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REVIEW ARTICLE

Botanicals for managing insect pests in rice : An eco-friendly strategy for sustainable rice production

K Ganesan[1], Bacham Anil kumar[1]*, RP Soundararajan[1], M Suganthy[1], Sheela Venugopal[1], V Manivannan[2], SV Sangeetha[1] & M Murugan[1]

[1]Department of Agricultural Entomology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: anilbacham6513@gmail.com

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Abstract

Rice, a staple crop for over half the global population, faces severe yield losses due to insect pests, such as the rice stem borer (*Scirpophaga incertulas*), brown planthopper (*Nilaparvata lugens*) and leaf folder (*Cnaphalocrocis medinalis*) and minor insect pests, which are significant threats to global food security. Traditional reliance on chemical pesticides for pest control has negatively impacted the environment, human health and non-target organisms. This has necessitated a shift toward sustainable pest management strategies that minimize chemical inputs. Botanicals, derived from plants as essential oils, extracts and secondary metabolites, have emerged as an eco-friendly alternative due to their biodegradability, targeted efficacy and reduced environmental footprint. These plant-based compounds act through various mechanisms, including antifeedant activity, growth inhibition, oviposition deterrence, ovicidal effects and toxicity, effectively disrupting pest lifecycles without harming non-target species. Studies underscore the potential of botanicals in suppressing pest populations and mitigating crop losses, making them vital components of Integrated Pest Management (IPM) strategies. When incorporated into IPM programs alongside biological control agents, cultural practices and resistant rice varieties, botanicals enhance pest control efficacy while preserving ecosystem balance and promoting biodiversity. Their use aligns with sustainable agriculture principles, offering a viable path to reduce pesticide dependency and ensure long-term agricultural resilience. This review highlights the critical role of botanicals in IPM for rice cultivation, emphasizing their potential to mitigate pest impacts while supporting environmentally sustainable and economically viable food production systems.

Keywords

botanicals; eco-friendly pest management; key pests; natural enemies; rice

Introduction

Rice, *Oryza sativa* (L), belonging to the family Poaceae, is one of the major staple food crops in the world, farming the staple diet for half of the worlds' population with the production of 523.9 million tonnes in an area of 166.31 million hectares. In India, rice production 2023 reached 1308.37 lakh tonnes, occupying 40 to 43 % of the total cultivable area (1). Rice is widely cultivated in tropical and sub-tropical regions and its significance as a food crop has earned it the title "King of Cereals"(1). Rice is recognized as a nutritious grain devoid of fats and cholesterol, making it an ideal component of a well-rounded diet (2). It serves as a rich source of carbohydrates, vitamins, proteins, calcium, thiamine, niacin, iron, riboflavin and fibre, with low sugar. Its gluten-free nature renders it a crucial option for individuals adhering to gluten-free diets and those with diabetes (2).

More than 175 species of insect pests have been identified on rice crops. Nearly 20 insect species are known to be critical in rice crops and are regularly noticed in tropical and subtropical regions in Asia (3). More than 25 % yield loss was recorded due to rices' infestation of various insect pests. Several previously considered minor pests have become prominent, causing severe yield loss in rice. The major insect pests of rice include yellow stemborer (*Scirpophaga incertulas*), leaf folder (*Cnaphalocrocis medinalis*), brown plant hopper (*Nilaparvata lugens*), white-backed planthopper (*Sogatella furcifera*), gall midge (O*roseolia oryzae*) and rice ear head bug (*Leptocorisa acuta*) (4). Rice farmers mostly prefer to use synthetic insecticides to control insect pests. However, continuous and indiscriminate use of insecticides has led to the development of resistance and resurgence of pest populations and residues in the final produce. Therefore, finding other alternatives for chemical pesticides is urgently needed. Botanicals may be the best insecticide alternatives due to their eco-friendly (5). Botanicals may also be considered plant protection inputs for future rice production (6).

Botanicals may improve the physical stability of food products and their applications enhance the stability of rice-based foods by inhibiting oxidative reactions (7). The bioactive molecules present in several plant extracts act as toxicants, repellents, phagodeterrents, ovideterrents, growth regulators, etc., offering viable alternatives to conventional chemical pesticides (8). Botanicals are cost-effective, target-specific, biodegradable and environmentally friendly, with a broad spectrum of activity and minimal harmful effects (9). Integrating botanicals for nutrient management with pesticide properties has been shown to enhance rices' growth and yield parameters (10). Despite regulatory and market challenges, botanical-based biopesticides have proven to be a safer, eco-friendly and sustainable pest management option for rice (11). Botanicals have been used in Indian agriculture for over a century to minimize the substantial yield losses caused by most insect pests in rice (12).

Overview of Botanicals in Pest Management

Botanicals have been derived from plant materials that act as insecticides and repellents, bactericides, fungicides, herbicides and nematicides. Around the world, there are about 2,121 plant species have been reported to have pest control capabilities, including 1,005 species with insecticidal, 384 antifeedant, 297 repellent and 31 growth-inhibiting properties, of which only a few have been validated and commercialized (13). Around 735 botanical-based pesticide products have been registered by various companies. Among them, 443 were Azadirachtin and 290 were Pyrethrum-based products. Plant extracts and their secondary metabolites, such as nicotine, Pyrethrum, rotenone, derris and sabadilla, are examples of "first generation" insecticides known as "botanicals" (13). Some of these plant chemicals lay the groundwork for developing synthetic "second-generation" insecticides. For example, Pyrethrum extracted from Chrysanthemum flowers has become the fundamental unit for developing synthetic pyrethroids (14). These second-generation insecticides are nerve toxins affecting both the target and non-target organisms. Neem-based products are considered second-generation insecticides, extensively used in managing various insect pests.

Among botanicals, neem products have an imperative role in IPM strategies of crops (15). Using plant products in pest management has a long history and is an essential indigenous traditional pest management practice in India (16). Botanicals can have tri-trophic effects, offering pest control equivalent to synthetic insecticides. Additionally, their proximity to natural enemies like predators and parasitoids indicates their potential for managing insect pests in sustainable organic agriculture (17).

Impact of Botanicals on Borers and Defoliators in Rice

Stem borer complex

Among the various insect pests of rice, stem borers are considered the most dangerous. Three species of the Noctuidae family and eighteen species of the Pyralidae family of stem borer have been documented in India (18). The yellow stem borer (*Scirpophaga incertulas)* is a monophagous pest that damages all rice growth stages (19). The rice stems borer larvae bore into the stem of the rice plant and arrest the supply of water and nutrients to the upper part of the plants, which resulted in "Dead hearts" during the vegetative stage and "white ears" during the reproductive stage (20). The plants' compensatory mechanism will compensate the dead hearts at the vegetative stage of the crop, but it was not possible at the reproductive stage, in which 4 % yield loss was observed for every 1 % of the white ear (21). At severe epidemic outbreaks, up to 63 % of tillers were damaged, 65 % of dead heads, and 95 % of white heads were observed (22). The yield losses by yellow stem borer alone ranged from 1% to 19 % at the early stage and 38-80 % at the late stage in rice (23).

Among various botanicals tested against stem borers, the application of Neem seed kernel extract (5 %) and a combination of neem oil (1 %) and pungam oil (1 %) recorded the lowest incidence of dead heart symptoms at 4.07 and 4.93 %, respectively in organic rice (24). Botanical extracts prepared from *Azadirachta indica, Vitex negundo, Ipomoea carnea and Adhatoda zeylanica* resulted in decreased rice stem borer population and increased larval mortality (25). The efficacy of extracts derived from *Neorautanenia mitis* and *Derris elliptica* was effective against the rice stem borer *Chilo partellus*(26). Three botanical leaf extracts *viz.,* tobacco, neem and karonja applied @ 15mL/L showed considerable population reduction in stem borers under field conditions with reduced dead hearts (38.38 %) and whiteears (58.08 %)(27) (Fig. 1).

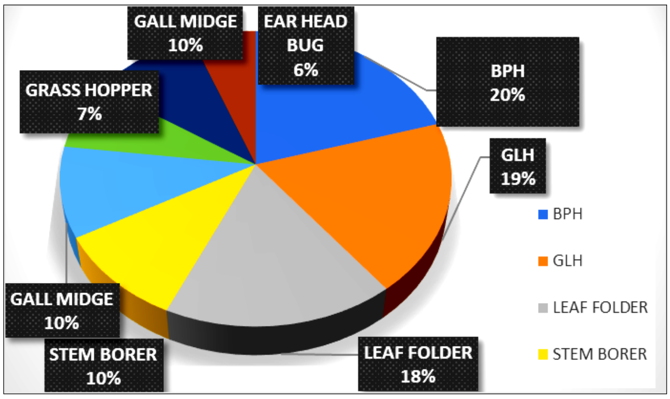

Fig 1. Comparative efficacy botanicals against significant insect pests of rice.

The neem seed kernel extract application @ 5 % concentration significantly reduced the dead hearts and white ears due to rice stem borer (28). Azadirachtin, derived from neem, acts as a potent insect growth regulator that interferes with the moulting process of stem borer larvae. Similarly, pongam extracts contain flavonoids and limonoids that exhibit insecticidal properties against rice stem borers (29). Garlic extracts, rich in sulfur compounds, act as repellents and disrupt the feeding behaviour of stem borers (30). The plant extracts with animal byproduct *viz.,* cow urine + *Azadirachta indica,* cow urine + *Melia azedarach*, cow urine + *Lantana camara*, cow urine + *Jatropha gossypiflora,* cow urine + *eucalyptus oblique*, cow urine + *Cannabis sativa* and Azadirachtin were found to effective against rice stem borer and among them, result suggested that neemoz @ 2500 mL/ha was the most effective in reducing the infestation of stem borer, *S. incertulas* in paddy followed by cow urine + *Melia azedarach* @ 7500 mL/ha (31). The application of neemarin @ 1500 ppm @ 3 L/ha reduced (5.60 %) of white ears in rice (32). Foliar application of nimbecidine and neemarin was efficient and cost-effective in decreasing the occurrence of *S. incertulas* in rice (33).

Rice gall midge

The gall midge, *Orseolia oryzae,* is often known as Wood-Mason, which results in an annual yield loss of 0.8 % of the overall production (34). Rice gall midges cause severe damage by forming a hollow cavity or tubular gall at the base of the infested tiller. The increased application of urea significantly increased the incidence of gall midges (35). The metabolic changes in rice plants due to gall midge feeding in different rice varieties were studied and they found that the metabolites could be considered a biomarker for insect-plant interaction, providing insights into the biochemical responses of rice plants to gall midge infestation and its impact on yield (36).

Plant-based essential oils like eucalyptus and cedarwood oil effectively suppressed gall midge incidence in rice (36). The efficacy of neem seed kernel extracts against the African rice gall midge was studied (35) and they found that the NSKE significantly reduced the gall midge damage and increased the grain yield. Applying neem oil @ 3 % significantly reduced the damage caused by rice gall midges(37). Spraying of neem oil @ 5 % significantly decreased the gall midge infestations in rice (38). A foliar spray of neem oil @ 2 % applied thrice @ 25, 40 and 55 days after transplantation substantially diminished the population of rice gall midges (39). The application of various neem derivatives was effective against cecidomyiid pests in rice (40) (Fig. 1).

Leaf folder

The rice leaf folder belonging to the order Lepidoptera represents a significant defoliating pest affecting various stages of the rice crop. This pest emerged seriously across Asian countries, leading to considerable yield losses, particularly in tropical and subtropical regions (41). Eight species of rice leaf folders have been recorded among them. *Cnaphalocrocis medinalis* is the most prevalent one, which caused substantial yield losses in rice (42). Leaf folders cause damage by folding rice leaves and feeding within, resulting in reduced photosynthetic area that can lead to significant yield loss. Moreover, the damaged leaves become vulnerable entry sites for fungal and bacterial pathogens (41). Yield losses due to leaf folders were ranged from 3 % to 10 % (43). A positive correlation between the extent of leaf damage and yield losses due to rice leaf folder indicated that 17.5 % of leaf damage led to a 16.5 % reduction in grain yield. In comparison, a higher damage rate of 26.6 % of leaves corresponded to a 21.3 % loss in yield was observed (44).

The percent reduction over control for leaffolder was more (76.23) in NSKE @ 5 %, followed by neem oil (1 %) + pungam oil (1 %), neem oil (2 %) alone (68.44) and pungam (2 %) oil alone (57.07) (45). A Foliar application with a combination of seaweed (*Sargassaum wightii*) extract (8 %) with neem leaf extract (5 %) exhibited the highest mortality of 66.66 % leaf folder larvae (46). Azadirachtin was most effective in reducing the incidence of leaf folders compared to untreated controls, showcasing the potential of neem-based products in managing rice leaf folder populations effectively under field conditions (47). Azadirachtin and neem extracts affect the rice leaf folder larvae and reduce food ingestion, detoxifying the enzyme activity of dysoxylum triterpenes (48). The combination of botanical insecticides and bacterial toxins affected the digestive enzymes like protease, amylase and lipase in rice leaf folder larvae, showing a synergistic effect at low doses, decreases in enzyme activity, indicating impaired larval digestion and nutrition, which could be an effective strategy for controlling leaf folder in rice (49).

Application of oil-based formulations extracted from the seeds of Custard apple (*Annona squamosa*), Punnai (*Calophyllum inophyllum)* and Mahua (*Madhuca indica)* each @ 1 % concentration reduced the rice leaf folder infestation (50). Neem seed kernel extract(NSKE) @ 5 % showed juvenile hormone mimic action and reduced the development of *C. medinalis* larvae when mixed with 0.16 percent teepol (51). Neem oil applied @ 1 % concentration on rice plants decreased the occurrences of leaf folder (52). Alternatively, neem cake (de-oiled) amendment in the soil at 150 kg/ha followed by neem oil (2 %) spray at 10-day intervals was found effective against leaf folder (53).

The extract from custard apple leaves showed decreased rice leaf folder infestation (50). Research indicates that the juvenile hormone mimicry activity of Neem Seed Kernel Extract (NSKE) and the inhibitory effect of NSKE against the growth and development of leaf folder larvae (Table 1).

Table 1. Botanicals for the management of borers and defoliators in rice

S.No.	Botanical plant	Plant part	Mode of action
Stem borer complex			
1	Neem (*Azadirachta indica)*	Seeds, leaves, Extracted as neem oil,	Antifeedant, growth inhibitor, oviposition deterrent
2	Datura *(Datura alba)*	leaf extract	Demonstrated contact toxicity
3	Ginger (*Zingiberofficinale)*	Rhizome extract	Insecticidal
4	Castor (*Ricinus communis)*	Leaf extract	Repellent and deterrent
5	Marigold (*Tagetes* sp.)	Aqueous root extract	Toxicity
6	Tobacco (*Nicotiana tabacum)*	Tobacco stems	Insecticidal
7	Garlic (*Allium sativum)*	Garlic oil	Repellent
8	Cedarwood *(Cedrus* sp.)	Cedar oil	Antifeedant
9	Chinaberry *(Melia azedarach)*	Seed oil	Antifeedant and insecticidal activity
10	*Chinaberry (Meliatoosendan)*	Seed oil	Antifeedant/ Insecticidal activity
11	Puna oil tree (*Pongamiaglabra)*	Mixture of Pongamia and neem oil (1:1)	Antifeedant and insecticidal activity
12	Chinese azalea *(Rhododendron molle)*	Root leaf, flower aqueous and alcohol	Toxicity
13	Thunder God vine (*Tripteryguimwiliford)*	Root and bark powder	Toxicity and Antifeedant activity
14	Karanja (*Pongamia pinnata)*	Seed oil and extracts	Antifeedant, insect growth regulator
15	Sweet flag (*Acorus calamus)*	Rhizomes	Neurotoxicant, repellent
16	Chinese chaste tree *(Vitex negundo)*	Leaves and extracts	Antifeedant and ovicidal activity
17	Tulasi (*Ocimum sanctum)*	Leaves and essential oil	Repellentand antifeedant
Gall midge			
1	Neem (*Azadirachta indica)*	Seeds, leaves, Azadirachtin and other limonoids	Insect growth regulator; affects moulting and larval development
2	Chinaberry (*Melia azedarach)*	Fruits, leaves and Meliatoxins, 2 %	Antifeedant, larvicidal
3	Sweetflag (*Acorus calamus)*	Rhizomes and β-Asarone	Repellentand oviposition deterrent
4	Garlic (*Allium sativum)*	Bulbs, Allicin and Diallyl disulfide	Fumigant and antifeedant
5	Tobacco (*Nicotiana tabacum)*	Leaves and Nicotine	Neurotoxic to insects
6	Citronella (*Cymbopogon nardus*)	Leaves, Citronellal and Geraniol	Repellent affects larval feeding
7	Turmeric (*Curcuma longa)*	Rhizomes and Curcumin	Oviposition deterrent, larvicidal
Defoliators			
1	Neem (*Azadirachta indica*)	Seeds, leaves extracted as neem oil and Azadirachtin	Antifeedant, growth inhibitor, oviposition deterrent
2	Garlic (*Allium sativum)*	Cloves, Aqueous and oil extracts and	Antifeedant, repellent, toxic to larvae
3	Tobacco (*Nicotiana* sp.)	Leaves and Nicotine sulfate extract	Neurotoxin, antifeedant
4	Chilli (*Capsicum* sp.)	Fruits and Capsaicinoid extracts	Repellent, toxic to larvae, antifeedant
5	Pyrethrum (*Chrysanthemum cinerariifolium*)	Flowers and pyrethrin extract	Neurotoxin, knockdown effect

Other defoliators

Six botanical preparations *viz.,* neem oil, mahogany oil, a mixture of neem and mahogany oil, bishkatali leaf extract, pitraj leaf extract and a mix of bishkatali and pitraj leaf extract were tested against rice his (*Dicladispa armigera).* among these, neem oil was most effective in controlling the pest (54). Neemazal, eucalyptus oil, lemongrass oil, cedarwood oil and camphor oil were evaluated to manage rice grasshoppers (*Oxyanitidula*) in rice. The neemazal was highly effective (Fig. 1) (55).

Botanicals Against Sucking Pests in Rice and their Impact on Yield

Brown plant hopper

The brown plant hopper (BPH), *Nilaparvata lugens*is an important sucking pest in rice (56). It directly damages rice crops by feeding on the phloem and indirectly by transmitting viral diseases, such as grassy stunt and wilted stunt viruses (57). In rice-growing areas of India, frequent crop failures were attributed to BPH outbreaks (58). The BPH outbreaks resulted in "Hopper burn" symptoms in the main field, leading to significant yield losses (59). The yield loss by BPH in rice ranges from 10 to 90 % (60). The application of NSKE @ 5 % and a combination of neem oil @ 1 % and pungam oil @ 1 % were most effective against BPH, with a more than 50 % reduction in BPH over the control (24). The BPH population was reduced when NSKE @ 5 % and Vitex leaf extracts @ 10 % were sprayed (61).

A significant decrease in BPH nymph emergence was observed with 2 % neem seed kernel extract and 1 % karanj oil foliar application (62). The extracts derived from *Ageratum conyzoides*, *Barringtonia asiatica, Melia azedarach* and *Tephrosia vogelii* caused significant mortality in brown planthopper populations (63). Applying eucalyptus oil @ 1000 mL/ha was effective against BPH and resulted in higher grain yield (64). The extracts of *Piper retrofractum* and *Tagetes erecta* show the highest mortality and feeding inhibition in the brown plant hopper population (65). Pyrethrum application increased BPH mortality within four days of application (66).

Neem seed kernel extract at 7.5 % reduced BPH population and increased grain yield (9). Spraying of Vitex leaf extract at 5 % showed a good knockdown effect against BPH under laboratory conditions (67). Multineem 300 ppm applied @ 1.25 L/ha was highly effective for managing BPH in rice (68). Applying 5 % bitter gourd leaf extract, 5 % garadi leaf extract and 5 % custard apple leaf extract was highly effective forBPH in rice, resulting in more nymphal mortality and higher feeding inhibition (69). The BPH was highly susceptible to neem oil, resulting in reduced food intake and nymphal mortality (70). Application of neem oil 3 % and NSKE 5 % was found superior to chemical pesticides against *Nilaparvata lugens* (71). A foliar spray of 2 % neem leaf extract reduced the overall population of BPH by 40 % (72). BPHs' longevity and survival were markedly decreased when the rice crop was sprayed with neem oil 3 % (73). BPHs' oviposition and survival rate were reduced when the crop was treated with petroleum ether-based extract of neem seed at 5 % (Fig. 1) (74).

White-backed plant hopper

The White-backed plant hopper (WBPH) is also a critical sucking pest in rice. It commonly feeds on the phloem tissues and causes a reduction in leaf area, plant height, dry weight, chlorophyll contents, photosynthetic rate and yield (75). Both adults and nymphs suck the plant sap and inject their toxic saliva into the plant, which results in the drying of leaves and hopper burn symptoms (58). The yield loss due to WBPH ranges from 11 to 39 percent in rice (76). Neem oil (1 %), mahua oil (1 %), neem seed kernel extract (5 %) and lemongrass leaf extract (5 %) affected the biological activities of WPBH, which resulted in reduced growth and development, decreased survival rates and lower adult emergence(77). Ethanol extracts of *Anredera cordifolia* leave at 1, 1.5 and 2 % caused nymphal and adult mortality @ 52.50 %, 56.25 % and 61.25 %, respectively, after 14 days of application. Multi-neem (300ppm) applied @ 1.25 L/ha was the most effective in managing WBPH in rice (68).

The application of NSKE (5 %), neem oil (3 %), neem leaf extract (3 %), vitex leaf extract (3 %), periwinkle leaf extract (3 %), palmarosa oil (0.05 %) and jatropha oil (1 %) resulted in higher nymphal mortality, lower adult survival and reduced honeydew excretions (78). Spraying neem kernel extract 5 % along with teepol (0.16 %) reduced the incidence of WBPH (79). Spraying of neem oil (1 %) @ 7.5 L/ha and root soaking of rice seedlings with NSKE (5 %) decreased the incidence of WBPH (80). Similarly, research indicates that applying 5 % neem cake extract reduced the emergence of WBPH (81). The relative effectiveness of aqueous custard apple leaf extracts exhibited the reduced population in rice (9). The efficacy of vitex, Pongamia and calotropis leaf extract @ 10 % was highly effective against WBPH in rice (77).

Green leaf hopper

The green leafhoppers (GLH), particularly the *Nephotettix virescenes* and *Nephotettix nigropictus,* are common in any rice production system. In addition to direct feeding damage, they also served as vectors for viral diseases like rice-tungro leaf yellowing viruses, resulting in reduced grain yield (81).A decreased nymphal survival rate and adult emergence due to applying Pongamia leaf extract @ 10 percent (50). Reduced growth development of GLH was observed when theyfed on rice plants treated with commercial neem formulations (82). Significant decreases in GLH populations were achieved by applying 8 % NSKE (83). Neem oil reduced *Nigropictus virescens* populations and tungro virus transmission capabilities, resulting in stable grain yield (70). Spraying custard apple leaf extract also reduced the spread of tungro viral disease in rice (84). The combination of neem oil (1 %) and pungam oil (1 %) resulted in 50 % reduction in GLH population over control in the organic rice experiment (24).

Ear head bug

The rice ear head bug, *Leptocorisa acuta,* is one of the most serious and harmful sucking insect pests during the maturity stages of the rice crop. Damages occur primarily during the flowering stage, where both nymphs and adults suck the sap from rice grains, resulting in shrivelled and chaffy grains. The feeding sites of ear head bugs promote the growth of sooty mould fungus, causing significant yield losses of up to 30 % (85). Direct feeding damage to ear head bugs reduces grain yield by up to 40 % in severe cases (86).

The extracts from Piperaceae plants showed a quick knockdown effect in addition to their repellent properties against rice ear head bugs in rice (87). Chloroform extract of *Pipercrocatum* was highly effective against rice ear bugs (88). Application of neem oil 3 % and NSKE 5 % showed a very low incidence of *Leptocorisa* spp in rice (71). Neem oil 2 % and neem seed kernel extract 5 % reduced *Leptocorisa acuta* to 69 and 39 % in rice (89) (Table 2). Foliar spraying of neem oil (3 %) at 15, 30 and 60 days after transplanting showed minimum black bug (*Scotinopharalurida*) incidence (6.60 %) and more grain yield (5279 kg/ha) in rice (90).

Impact of Botanicals on Natural Enemies

Natural enemies are essential components of integrated pest management in organic farming (91). Applying botanical pesticides on rice crops showed a synergistic effect and indirectly benefitted the natural enemies by

Table 2. Botanicals for the management of sucking pests in rice

S. No.	Botanical plant	Plant part	Mode of action
Plant and leaf hoppers			
1	Neem (*Azadirachta indica*)	Seeds, leaves and neem oil 0.5-2.0 % azadirachtin	Antifeedant, growth inhibitor, oviposition deterrent and insecticidal activity
2	Barnyard grass (*Echinochloa crusgalli)*	Transaconitic acid isolated from *E.crusgalli*	Antifeedant activity
3	Morchand (*Eclipta alba)*	Root and shoot extracts	Antifeedant activity
4	Cleome *(Gynandropsis pentaphylla)*	Petroleum seed extract	Reduced oviposition
5	Lantana (*Lantana camara)*	Flower extract in water	Toxicity, when tested as a topical application
6	Marigold (*Tagetespafula)*	Aqueous root extract	Toxicity
7	Ginger (*Zingiber officinale)*	Rhizome extract	Insecticidal
8	Basil (*Ocimum sanctum)*	Plant extract	Repellent
9	Mugwort *(Artememisla kurramensis*)	Seed oil alone or in combination with organic materials	Insecticidal activity
10	Polang/und *(Calophylluminophyllum)*	1 %seed oil of Indian lurvel	Check population and RTV transmission
11	Amalghota/ croton (*Croton sparsiflorum)*	Seed oil	Reduced survival and longevity
12	Mahua *(Madhucaindica)*	Seed oil	Reduced survival of insects
13	Eucalyptus (*Eucalyptus* sp.)	Eucalyptus oil	Insect repellent
14	Citronella (*Cymbopogon* sp.)	Citronella oil	Repelling pests
15	Lemongrass (*Cymbopogon citratus*)	Essential oil	Repelling pests
16	Custard apple *(Annona squamosa)*	Seed oil	Effectively reduce survival of adults
Ear head bug			
1	Neem (*Azadirachta indica)*	Seeds and leaves - Extracts contain Azadirachtin, salannin and Nimbin 10 %	Insect growth regulator; antifeedant, disrupts moulting and reproduction
2	Pyrethrum (*Chrysanthemum cinerariifolium*)	Flowers - Pyrethrins 1 %	Neurotoxin to insects, causing paralysis and death
3	Garlic (*Allium sativum)*	Cloves - Allicin, diallyl disulfide	Repellent, antifeedant and toxic to insects
4	Eucalyptus (*Eucalyptus* sp.*)*	Leaves - Eucalyptol, cineole	Fumigant, repellent, insecticidal activity
5	Turmeric (*Curcuma longa)*	Rhizomes and Curcumin	Repellent, antifeedant, affects insect growth and devel-opment
6	Tobacco (*Nicotiana tabacum)*	Leaves - Nicotine	Neurotoxin affects the nervous system of insects

weakening antagonistic pests (49). The application of Azadirachtin does not affect the coccinellid predators in the rice ecosystem. Neem oil 50 EC spray did not impact the predatory green lacewing bugs (*Chrysoperla carnea*) in rice (IRRI1992) (92). The Application of Azadirachtin to manage rice pests showed less impact on the population reduction of parasitoid predators in the rice ecosystem (93). Neem oil and various non-edible oil sprays were considered safer for beneficial insects (94). Neemax, Rakshak and Fortune Aza were lesser risk to the predators of plant hoppers such as the velid bugs (*Microvelia douglasiatrolineata*), mirid bugs and *Trichogramma japonicum* egg parasitoids (95). A higher spider population of 1.30-1.70 per hill was observed at 3 Days after treatment (DAT) and 1.50-2.00 per hill at 7 DAT was recorded in neem oil (1 %) + pungam oil (1 %) as foliar spray in organic rice (91). The use of botanicals is one of the essential components in organic plant protection strategy, is safe for biological control agents and saves the environment from pesticide pollution (96).

Mode of Action of Botanicals on Rice Insects

Understanding the mode of action of botanicals through physical, biological and chemical interactions between the insect and the product is crucial for managing pests successfully (13). The mode of action of botanicals involves repulsiveness, inhibition, dehydration of proteins, etc., depending on the botanical ingredient and nature of the insect pests. Neem-based pesticides have antifeedant and repellent properties. Additionally, moulting aberrant, oviposition deterrent and endocrine system disruption. Pyrethrum-based bio-pesticides damaged the insect nerve cells, followed by paralysis and death (14). A combination of botanicals was more effective, significantly reducing enzyme activity, including acetylcholinesterase (AChE), glutathione S-transferase (GST), and cytochrome P450 monooxygenases. The synergistic effect of botanicals was observed when combined with bacterial toxins in disrupting the digestive processes of most rice pests, resulting in impaired nutrition and eventual mortality (49).

Neem exhibits a broad range of activities against most rice pests, acting as a feeding deterrent, repellent, growth regulator and oviposition inhibitor (96). Apart from neem formulations, the solvent-free neem formulation is also effective against sucking pests (96). Pyrethrin interference in the sodium and potassium ion exchange mechanism within insect nerve fibres was noticed, thereby disrupting nerve impulse transmission. Nevertheless, due to the rapid metabolization property of pyrethrins, many insects experienced paralysis and death (13). In agricultural pest management, using plant-based products and identifying toxic principles in the plant parts are imminent research areas to focus (14). Alkaloids derived from *sabadilla* were toxic to insect pests, disrupting nerve cell membranes and leading to loss of nerve function, paralysis and death (11). Findings on the mode of action of plant-derived compounds have led to the identification of novel compounds with unique modes of action to combat pest resistance and resurgence (12) (Table 3).

Table 3. Mode of action of botanicals on rice insect pests

S. No	Plant	Compound	Mechanism of action	Impact of insect system
1	*Mentha* sp. *Lavendula* sp.	Essential oils	Inhibition of acetylcholinesterase (AChE)	Cholinergic system
2	*Nicotiana* sp.*Haloxylonsalicornicum, Stemona Jap*	Nicotine	Cholinergic acetylcholine nicotinic receptor Agonist/ antagonist	Cholinergic system
3	*Chrysanthemum cinerariaefolium*	Pyrethrin	Sodium and potassium ion exchange disruption	Mitochondrial system
4	*Lonchocarpus* sp.	Rotenone	Inhibitor of cellular respiration(mitochondrial complex I electron transport inhibitor (METI)	Mitochondrial system
5	*Ryania* sp.	Ryanodine	Affect calcium channels	Mitochondrial system
6	*Cedrus* sp. *Eucalyptus* sp.	Essential oils	Octopaminergic receptors	Octopaminergic system
7	*Thymus vulgaris*	Thymol	Block octopamine receptors by working through tyramine receptors cascade	Octopaminergic system
8	*Schoenocaulon officinale*	Sabadilla	Affect nerve cell membrane action	Mitochondrial system
9	*Nicotiana tabacum*	Nicotine	Mimics acetylcholine, causing overstimulation of the nervous system	Nervous system
10	*Azadiractina indica*	Azadirachtin	Hormonal balance disruption	Hormonal system
11	*Allium sativum*	Allicin	Antifeedant and repellent; also has fungicidal and bactericidal effects	Digestive system

Conclusion

Botanicals represent a viable and sustainable component of integrated pest management in rice. Future research should focus on identifying novel plant-derived compounds, optimizing formulation techniques and conducting long-term field studies to evaluate the efficacy of botanicals within IPM frameworks. Botanicals offer a promising avenue for enhancing rice yields through natural and sustainable pest management methods. Integrating botanicals into rice cultivation can improve crop growth and yield while increasing resilience to environmental stresses. Future research should focus on exploring the potential of botanical compounds, optimizing application techniques and understanding the unique mode of action for better pest control efficiency. Development of guidelines for the use of botanicals can further promote their adoption, ensuring food security and environmental health. Botanical pesticides may play a significant role in food production and postharvest protection in developing countries like India. Hence, there is tremendous potential in the future for business start-ups to develop new botanical formulations for eco-friendly pest management.

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Authors' contributions

KG and BA wrote the first draft of the paper. KG and RPS conceptualized, reviewed, and edited the review paper holistically. MS, VM, SV, SVS, and MM reviewed the paper and shared their input for upscaling. All authors read and approved the final manuscript.

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