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ORIGINAL RESEARCH PAPER

Eco-friendly botanical insecticides to control brown leafhoppers and their effects on the predators and aquatic environment

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ABSTRACT

BACKGROUND AND OBJECTIVES: The brown planthopper (*Nilaparvata lugens*) (Hemiptera: Delphacidae) is a major pest in rice cultivation, frequently causing severe crop losses. Traditionally, the approach to managing this problem has been predominantly reliant on synthetic insecticides, which carry substantial environmental and health hazards. The objective of this field study was to evaluate the performance of a botanical insecticide in lowering pest populations, boosting rice yield, and sustaining ecological equilibrium.
METHODS: The research tested Rajam 65 emulsifiable concentrate (patent number individual development plan 00202007448), a botanical insecticide, alone and in combination with a synthetic insecticide containing buprofezin as the active ingredient. Treatments were applied four times at weekly intervals. The study included observations on pest reduction rates, improvements in rice yields, the dynamics of predator populations, and laboratory toxicity tests conducted on tilapia and common carp to determine aquatic safety.
FINDINGS: Results showed that the botanical insecticide alone achieved 97 percent pest mortality, reducing the population from 16.3 to 0.73 individuals per clump and keeping infestations below the economic threshold. Following the combination treatment, pest populations were significantly reduced from 26.63 to 2.17 individuals per clump. Furthermore, there was a notable increase of 16.39 percent in rice yield as a result of the treatment. Natural predator populations, such as spiders and *Cyrthorinus lividipennis*, remained stable across treatments, demonstrating the insecticide's compatibility with integrated pest management systems. The results of toxicity testing showed that there is a low level of risk to aquatic species like common carp and tilapia. The 96-hour lethal concentration caused 50 percent mortalities values of the botanical insecticide for common carp and tilapia are 0.101 and 0.144 critical concentrate per liters, with toxicity units of 0.025 and 0.017, respectively. Given that these values fall below 0.3, the insecticide poses no harm and is deemed safe for fish farming in the waters of paddy fields.
CONCLUSION: The botanical insecticide proved highly effective in controlling N. lugens populations while demonstrating ecological and economic benefits. By applying treatments on a weekly basis, pest populations were effectively diminished to levels far below the economic threshold, which in turn enhanced rice yield. The insecticide's sustainable attributes, including its eco-friendliness, scalability, and compatibility with integrated pest management, emphasize its potential as a viable alternative to synthetic chemicals for controlling pests in rice cultivation.

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INTRODUCTION

Plant-damaging organisms, particularly those affecting rice crops, represent a serious threat to global food security and crop productivity. The absence of effective pest management strategies may result in considerable crop losses, potentially reducing yields by up to 27.9 percent (%) (Mondal *et al.*, 2017). Every year, up to 40% of global crop production is lost due to plant pests and diseases (FAO, 2022), underscoring the urgent need for sustainable pest control measures. For many years, synthetic insecticides have proven to be a trustworthy and effective approach to addressing pest infestations. However, their widespread and uncontrolled use has led to unintended consequences for ecosystems, non-target species, and human health. An over-dependence on these substances can hinder pest management strategies by promoting resistance among pests and causing ecological disruptions (Damalas, 2016). The overuse of synthetic chemicals has caused numerous invasive species to develop resistance (Siddiqui *et al.,* 2023). Excessive pesticide application not only fails to increase yield but also exacerbates pest resistance, threatens the health of farmers and consumers, and leads to a decline in beneficial insect species (Quandahor *et al.,* 2024). Moreover, Additionally, the use of synthetic insecticides results in toxic residues in both soil and water, which can be absorbed by agricultural crops, thereby compromising environmental integrity and posing health risks to humans. These residues threaten other organisms, including natural predators, parasites, and pollinators, thereby disrupting ecosystems and reducing biodiversity (Mubushar *et al.,* 2019). The decline in natural predator populations often intensifies pest resurgence and increases the likelihood of secondary pest outbreaks. Furthermore, the decrease in pollinator numbers significantly influences agricultural output, as effective pollination is vital for both crop development and overall yield (Ndakidemi *et al.,* 2016). Sub-lethal effects of the pesticide Spinosad accumulated in the ovaries of the parasitoid, *Hyposoter didymator*, were documented in Reproductive Impairment of Predators and Parasitoids (Samanta *et al.,* 2023). This disruption of ecological balance compromises both pest control and crop yields, placing additional pressure on agricultural systems. It is vital to limit the application of synthetic insecticides to protect the environment and maintain biodiversity. This reduction not only protects ecosystems and non-target species but also fosters the adoption of sustainable pest management approaches. The use of plant secondary compounds as active ingredients in insecticides presents a sustainable alternative for pest control, supporting more environmentally friendly agricultural practices (Lengai *et al.,* 2020). Compounds known as secondary metabolites, sourced from bacteria, fungi, or plants, including naturally occurring microbiological, biochemical, and microbiological elements, can serve as effective agents for the control of pests, weeds, and phytopathogens (Šunjka and Mechora, 2022). To advance sustainable pest control strategies, considerable efforts have been made in identifying secondary botanical chemicals, pheromones, and RNA pesticides, as well as optimizing feeding conditions for biocontrol agents and defensive phytohormone treatments (Shang, 2024). Importantly, previous studies on botanical pesticides have demonstrated that secondary compounds are not phytotoxic, indicating that they do not negatively impact plant growth (Rismayani *et al.,* 2023). Bioassays have demonstrated the effectiveness of botanical insecticides such as cajuput oil (*Melaleuca leucadendra*) and patchouli oil (*Pogostemon cablin*) against *Nilaparvata lugens*, with lethal concentration caused 50 percent mortalities (LC_{50}) and lethal concentration caused 95 percent mortalities (LC_{95}) values comparable to synthetic insecticides (Mardiningsih, 2021). Given the promising results from laboratory studies, it is essential to conduct field evaluations to assess the efficacy of botanical insecticides like Rajam 65 emulsifiable concentrate (EC) (patent number individual development plan: 00202007448). This study delivers vital empirical evidence regarding the performance of botanical insecticides in actual field conditions, particularly in the context of a major brown planthopper outbreak in Sumedang Regency, Indonesia. The Rajam 65 EC formulation offers a targeted, eco-friendly alternative for managing *N. lugens* populations and preserving natural predators, all while ensuring environmental safety in aquatic ecosystems. This study aims to evaluate the effectiveness of botanical insecticides in controlling brown planthopper populations, examine their effects on natural predator species, and determine their safety within aquatic ecosystems. By conducting this study during a major pest outbreak in 2022, it is also aimed to demonstrate the potential of botanical insecticides as a sustainable alternative to synthetic chemical insecticides, reducing environmental residues and promoting eco-friendly agricultural practices.

MATERIALS AND METHODS

Study area and context

This study was based in Sumedang, this region's tropical climate and agricultural conditions are representative of many rice-growing areas in Southeast Asia, supporting the broader applicability of our findings to similar agroecological zones. The study compared two insecticide formulations: a botanical insecticide containing 6.5% eugenol, enhanced with lemongrass oil *Cymbopogon citratus* (Poales: Poaceae) for fragrance, and a synthetic insecticide featuring 10% buprofezin as the active ingredient. The purpose of this comparative analysis was to examine how effectively both insecticides control the brown planthopper population in the rice fields that have been affected.

Treatments

The experiment followed a randomized block design (RBD), with two main treatments: 1) the botanical insecticide, and 2) a combination of the botanical and synthetic insecticide with a total of 16 replications. Each treatment was replicated three times to ensure reliability. A mixture of insecticide and water was prepared and applied with a knapsack sprayer, specifically aimed at the leaves and stems of rice plants. Each treatment covered a 500 square meters (m^2) area of paddy field, with a planting distance of 30 x 30 centimeters (cm) Spraying was performed four times, spaced at weekly intervals. This methodology is flexible enough to be applied to different tropical agricultural systems, provided that it is adjusted for local pest interactions, types of crops, and specific environmental conditions. The botanical insecticide concentration was 5 milliliters per liter (mL/L), and the synthetic insecticide was applied at 3 gram (g) per liter.

Variables observed

Observations were conducted periodically, starting one day prior to the insecticide application. The analyses examined the populations of pests and their natural enemies, along with the degree of damage to the plants. For each treatment, samples were collected from 30 clumps selected diagonally across the treatment area to ensure representative sampling. The findings from this study contribute to our understanding of pest management strategies, which could be applicable to other areas experiencing similar pest pressures and environmental conditions. Technical observations, including the calculation of attack intensity, were carried out in accordance with the Indonesian technical guidelines for observing and reporting plant destructive organisms and climate change impacts (Ministry of Agriculture, 2018). These guidelines establish uniform data collection techniques and facilitate precise assessment of pest pressure and plant health throughout the study region.

Intensity measurement

Measurement of the intensity of the damage using Eq. 1 (Apriliyanto and Setiawan, 2019):

$$I \; \frac{\sum_{i=0}^{Z}(ni \; x \; vi)}{ZxN} x100\% \qquad (1)$$

Where,

I = Attack intensity (%)

ni = Number of plants or plant parts sample with damage scale vi

vi = Sample damage scale i-value

N = Number of plants or plant parts observed in the sample

Z = Highest damage scale value

The scale value for attack intensity is based on a scoring system categorized by attack severity, using the evaluation criteria from the International Rice Research Institute's standard system (Tulasinathan, 2020) (Table 1).

Toxicological test of the botanical insecticide formula on common freshwater fish

The experiment was conducted using common carp and tilapia, following the methods by Fish (2000). The study had two stages: preliminary tests to establish lethal concentrations (24-hour LC_{100} and 48-hour LC_0) of an insecticide using concentrations of 0.001, 0.003, and 0.009 critical concentration/liter (cc/L), based on the Eq. 1, plus a control of freshwater. Final tests employed six botanical insecticide concentration

Table 1: Scale value of each attack category

Score	Leaf damage area	Criteria
0	No symptoms	No symptoms
1	1-5%	Resistant
3	6-12%	Somewhat resistant
5	13-25%	Somewhat Vulnerable
7	26-50%	Vulnerable
9	51-100%	Very vulnerable

Fig. 1: Condition of rice plants attacked by brown plant-hopper

levels between the lethal thresholds, organized in a geometric sequence, using Eqs. 2 and 3 (Wiratno *et al.,* 2020):

$$\text{Log } (N/n) = K. \log (a/n) \quad (2)$$

$$a/n = b/a = c/b = d/c = e/d = f/e = g/f = N/g \quad (3)$$

Where,
N = Upper threshold concentration
n = Lower threshold concentration
K = Total number of concentrations tested
a, b, c, d, e, f, g = Tested concentrations, with a representing the smallest concentration.

Each test concentration used three aquariums, each containing 10 liters of the test solution and 10 fish. The final test was conducted over a period of 96 hours, with cumulative fish mortality recorded at 24, 48, 72, and 96 hours after exposure. Fish were considered dead when operculum movement had completely ceased.

Data analysis

Data from the bioassays of *N. lugens* were statistically analyzed using GraphPad Prism (GraphPad Software, San Diego, California, USA). Meanwhile, data from the toxicological assays were analyzed using the EPA Probit Analysis Program Version 1.5 to determine the median lethal concentrations (LC_{50} and LC_{95}).

RESULTS AND DISCUSSION

Pest population and plant damage development

The research took place in rice plantations that were severely infested with the brown planthopper, resulting in diverse initial population sizes across the treatments, thereby representing real field conditions. Initial observations showed that the average brown planthopper population ranged from 16.30 to 26.63 insects per clump. Under these conditions, many rice plants had already begun turning brownish-green, as shown in Fig. 1, with stems starting to yellow and dry (Fig. 2).

According to Humaidi and Daryanto (2020), the level of damage caused by brown planthoppers

Fig. 2: Some of the stems of the rice plants had turned yellow and dried out

Table 2: Insect population and level of damage after insecticide application

Insecticides	74 (DAA)		81 (DAA)		88 (DAA)		95 (DAA)	
	Insect Population	Level of damage	Insect Population	Level of damage	Insect Population	Level of damage	Insect Population	Level of damage
Botanical Insecticide	16.30b	4.44a	13.23b	14.80a	0.73b	14.80a	0.49a	12.95b
Botanical + Synthetic Insecticides	26.63a	8.88a	17.37a	21.46a	2.11a	21.83a	0.82a	27.38a
Coefficient of variation (CV)	11,72	41.88	7,14	23.03	18,78	23.03	21,63	29.18

Notes : Numbers followed by the same letter in the same columns are not significantly different

attacks is categorized as follows: 1) mild, where the population of brown planthoppers is 1 insect per shoot, 2) moderate, when 25% of the planted area changes from green to yellowish or begins drying, 3) severe, when 25-85% of the planted area turns yellow or dries to a brown color, and 4) 'puso,' where >85% of the planted area shows yellowing or drying. Based on field observations, the pest attack level was classified as moderate. The clumps treated with botanical insecticide exhibited a significantly reduced pest population compared to those treated with a mixture of botanical and synthetic insecticides. During the first two weeks of the observation period after insecticide application as 74-88 days after application (DAA), the pest populations in both treatments decreased from 16.3 and 26.63 to 13.23 and 17.37 insects per clump, respectively. In the fourth week, pest populations in both treatments continued to decline, measuring 0.49 and 0.82 insects per clump (Table 2), which is below the economic threshold. According to Sianipar (2018), the economic threshold for the pest is 15 insects per clump.

These results demonstrate the superior performance of Rajam 65 EC, which combines high pest mortality (97%) with practical benefits such as ease of application and compatibility with integrated pest management (IPM) practices. his indicates the strong efficacy of the botanical formulation, contributing to a 16.39% enhancement in rice yields. Such yield improvements demonstrate clear economic benefits for farmers, particularly in areas where pest outbreaks significantly threaten productivity. The assessment of damage levels revealed that the two treatment types were largely comparable, with no significant differences observed. During the fourth observation, a solitary application of botanical insecticide achieved a damage reduction of 12.95%, in contrast to the 27.38% damage observed with the combination treatment. Therefore, botanical insecticide alone effectively controls insect populations and damage faster than the combination. These outcomes are in agreement with prior studies that highlight the effectiveness of botanical pesticides against initial pest stages, including *N. lugens*. At a concentration of 4.5 cc/L, these botanical insecticides achieved a highly mortality rate among target pests. In field trials, plants attacked by pests exhibited significant recovery, resumed growth, and continued production. Botanical pesticides demonstrated a dual benefit by significantly controlling pest populations and improving crop yields relative to the control treatments. Additionally, the implementation of these pesticides did not harm the natural enemies of the pests, which supports a balanced and sustainable strategy for pest control (Rismayani *et al.,* 2023). Rajam 65 EC's unique emulsifiable concentrate formulation ensures uniform dispersion and enhances contact efficacy against pests, distinguishing it from conventional botanical insecticides. Its high emulsifiability also prolongs residual activity under field conditions, providing consistent pest control over multiple weeks. The findings revealed that the botanical insecticide can be adapted for extensive farming practices, requiring little additional equipment or specialized skills for its application. Its low cost enhances its availability for smallholder farmers, particularly in less developed regions. These findings highlight its practical value as an eco-friendly pest management option. The mode of action of eugenol, a key active compound in the botanical insecticide Rajam 65 EC, involves disrupting the nervous system of brown planthoppers. Eugenol interferes with gamma-aminobutyric acid (GABA) receptor pathways, causing hyperexcitation, paralysis, and ultimately insect death. This mechanism is highly selective for pests like brown planthoppers, minimizing risks to non-target organisms (Regnault-Roger *et al.,* 2012). Additionally, eugenol along with other essential oils, including clove oil, shows insecticidal effects by modulating neuromodulatory functions that target octopamine synapses and by inhibiting the enzyme acetylcholinesterase (Price and Berry, 2006). Anticholinesterases inhibit acetylcholinesterase (AChE), preventing the breakdown of acetylcholine at synapses. This process causes an excess of acetylcholine, which triggers ongoing neuron activation and overexcitation of the nervous system, ultimately resulting in the death of the insect (Sylvestre et al., 2022). These findings demonstrate the effectiveness of eugenol-based botanical insecticides as a targeted, eco-friendly pest control solution. When combined with secondary compounds like citronella oil, eugenol's efficacy increases by targeting multiple neural and enzymatic pathways (Lengai *et al.,* 2020). Phytocompounds like terpenoids in citronella oil work as contact poisons, disrupting GABA receptors and inducing dehydration that leads to sustained fluid loss, paralysis, and insect death (Firdausiah *et al.,* 2023). Study by Himawan *et al.* (2016) showed that the citronella's insecticidal properties with an LC_{50} value of 8233.34 ppm (0.8%) against brown planthoppers and a repellency index of 88.83 at a concentration of 1600 ppm. Furthermore, the application of citronella extract at a concentration of 8.5% DAA led to a mortality rate of 66.67% in *P. xylostella* and a significant inhibition of larval feeding activity, measured at 82.66% (Shahabuddin and Anshary, 2010). These interactions minimize harm to non-target species while enhancing the pest-specific efficacy of botanical insecticides (Mardiningsih, 2021). Disruption of octopamine function results in complete damage to the insect's nervous system (Fenibo *et al.,* 2022; Samada and Tambunan, 2020); Yadav, 2022). Utilizing botanical insecticides may cause insects to die as their food consumption decreases, leading to disturbances in their digestive systems and hindering their growth. Other study tested citronella (*Cymbopogon nardus* L.) at concentrations of 1, 2, and 3 mL per petri dish using filter papers with test insects. The highest concentration (3 mL) caused 85–95% mortality after 3 hours, showing its effectiveness as a natural insecticide (Telaumbanua *et al.,* 2021). Plant extracts contain phytochemical compounds that show repellent properties influenced by dosage, offering a dual action as both an insecticide and a repellent (Widiyaningrum *et al.,* 2019). These attributes collectively highlight botanical insecticides as efficient and sustainable alternatives to synthetic chemicals for managing pests in an integrated manner.

Development of natural enemy populations

In the studied regions, the predominant natural enemy species consisted of spiders, along with Phaederus, and Cyrthorinus. The ongoing presence of these natural enemies within the experimental plots indicates that the botanical insecticide applied, despite its classification as a contact poison, posed a

Table 3: Population of spider after treatment

No.	Treatment	Spider population (insects/clump)			
		74 DAA	80 DAA	88 DAA	95 DAA
1	BI	2.3a	1.74a	0.93a	0.16a
2	BI+SI	2.78a	1.03b	0.43b	0.40a
	CV (%)	7.72	22.08	10.5	13.42

Notes: BI=Botanical insecticide; SI=Synthetic insecticide, DAA=day after application

Table 4: Population of *Phaederus* after treatment

No.	Treatment	Population of *Phaederus* (insects/clump)			
		74 DAA	80 DAA	88 DAA	95 DAA
1	BI	0	2.85a	2.94a	0
2	BI+SI	0	1.44b	1.20b	0
	CV (%)	-	8.78	12.22	-

Notes: BI=Botanical Insecticide; SI=Synthetic Insecticide; DAA=day after application

relatively low risk to non-target insects (Table 3).

This selective toxicity to pests, coupled with the ecological safety of Rajam 65 EC, further differentiates it from conventional botanical formulations that may lack precision in their effects on pest populations and natural predators. By conserving natural predator populations, the dependence on external pest management strategies is diminished, which facilitates the scalability in IPM systems. The effectiveness of botanical insecticides, including Rajam 65 EC, is influenced by the initial population density of pests. The insecticide demonstrated its efficacy at moderate densities by decreasing brown planthopper populations to levels below the economic threshold, which is consistent with its selective neurotoxic effects (Ganesh *et al.,* 2021; Regnault-Roger *et al.,* 2012). However, under severe infestations, pest pressure overwhelmed the capacity of the insecticide to control populations, requiring additional measures such as the integration of mechanical or supplementary chemical controls (Das, 2018). Early intervention is crucial in mitigating high pest densities, as timely applications of botanical insecticides disrupt pest reproduction cycles and limit population growth (Lengai *et al.,* 2020). Evidence suggests that when treatment is delayed in environments with high pest density, it can lead to a quick resurgence of pests, ultimately lowering the overall success of the intervention (Mardiningsih, 2021). These findings underscore the need for proactive pest monitoring and timely insecticide application to optimize pest management outcomes in rice ecosystems. The population of *Phaederus* observed in rice plantations at 80 and 88 DAA following a single application of botanical insecticide was significantly higher than that in the control plots treated with a combination of botanical and synthetic insecticides (Table 4).

The *Phaederus* (Coleoptera: Staphylinidae) beetle is a predatory insect that actively preys on planthoppers at night. The large population of Phaederus observed at 80-88 DAA contributed to the decline in the planthopper population. However, by 95 DAA, no *Phaederus* beetles were found in the plantations, coinciding with the decrease in the planthopper population. This implies that variations in the numbers of these predatory insects may be caused by migration triggered by a decline in their food resources. According to Telaumbanua *et al.* (2021), the observed decrease in predator populations on rice plants after applying botanical insecticides derived from citronella is an unintended result of the reduction in insect pest numbers. Predatory insects hunt pest insects, so when pest populations diminish in rice fields, the predatory insects also tend to disappear. The single application of botanical insecticide on rice effectively maintained the Phaederus beetle population in the crop. In contrast, the combination of synthetic and botanical insecticides suppressed the Phaederus population in the field. The results of this study corroborate the findings of Subandi *et al.* (2016), which indicated that

Table 5: Population of *Cyrthorinus lividipennis* after treatment

No.	Treatment	Cyrthorinus population (insects/clump)			
		74 DAA	80 DAA	88 DAA	95 DAA
1	BI	3.33a	0	0	0.32a
2	BI+SI	2.20b	0	0	0.36a
	CV (%)	37.13	-	-	19.75

BI=Botanical Insecticide; SI=Synthetic Insecticide; DAA=day after application

Table 6: Lethal Concentration (LC_{50}) of botanical insecticide for common carp

Hours after application (hours)	LC_{50} (cc/L)	95% confidence limit	Estimated probate line
24	0.220	0.183 – 0.393	Y = 5.52 X + 8.63
48	0.206	0.151 – 0.373	Y = 2.35 X + 6.61
72	0.150	0.119 – 0.214	Y = 2.61 X + 7.15
96	0.101	0.079 – 0.140	Y = 2.02 X + 7.01

Table 7: Lethal concentration (LC_{50}) of botanical insecticide for tilapia

Hours after application (hours)	LC_{50} (cc/L)	95% Confidence limit	Estimated probit line
24	0.177	0.164 – 0.192	Y = 10.51 X + 12.91
48	0.162	0.149 – 0.179	Y = 8.02 X + 11.33
72	0.153	0.120 – 0.207	Y = 7.92 X + 11.45
96	0.144	0.132 – 0.156	Y = 8.62 X + 12.27

the use of botanical insecticide based on *Toona sureni* leaf extract did not affect the tomcat population. However, the combination of synthetic insecticide and botanical insecticide management control (BIMC) at a concentration of 1.5 mL/L after the third application significantly suppressed the tomcat population. The predatory ladybug, *Cyrthorinus lividipennis* (Hemiptera: Miridae), is a planthopper-specific predator that actively hunts from morning to noon. This predator was first observed in the field when pest symptoms appeared (74 DAA). The population of *C. lividipennis* following the first application of botanical insecticide was significantly higher than that of the combined application of botanical and synthetic insecticides (Table 5).

In comparison, the systemic functioning of the synthetic insecticide did not detrimentally influence the natural enemies. The spider population observed between 74 and 88 DAA following single insecticide application exceeded that of the combination treatment. According to the study by Meidalima *et al.* (2017), synthetic pesticides negatively impact the abundance of arthropod predators. Fortunately, botanical insecticides were able to maintain populations of natural enemies. The enhanced safety profile of Rajam 65 EC, alongside its efficacy, ensures its suitability for sustainable pest management systems. By adhering to IPM strategies, this approach facilitates sustainable pest management and lessens the environmental disruptions frequently caused by synthetic insecticides. They tend to be more abundant in cultivation systems that employ an IPM approach compared to conventional methods (Jayakumar and Sankari, 2010). Eugenol oil-based insecticides are equally effective as their synthetic counterparts in managing pest populations, and they also contribute positively to the environment. They are biodegradable, minimizing environmental persistence and bioaccumulation risks, and preserve natural predators critical for ecological balance. These characteristics render them a sustainable choice for eco-friendly agricultural practices and integrated pest management.

Bioassay on tilapia and common carp

The results of the toxicity tests indicated low toxicity for tilapia and common carp, even at high concentrations, suggesting that the botanical insecticide is suitable for rice-fish farming systems.

Tables 6 and 7 provide a comprehensive analysis of the mortality data for common carp and tilapia that were exposed to botanical insecticides.

Toxicity of botanical insecticides to aquatic life

The 96-hour LC_{50} for the botanical insecticide was determined to be 0.101 cc/L for common carp and 0.144 cc/L for tilapia, indicating low acute toxicity as both values exceed the 0.10 cc/L threshold. At the recommended field application rate of 5.0 cc/L, the nominal water concentration is 0.0025 cc/L in paddy fields. The toxicity units (TU) determined for common carp (0.025) and tilapia (0.017) fall well below the established safety threshold (TU < 0.3), demonstrating a low risk to aquatic life. Therefore, this formulation is deemed suitable for implementation in rice-fish farming systems (Dubois *et al.,* 2019). In bioassays, six concentrations (0.003 to 1.0 cc/L) were tested. Results showed that higher concentrations and longer exposure times increased mortality rates. For common carp, the highest mortality (80%) was observed at 0.185 cc/L, with lower rates at decreasing concentrations (Fig. 3). Tilapia exhibited 100% mortality at 0.219 cc/L, with reduced mortality at lower concentrations (Fig. 4). These findings align with prior research, demonstrating that pollutant effects on organisms depend on concentration and exposure duration (Rai *et al.,* 2011). The results indicate that Rajam 65 EC has low acute toxicity; nevertheless, further investigation into chronic exposure and bioaccumulation risks is required to understand the potential long-term consequences for non-target aquatic.

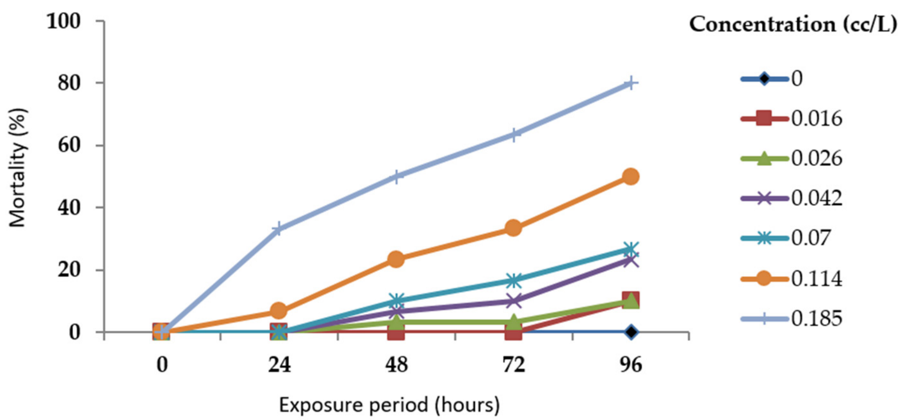

Fig. 3: Mortality of common carp exposed to botanical insecticide during toxicity test

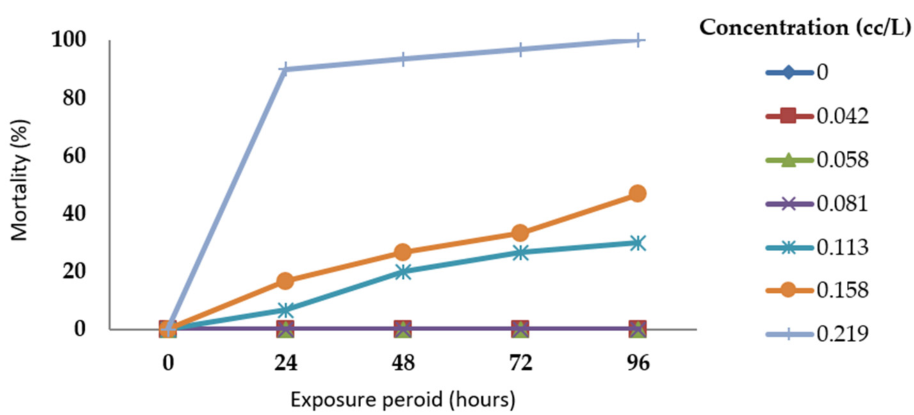

Fig. 4: Mortality of tilapia exposed to botanical insecticide during toxicity test

Another study by Rašković *et al.* (2022) indicates that botanical pesticides containing the active ingredient stabazadirachtin have mild side effects on fish, with precise measurement of its concentration in water proving challenging. Investigations into botanical pesticides featuring active ingredients like pyrethrum and spinosad reveal that they pose minimal risk to fish in aquaponic environments. Likewise, the Rajam 65 EC pesticide, which contains eugenol and lemongrass oil (*Cymbopogon citratus*), has been shown to be safe for fish raised in rice fields.

Environmental persistence and ecological impacts

The rapid degradation of eugenol-based insecticides in soil and water helps to minimize their persistence in the environment and reduces the risk of bioaccumulation (Fenibo *et al.,* 2022). Studies show that these compounds break down into non-toxic byproducts, reducing harm to soil microbial communities and supporting soil health (Regnault-Roger *et al.,* 2012). In aquatic environments, eugenol has a half-life of less than 24 hours, which greatly minimizes its influence on non-target organisms, including fish and amphibians (Nnamonu and Onekutu, 2015). Additionally, rapid degradation prevents disruption to natural predators and pollinators, which are essential for ecosystem stability (Mardiningsih, 2021). Within aquatic ecosystems, the degradation of botanical insecticides, including eugenol, occurs via hydrolysis and microbial action, resulting in the creation of non-toxic metabolites like vanillin and guaiacol. These byproducts are eco-friendly and have a negligible impact on aquatic life. The natural breakdown process ensures that the insecticide does not remain or accumulate within these crucial ecosystems (Sharma *et al.,* 2012; Ribeiro, 2022; Campos *et al.,* 2019). However, short-term studies alone are insufficient to fully evaluate the ecological safety of botanical insecticides. Long-term field trials are necessary to investigate chronic exposure effects on soil fauna, aquatic ecosystems, and trophic interactions (Samada and Tambunan, 2020). Predator populations (e.g., spiders, *Cyrthorinus lividipennis*) remained stable during the study, suggesting compatibility with natural enemy conservation. Due to their natural origins, botanical insecticides are unlikely to cause significant ecological impacts over time (Telaumbanua, 2021). These results emphasize the viability of botanical insecticides as sustainable alternatives to synthetic chemicals, contingent upon their responsible use and thorough monitoring of their long-term consequences (Campos *et al.,* 2019).

Efficacy and adaptability across agroecosystems

The findings demonstrate the efficacy of Rajam 65 EC in reducing brown planthopper populations and minimizing crop damage while preserving natural predator populations. The fast degradation of eugenol makes it ideally suited for wet climates or locations that receive substantial rainfall (Fenibo *et al.,* 2022). Its broad-spectrum activity suggests efficacy against other Hemipteran pests, such as leafhoppers and planthoppers, commonly found in rice ecosystems (Rahman *et al.,* 2023; Lengai *et al.,* 2020). Additionally, the formulation's ability to biodegrade and its targeted toxicity to pests render it appropriate for diverse agricultural systems, including rice, maize, and various horticultural crops. These attributes align with IPM principles, promoting ecological balance and flexibility in pest control strategies. However, pest behavior and environmental conditions, such as temperature fluctuations and crop phenology, may influence effectiveness. For instance, cooler climates may require adjusted application rates or timing. More extensive studies are necessary to establish the formulation's effectiveness across various agricultural systems and differing environmental conditions (Mardiningsih, 2021).

Cost-effectiveness and farmer adoption

The cost-effectiveness of Rajam 65 EC lies in its affordable production and minimal need for specialized application equipment, making it accessible to smallholder farmers in resource-limited settings (Lengai *et al.,* 2020). To promote the use of botanical insecticides among farmers, it is essential to implement training programs and extension services that focus on their efficacy, safety, and the environmental benefits they offer in contrast to synthetic alternatives (Samada and Tambunan, 2020). Effective tools for highlighting practical benefits, including pest management and increased yields, are demonstration plots and trials conducted by farmers (Das, 2018).

Resistance management

These approaches ensure the sustainability of pest management systems while minimizing ecological and economic risks. However, the potential for resistance development in pests remains a critical challenge. Continuous use of botanical insecticides featuring a singular mode of action can potentially induce resistance, a phenomenon already seen with synthetic pesticides in different agricultural systems (Siddiqui *et al.,* 2023). To mitigate this, resistance management strategies such as alternating botanical insecticides with different active compounds, integrating synthetic and botanical products, and employing mixed-mode action formulations are recommended (Regnault-Roger *et al.,* 2012). These strategies promote the long-term viability of pest management systems while reducing both ecological and economic risks. Rotating botanical insecticides with other control methods (e.g., synthetic or biological insecticides) to prevent resistance buildup, moreover the Implementing resistance monitoring programs to track potential shifts in pest susceptibility over time (Wang *et al.,* 2023). Insecticides derived from botanical sources, including eugenol-based formulations, are characterized by their swift degradation in both soil and water, thereby limiting their persistence and environmental accumulation (Lengai *et al.,* 2020). Studies have shown that these compounds break down into non-toxic byproducts, reducing potential harm to soil microbial communities and maintaining soil health (Regnault-Roger *et al.,* 2012). In aquatic environments, eugenol-based formulations demonstrate a half-life of less than 24 hours, thereby limiting their ability to bioaccumulate and minimizing their harmful effects on non-target species, including fish and amphibians (Fenibo *et al.,* 2022). Additionally, the low persistence of botanical insecticides prevents disruption of natural predators and pollinators, which are critical for ecosystem stability (Mardiningsih, 2021). While short-term research suggests their environmental safety, comprehensive long-term field trials are required to investigate possible chronic effects on soil fauna, aquatic ecosystems, and trophic dynamics (Samada and Tambunan, 2020). These findings suggest that botanical insecticides, when used responsibly, represent an eco-friendly alternative to synthetic chemicals, offering sustainable pest management with minimal long-term ecological risks. The findings from this study demonstrate that Rajam 65 EC effectively manages brown planthopper populations and minimizes crop damage while preserving natural predators. The quick decomposition of this material minimizes residue accumulation, rendering it highly suitable for moist climates or regions that experience heavy rainfall (Fenibo *et al.,* 2022). The broad-spectrum activity of eugenol and related compounds indicates potential efficacy against other Hemipteran pests, such as leafhoppers and planthoppers, commonly found in rice ecosystems (Rahman *et al.,* 2023; Lengai *et al.,* 2020). In addition, its biodegradability and targeted toxicity to pests make it appropriate for a wide range of crop systems, including rice, maize, and horticultural varieties. This alignment with IPM principles encourages ecological harmony and sustainable approaches to pest control. Despite its adaptability, variations in pest behavior and environmental conditions, such as temperature fluctuations and crop phenology, may influence effectiveness. In cooler climates, it may be necessary to alter the application rates or timing to ensure optimal results are achieved. Further studies are recommended to validate the formulation's performance across diverse agricultural systems under varying climatic and pest conditions (Mardiningsih, 2021).

CONCLUSION

This study highlights the efficacy of eugenol oil-based botanical insecticides as an innovative and sustainable strategy for controlling brown planthopper infestations in rice fields. The outcomes significantly endorse the promise of botanical insecticides as a realistic alternative to synthetic chemical pesticides, highlighting their effectiveness and ecological safety. The botanical insecticide alone demonstrated remarkable pest control capabilities, reducing the number of insects per clump from 16.3 to 0.73 within three weeks, consistently maintaining pest populations below the economic threshold. When combined with synthetic insecticides, the pest counts further dropped from 26.63 to 2.17 insects per clump. Importantly, this botanical solution showed superior efficacy in minimizing crop damage (12.95%) compared to synthetic alternatives (27.38%). hese notable declines in pest numbers and the associated decrease in crop damage demonstrate the effective protective qualities of the botanical formulation on rice crops. In addition to its immediate impact on pests, this botanical insecticide also offers the significant benefit of protecting beneficial natural predators like spiders and beetles, which are essential for maintaining ecological stability. This characteristic positions the botanical formulation as an essential component of integrated pest management (IPM) systems. Furthermore, toxicity assessments indicate that this insecticide is environmentally safe, posing minimal risks to aquatic life and the surrounding ecosystem at field concentrations. This safety profile ensures compatibility with sustainable agricultural practices, particularly in regions where environmental conservation is critical. The optimal dosage of 4.5–5.0 cc/L resulted in an impressive 97% mortality rate of the target pest, highlighting its potency in pest control. Additionally, the use of this botanical insecticide significantly enhanced rice yields, with a 16.39% increase compared to untreated controls. This enhancement in yield emphasizes the economic advantages associated with the adoption of sustainable pest management techniques, particularly for smallholder farmers who are reliant on stable production for their economic well-being. Interestingly, the study also revealed that the botanical insecticide exhibited a longer-lasting effect on pest suppression compared to synthetic options. The ongoing decline in pest populations over a span of weeks, even after the first application, emphasizes its long-lasting impact. This extended effectiveness decreases the frequency of required applications, making it both a cost-efficient and practical solution for large-scale farming. Additionally, its ability to integrate seamlessly with synthetic insecticides offers flexibility in pest management programs, allowing farmers to tailor solutions to specific infestation levels and environmental conditions. This study's outcomes present strong justification for the broad implementation of botanical insecticides based on eugenol oil in rice agriculture. Their high efficacy, environmental safety, and compatibility with sustainable farming practices make them a valuable tool for achieving integrated pest control while safeguarding both productivity and ecological integrity. It is advisable to conduct additional studies and scaling initiatives to enhance application strategies and broaden their implementation in various agricultural systems.

AUTHOR CONTRIBUTIONS

Wiratno performed the literature review, conceptualized the central research idea (as inventors of the botanical pesticide), designed the study, and manuscript preparation. N. Sutrisna performed the literature review, conceptualized the central research idea, designed the study, and analyzed and interpreted the data. Y. Surdianto performed conceptualized the central research idea, and analyzed and interpreted the data. K.D. Sutanto Performed the literature review, analyzed and interpreted the data, manuscript preparation and helped in improvement of the manuscript. A. Nurawan Conducted field experiments, analyzed the data, and contributed to manuscript writing. I. Taufik and M. Rizal performed on analyzing and interpreting data related to the safety levels of the botanical insecticide for fish. E. Karmawati performed the literature review and contributed to manuscript preparation. Siswanto performed Analyzed and interpreted data and helped in preparing the manuscript text. D. Soetopo performed helped in the literature review and manuscript preparation I.B. Rahardjo performed in manuscript edition and helped in improvement of the manuscript, I.M. Trisawa performed in manuscript edition and helped in improvement of the manuscript, Rismayani performed literature review, and helped in improvement of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
AChE	Anticholinesterases inhibit acetylcholinesterase
BIMC	Botanical insecticide management control
cm	centimeter
Cc/L	Critical concentrate per liter
CV	Coefficient variation
DAA	day after application
DAP	days after rice planting
EC	Emulsiafiable concentrate
EPA	Environmental Protection Agency
Fig.	Figure
g	gram
GABA	Gamma-aminobutyric acid
I	Attack intensity in percentage
IDP	Individual development plan
IPM	with integrated pest management
LC_0	Lethal concentration caused 0% mortalities
LC_{50}	Lethal concentration caused 50% mortalities
LC_{90}	Lethal concentration caused 90% mortalities
LC_{95}	Lethal concentration caused 95% mortalities
LC_{100}	Lethal concentration caused 100% mortalities
LT_{50}	Lethal time that the concentration caused 50% mortalities
m^2	Square meters
mL/L	Milliliter per liter
ni	Number of plants or plant parts sample with damage scale vi
N	Number of plants or plant parts observed in the sample
ppm	Part per million
SI	Synthetic insecticide
TU	Toxicity unit
Z	Highest damage scale value

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