few dozen are economically significant in a specific rice environment at any given moment. Several of them have coevolved with their host over thousands of years, and many have no substitute host. Rice pests include insects from all feeding guilds, ranging from defoliators, tissue borers, and sap-suckers to gall formers and several of these are occupied by a complex of species (Heinrichs, 1994). Most important among these are stem borers: yellow stem borer (YSB), *Scirpophaga incertulas*; planthoppers: brown planthopper (BPH), *Nilaparvata lugens*; white-backed planthopper (WBPH), *Sogatella furcifera*; leafhoppers: green leafhopper; (GLH), *Nephottetix virescens* and zigzag leafhopper (ZLH), *Recilia dorsalis*; gall midge: *Orseolia oryzae* and leaf folders: *Cnaphalocrocis medinalis*. Several other insects such as rice hispa, grain bugs, aphids, mealy bugs and stem flies are of minor or regional importance (Bentur, 2010). The main rice growing season in the country is the 'Kharif'. It is known as winter rice as per the harvesting time. The sowing time of winter (*Kharif*) rice is June-July and it is harvested in November-December. About 84% of the country's rice crop is grown in this season and generally, medium to long-duration varieties are grown in this season. Summer rice is called *Rabi* rice. The sowing time of summer rice is November



Traditional/current management practices for rice pest management.

Table 1 : Economic thresholds of common insect pests of rice.

Pest	Economic thresholds	Reference
Stem borer	10% dead hearts or 1 egg mass or 1 moth/m^2	Pasalu *et al*. (2004)
BPH and WBPH	10 insects/ hill at veg. Whereas 20 insects/hill at a later stage	Pasalu *et al*. (2004)
Green leaf hopper	2 insects/hills in Tungro endemic areas. 20-30 insects/hill in other areas	Pasalu *et al*. (2004)
Gall midge	1 gall/m2 or 10% silver shoot	Pasalu *et al*. (2004)
Leaf folder	2-3 damaged leaves/ hill post active tillering stage	Pasalu *et al*. (2004)
Case worm	1-2 cases/hill	Misra and Jena (2007)
Cutworm	1 damaged tiller/hill or 2 larvae/m^2	Prakash *et al*. (2014)
Earhead bug	1 nymph or adult/hill	Prakash *et al*. (2014)
Rice hispa	2 adults or 2 dead leaf/hill	Prakash *et al*. (2014)
Rice black bug	5 bugs/hill	Prakash *et al*. (2014)
Whorl maggot	25% damage leaves	Misra and Jena (2007)

Table 2 : Yield loss caused by major insect pests of rice.

Insect	Yield loss	Reference
Yellow stem borer	1-19% in early planted and 38-80% in late transplanted crop	Catinding and Heong (2003)
Plant hopper	10- 90%	Seni and Naik (2017)
Gall midge	0.8% of the total production	Krishnaiah (2004)
Leaf folder	10% flag leaf infestation reduces grain yield by 0.13 g per tiller and the number of fully filled grains by 4.5%.	Murugesan and Chelliah (1983)
Earhead bug	10-40%	Israel and Rao, 1954

to February and harvesting time is March to June. The area under summer rice is only 9% and early-maturing varieties are mostly grown in this season.

Cultural practices

As essential agronomic techniques, cultural practices play a dual role in enhancing crop productivity and concurrently suppressing pest populations (Reddy *et al*., 1979). Techniques such as crop rotation, intercropping, tillage, cover cropping, mulching, irrigation and drainage management, maintaining appropriate spacing, and timed planting are key practices for effective pest management (Chandola *et al*., 2011; Faust, 2008). Crop rotation, for instance, disrupts the life cycles of insect pests like gall midges in rice fields, effectively reducing their populations (Heinrichs and Muniappan, 2017). Tillage is another fundamental practice that disturbs the natural habitats of soil-borne insects, targeting the eggs, larvae, and pupae stages, thus reducing pest pressure.

Research has shown that trap cropping with Barnyard millet (*Echinochloa* sp.) and foxtail millet around rice fields effectively mitigates pest damage by attracting pests away from the main crop (Chandola *et al*., 2011). Fertilizer management, particularly nitrogen application at optimal rates and split doses, has also been noted to control pests, as excessive nitrogen can increase the populations of pests like gall midges, leaf folders, brown plant hoppers and white-backed plant hoppers in rice fields (Reddy *et al.*, 1979). Transplanting older seedlings, for example, can minimise the risk of vegetative-stage pests, such as caseworms and whorl maggots, by reducing their window of vulnerability. Additional cultural techniques include adjusting planting times; early planting can lower gall midge populations, while delayed planting reduces leaf folder infestations. Post-harvest flooding of rice stubble has been found to suppress pests like armyworms and stem borers in the subsequent season (Heinrichs and Muniappan, 2017). The use of undecomposed farmyard manure is discouraged, as it can foster pest infestations, particularly from white grubs, whose larvae are drawn to organic material in early decomposition stages, often leading to increased crop damage. Traditional pest control methods in the Indian subcontinent include the application of table salt and controlled field fires. Table salt helps to control white grub, stem borer, and even certain fungal diseases, while field fires sterilize the soil, reducing pest populations in the treated area (Chandola *et al.*, 2011). These cultural practices collectively offer an effective, ecologically sound approach to integrated pest management, contributing to sustainable agriculture.

Use of resistant varieties

The adoption of resistant cultivars in rice production can be considered a safer alternative to pesticides. Mutagenesis, the introduction of foreign genes (single-gene and gene pyramiding), transplastomic approaches, genetically engineered/modified Bt Toxins, oligonucleotide-directed mutagenesis, engineered nucleases, engineered plant membrane transporters and antisense technologies are all used to develop insect-resistant rice crop varieties.

Mechanical practices

Collection of egg masses and larvae of pests to be placed in bamboo cages for conservation of biocontrol agents. Removal and destruction (burn) of diseased/pest-infested plant parts. Clipping of rice seedlings tips at the time of transplanting to minimize carryover of rice hispa, case worm, and stem borer infestation from the seedbed to the transplanted fields. Use of coir rope in rice crop for dislodging case worms, cutworms and swarming caterpillar and leaf folder larvae, etc. onto keratinized water (1 L of kerosene mixed on 25 kg soil and broadcast in 1ha).

Biological control

Biological control agents are essential for managing crop pests within Integrated Pest Management (IPM) frameworks. Predators and parasitoids, particularly for pests like the yellow stem borer and leaf folder, offer promising alternatives to chemical methods. However, their effectiveness is often limited to these key pests and less so for sporadic ones, such as gundhi bug, rice hispa, and cutworm (Pasalu *et al.*, 2004). In rice, the use of biocontrol through inundative and inoculative releases has shown variable success compared to other crops (Pathak *et al.*, 1996). In India's rice ecosystems, inundative releases primarily involve egg parasitoids, especially *Trichogramma japonicum* and *T. chilonis*, as they are easily mass-reared (Pasalu *et al.*, 2004). Effectiveness depends on environmental conditions and species selection; for instance, *T. dendrolimi* thrives in 18–26ºC, while *T. japonicum* is optimal at 30–34ºC (Yuan *et al.*, 2012; Guo *et al.*, 2012; Hong-xing *et al.*, 2017). In India, releasing *T. japonicum* at 20,000 per acre has effectively reduced stem borer populations, and releasing 100,000 adults per hectare at intervals of 7-10 days has resulted in up to 59% reduction in leaf folder damage (Pasalu *et al.*, 2004). However, in China, *T. japonicum* achieved only 9% parasitism in yellow stem borer eggs, compared to 15% for *T. chilonis* (Tang *et al.*, 2017). Studies indicate that *Trichogramma* species perform better on newly laid pest eggs (<24 hours old) than on older ones (Babendreier *et al.*, 2020; Hong-xing *et al.*, 2017).

Microbial pesticides like *Bacillus thuringiensis* (Bt) and certain viruses and fungi are also effective, eco-

Table 3 : Varieties resistant/tolerant to various insect pests.

Insect pests	Resistant/tolerant varieties
Gall midge	IR 36, Asha, Samalei, Samariddhi, Pusa, Surekha, Phalguna, Vikram, Shakti, Jyoti, Kakatiya, Kanchan and Birsa Dhan 202.
Brown plant hopper	CO 42, Jyoti, Chandana, Nagarjuna, Sonasali, Rasmi, Neela, Annanga, Daya, Bhadra, Karthika, Aruna, Remya, Kanakam, Bharathidasan, Remya, Triguna, IET 8116, Rajendra Mahsuri-l, Pant dhan 11, Rajshree, Bhudeb and Hanseshwari.
White-backed plant hopper	HKR 120, HKR 126, HKR 228, PR 108, Menher, Pant dhan 10, Pant dhan 11, Mahananda and Hanseshwari
Green leaf hopper	Vikramarya, Nidhi, IR 24, Radha, Mahananda and Kunti.

(Source:https://niphm.gov.in/IPMPackages/Rice.pdf) friendly options for rice pest control. *Bt* has shown efficacy against rice yellow stem borers' larval stages, reducing dead hearts and white heads by 76.36% and 67.45%, respectively, in controlled studies (Nayak *et al.*, 1978). Similarly, *Mamestra brassicae* nuclear polyhedrosis virus has achieved over 83% efficacy against leaf folder larvae (Hong-xing *et al.*, 2017) and the combination of *C medinalis* granulovirus (CnmeGV) with *Bt* significantly enhanced mortality rates and pest control duration for leaf folders (Liu *et al.*, 2013). Fungal pathogens like *Beauveria bassiana* have shown promise against rice hispa in India (Hazarika and Puzari, 1997), while *Pandora delphacis* has been effective against brown planthopper (BPH) (Narayanasamy, 1995).

Chemical control

Chemical control remains one of the most effective and rapid methods for reducing rice pest populations, particularly during emergencies when other options are unavailable. However, studies indicate that improper insecticide use can lead to pest outbreaks, ultimately posing a risk to entire rice-growing regions (IRRI, 2011; Ali *et al.*, 2019). The effectiveness of chemical control relies on selecting the appropriate active ingredient, formulation, and application method, with a solid understanding of pest life cycles and crop phenology (Pasalu *et al.*, 2004). Additionally, information on the pest's most susceptible stage, population intensity, and impact on yield and natural enemies is critical for economically sound and successful pest control. Awareness of the potential negative effects of pesticides on applicators, consumers and the environment is also essential.

Among granular insecticide formulations, chlorantraniliprole 0.4 GR at 10 kg/ha and fipronil 0.3 GR at 12 kg/ha have proven effective against stem borers and leaf folders. In cases where both leaf folder and stem borer are present, spray formulations such as cartap hydrochloride 50 SP at 750 g/ha, fipronil 5 SC at 1500 ml/ha and rynaxypyr 20 SC at 150 ml/ha are recommended (Seni and Naik, 2020). For controlling plant and leaf hoppers, flonicamid 50 WG at 150 g/ha, pymetrozine 50 WG at 300 g/ha, and triflumezopyrim 10 SC at 240 ml/ha have shown high efficacy (Seni and Naik, 2017; Seni *et al.*, 2019; Seni and Naik, 2020). Insecticides should be used by farmers as a last resort to prevent economic damage to rice crops.

Modern techniques and novel approaches for the control of rice pest

Host plant resistance

Host Plant Resistance (HPR) plays a crucial role in crop insect pest and disease management. As the cornerstone of integrated pest management (IPM), HPR contributes to enhancing agricultural productivity to meet the demands of a growing global population (Godfray *et al.*, 2010). Resistant crop varieties offer an efficient and cost-effective strategy for controlling insect pests and diseases. The identification and deployment of new resistance genes and quantitative trait loci (QTLs) require continuous efforts to counter virulent pest and pathogen biotypes. Understanding the genetic diversity and variability within pest and pathogen populations remains a critical factor in ensuring the long-term effectiveness and durability of host plant resistance.

Exploration and deployment of new sources of resistance from wild and cultivated species

Wild species serve as crucial reservoirs of host plant resistance (HPR) genes and quantitative trait loci (QTLs) for insect pests and diseases, harbouring diverse gene pools with significant resistance traits. Genotypes exhibiting strong resistance are essential for wide-hybridization programs aimed at enhancing tolerance to biotic stressors. However, breeding efforts often face challenges due to incompatibility issues, particularly among divergent taxa, and the association of resistance genes with undesirable agronomic traits. The introgression of resistance genes from wild relatives has been linked to reduced yield, poor grain quality, and undesirable plant architecture (Tanksley and McCouch, 1997). Despite these constraints, recent studies indicate that certain wild species possess genetic components that not only confer pest resistance but also improve agronomic performance.

Genome-wide association studies (GWAS) have identified significant loci associated with brown planthopper (BPH) resistance, including key candidate genes involved in receptor-like protein kinase (RLK), NB-LRR, and LRR protein functions, with two novel loci discovered (Zhou *et al.*, 2024). Genomic selection models, particularly the random forest model, achieved a prediction accuracy of 0.633 for BPH resistance, which improved with an increasing number of SNP markers and larger training populations. Feng *et al.* (2019) conducted a GWAS on rice black-streaked dwarf virus (RBSDV) resistance in the RDP1 cultivar panel using a 44K SNP array. Their study revealed that less than 15% of cultivars were resistant, with aus, indica, and tropical japonica sub-populations showing greater resistance than aromatic and temperate japonica sub-populations. Four varieties exhibited stable RBSDV resistance across multiple environments, with GWAS identifying 84 SNP loci linked to resistance and 13 QTLs, including qRBSDV-

4.2 and qRBSDV-6.3, which conferred stable resistance across field conditions. Notably, qRBSDV-6.3 reduced disease severity by 20% and its introgression into susceptible cultivars via marker-assisted selection successfully enhanced resistance.

Further GWAS studies identified 3,502 SNPs and 59 loci associated with resistance to three BPH biotypes, including the newly identified Bph37 gene, with evidence of ancient balancing selection at resistance-associated loci, particularly in response to virulent BPH biotypes II and III (Zhou *et al*., 2024). High-SNP-density regions on chromosomes 4 and 6 were enriched with resistance loci, potentially retained from *Oryza nivara*. Shi *et al*. (2023) evaluated 123 rice varieties for BPH resistance, identifying three immune and nine highly resistant varieties. Whole-genome resequencing revealed 1,897,845 SNPs, with linkage disequilibrium (LD) decay occurring at approximately 233 kb. A GWAS using the Fast-MLM model identified a major QTL on chromosome 2, containing 13 candidate genes, including those with leucine-rich repeat and CC-NBS-LRR or NB-ARC domains, potentially contributing to pest resistance. Among them, LOC_Os02g27540 exhibited high expression upon BPH induction, highlighting its role in durable BPH resistance. These findings provide critical genetic resources for developing resilient rice varieties with enhanced pest resistance.

Application of molecular markers in host plant resistance against insect pest

Over the past several decades, various molecular techniques have been developed and successfully applied to characterize genetic diversity, detect DNA sequence polymorphisms, perform genome sequencing and fingerprinting, map genes and quantitative trait loci (QTLs), conduct population genetics studies, and facilitate plant breeding. Molecular markers have been instrumental in constructing high-density genetic linkage maps for rice (Sharma *et al*., 2009). Traditionally, breeding programs require six generations to introgress pest and pathogen resistance traits from donor sources into high-yielding cultivars. However, molecular marker-assisted selection (MAS) has significantly reduced the time and resources required for resistance breeding by streamlining the transfer of desired traits from wild sources (Sharma *et al*., 2009).

Advanced breeding populations such as near-isogenic lines (NILs), recombinant inbred lines (RILs), F, populations, and backcross populations, along with doubled haploid technologies, have been extensively utilized in rice gene mapping programs (Mohan *et al*., 1997; Sharma *et al*., 2009). Several DNA markers, including Random Amplified Polymorphic DNA (RAPD), Restriction Fragment Length Polymorphism (RFLP), Amplified Fragment Length Polymorphism (AFLP), Simple Sequence Repeats (SSRs)/microsatellites, Sequence Tagged Sites (STS) and Single Nucleotide Polymorphisms (SNPs), have been widely used for molecular characterization of rice genotypes (Botstein *et al*., 1980; Williams *et al*., 1990; Vos *et al*., 1995). These markers have been successfully employed in identifying resistance genes and QTLs for major rice pests, including stem borers (Mohan *et al*., 1994; Jain *et al*., 2004), brown planthopper (Sharma *et al*., 2002; Jena *et al*., 2010) and gall midge (Du *et al*., 2020). The integration of molecular marker technologies with conventional breeding strategies has greatly enhanced the efficiency of rice improvement programs, facilitating the development of resistant cultivars with minimal linkage drag.

Marker-assisted selection (MAS) is a breeding strategy that utilizes molecular markers linked to desired traits for the indirect selection of superior genotypes (Wakchaure *et al*., 2015; Rani *et al*., 2014). MAS is particularly beneficial for traits that are challenging or expensive to measure, exhibit low heritability, or are controlled by recessive alleles (Wakchaure *et al*., 2015). This approach facilitates the precise transfer of specific genomic regions while expediting the recovery of the recurrent parent genome in breeding programs (Babu *et al*., 2004). MAS has been successfully applied to both simple and complex traits, with more widespread implementation in the former (Babu *et al*., 2004; Collard and Mackill, 2008). It offers several advantages, including early-stage screening, cost reduction, and increased selection precision (Shrestha *et al*., 2020).

MAS has been extensively employed in crop improvement programs to enhance various agronomic traits across cereals, legumes, and oilseeds. In cereals such as wheat, maize and rice, MAS has facilitated the improvement of disease resistance, insect resistance, abiotic stress tolerance and yield components (Liu *et al*., 2007). In rice breeding, MAS has played a crucial role in incorporating resistance against bacterial blight and blast disease (Henkrar, 2020). Furthermore, MAS has been instrumental in germplasm characterization, genetic diversity analysis, and targeted trait improvement in pulses, oilseeds and fiber crops (Kumawat *et al*., 2020).

In rice, MAS has emerged as a promising tool for developing varieties resistant to insect pests, particularly the brown planthopper (BPH). The Bph3 gene, mapped to chromosome 4, has been successfully introgressed into susceptible rice lines, significantly enhancing their BPH resistance (Qing *et al*., 2019). Similarly, Prahalada *et al*. (2017) identified BPH31 on chromosome 3, while pyramiding Bph14 and Bph15 genes resulted in superior BPH resistance (Jiang *et al*., 2018). These MAS-derived resistant lines exhibit not only improved pest resistance but also maintain yield potential comparable to their susceptible counterparts (Jiang *et al*., 2018). This approach has been effective in developing varieties resistant to multiple BPH biotypes (Qing-li *et al*., 2011). The use of DNA markers linked to resistance genes allows for efficient screening of breeding populations and the development of broad-spectrum resistant cultivars (Jena and Mackill, 2008).

Recent studies have identified several SSR markers significantly associated with BPH resistance, including RM401, RM5953, and RM217, which contribute to phenotypic variation in resistance to BPH biotypes 2 and 3 (Shabanimofrad *et al*., 2015). Researchers have successfully introgressed and pyramided multiple BPH resistance genes, such as Bph3, Bph27(t), Bph14, and Bph15, into elite rice cultivars using MAS, thereby improving resistance and minimizing yield losses (Liu *et al*., 2016; Xu, 2013). MAS has also been employed in identifying genomic regions associated with gall midge resistance, such as the gm3 gene linked to marker RM17480 on chromosome 4 (Sahu *et al*., 2023). Additionally, MAS has facilitated the introduction of multiple resistance genes, including Gm8 for gall midge resistance, into elite Indian rice varieties like Naveen (Ramayya *et al*., 2021). Similarly, the Gm4 gene has been successfully incorporated into the Tellahamsa cultivar along with bacterial blight resistance (Hari *et al*., 2022). These advancements underscore the potential of MAS as a powerful tool for rice breeders in developing high-yielding, stress-resistant cultivars capable of withstanding evolving pest pressures.

RNAi for pest management

Crop damage and losses due to insect pests' amount to billions of dollars annually, with heavy reliance on synthetic chemical insecticides leading to unintended consequences such as insect resistance, non-target effects on beneficial insects, and environmental pollution (Kumar *et al*., 2019). Therefore, a major focus of researchers is to develop more target-specific pest management strategies, one of which is RNA interference (RNAi). RNAi is an emerging technology that silences key genes in insects or plants, offering a highly specific and environmentally friendly alternative to synthetic chemical pesticides, leading to selective mortality of target species (Joga *et al*., 2016; Christiaens *et al*., 2020). Originally tested in *Caenorhabditis* worms (Fire et al., 1998), RNAi functions by down-regulating gene expression through post-transcriptional gene silencing using artificial RNA molecules (Whangbo and Hunter, 2008).

RNAi technology provides a suite of molecular tools with diverse applications in genetic studies and agriculture, including the protection of beneficial insects from viruses and parasites (Hunter *et al*., 2010; Zotti and Smagghe, 2015), pest resistance management (Zhu *et al*., 2014), and plant defence against insect pests (Huvenne and Smagghe, 2010; Joga *et al*., 2016; San Miguel and Scott, 2016; Andrade and Hunter, 2016). This technology enables the silencing of genes crucial for insect development, reproduction, and insecticide detoxification (Jindal and Grover, 2019). It has been effectively utilized to identify and validate genes encoding insecticide target proteins and to study mechanisms of insecticide resistance (Kim *et al*., 2015).

RNA silencing is a homology-based process initiated by double-stranded RNA (dsRNA), leading to gene expression suppression. Initially discovered in plants, RNA silencing was hypothesised to function as a defence mechanism against viruses (Lindbo, 2012). It operates at three distinct levels in plants: (i) cytoplasmic silencing via dsRNA, resulting in mRNA cleavage, known as post-transcriptional gene silencing (PTGS); (ii) micro-RNAs (miRNAs) regulating endogenous mRNAs through base-pairing, leading to RNA cleavage or inhibition of protein translation; and (iii) transcriptional gene silencing (TGS), wherein sequence-specific DNA methylation suppresses transcription.

The RNA interference (RNAi) mechanism specifically targets and degrades RNAs, utilizing either exogenous/endogenous small interfering RNA (siRNA) or endogenous microRNA (miRNA). While siRNAs are double-stranded, miRNAs are single-stranded and both function as ~21 nucleotide RNA duplexes that induce mRNA silencing. However, they differ in precursor structures, biogenesis pathways and modes of action (Wang *et al*., 2021). SiRNAs typically lead to the direct cleavage of fully complementary target RNAs, whereas miRNAs induce translational inhibition and exonucleolytic decay due to partial complementarity (Neumeier and Meister, 2021). MiRNA-based approaches may offer advantages over siRNA, including reduced off-target effects and the potential to regulate multiple genes simultaneously (Wang *et al*., 2021).

RNAi-based strategies have shown potential against various rice insect pests, including the brown planthopper (*Nilaparvata lugens*) and the striped stem borer (*Chilo suppressalis*). Transgenic rice plants expressing dsRNA targeting insect genes have demonstrated significant impacts on pest survival and reproduction (Yu *et al.*, 2014; Mao *et al.*, 2021; Zha *et al.*, 2011). Effective target genes include the ecdysone receptor (EcR) in *N. lugens* and a small heat shock protein gene (CssHsp) in *C. suppressalis* (Yu *et al.*, 2014; Mao *et al.*, 2021). Additionally, nanomaterial-wrapped dsRNA targeting the *CYP15C1* gene in *C. suppressalis* has demonstrated enhanced efficacy compared to naked dsRNA (Sun *et al.*, 2020).

Shen *et al*. (2021) identified three ferritin genes in *N. lugens*: ferritin 1 Heavy Chain (NlFer1), ferritin 2 Light Chain (NlFer2), and soma ferritin (Nlsoma-Fer). RNAi-mediated knockdown of *Nlsoma-Fer* resulted in < 14% mortality, whereas silencing *NlFer1* or *NlFer2* led to retarded growth, 100% mortality in young nymphs, undeveloped ovaries in newly emerged females, extremely low fecundity, and a zero hatching rate due to inhibited oocyte growth. These findings suggest that *NlFer1* and *NlFer2* are essential for *N. lugens* development and reproduction and may serve as promising targets for RNAi-based pest management.

Furthermore, Zheng *et al*. (2021) developed a transgenic rice line, 'csu260,' for striped stem borer (*C. suppressalis*) resistance using miRNA expression technology. This line expresses CSU-novel-miR260, an endogenous miRNA that inhibits ecdysteroid production in SSB, thereby disrupting its development and reproduction.At 35 days after feeding, larval mortality in *csu260-16* and *csu260-18* engineered rice-fed SSB larvae was 55.6% and 53.3%, respectively, compared to only 20% in control larvae. Additionally, repeated feeding of SSB larvae with transgenic rice expressing the SSB-specific miRNA candidate *csu-novel-miR15* (*csu-15* rice) delayed pupation by four days (Jiang *et al*., 2017). While these studies highlight the potential of RNAi-based pest control in rice, careful selection of target genes and optimization of dsRNA delivery methods are essential for effective field-level pest management. Unlike conventional insecticides, targeting fundamental cellular processes such as gene expression and protein homeostasis has shown high efficacy (Buer *et al*., 2024).

Despite its promise, challenges such as potential off-target effects and the need for efficient delivery systems remain (Munawar, 2023). Recent advancements have focused on improving RNAi efficiency through optimized target gene selection, dsRNA design refinement, and enhanced delivery technologies (Silver *et al*., 2021). Approaches such as dsRNA encapsulation and microbial or plant-based dsRNA production have been explored to increase stability and cellular uptake. Oral and topical delivery methods targeting key physiological pathways—such as energy metabolism, hormone regulation, and insecticide resistance—offer potential for field applications (Lu *et al*., 2023). RNAi-based solutions, including genetically modified crops and foliar spray formulations, are emerging as viable alternatives for pest management (Lu *et al*., 2023). Future research should focus on enhancing RNAi efficacy while minimizing off-target effects, ensuring its compatibility with integrated pest management strategies (Willow *et al*., 2021).

CRISPR/CAS approach for pest management

Though pesticides were effective at controlling pests, the detrimental environmental impact and pesticide resistance were key issues (Damalas and Eleftherohorinos, 2011). Recently, genome editing technology, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)/ Cas (CRISPR-associated protein) has gained popularity due to its precision and efficiency in understanding the biological function of genes in crop plants (Ishino *et al*., 2018). Furthermore, CRISPR-Cas is more robust in terms of total gene knockdown than RNAi, which induces partial gene silencing (Shelake *et al*., 2019) and has higher specificity (Brandt and Barrangou, 2019). In rice, serotonin is known to increase attractiveness to brown planthopper (BPH) nymphs, enhances their feeding behaviour, and promotes their survival (Chen *et al*., 2022). In contrast, salicylic acid (SA) levels increased in resistant rice varieties after BPH infestation, suggesting SA's importance in BPH resistance (Li *et al*., 2017). The use of the CRISPR/Cas tool to knock out the cytochrome P450 gene, CYP71A1, which encodes tryptamine 5-hydroxylase which catalyzes the conversion of tryptamine to serotonin, resulted in decreased serotonin and elevated SA levels in rice plants, conferring enhanced resistance against the brown planthopper, the most notorious pest of rice (Lu *et al*., 2018). *NlCSAD*-edited mutants created using CRISPR/Cas9 exhibited darker pigmentation with homozygous mutants showing fewer eggs and lower hatchability compared to heterozygotes. This study establishes *NlCSAD* as essential for normal pigmentation and reproductive traits, highlighting its potential as a visible marker for genetic manipulation in pest management strategies for *N. lugens* (Chen *et al*., 2021). Using CRISPR/Cas9 with HDR, Zhang *et al*. (2024) generated a knock-in homozygous strain (Nl-G932C) confirming this mutation confers a 94.9-fold resistance to buprofezin, though field strains showed higher resistance (2078.8-fold), indicating additional mechanisms. This is the first study to use CRISPR in hemipteran insects to validate a mutation's role in pesticide resistance, providing a foundation for resistance management strategies. Since limited information is available on the genome editing application using CRISPR/CAS the use of this tool in rice insect pest management holds a bright prospective.

Nanotechnology in plant protection

Nanoparticles with different properties can play an important role in agriculture, particularly crop protection (Adenubi *et al*., 2024). There has been an increase in research on nanotechnology in agriculture in recent years, as evidenced by the number of patents registered and publications published in this sector (Yata *et al*., 2017). Nano-based kits can treat plant diseases, nano-sensors can detect crop pests, and nano-pesticides can be used to manage pests in an effective and environmentally benign manner.

In general, nanotechnology in agriculture does not exactly adhere to the size dimension (100nm in any one dimension), but the product-saving features connected with the small size fall under the purview of nanotechnology. Nanotechnology pesticide applications can minimize the dose, enhance plant absorption, and deliver pesticides to the intended target. This will lower the total amount of pesticides used, saving money while also being environmentally friendly (Yousef *et al*., 2023). Pesticide requirements will be reduced due to the smaller size of nano-pesticides with a large surface area, which will result in greater absorption (Zannat et al., 2021). As a result, nanotechnology is commonly promoted as harmless to the environment (Kah, 2015; Liu and Lal, 2015). Inorganic nano-materials with the ability to kill pests, such as nano-silica, nano-copper, nano-silver, nano-zinc, and nano-aluminium, are one class of nano pesticides for pest management (Kah and Hofmann, 2014; Adak *et al*., 2020). While nanometal pesticides may not have much potential as plant protection agents, pesticide formulation employing nanotechnology has the potential to revolutionize the future of pesticide formulation technology. The recent interest in organic-based nanomaterials as formulation adjuvants is gaining traction. Amphiphilic polymer-based nano-formulations of several pesticides, such as carbofuran, imidacloprid, thiamethoxam and others are being developed for longer residual life and maintained efficacy (Shakil *et al*., 2010; Adak *et al*., 2012). These polymers self-assemble into nano micelles (10-300 nm) in aqueous media, offering controlled release of pesticides (Sarkar *et al*., 2023). Poly (ethylene glycol) —based ACPs have shown efficacy in developing nano formulations for various pesticides, including mancozeb and imidacloprid (Majumder *et al*., 2020; Adak *et al*., 2012). These formulations demonstrate improved pest management with reduced pesticide doses compared to conventional formulations. Recent research has explored renewable plant oil-based polymers as sustainable alternatives to petroleum-based nanocarriers, with bottlebrush copolymers showing superior loading capacity and sustained release efficacy (Wang *et al*., 2022). Despite their potential, ACP-based pesticide nano formulations face challenges such as limited loading capacity and lack of biosafety data (Sarkar *et al*., 2023).

Pesticide nano-emulsions containing botanicals may have increased efficacy and targeted activity (Adak *et al*., 2019). Nano-emulsions containing glyphosate, acephate, eucalyptus oil and neem oil outperform traditional formulations (Anjali *et al*., 2012; Jiang *et al*., 2012). Another area of the formulation is nano-composites, which trap volatile compounds such as essential oils and pheromones for gradual release (Abreu *et al*., 2012; Bhagat *et al*., 2013). Through the prolonged release of active components, nano-pesticide formulations can improve the solubility of poorly soluble compounds, defend against hostile environments and reduce losses.

Despite substantial developments in agricultural nanotechnology application techniques, a few difficulties must be addressed more efficiently. More research is needed to develop hybrid carriers for pesticide and fertilizer delivery that adhere to green chemistry and environmental sustainability principles to maximize their efficiency. The current technology is on a laboratory scale and is not cost-effective. As a result, solutions will be developed at the industrial level to lower the cost of preparation. The risk and lifecycle evaluation of nano-pesticides should be verified, and adequate nanomaterials legislation should be implemented.

Microbial biopesticides

The persistence of hazardous contaminants has heightened global environmental challenges, threatening countless species survival. Traditional chemical and physical remediation methods are often costly and environmentally damaging, leading to a growing preference for bioremediation through genetically engineered microbes (GEMs). Microbial biopesticides are emerging as a sustainable alternative to chemical pesticides in agriculture, offering environmental safety and pest control efficacy (Manda *et al*., 2020; Kumari *et al*., 2022). These engineered organisms outperform natural microbes in adaptability and degradation speed, offering a safer and more sustainable solution for environmental remediation (Rafeeq *et al*., 2023). The global biopesticide market is valued at approximately $3 billion, accounting for 5% of the total crop protection market (Damalas and Koutroubas, 2018). India's biopesticide market is also expanding, with microbials comprising about 5% of the pesticide market and 970 microbial formulations registered (Kumar *et al*., 2019). Entomopathogenic bacteria (EPBs), particularly from families like Bacillaceae and Pseudomonadaceae, are essential in pest control, with Bacillus thuringiensis (Bt) being the most prominent (Karabörklü *et al*., 2022). However, due to rising insect resistance to Bt toxins, alternatives from the Pseudomonadaceae and Enterobacteriaceae families are being explored. Genetic engineering efforts on EPBs, such as *Bacillus*, *Pseudomonas* and *Serratia* aim to create new toxin combinations, expanding the target pest range for more effective control (Azizoglu *et al*., 2020). Entomopathogenic fungi (EPF) like *Beauveria*, *Metarhizium*, *Lecanicillium* and *Isaria* are increasingly used to manage crop pests due to their safety, environmental sustainability and specificity (Bergman *et al*., 2019). EPFs insect pests by degrading their cuticle and proliferating in hemolymph, ultimately causing death. They offer cost-effectiveness, minimal residual impact, and overcome insect resistance issues. Commercial EPF formulations (liquid, powder, granules) are available globally, with optimized storage conditions required for efficacy (Sinha *et al*., 2016; Sharma *et al*., 2023). Advances in biotechnology may further enhance EPF effectiveness, supporting sustainable agriculture. Genetic engineering enhances viral insecticides by accelerating the killing time and boosting their pesticidal potential (Agboola *et al*., 2022; Yu *et al*., 2023). Research has focused on genetically engineered recombinant viruses that reduce the lethal time (LT50) and lethal dose (LD50) of viral pathogens like baculoviruses, they initiate infection in the insect midgut and then spread the infection to other tissues throughout the insect, thereby increasing virulence and potentially expanding host ranges. This approach aims to make viral biocontrol agents faster-acting and more effective, ultimately reducing crop damage and improving pest control outcomes (Yu *et al*., 2023). Historical development of *Bacillus thuringiensis* (Bt) as a biocontrol agent, detailing the classification of Cry proteins, their specific modes of action against various insect pests, and the integration of cry genes into plants to create transgenic Bt crops like cotton, potato, and maize (Kumar *et al*., 2021). The study by Lian *et al.* (2022), demonstrates the development of insecticide-tolerant *Trichogramma* strains (*T. japonicum* and *T. chilonis*) through exposure to sub-lethal doses of insecticides targeting rice planthoppers. *T. japonicum* showed the highest tolerance to imidacloprid (17.8-fold) after multiple treatments, indicating its potential for integrated pest management (IPM) in rice fields where insecticides are used, enhancing compatibility with chemical control strategies. In India, eight microbial pesticides have been registered, comprising five bacteria (four *Bacillus* spp. and one *Pseudomonas fluorescens*), three fungi (*Trichoderma* spp. and *Beauveria bassiana*), and one virus (Nuclear Polyhedrosis Virus, NPV). Research on other microbial insecticides in rice is limited, with a few studies evaluating *Beauveria bassiana* products against rice leaf folder but with limited success (Katti *et al*., 2023).

Conclusion

The future of managing rice pests lies in the effective integration of advanced scientific techniques with traditional breeding methods. Research should continue to focus on discovering new pest-resistant genes and quantitative trait loci (QTLs), and the development of varieties with stacked resistance genes to ensure long-term pest control. RNA interference (RNAi) offers a promising, environmentally friendly alternative to chemical pesticides by targeting specific genes to disrupt pest growth, reproduction, and survival. Genome editing technologies, such as CRISPR/Cas9, provide precise and efficient methods for enhancing resistance against pests like the brown planthopper (BPH) and gall midge. Additionally, the potential of nanotechnology in targeted pesticide delivery and controlled release systems offers significant advantages in improving pest management sustainability. By combining these innovative strategies with integrated pest management approaches, rice farming can achieve enhanced resilience, productivity and environmental sustainability, ensuring food security for future generations.

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