

Supplementary Table 1. Bioactive compounds and multi-dimensional modes of action of botanical insecticides against rice insect pests.

Plant Species	Bioactive Compound	Mechanism of Action	Affected Insect System	References
<i>Azadirachta indica</i> A. Juss.	Azadirachtin	Disrupts ecdysteroid titers to cause ecdysis failure, while acting as a primary gustatory deterrent via chemosensory receptors.	Endocrine and gustatory systems	Katti, 2013 Sutherland et al., 2002 Pinheiro & Quintela, 2010 Jordán-Sánchez, 2020
<i>Lonchocarpus</i> spp. and <i>Derris</i> spp.	Rotenone	Shuts down cellular respiration by binding to iron-sulfur clusters, which blocks electron transport at mitochondrial complex I.	Mitochondrial respiratory chain	Guleria & Tikku, 2009
<i>Ryania</i> spp.	Ryanodine	Modulates and interferes with calcium channels within muscle tissues.	Neuromuscular/ Mitochondrial system	Das & Yadav, 2024
<i>Calotropis gigantea</i> (L.) W.T. Aiton	Saponins	Expresses antifeedant properties and destabilises cellular membranes.	Cellular membranes and ecdysteroid synthesis	Deolall et al., 2022 Roopashree & Naik, 2019
<i>Allium sativum</i> L.	Allicin; Diallyl sulphide	Exhibits repellent and antifeedant effects alongside bactericidal and fungicidal activity.	Olfactory, gustatory, and digestive tissues	Prowse et al., 2006
<i>Cymbopogon nardus</i> (L.) Rendle	Monoterpenes (Citronellal, Limonene, Geraniol)	Repels pests and disrupts neural and endocrine signalling.	Central nervous and endocrine networks	Telaumbanua et al., 2021
<i>Cedrus</i> spp. and <i>Eucalyptus</i> spp.	Essential oils	Interacts with and modulates octopaminergic receptors	Sympathetic Octopaminergic system	Danna et al., 2024; Rajpoot et al., 2020
<i>Mentha</i> spp. and <i>Lavandula</i> spp.	Essential oils	Inhibits acetylcholinesterase (AChE) and induces metabolic dysfunction.	Cholinergic synapses and cell membranes	Bosly, 2013
<i>Thymus vulgaris</i> L.	Thymol	Exerts fumigant action that blocks octopamine receptors via tyramine cascades.	Octopaminergic system	Jung et al., 2025
<i>Schoenocaulon officinale</i> (Schltld. & Cham.) A. Gray	Veratridine and Cevadine	Causes nerve poisoning by altering nerve cell membrane permeability.	Nervous/ Mitochondrial system	Guleria & Tikku, 2009
<i>Nicotiana</i> spp., <i>Haloxylon salicornicum</i> (Moq.) Bunge, and <i>Stemona japonica</i> (Blume) Miq.	Nicotine	Acts as an agonist or antagonist at nicotinic acetylcholine receptors.	Cholinergic system	Das & Yadav, 2024

Plant Species	Bioactive Compound	Mechanism of Action	Affected Insect System	References
<i>Tanacetum cinerariifolium</i> (Trevir.) Sch. Bip. (Syn: <i>Chrysanthemum cinerariifolium</i>)	Pyrethrin	Disrupts sodium and potassium ion exchange mechanisms within nerve fibres.	Nervous/ Mitochondrial system	Das & Yadav, 2024
<i>Nicotiana tabacum</i> L.	Nicotine	Mimics acetylcholine, leading to lethal overstimulation of the nervous system.	Central and peripheral nervous systems	Sarkar & Lim, 2018
<i>Datura</i> spp.	Hyoscyamine, Atropine, and Scopolamine	Exhibits repellent and cytotoxic effects to deter oviposition.	Nervous and metabolic systems	Devi et al., 2011; Zimmermann et al., 2021
<i>Calotropis</i> spp.	Calatropin and Calotoxin	Regulates growth and repels pests via proteolytic enzyme interaction.	Cardiac and growth systems	Jency et al., 2013 Suresh Kumar et al., 2013
<i>Justicia adhatoda</i> L. (Syn: <i>Adhatoda vasica</i>).	Vasicine, Vasicinone, and Adhatodin	Induces larval-pupal toxicity and disrupts reproductive cycles.	Reproductive and developmental systems	Emimal Victoria, 2010 Nandre et al., 2012
<i>Pongamia pinnata</i> (L.) Pierre	Karanjin	Functions as a stomach poison, juvenile hormone analogue, and antifeedant.	Digestive and developmental systems	Kumar, 2006
<i>Lantana camara</i> L.	Lantanolic acid and Lantic acid	Induces oxidative stress and mitochondrial damage leading to enzyme inhibition.	Mitochondrial and metabolic systems	Nirmal et al., 2009

Supplementary Table 2. Morphological and biochemical traits associated with host plant resistance against major insect pests in diverse rice (*Oryza sativa* L.) cultivars.

Category	Resistance Traits	Insect Pests	References
Morphological	Dense, elongated trichomes on rice nodes that physically block female insects from successfully attaching and laying eggs.	Rice gall midge (<i>Orseolia oryzae</i> (Wood-Mason))	Nawaz et al., 2022
	Exceptionally tight, compacted panicle architectures in the IR36 variety that limit the physical space available for egg deposition.	Yellow stemborer (<i>Scirpophaga incertulas</i> (Walker))	Samal et al., 2021
	Highly lignified, rigid culms in the "TNAU Samba Sub1" cultivar that act as structural barriers to restrict boring and oviposition.	Yellow stemborer (<i>Scirpophaga incertulas</i> (Walker))	Chander, 2022
	Increased tillering capacity that spreads feeding injuries across a larger stem volume, reducing overall localized pest pressure.	Rice leaffolder (<i>Cnaphalocrocis medinalis</i> (Guenée)) and yellow stemborer (<i>Scirpophaga incertulas</i> (Walker))	Samal et al., 2021
	Distinctive foliar pigmentations and atypical leaf colorations that serve as visual antixenotic deterrents, throwing off host selection.	Brown planthopper (<i>Nilaparvata lugens</i> (Stål)) and rice leaffolder (<i>Cnaphalocrocis medinalis</i> (Guenée))	Mookiah et al., 2021 Roy et al., 2022
	Reduced total leaf surface area and lower leaf counts that minimize the absolute feeding space and food availability.	Brown planthopper (<i>Nilaparvata lugens</i> (Stål))	Muduli et al., 2023
	High epidermal trichome densities that physically impede stylet penetration and disrupt the movement of young nymphs.	Brown planthopper (<i>Nilaparvata lugens</i> (Stål))	Khetnon et al., 2022
	High density of vascular bundles and silicified microstructures in the RG109 variety which reduce penetration and oviposition	Yellow stemborer (<i>Scirpophaga incertulas</i> (Walker))	Natarajan et al., 2022
Biochemical	Upregulated synthesis of oxidative enzymes, including peroxidase, polyphenol oxidase, catalase, and superoxide dismutase, in traditional red rice.	Brown planthopper (<i>Nilaparvata lugens</i> (Stål))	Pati et al., 2023
	Accumulation of total phenols, soluble proteins, and crude silica that reduce phloem sap ingestion and inhibit insect digestive enzymes.	Brown planthopper (<i>Nilaparvata lugens</i> (Stål))	Pati et al., 2023
	Inducible production of lytic enzymes, specifically chitinases and glucanases, that break down the protective chitinous lining of the insect gut.	Rice gall midge (<i>Orseolia oryzae</i> (Wood-Mason))	Vaghela et al., 2022
	Synthesis of specialized diterpenoid phytoalexins, including momilactones and phytocassanes, that act as internal feeding deterrents.	Rice leaffolder (<i>Cnaphalocrocis medinalis</i> (Guenée))	Ramadass & Thiagarajan, 2021
	Increased levels of condensed tannins, ortho-dihydroxy phenols, and	Rice leaffolder (<i>Cnaphalocrocis medinalis</i> (Guenée))	Punithavalli et al., 2013

Category	Resistance Traits	Insect Pests	References
	defensive enzymes like phenylalanine ammonia-lyase.		
	Rapid induction of the jasmonic acid pathway, triggering downstream defensive traits that systematically disrupt larval weight gain.	Rice leaffolder (<i>Cnaphalocrocis medinalis</i> (Guenée))	Roy et al., 2023
	High systemic concentrations of hydroxycinnamic acids, including ferulic, caffeic, and p-coumaric acids, which impair gut function.	Yellow stemborer (<i>Scirpophaga incertulas</i> (Walker)) and rice gall midge (<i>Orseolia oryzae</i> (Wood-Mason))	Sahu et al., 2024
	Accumulation of plant proteinase inhibitors that bind tightly to insect digestive proteases, causing severe nutrient deprivation.	Yellow stemborer (<i>Scirpophaga incertulas</i> (Walker)), rice gall midge (<i>Orseolia oryzae</i> (Wood-Mason)), and rice leaffolder (<i>Cnaphalocrocis medinalis</i> (Guenée))	Divekar et al., 2023
	Intentionally low tissue nitrogen content, which acts as a nutritional bottleneck to slow down rapid population buildup.	White-backed planthopper (<i>Sogatella furcifera</i> (Horvath))	Suri & Singh, 2011

Supplementary Table 3. Nature-based solutions and their multifaceted mechanisms for managing rice stemborers (*Scirpophaga incertulas* and *Chilo suppressalis*).

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Augmentative Biological Control	<i>Trichogramma japonicum</i> Ashmead (Hymenoptera: Trichogrammatidae) and <i>Telenomus</i> spp. (Hymenoptera: Scelionidae)	Egg parasitism prevents larval hatching by consuming the host embryo from within the egg mass.	Egg	Rai <i>et al.</i> , 2022 Hajjar <i>et al.</i> , 2023 Yuan, <i>et al.</i> , 2012
Interspecific Competition	<i>Spodoptera frugiperda</i> (J.E. Smith) (Lepidoptera: Noctuidae)	High larval densities of this polyphagous invader cause severe interspecific food competition, which appears to crowd out native borers from shared whorl tissues.	Larva	Divya <i>et al.</i> , 2021
Ecological Engineering	Nectar-rich border crops, such as cowpea (<i>Vigna unguiculata</i> (L.) Walp.)	Establishing flowering borders provides accessible floral nectar, which refuels adult parasitoids, extending their field longevity and egg-laying capacity.	Adult (Parasitoid support)	Singh & Rai, 2023 Hajjar <i>et al.</i> , 2023 Zhu <i>et al.</i> , 2015
Habitat Diversification	Trap cropping, such as Napier grass (<i>Cenchrus purpureus</i> (Schumach.) Morrone)	An aromatic pull strategy coaxes female moths to lay eggs on an alternative host that looks attractive but fails to support larval tunneling and survival.	Adult and Larva	Khan <i>et al.</i> , 2004
Cultural Control	Post-harvest tillage and strategic pre-sowing flooding	Deep plowing mechanically breaks up stubble shelters, while subsequent flooding drowns larvae and pupae trying to ride out the dry season.	Over wintering Larva and Pupa	Lalita <i>et al.</i> , 2025
	Strategic planting density and upright canopy architecture	Optimizing hill spacing thins out the dense canopy, letting in light and dropping localized humidity to make the microclimate less inviting for mating moths.	Adult	January <i>et al.</i> , 2021 Samal <i>et al.</i> , 2021
	Regional synchronous sowing and transplanting	Coordinated regional planting prevents isolated early or late fields from acting as pest magnets, keeping localized populations from compounding.	Future population buildup	Lalita <i>et al.</i> , 2025
Nutrient Management	Site-specific nutrient management	Calibrating nitrogen doses avoids the nitrogen-soaked, ultra-succulent tissue growth that acts as a nutritional fuel for borer outbreaks.	Reproductive cycle and pest buildup	Lalita <i>et al.</i> , 2025 Devi & Sowndarya, 2022
Botanical Interventions	Neem Seed Kernel Extract (5% NSKE) from <i>Azadirachta indica</i> A. Juss.	Acts as an insect growth regulator (IGR) by interfering with ecdysone to disrupt larval moulting.	Larva	Ganesan <i>et al.</i> , 2014 Khan <i>et al.</i> , 1996

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Phytochemical Deterrence	Plant essential oils, including <i>Cedrus</i> spp., <i>Eucalyptus</i> spp., and garlic (<i>Allium sativum</i> L.)	Strong volatile aromatic compounds blanket the crop canopy, masking standard host plant odors to discourage female moths from landing and ovipositing.	Adult	Kumari & Kaushik, 2016
Soil-Mediated Resistance	Silicon and Biochar amendments	Increases silica deposition in stalks, creating a physical barrier that wears down larval mandibles.	Larva	Hall et al. 2020 Hartley et al. 2015 Panda et al., 2022 Natarajan et al., 2022
Induced Immunity	Microbial priming via soil biochar	Introducing biochar alters the rhizosphere microbial mix, turning on systemic acquired resistance paths for faster biochemical defense mobilization.	Larva	Jeer et al. 2018
Animal Husbandry Integration	Rice–duck integration using duck <i>Anas platyrhynchos domesticus</i> L.	Active foraging allows ducks to consume larvae on leaf blades and moths resting within the canopy.	Larva and Adult	Yang, et al., 2004 Long, et al., 2013 Zhu et al., 2015 Hossain et al., 2005 Furuno, 2001 Li et al., 2019
Aquatic Biocontrol	Rice–fish integration using common carp (<i>Cyprinus carpio</i> L.)	Fish prey upon larvae that fall into the water or migrate between tillers during developmental stages.	Larva	Tuan, 1994 Yu et al., 1995 Halwart, 1994 Hendarsih et al., 1994
Microbial Control	<i>Bacillus thuringiensis</i> Berliner (<i>Bt</i>)	Ingested crystalline delta-endotoxins bind tightly to midgut epithelial receptors, puncturing cell walls and causing rapid fatal septicaemia.	Larva	Litsinger et al., 2005 Rombach et al., 1989 Devi & Sowndarya, 2022
Entomopathogenic Fungi	<i>Metarhizium anisopliae</i> (Metsch.) Sorokin and <i>Beauveria bassiana</i> (Bals.) Vuill.	Conidia anchor to the exoskeleton, using mechanical pressure and chitinases to drill through the cuticle and grow through the hemocoel.	Larva and Pupa	Roopan et al., 2023 Majidi-Shilsar, 2017 Dhuyo & Soomro, 2008

Supplementary Table 4. Nature-based solutions and their multifaceted mechanisms for managing rice planthoppers (*Nilaparvata lugens*, *Sogatella furcifera*) and leafhoppers (*Nephotettix virescens*).

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Natural Enemy Conservation	Nectar-rich bund vegetation, such as marigolds (<i>Tagetes erecta</i> L.)	Provides alternative sugar fuels that boost the field density and searching efficiency of the predatory mirid bug, <i>Cyrtorhinus lividipennis</i> Reuter.	Egg and Nymph	Krishnan et al., 2026 Schaller & Nentwig, 2000
Habitat Diversification	Strategic grass bunds and non-crop vegetation refugia	Serves as critical overwintering shelter and alternative prey reservoirs for generalist spiders, like the wolf spider <i>Pardosa pseudoannulata</i> (Bösenberg & Strand).	Nymph and Adult	Schaller et al., 2000 Nentwig et al., 2019
Cultural Control	Crop spacing and plant canopy density management	Alters light penetration and lowers humidity, which appears to disrupt insect movement and induce stress-related antioxidant enzyme imbalances in the pest.	Nymph and Adult	Horgan <i>et al.</i> , 2022 Ishii-Eiteman <i>et al.</i> , 1997 Wang <i>et al.</i> , 2022
	Leaf tip clipping	Manual removal of the leaf apex prior to transplanting to eliminate microhabitats and physically remove hidden egg clusters.	Egg-laying period	Lalita et al., 2025
	Synchronized regional sowing and transplanting schedules	Synchronises sowing and transplanting times to prevent isolated early plots from acting as nurseries for migrating cohorts.	Suppress future population buildup	Lalita et al., 2025
	Alternate Wetting and Drying (AWD) irrigation	Controlled periodic drainage lowers canopy moisture, restricting hemipteran climbing behaviors while reducing overall pest biological fitness and alter the plant's antioxidant enzyme activity.	Nymph and Adult	Horgan <i>et al.</i> , 2022 Ishii-Eiteman <i>et al.</i> , 1997 Wang <i>et al.</i> , 2022 Oyediran & Heinrichs, 2001
Ecological Engineering	Flower strips, including sesame (<i>Sesamum indicum</i> L.)	Parasitoid-optimized nectar strips provide floral sugars that increase longevity and the parasitism rates of specialist egg wasps, such as <i>Anagrus</i> species.	Egg	Segoli & Rosenheim, 2013 Shanker & Billa, 2022
Botanical Interventions	Standardized azadirachtin extracts from <i>Azadirachta indica</i> A. Juss.	Functions as a systemic growth regulator and deterrent, inducing ecdysis failure during nymphal molting and lowering female egg production.	Nymph and Adult	Prakash et al., 1990; 2008 Ganesan et al., 2014 Rajasekaran et al., 1987
Phytochemical Repellency	Essential oils from citronella grass (<i>Cymbopogon nardus</i> (L.) Rendle)	Volatile aromatic terpenes blanket the canopy, interfering with host odor recognition and lowering landing rates of migrating adults.	Adult	Ramaraju & Sundarababu 1989 Rao and Rao, 1979 Saxena et al., 1984 Wang <i>et al.</i> 2015a, 2015b
Physical Plant Defence	Soluble silicon (Si) soil loading	Silica deposition in vascular bundles forms "silica cells" that physically obstruct stylet penetration into the phloem.	Nymph and Adult	Dileep Kumar <i>et al.</i> , 2024 Roy et al., 2023

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Biochemical Resistance	Induced defense via pyrolysis biochar amendments	Soil amendments turn on systemic acquired resistance pathing, inducing the production of defensive plant phenolics that reduces phloem sap quality.	Nymph and Adult	Reynolds <i>et al.</i> , 2016 Liang <i>et al.</i> , 2015 Leroy <i>et al.</i> , 2019 Waqas et al. 2018 Ratnadass et al., 2024
Animal Foraging Integration	Integrated rice–duck co-culture using <i>Anas platyrhynchos domesticus</i> L.	Ducks physically shake the rice canopy, causing hoppers to fall into the water for immediate consumption.	Nymph and Adult	Hossain et al., 2002, 2005, Furuno, 2001 Li et al., 2019
Aquatic Predation	Integrated rice–fish co-culture using common carp (<i>Cyprinus carpio</i> L.)	Fish species (e.g., common carp) prey upon nymphs and adults that fall from the lower stems onto the water surface.	Nymph and Adult	Langhu, 1965, Yu et al., 1995, Tuan, 1993, Halwart, 1994, Hendarsih et al., 1994
Microbial Control	<i>Beauveria bassiana</i> (Bals.) Vuill. and <i>Metarhizium anisopliae</i> (Metsch.) Sorokin	Fungal spores germinate on the cuticle and penetrate the exoskeleton via enzymatic lysis and draining host nutrients from within the hemocoel.	Nymph and Adult	Aguda <i>et al.</i> (1984); Kiran and Veeranna 2012; Li et al., 2012
Varietal Resistance	Traditional landraces and gene-mapped cultivars	Uses specific resistance traits that lack the distinct volatile profiles and chemical cues migrating pests need for suitable host identification.	Nymph and Adult	Pandi et al., 2025
Gene Silencing	Topical RNAi (dsRNA sprays)	Targeted topical applications initiate post-transcriptional gene silencing, knocking out vital metabolic paths to trigger species-specific mortality.	Nymph and Adult	Ge et al., 2015, Shen, et al., 2021

Supplementary Table 5. Nature-based solutions and their multifaceted mechanisms for managing the rice leaffolders (*Cnaphalocrocis medinalis*, *Marasmia patnalis*).

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Augmentative Biocontrol	<i>Trichogramma chilonis</i> Ishii and <i>Trichogramma japonicum</i> Ashmead (Hymenoptera: Trichogrammatidae)	Endoparasitoid wasps inject eggs directly into lepidopteran hosts, destroying the embryo and preventing larval hatching.	Egg	Chhavi et al., 2019 Parera et al., 2015 Wang et al., 2017 Xu et al., 2016
Larval Parasitism	<i>Goniozus</i> spp. (Hymenoptera: Bethyridae) and <i>Cotesia</i> spp. (Hymenoptera: Braconidae)	Penetrates the leaf fold to oviposit on or in the host larvae, eventually killing the larvae.	Larva	Kumar et al., 2013 Saikia et al., 2017
Behaviour Regulation	Synthetic sex pheromones	Disrupts mating through pheromone-mediated communication interference, reducing reproductive cycles, and reducing overall egg-laying.	Adult	Ye et al., 2017 Guo et al., 2019 Mazzoni et al., 2019
Ecological Engineering	Nectar-rich border strips, such as cowpea (<i>Vigna unguiculata</i> (L.) Walp.) and sesame (<i>Sesamum indicum</i> L.)	Provision of floral nectar increases the longevity and searching efficiency of adult parasitoids.	Adult	Zou et al., 2023 Zhu et al., 2015
Habitat Management	Non-crop bund vegetation and structural refugia	Provides alternative hosts and essential shelter for generalist predators like <i>Ophionea</i> species.	Larva and Adult	Desai et al., 2017
Botanical Interventions	Neem Seed Kernel Extract (5% NSKE) from <i>Azadirachta indica</i> A. Juss.	Acts as a juvenile hormone mimic and feeding deterrent to disrupt larval moulting.	Larva	Muralidharan & Pasalu, 2006 Nathan et al., 2006 Nathan et al., 2007
Plant-Derived Oils	Custard apple (<i>Annona squamosa</i> L.) and mahua (<i>Madhuca longifolia</i> (L.) J.F. Macbr.) seed oils (1%)	Coats the foliage to reduce palatability, while structurally interfering with the caterpillar's ability to anchor silk threads and fold leaves.	Larva	Norton et al., 2010
Varietal Traits	High-tillering cultivars	Distributes feeding pressure across more stems, effectively reducing overall pest damage per tiller.	Larva	Samal et al., 2021
	Purple leaf margins varieties	Alters typical foliar spectral reflectance, acting as a visual deterrent that disrupts standard host selection and oviposition cues.	Larva and Adult	Mookiah et al., 2021
Physical Defense	Soluble silicon (Si) and pyrolysis biochar amendments	Facilitates silica accumulation in epidermal cells to toughen leaf tissue and wears down larval mandibles.	Larva	Hou et al., 2015 Panda et al., 2022 Xu, 2008 Han et al., 2015
Nutrient Management	Site-specific Nitrogen Management	Reduces leaf tissue succulence, making the plant less attractive for larval feeding and ovipositing moths.	Larva and Adult	Dan & Chen, 1990 Devi & Sowndarya, 2022 de Kraker et al., 2000

Integrated Systems	Rice–duck co-culture systems using <i>Anas platyrhynchos domesticus</i> L.	Ducks physically dislodge larvae from folded leaves and prey upon both larvae and adult moths in the lower canopy.	Larva and Adult	Furuno, 2001 Hossain et al., 2002, 2005 Huang et al., 2017 Xia, 2019 Chen S, 2021
Aquatic Predation	Rice–fish integration using common carp (<i>Cyprinus carpio</i> L.)	Common carp devour larvae that fall into the water from the leaves by wind, heavy rain, or animal movement.	Larva	Hendarsih et al., 1994 Halwart, 1994 Ji & Chen, 2015 Wu et al, 2016
Microbial Control	<i>Bacillus thuringiensis</i> Berliner (<i>Bt</i>)	Ingested crystalline endotoxins puncture midgut epithelial cells, causing rapid midgut paralysis and lethal septicemia.	Larva	Das et al., 2025
Viral Biopesticides	<i>Cnaphalocrocis medinalis</i> granulovirus (<i>CnmeGV</i>)	Proliferates within the larval tissues, triggering lethal granulosis disease and long-term population suppression.	Larva	Szewczyk et al. 2006 Liu et al., 2013 Xu et al., 2019

Supplementary Table 6. Nature-based solutions and their multifaceted mechanisms for managing the rice gall midge (*Orseolia oryzae*).

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Augmentative Biocontrol	<i>Platygaster oryzae</i> (Cameron) (Hymenoptera: Platygasteridae)	Gregarious egg-larval endoparasitoid wasps inject embryos into midge eggs, allowing the offspring to grow within the host and destroy it inside the silver shoot gall.	Egg and Larva	Shrivastava <i>et al.</i> 1987 Chandrakar <i>et al.</i> (1991) Mardi <i>et al.</i> , 2009 Devi, & Sowndarya, 2022
Pupal Parasitism	<i>Neanastatus cinctiventris</i> Girault (Hymenoptera: Eupelmidae)	Specialist ectoparasitoid targets the midge pupa during its later developmental phase within the gall tube, preventing adult emergence.	Pupa	Li & Chiu, 1951 Kobayashi, <i>et al.</i> , 1990
Ecological Engineering	Nectar-rich border crops, such as marigolds (<i>Tagetes</i> spp.)	Provides energy and nutrients to increase the longevity and searching efficiency of adult parasitoid wasps.	Adult (Parasitoid support)	Zhu <i>et al.</i> , 2023
Varietal Traits	Excessive hairy rice nodes	Dense, elongated trichomes create a mechanical barrier on the stem, which is likely to prevent successful attachment and egg-laying by fragile adult flies.	Adult	Nawaz <i>et al.</i> , 2022
	Specific leaf pigmentations, such as purple leaf margins	Alters typical foliar spectral reflectance, acting as a visual antixenotic deterrent that appears to disrupt standard adult host selection and attraction cues.	Adult	Mookiah <i>et al.</i> , 2021 Pandi <i>et al.</i> , 2025
Phytochemical Repellency	Plant essential oils, including <i>Eucalyptus</i> spp. and cedarwood (<i>Cedrus</i> spp.)	Volatile aromatic terpenes saturate the local canopy, masking the natural chemical indicators of the plant to deter host-seeking flies from landing and oviposition.	Adult	Ladja <i>et al.</i> , 2011
Botanical Interventions	Neem oil (3% to 5%) and Neem Seed Kernel Extract (NSKE) from <i>Azadirachta indica</i> A. Juss.	Absorbed triterpenoids, such as azadirachtin, provide systemic deterrence through the vascular tissue, inducing developmental abnormalities and mortality in larvae and pupae.	Larva and Pupa	Krishnaiah & Kalode, 1984 Lakshmi <i>et al.</i> , 1997 Laskowski <i>et al.</i> , 2019 Litsinger <i>et al.</i> , 2006
Habitat Manipulation	Alternate host management on field margins, such as knotgrass (<i>Paspalum</i> spp. L.)	Regulates initial reservoir populations by eliminating wild grasses that host the midge during the dry fallow seasons.	Larva and Adult	Mardi, <i>et al.</i> , 2009 Devi & Sowndarya, 2022
Agronomical Management	Site-specific Nitrogen Management	Reduces host tissue succulence and rendering the plant physiologically less attractive to ovipositing midges.	Adult and Larva	Devi & Sowndarya, 2022
Escape Strategies	Strategic planting schedules and early-maturing cultivars	Synchronizes the regional crop cycle to ensure that vulnerable early vegetative phases bypass predictable peaks of high rainfall and humidity that drive midge outbreaks.	All Stages	Devi & Sowndarya, 2022

Supplementary Table 7. Nature-based solutions and their multifaceted mechanisms for managing the rice earhead bug (*Leptocorisa* spp.).

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Conservation Biocontrol	<i>Gryon</i> species (Hymenoptera: Scelionidae), <i>Ooencyrtus</i> species (Hymenoptera: Encyrtidae), and <i>Trissolcus</i> species (Hymenoptera: Scelionidae)	Tiny solitary endoparasitoid wasps inject their offspring directly into heteropteran egg clusters, completely destroying the host embryo before the mobile nymphs can emerge.	Egg	Barrion et al., 1981 Huang & Noyes, 1994 Purihit et al., 2013 Kumar & Goswami, 2020
Natural Predation	Tiger beetles, including <i>Cicindela whitthilli</i> Hope, <i>Cicindela flavomaculata</i> Hope, and <i>Cicindela duponti</i> Dejean (Coleoptera: Cicindela)	Aggressive, fast-moving generalist hunters actively prey on young nymphs and adult bugs within the canopy.	Nymph and Adult	Parasappa, et al., 2017 Sinu et al., 2006 Saxena, 1952
Phytochemical Repellency	Piperaceae extracts from Celebes pepper leaf (<i>Piper crocatum</i> Ruiz & Pav.)	Standardized foliar sprays deliver quick behavioral knockdown while releasing strong pungent volatiles that repel adult bugs from settling on the panicles.	Adult	Salaki & Montong, 2019 Nugroho et al., 2020
Botanical Interventions	Neem oil (2% to 3%) and Neem Seed Kernel Extract (5% NSKE) from <i>Azadirachta indica</i> A. Juss.	Functions as a potent antifeedant and growth regulator, reducing stylet probing and feeding on the developing grain milk.	Nymph and Adult	Poudel et al., 2025 Ponnusamy, 2003 Basavaraj Ashokappa, 2011 Durairaj & Venugopal, 1993
Microbial Control	<i>Bacillus thuringiensis</i> Berliner, <i>Metarhizium anisopliae</i> (Metsch.) Sorokin, and <i>Beauveria bassiana</i> (Bals.) Vuill.	Ingested bacterial proteins induce midgut cell lysis, while fungal conidia drill through the outer abdominal cuticle to colonize the hemocoel.	Adult	Poudel et al., 2025 Nguyen & Thi, 2005
Sensory Manipulation	Aromatic olfactory traps using decomposing animal tissues (rotten meat/fish) or foul carcass baits	Utilises strong olfactory cues for carrion odors, using localized traps to lure adult bugs away from the crop for physical removal.	Adult	Taek, 2023 Rahmawati et al., 2026
Habitat Regulation	Alternate host management on field margins, specifically common barnyard grass (<i>Echinochloa crus-galli</i> (L.) Beauv.)	Regulates early migratory populations by clearing or mowing wild reservoir grasses that host the bugs before the primary rice crop reaches the milky phase.	Nymph and Adult	Basavaraj Ashokappa, 2011 Rajapakse & Kulasekera, 1980 Rothschild, 1970 Sands, 1977 Morill et al., 1990
Physical Barrier	Cultivation of long-awned rice (<i>Oryza sativa</i> L.) varieties	Elongated, rigid awns wrap around the glumes, creating a mechanical barrier that prevents the insect from easily aligning its stylets to pierce the grain.	Adult	Pathak & Khan, 1994
Biotic Pressure	Integrated rice–duck co-culture systems using <i>Anas platyrhynchos domesticus</i> L.	Foraging ducks push through the crop rows, creating a physical disturbance that discourages colonization and consuming resting bugs from the lower panicles.	Adult	Hossain et al., 2002, 2005 Furuno, 2001

Supplementary Table 8. Nature-based solutions and their multifaceted mechanisms for managing other rice defoliators (e.g., *Spodoptera mauritia*, *Dicladispa armigera*, *Parnara guttata*).

Category	Specific Intervention	Mechanism of Action	Target Life Stage	References
Augmentative Biocontrol	<i>Trichogramma</i> spp. (Hymenoptera: Trichogrammatidae) and <i>Scutibracon hispae</i> (Viereck) (Hymenoptera: Braconidae)	Parasitizes eggs masses of lepidopteran defoliators and larvae of rice hispa to prevent population buildup.	Egg and Larva	Prakash et al., 2014
Avian Predation	T-shaped bamboo bird perches	Serves as structural hunting platforms that attract native insectivorous birds, such as the black drongo (<i>Dicrurus adsimilis</i> Bechstein), to hunt and consume caterpillars.	Larva and Adult	Horgan et al., 2017
Ecological Engineering	Floral resource strips, such as marigolds (<i>Tagetes erecta</i> L.)	Provides energy via nectar to bolster the searching efficiency of adult parasitoid wasps and predatory dipterans.	Adult (Parasitoid support)	Gurr, 2009 Horgan et al., 2012
Habitat Regulation	Strategic non-crop bund mowing	Manages wild grass reservoirs on peripheral field bunds, establishing a physical barrier that restricts larval migration into the primary rice crop.	Larva	Yang et al., 2025
Botanical Interventions	Sugar-apple seed oil (<i>Annona squamosa</i> L.) (1%)	Functions as a powerful antifeedant that deters leaf scraping and induces larval starvation.	Larva	Narayan & Yadav, 2015
Growth Regulation	Neem Seed Kernel Extract (NSKE) from <i>Azadirachta indica</i> A. Juss.	Translocate bioactive azadirachtin to induce severe ecdysial abnormalities, which is likely to prevent successful pupation.	Larva	Narayan & Yadav, 2015
Physical Defence	Soluble silicon (<i>Si</i>) and pyrolysis biochar soil amendments	Increases leaf abrasiveness to wear down insect mandibles and reduce feeding or scraping efficiency.	Larva	Panda et al., 2022
Animal Foraging	Integrated rice–duck farming using domestic mallard ducks (<i>Anas platyrhynchos domesticus</i> L.)	Introduces active generalist foragers that clear the dense under canopy, physically shaking foliage to dislodge and consume hidden larvae sheltered within the leaf sheaths.	Larva and Adult	Li et al., 2019
Aquatic Predation	Integrated rice–fish farming using common carp (<i>Cyprinus carpio</i> L.)	Establishes a permanent aquatic biological sink below the canopy, wherein fish prey upon defoliator larvae dislodged from foliage by environmental or biotic factors.	Larva	Hendarsih et al., 1994
Microbial Control	<i>Bacillus thuringiensis</i> Berliner (<i>Bt</i>)	Expresses specific crystalline delta-endotoxins that bind to midgut receptors, inducing gut epithelium lysis, paralysis, and rapid feeding cessation.	Larva	Alam, 1962
Viral Biopesticides	Host-specific Nuclear Polyhedrosis Virus (<i>NPV</i>)	Initiates viral systemic replication within larval tissues, inducing polyhedrosis and causing population-wide collapse during severe defoliator outbreaks.	Larva	Ganesan et al., 2025