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Research Article
Eco-Friendly Toxicity and Repellent Effects of Selected Medicinal Plant Extracts against the Rice Weevil, *Sitophilus oryzae* (L.)

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Abstract
Background and Objective: Rice weevils, *Sitophilus oryzae* (L.), are major pests of stored grains, causing substantial post-harvest losses. This study evaluated the efficacy of selected medicinal plant extracts for the control and repellency of rice weevils as eco-friendly alternatives to synthetic pesticides. **Materials and Methods:** Twenty-one medicinal plants were initially screened and four plants were selected for extraction using 70% ethanol and distilled water. Contact toxicity was assessed at concentrations of 5, 10 and 15% (w/v) using plastic cup bioassays. Repellency tests were conducted to determine the effectiveness of extracts over time. Data were analyzed using one-way ANOVA followed by Tukey's HSD test ($p<0.05$) in SPSS. **Results:** Among ethanolic extracts, tobacco leaves at 15% showed the highest insect mortality (93.3±3.3%), significantly higher than clover flowers (29.9±15.3%). All concentrations of aqueous tobacco extract resulted in 100% mortality, while lemon and long pepper extracts demonstrated moderate toxicity (>50%). In repellency assays, ethanolic clover flowers (10%) and aqueous clover flowers (15%) exhibited the highest average repellent efficiencies of 95.6±2.9 and 92.2±4.8%, respectively, with maximum repellency observed within 30 min. **Conclusion:** The findings indicate that selected medicinal plant extracts, particularly tobacco and clover, are effective and eco-friendly agents for the control and repellency of rice weevils. These plant-based extracts show promise as sustainable alternatives to synthetic pesticides for stored grain protection.

Key words: Eco-friendly pest control, medicinal plants, repellency, rice weevil, toxicity

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the world's most important food crops, serving as the primary staple for more than half of the global population, particularly in Asia, parts of the Americas and some European countries[1]. Despite its central role, rice becomes highly vulnerable to insect infestation once harvested, particularly during storage, processing, transport and distribution. The problem is even more pronounced in warm and humid climates, where insects reproduce rapidly and cause substantial postharvest losses[2]. These conditions lead to significant reductions in both the quantity and quality of rice available for consumption.

Postharvest grain loss includes both quantitative and qualitative dimensions: The former refers to reductions in grain weight or volume, while the latter involves declines in nutritional value and undesirable changes in taste, color, texture, or other quality attributes. Storage-related deterioration accounts for a major share of these losses and remains one of the most difficult challenges in rice value chains[3].

Among the many insects associated with stored grains, the rice weevil *Sitophilus oryzae* (L.) is one of the most destructive[4]. It attacks a wide range of cereals and grain products and is especially problematic in regions where warm conditions allow the species to reproduce continuously[5,6]. Stored and milled rice grains are highly vulnerable to infestation. Both the larvae and adults feed inside the grain, resulting in weight loss, contamination and a steady decline in market quality[7]. Under typical storage conditions, losses of 10-65% have been reported and in long-term or poorly managed systems, losses can exceed 80%. Infestation also creates hotspots of elevated temperature and humidity within the grain mass, encouraging fungal growth and accelerating spoilage[8].

Traditional control methods rely heavily on chemical fumigants such as phosphine and methyl bromide[9]. In practice, however, these chemicals come with major drawbacks, including growing pest resistance, environmental and health risks and increasing regulatory restrictions linked to their toxicity and residues[10,11]. These issues underscore the need for safer and more sustainable pest management strategies for grain storage.

Botanical insecticides are now receiving growing attention as viable alternatives to synthetic chemicals. Many medicinal plants contain bioactive compounds in their leaves, flowers, stems and roots that exhibit strong insecticidal or repellent activity[4]. Recent studies show that plant extracts can offer cost-effective, environmentally friendly and low-toxicity options for pest control, making them increasingly relevant for protecting stored grains[10].

Although plant extracts have been widely investigated for controlling stored-product insect pests[4], studies have primarily focused on a limited number of well-known botanical species, while the insecticidal potential of many medicinal plants commonly found in Northeast Thailand remains largely unexplored. Northeast Thailand possesses rich plant biodiversity and a long history of traditional use of medicinal plants, many of which are readily available, inexpensive and environmentally friendly sources of bioactive compounds. However, comparative information on their effectiveness against *S. oryzae* is scarce. Furthermore, previous studies have typically evaluated individual plant species or single extraction methods, making it difficult to identify the most promising candidates for practical application. Therefore, this study aimed to (i) Screen twenty-one commonly available medicinal plants for their insecticidal activity against adult *S. oryzae* under laboratory conditions and (ii) Evaluate the contact toxicity and repellency of selected plant extracts prepared using two solvents (70% ethanol and distilled water) at different concentrations to determine their optimal effective levels against *S. oryzae*.

MATERIALS AND METHODS

Study area and duration: The study was conducted at the Department of Plant Science, Faculty of Agricultural Innovation and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand, from January to March 2024. Experimental activities, including plant extract preparation, toxicity and repellency bioassays and data collection, were carried out under laboratory conditions.

The study site is located at Rajamangala University of Technology Isan, Nong Rawiang Education Center, Mueang Nakhon Ratchasima District, Nakhon Ratchasima Province, Thailand (14.939886° N, 102.164396° E). The area is situated on the Khorat Plateau in Northeastern Thailand and is characterized by predominantly agricultural landscapes with relatively flat terrain. The region experiences a tropical savanna climate with distinct dry and rainy seasons. During the study period (January-March 2024), the average ambient temperature ranged from approximately 30.7 to 35.6°C, while the average relative humidity ranged from 61 to 64%. The agricultural importance of the region and its warm tropical climate make it relevant for studies on stored-product insect pests such as *S. oryzae* and the development of eco-friendly pest management strategies.

Table 1: List of medicinal plants reported for insect control collected in Mueang District, Nakhon Ratchasima Province

Medicinal plant	Plant part used
Long pepper (*Piper longum*)	Fruit
Clove (*Syzygium aromaticum*)	Flower
Lemon (*Citrus limon*)	Leaf
Tobacco (*Nicotiana tabacum*)	Leaf
Custard apple (*Annona reticulata*)	Leaf
Kaffir lime (*Citrus hystrix*)	Fruit peel
Cleome (*Cleome viscosa*)	Leaf
Moringa (*Moringa oleifera*)	Leaf
Papaya (*Carica papaya*)	Leaf
Wild betel (*Piper sarmentosum*)	Leaf
Chili (*Capsicum annuum*)	Fruit
Cinnamon (*Cinnamomum verum*)	Bark
Castor (*Ricinus communis*)	Leaf
Holy basil (*Ocimum tenuiflorum*)	Leaf
Basil (*Ocimum basilicum*)	Leaf
Neem (*Azadirachta indica*)	Leaf
King of bitters (*Andrographis paniculata*)	Leaf
Parsley (*Petroselinum crispum*)	Leaf
Lemongrass (*Cymbopogon citratus*)	Leaf
Wild asparagus (*Stemona tuberosa*)	Rhizome

Preparation of test insects: Adult *S. oryzae* were collected from naturally infested rice grains and reared to establish a laboratory colony. The culture was maintained at 28±2°C and 75±5% relative humidity in plastic containers (15.5×21.5×7.6 cm) containing organic brown rice previously sterilized at 60°C for 12 hrs to prevent contamination by other stored-grain insects. Adults were allowed to mate and oviposit for 14 days, after which all parental individuals were removed using a fine-mesh sieve. The infested grains were held under the same environmental conditions until adult emergence (~30 days). Newly emerged adults (7-10 days old) were used in all experiments to ensure physiological uniformity.

Screening of botanical materials for insecticidal activity: Twenty-one plant species traditionally recognized for insecticidal or repellent properties were surveyed and collected from local sites in Nakhon Ratchasima Province, Thailand. Species selection was based on ethnobotanical records and previous scientific reports on plant-based pest control. The list of all species is provided in Table 1. Plant materials were washed with clean water, sun-dried for 24 hrs and oven-dried at 60°C for an additional 24 hrs. Dried samples were ground into a fine powder using an electric grinder. For each species, 0.5 g of powdered material was thoroughly mixed with 20 g of rice grains in 6-oz plastic cups, after which 10 adult *S. oryzae* were introduced. Each treatment included three replicates, arranged in a completely randomized design. Adult mortality was recorded daily for 7 days using a stereo microscope. Mortality (%) was calculated as:

$$\text{Mortaliy (\%)} = \frac{\text{Number of dead adults}}{\text{Total number of adults}} \times 100$$

If control mortality exceeds 5%, Abbott's correction can be applied.

Preparation of plant extracts: Plant species selected from preparation of test insects were subjected to aqueous and ethanolic extractions. For aqueous extraction, powdered plant material was soaked in distilled water for 72 hrs at concentrations of 5, 10 and 15% (w/w). For ethanolic extraction, the same quantities of powdered material were soaked in 70% ethanol for 72 hrs at the corresponding concentrations. Extracts were filtered through muslin cloth and the ethanol extracts were further concentrated using a rotary evaporator at 40°C. All extracts were transferred to sterile bottles and stored at 4°C until use.

Contact toxicity bioassay: The contact toxicity of plant extracts from four species long pepper (fruit), clove (flower), tobacco (leaf) and lime (leaf) was evaluated following a modified method of[12]. Plastic cups (6 oz) were evenly coated with extract using cotton swabs and allowed to air-dry completely. Aqueous and ethanolic extracts were tested at 5, 10 and 15%. Ten adult *S. oryzae* were introduced into each treated cup. A distilled-water coating served as the solvent control. The experiment followed a completely randomized design with three replicates per treatment. Mortality was recorded at 30, 60, 90, 120, 150 and 180 min after exposure.

Repellency assay: Repellent activity was assessed using a modified area-preference method[13]. Filter papers (9 cm diameter) were cut into two equal halves; 0.1 mL of plant extract was applied to one half, while the other half remained untreated as the control. After air-drying for 10 min, both halves were reassembled in Petri dishes with a neutral zone at the center. Five adult *S. oryzae* were released in the neutral zone and each treatment was replicated three times. The number of insects on treated and untreated halves was recorded at 30, 60, 90, 120, 150 and 180 min. Repellency (%) was calculated using the formula proposed by[14]:

$$PR = \frac{N_c - N_t}{N_c + N_t} \times 100$$

Where:

N_c = Number of insects on the extract-treated half

N_t = Number of insects on the untreated half

Statistical analysis: Data from all bioassays were analyzed using One-way Analysis of Variance (ANOVA) to determine the effects of treatments. Significant differences among treatment means were assessed using Tukey's HSD and Duncan's Multiple Range Test (DMRT) at $p<0.05$. All statistical analyses were performed using SPSS (Statistical Package for the Social Sciences).

RESULTS

Screening of botanical materials for the control of rice weevil: Screening of 21 plant species for insecticidal activity against adult weevil (Table 2) revealed that long pepper fruit extract produced the highest mortality (90.00%). This was followed by clove flower extract (80.67%), lime leaf extract (60.00%) and tobacco leaf extract (50.33%). The remaining 17 plant species resulted in <50% adult mortality and were therefore excluded from subsequent bioassays.

Insecticidal activity of plant extracts against rice weevil: Based on the preliminary screening of botanical materials for the control of rice weevil, four plant species that induced >50% adult mortality were selected for further evaluation using extracts prepared with 70% ethanol and distilled water. The mortality responses to the ethanol extracts are summarized in Table 3. Among all treatments, tobacco leaf extract at 15% produced the highest cumulative mortality (93.32±3.33%), followed closely by the 5% and 10% concentrations (89.99±5.77 and 86.65±8.82%, respectively). These three concentrations did not differ significantly from one another ($p>0.05$). In contrast, clove extract (10%) resulted in the lowest mortality (29.99±15.28%) and was significantly less effective than all tobacco treatments ($p<0.05$). After only 30 min of exposure, all concentrations of tobacco extract and long pepper extract at 5% had already caused >50% adult mortality.

For the distilled-water extracts (Table 4), tobacco extracts at 5%, 10% and 15% achieved 100% mortality within 30 min, representing the most effective treatments overall. Lime leaf and long pepper extracts at all concentrations also produced >50% mortality and differed significantly from clove extract ($p<0.05$), which consistently resulted in <50% mortality.

A comparison between extraction solvents revealed that the extraction medium strongly influenced insecticidal performance, particularly for tobacco. Distilled-water extracts of tobacco displayed higher bioactivity than the corresponding ethanol extracts.

Despite differences in mortality levels among treatments, adult weevil exhibited similar external symptoms of mortality across both solvent systems. Dead adults consistently showed inward curling of the legs and rostrum, rigidity of the body and complete immobility, characteristic of neurotoxic action.

Repellent activity of herbal plant extracts against rice weevil: The repellent activity of the four medicinal plant extracts prepared using 70% ethanol is presented in Table 5. Clove extract at 10% produced the highest repellency (95.56±2.94%), followed by 5% lime leaf extract (88.89±4.01%) and 5% clove extract (85.56±13.92%), with no significant differences among these treatments ($p>0.05$). In contrast, long pepper extract at 5% exhibited the lowest repellency (52.22±16.37%). Based on exposure time, 5% lime leaf extract achieved 100% repellency at 30 and 60 min, whereas 10% clove extract reached 100% repellency at 120 and 180 min.

For the distilled-water extracts (Table 6), clove extract at 15% showed the strongest repellency (92.22±4.84%), followed by 5 and 10% clove extracts (88.89±8.01 and 88.89±5.88%), with no significant difference among these concentrations ($p>0.05$). All clove treatments produced significantly higher repellency than tobacco leaf extract at all concentrations ($p<0.05$). At 30 min, both 15% clove extract and 15% long pepper extract produced repellency levels of 93.33±6.67%, while tobacco extracts at all concentrations remained below 50%.

Across both solvent systems, the behavioral pattern of rice weevil adults was consistent. In treatments with repellent activity, the insects consistently moved toward the untreated area of the arena, whereas in treatments lacking repellency, adults were observed in both treated and untreated sections.

Table 2: Screening of 21 herbal plant species for insecticidal activity against rice weevil mortality over 7 days

	Mortality of rice weevil (%)							
Herbal plant (part used)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Cumulative mortality (%)
Long pepper (fruit)	6.67	16.67	30.00	30.00	6.67	0.00	0.00	90.00
Clove (flower)	0.00	20.00	23.33	23.33	13.33	6.67	0.00	86.67
Lime (leaf)	6.67	13.33	13.33	0.00	3.33	6.67	16.67	60.00
Tobacco (leaf)	0.00	3.33	3.33	3.33	20.00	13.33	10.00	53.33
Soursop (leaf)	0.00	6.67	13.33	3.33	10.00	3.33	0.00	36.67
Kaffir lime peel (fruit)	0.00	10.00	6.67	3.33	3.33	3.33	3.33	30.00
Siam weed (leaf)	0.00	10.00	0.00	6.67	0.00	6.67	3.33	26.67
Oleander (leaf)	6.67	0.00	6.67	6.67	3.33	0.00	3.33	26.67
Oleander (leaf)	3.33	6.67	3.33	6.67	3.33	0.00	3.33	26.67
Piper sarmentosum (leaf)	0.00	0.00	0.00	0.00	10.00	10.00	3.33	23.33
Chili (fruit)	3.33	0.00	3.33	6.67	0.00	10.00	0.00	23.33
Cinnamon (bark)	3.33	0.00	6.67	3.33	0.00	0.00	3.33	16.67
Castor (leaf)	3.33	0.00	3.33	0.00	0.00	3.33	6.67	16.67
Holy basil (leaf)	6.67	0.00	3.33	0.00	3.33	3.33	0.00	16.67
Sweet basil (leaf)	0.00	0.00	0.00	10.00	0.00	3.33	0.00	13.33
Neem (leaf)	0.00	0.00	0.00	13.33	0.00	0.00	0.00	13.33
Culantro (leaf)	0.00	3.33	0.00	0.00	0.00	6.67	3.33	13.33
Moringa (leaf)	10.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00
Andrographis paniculata (leaf)	0.00	0.00	3.33	3.33	0.00	0.00	0.00	6.67
Stemona tuberosa (rhizome)	0.00	0.00	3.33	0.00	3.33	0.00	0.00	6.67
Citronella (leaf)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3: Effects of 70% ethanol herbal extracts on rice weevil mortality

		Mortality of rice weevil (%)						
Herbal extract	Concentration (%)	30 min	60 min	90 min	120 min	150 min	180 min	Cumulative mortality (%)
Long pepper	5	53.33 ± 6.67^{ac}	3.33 ± 3.33^{bc}	3.33 ± 3.33^{bc}	0.00 ± 0.00^{b}	3.33 ± 3.33	6.66 ± 6.67	69.98 ± 5.77^{ab}
	10	23.33 ± 3.33^{df}	23.33 ± 8.81^{a}	0.00 ± 0.00^{c}	6.66 ± 3.33^{ab}	0.00 ± 0.00	0.00 ± 0.00	53.32 ± 6.67^{bc}
	15	43.33 ± 3.33^{bd}	20.00 ± 0.00^{ab}	3.33 ± 3.33^{bc}	0.00 ± 0.00^{b}	0.00 ± 0.00	6.66 ± 3.33	73.32 ± 3.33^{ab}
Clove	5	36.66 ± 3.33^{bd}	10.00 ± 0.00^{ac}	00.00 ± 0.00^{c}	3.33 ± 3.33^{ab}	0.00 ± 0.00	3.33 ± 3.33	53.32 ± 3.33^{b}
	10	23.33 ± 8.81^{df}	3.33 ± 3.33^{bc}	3.33 ± 3.3^{bc}	0.00 ± 0.00^{b}	0.00 ± 0.00	0.00 ± 0.00	29.99 ± 15.28^{c}
	15	30.00 ± 5.77^{df}	0.00 ± 0.00^{c}	0.00 ± 0.00^{c}	0.00 ± 0.00^{b}	0.00 ± 0.00	0.00 ± 0.00	30.00 ± 5.77^{c}
Tobacco leaf	5	73.33 ± 3.33^{a}	3.33 ± 3.33^{bc}	10.00 ± 5.78^{bc}	3.33 ± 3.33^{ab}	0.00 ± 0.00	0.00 ± 0.00	89.99 ± 5.77^{a}
	10	60.00 ± 15.27^{ab}	16.66 ± 3.33^{ac}	6.66 ± 3.33^{bc}	3.33 ± 3.33^{ab}	0.00 ± 0.00	0.00 ± 0.00	86.65 ± 8.82^{a}
	15	60.00 ± 5.77^{ab}	6.66 ± 3.33^{ac}	23.33 ± 3.33^{a}	0.00 ± 0.00^{b}	3.33 ± 3.33	0.00 ± 0.00	93.32 ± 3.33^{a}
Lime leaf	5	20.00 ± 0.00^{f}	10.00 ± 5.77^{ac}	3.33 ± 3.33^{bc}	0.00 ± 0.00^{b}	0.00 ± 0.00	0.00 ± 0.00	33.33 ± 6.67^{c}
	10	30.00 ± 5.77^{df}	10.00 ± 5.77^{ac}	13.33 ± 6.67^{ab}	10.00 ± 0.00^{a}	3.33 ± 3.33	0.00 ± 0.00	66.66 ± 8.82^{ab}
	15	30.00 ± 11.55^{df}	16.66 ± 12.01^{ac}	6.66 ± 3.33^{bc}	3.33 ± 3.33^{ab}	0.00 ± 0.00	6.66 ± 3.33	66.64 ± 18.56^{ab}
Distilled water (control)		0.00 ± 0.00^{f}	0.00 ± 0.00^{c}	00.00 ± 0.00^{c}	0.00 ± 0.00^{b}	0.00 ± 0.00	0.00 ± 0.00	$0.00.\ \pm0.00^{d}$
p-value		<0.001**	0.043*	0.002**	0.034*	0.693ns	0.215ns	<0.001**
C.V. (%)		8.319	2.226	3.774	2.333	0.750	1.429	10.434

Means followed by the same letter within the same column are not significantly different according to DMRT ($p>0.05$) and Significance levels: **Indicates significance at the 99% confidence level, *indicates significance at the 95% confidence level and ns indicates no significant difference

DISCUSSION

This study assessed the toxicity and repellency of selected medicinal plant extracts against *Sitophilus oryzae*, a major pest of stored grains worldwide. Botanical extracts have increasingly been investigated as eco-friendly alternatives to synthetic insecticides for stored-product pest management, focusing on mortality and repellency responses[10]. The present findings demonstrate that several plant extracts exhibit significant insecticidal and repellent activities, although their efficacy varies depending on plant species, concentration and extraction solvent.

The initial screening of 21 plant species showed that only long pepper, clove, lime and tobacco produced >50% adult mortality, supporting their selection for detailed evaluation. Among these, tobacco emerged as the most potent, exhibiting rapid knockdown and consistently high mortality across all tested concentrations. In contrast, clove and long pepper demonstrated only moderate insecticidal activity, indicating substantially lower toxicity than tobacco under the conditions tested.

Previous studies have similarly evaluated these botanicals against stored-grain pests, including *S. oryzae* and reported considerable variation in efficacy depending on plant part,

Table 4: Effects of aqueous herbal extracts on rice weevil mortality

Herbal extract	Concentration (%)	Mortality of rice weevil (%) 30 min	60 min	90 min	120 min	150 min	180 min	Cumulative mortality (%)
Long pepper	5	50.00±15.27^{bd}	16.67±6.67^{ab}	0.00±0.00^{b}	0.00±0.00^{b}	3.33±3.33	3.33±3.33	73.33±17.64^{bc}
	10	46.67±3.33^{bd}	3.33±3.33^{ab}	6.67±3.33^{a}	13.33±6.67^{a}	0.00±0.00	0.00±0.00	70.00±11.55^{bc}
	15	40.00±11.54^{bd}	10.00±0.00^{ab}	6.67±3.33^{a}	0.00±0.00^{b}	0.00±0.00	3.33±3.33	60.00±11.55^{cd}
Clove	5	23.33±3.33^{d}	6.67±3.33^{ab}	3.33±3.33^{ab}	0.00±0.00^{b}	0.00±0.00	0.00±0.00	33.33±3.33^{e}
	10	43.33±3.33^{bd}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.00^{b}	00.00±0.00	0.00±0.00	43.33±3.33^{de}
	15	33.33±8.81^{cd}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.000	0.00±0.00	33.33±8.81
Tobacco leaf	5	90.00±5.77^{a}	10.00±5.77^{ab}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.00	0.00±0.00	100.00±0.00^{a}
	10	100.00±0.00^{a}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.000	0.00±0.00	100.00±0.00^{a}
	15	100.00±0.00^{a}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.000	0.00±0.00	100.00±0.00^{a}
Lime leaf	5	66.67±24.03^{ac}	16.67±16.67^{ab}	0.00±0.00^{b}	6.67±3.33^{ab}	3.33±3.33	0.00±0.00	93.34±3.33^{ab}
	10	66.67±8.81^{ac}	23.33±8.81^{a}	0.00±0.00^{b}	3.33±3.33^{b}	0.00±0.000	0.00±0.00	93.33±3.33^{ab}
	15	70.00±15.27^{ab}	10.00±5.77^{ab}	0.00±0.00^{b}	6.67±6.67^{ab}	3.33±3.33	0.00±0.00	90.00±5.77^{ab}
Distilled water (control)		0.00±0.00^{e}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.00^{b}	0.00±0.000	0.00±0.00	0.00±.00^{f}
p-value		<0.001**	0.143ns	0.022*	0.063ns	0.618ns	0.545ns	<0.001**
C.V. (%)		8.286	1.633	2.556	2.033	0.833	0.917	18.568

Means followed by the same letter within the same column are not significantly different according to DMRT (p>0.05) and Significance levels: **Indicates significance at the 99% confidence level, *indicates significance at the 95% confidence level and ns indicates no significant difference

Table 5: Effects of 70% ethanol herbal extracts on the repellency of the rice weevil

Herbal extract	Concentration (%)	Repellency of rice weevil (%) 30 min	60 min	90 min	120 min	150 min	180 min	Mean repellency (%)
Long pepper	5	53.33±29.05^{a}	46.66±24.03^{b}	53.33±29.05^{b}	46.67±6.67^{b}	53.33±13.33^{a}	60.00±0.00^{ab}	52.22±16.37^{c}
	10	93.33±6.67^{a}	80.00±11.54^{ab}	73.33±6.67^{ab}	93.33±6.67^{a}	73.33±17.63^{a}	80.00±11.54^{ab}	83.33±3.85^{ac}
	15	73.33±13.33^{a}	66.67±17.63^{ab}	86.67±13.33^{ab}	86.67±13.33^{ab}	93.33±6.67^{a}	80.00±11.54^{ab}	81.11±10.60^{ac}
Clove	5	93.33±6.67^{a}	93.33±6.67^{ab}	86.67±13.33^{ab}	80.00±20.00^{ab}	80.00±2.00^{a}	73.33±17.63^{ab}	85.56±13.92^{ac}
	10	93.33±6.67^{a}	93.33±6.67^{ab}	93.33±6.67^{ab}	100.00±0.00^{a}	93.33±6.67^{a}	100.00±0.00^{a}	95.56±2.94^{a}
	15	80.00±11.54^{a}	86.67±6.67^{ab}	80.00±0.00^{ab}	80.00±0.00^{ab}	86.67±6.67^{a}	86.67±6.7^{ab}	83.34±3.33^{ac}
Tobacco leaf	5	80.00±11.54^{a}	86.67±13.33^{ab}	86.67±13.33^{ab}	73.33±13.33^{ab}	53.33±24.03^{a}	60.00±20.00^{ab}	73.33±11.71^{ac}
	10	80.00±11.54^{a}	73.33±17.63^{ab}	80.00±11.54^{ab}	73.33±6.67^{ab}	73.33±17.63^{a}	86.67±6.67^{ab}	77.78±2.94^{ac}
	15	53.33±17.63^{a}	73.33±13.33^{ab}	73.33±6.67^{ab}	46.67±6.67^{b}	53.33±6.67^{a}	53.33±6.67^{b}	58.89±5.88^{bc}
Lime leaf	5	66.67±6.67^{a}	100.00±0.00^{a}	100.00±0.00^{a}	86.67±13.33^{ab}	93.33±6.67^{a}	86.67±13.33^{ab}	88.89±4.01^{ab}
	10	86.67±13.33^{a}	80.00±20.00^{ab}	73.33±17.63^{ab}	73.33±26.67^{ab}	66.67±13.33^{a}	86.67±6.67^{ab}	78.89±15.55^{ac}
	15	73.33±13.33^{a}	66.67±24.03^{ab}	73.33±13.33^{ab}	60.00±0.00^{ab}	53.33±29.05^{a}	46.67±24.03^{b}	62.22±14.17^{bc}
Distilled water (control)		0.00±0.00^{b}	0.00±0.00^{c}	0.00±0.00^{c}	0.00±0.00^{c}	0.00±0.00^{b}	0.00±0.00^{c}	0.00±0.00^{d}
p-value		0.05**	0.007**	0.002**	<0.001**	0.012*	<0.001**	<0.001**
C.V. (%)		3.284	3.146	3.813	4.943	2.850	4.947	6.270

Means followed by the same letter within the same column are not significantly different according to DMRT (p>0.05) and Significance levels: ** Indicates significance at the 99% confidence level and *indicates significance at the 95% confidence level

Table 6: Effects of aqueous herbal extracts on the repellency of the rice weevil

Herbal extract	Concentration (%)	Repellency of rice weevil (%) 30 min	60 min	90 min	120 min	150 min	180 min	Mean repellency (%)
Long pepper	5	93.33±6.67^{a}	93.33±6.67^{a}	86.67±13.33	86.67±13.33^{a}	66.67±24.03^{ab}	73.33±17.63^{ab}	83.33±13.47^{ab}
	10	86.67±6.67^{a}	86.67±6.67^{ab}	80.00±11.54	93.33±6.67^{a}	86.67±6.67^{ab}	86.67±6.67^{ab}	87.78±5.77^{ab}
	15	46.67±29.05^{bc}	86.67±6.67^{ab}	53.33±24.03	40.00±30.55^{bc}	40.00±30.55^{bd}	40.00±30.55^{bc}	44.45±27.78^{cd}
Clove	5	86.67±6.67^{a}	86.67±6.67^{ab}	93.33±6.67	93.33±6.67^{a}	86.67±13.33^{ab}	86.67±13.33^{ab}	88.89±8.01^{ab}
	10	86.67±6.67^{a}	86.67±6.67^{ab}	86.67±6.67	93.33±6.67^{a}	86.67±6.67^{ab}	93.33±6.67^{a}	88.89±5.88^{ab}
	15	93.33±6.67^{a}	93.33±6.67^{a}	93.33±6.67	86.67±6.67^{a}	93.33±6.67^{a}	93.33±6.67^{a}	92.22±4.84^{a}
Tobacco leaf	5	13.33±13.33^{cd}	13.33±13.33^{c}	13.33±13.33	13.33±13.33^{bc}	6.67±6.67^{cd}	6.67±6.67^{c}	11.11±11.11^{de}
	10	33.33±6.67^{bd}	33.33±6.67^{c}	26.67±6.67	13.33±13.33^{bc}	6.67±6.67^{cd}	6.67±6.67^{c}	20.00±3.33^{ce}
	15	20.00±11.54^{cd}	20.00±11.54^{c}	0.00±0.00	6.67±6.67^{c}	6.67±6.67^{cd}	6.676.67^{c}	10.00±5.09^{de}
Lime leaf	5	86.67±11.54^{a}	86.67±6.67^{ab}	80.00±11.54	86.67±13.33^{a}	80.00±20.00^{ab}	86.67±13.33^{ab}	84.45±7.29^{ab}
	10	60.00±11.54^{ab}	60.00±11.54^{b}	33.33±24.03	53.33±29.05^{ab}	53.33±29.05^{ab}	46.67±29.05^{ac}	51.11±22.14^{bc}
	15	66.67±6.67^{ab}	66.67±6.67^{ab}	13.33±6.67	13.33±6.67^{bc}	6.67±6.67^{cd}	13.33±13.33^{c}	30.00±3.33^{ce}
Distilled water (control)		0.00±0.00^{d}	0.00±0.00^{d}	0.00±0.00	0.00±0.00^{c}	0.00±0.00^{d}	0.00±0.00^{c}	0.00±0.00^{e}
p-value		<0.001**	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**
C.V. (%)		8.811	12.383	9.078	7.486	5.724	6.718	9.068

Means followed by the same letter within the same column are not significantly different according to DMRT (p>0.05) and Significance levels: **Indicates significance at the 99% confidence level extraction method and bioassay conditions. Long pepper, for example, caused strong toxicity in bruchid beetles (LC_{50} = 5.57-6.75 μg/cm^2 at 24 hrs) but was markedly less effective against the maize weevil (LC_{50} = 58.04 μg/cm^2), illustrating species-specific susceptibility and differential responsiveness to bioactive constituents[15]. Clove by-products also displayed high activity, with stem essential oil achieving 100% repellency, 96.67$\pm$3.33% mortality and the lowest LD_{50} (28.06 μL/L) after 5 days substantially outperforming leaf oil, likely due to its high eugenol and β-caryophyllene content[16]. Likewise, extracts from *Citrus aurantifolia* have shown strong performance, achieving 100% mortality in *Aedes aegypti* and an LC_{50} of 9 mg/mL after 6 hrs[17]. The extracts of tobacco further reinforce the high insecticidal potential of certain botanicals. Tobacco extracts exhibited strong activity against *S. oryzae*, as indicated by their low LD_{50} values across exposure periods. The acetone extract was the most potent (LD_{50} = 0.48 mg/L at 72 hrs), while the chloroform extract showed a comparable increase in toxicity over time, also reaching an LD_{50} of 0.48 mg/L at 72 hrs. Petroleum ether extract produced substantial mortality as well (LD_{50} = 0.53 mg/L at 72 hrs), confirming the overall effectiveness of tobacco-derived compounds for managing *S. oryzae*[18].

Collectively, these comparisons highlight the wide variability in insecticidal potency among botanicals and underscore that species rich in alkaloids or phenylpropanoids tend to exhibit superior activity relative to crude plant materials.

The insecticidal activity of tobacco extract is mainly attributed to nicotine, a neurotoxic alkaloid that targets nicotinic acetylcholine receptors and disrupts synaptic transmission in insects[19]. The observation that distilled-water extracts of tobacco were more effective than ethanol extracts suggests that nicotine and other polar compounds are more efficiently extracted in aqueous media[20]. This is consistent with earlier findings[21,22], reinforcing the importance of solvent selection in maximizing bioactivity.

Although clove extract exhibited relatively low toxicity, its bioactivity is likely associated with compounds such as eugenol and caryophyllene and methyl eugenol, which are widely reported to possess insecticidal and behavioral effects[23]. The moderate toxicity of long pepper may be linked to alkaloids such as piperine[15], while lime leaf extracts likely contain terpenoids and essential oils contributing to their insecticidal properties[24,25].

The consistent external symptoms observed in treated insects such as leg and rostrum curling, body rigidity and immobility suggest a neurotoxic mode of action across treatments. This indicates that, despite differences in potency, many of these plant extracts may act on similar physiological targets in insects.

Repellency is a critical defense mechanism in stored-grain protection, as it prevents initial colonization and reduces the likelihood of reinfestation[26]. In this study, clove extracts showed the strongest repellent activity in both ethanol- and water-based systems, exceeding 90% at higher concentrations. This high repellency aligns with previous work reporting that clove stem essential oil achieved 100% repellency and 96.7% adult mortality at a 100 μL dose, with an LD_{50} of 28.06 μL/L after 5 days effects attributed to its high eugenol content[16]. Consistently, another study demonstrated clear repellency at 1-10 μL and concentration-dependent toxicity of clove essential oil against both *Sitophilus oryzae* and *Callosobruchus maculatus*[7]. Comparable efficacy was also reported for clove powder, which produced ~48.75% mortality, 84.41% progeny reduction and 64.17% repellency, alongside declining LC_{50} values over time that indicate increasing toxicity with prolonged exposure[27]. Mechanistically, eugenol the dominant volatile in clove has been shown to disrupt olfactory perception and host recognition in insects, leading to strong avoidance behavior[28], further supporting the behavioral disruption observed in our assays. Collectively, these quantitative and mechanistic findings support that the >90% repellency observed in our crude extracts is driven by similar volatile constituents, reinforcing the role of clove-derived materials as potent, behavior-modifying agents for sustainable stored-grain protection.

Lime leaf extract also showed rapid and complete repellency at early exposure times, highlighting its potential for immediate protection. Similar fast-acting repellency has been documented in other citrus-based extracts, likely due to volatile monoterpenes such as D-limonene, which have been reported to induce avoidance behavior in *S. oryzae* and related species[24,29].

In contrast, tobacco extract displayed relatively low repellency despite its high toxicity, suggesting that its insecticidal activity is driven primarily through contact or ingestion rather than behavioral avoidance. This pattern is consistent with studies showing that nicotine-rich extracts often exhibit limited repellency but strong neurotoxic effects on stored-grain pests[18].

From an applied perspective, integrating extracts with complementary modes of action for example, pairing a highly toxic extract such as tobacco with strong repellent extracts like clove or lime leaf could enhance overall protection. Similar synergistic or complementary approaches have been recommended in botanical pest management systems[10,27], where combining deterrence and lethality improves both immediate and long-term control of *S. oryzae*. Such combinations may reduce infestation pressure, slow resistance development and improve the reliability of botanical alternatives in real storage conditions.

Despite the promising results, several limitations should be considered. First, the experiment was conducted under controlled laboratory conditions, which may not fully reflect the complexity of real storage environments where temperature, humidity, grain variety and storage duration influence insect behavior and treatment performance[4,30]. Second, the study focused exclusively on adult *S. oryzae*, even though other life stages (eggs, larvae and pupae) may exhibit different levels of susceptibility to plant-derived compounds[31,32].

Additionally, extraction methodology is known to significantly affect the phytochemical composition and bioactivity of plant-based mixtures, which in turn impacts reproducibility, scalability and consistency across batches[33,34]. Addressing these issues will require efforts to standardize extraction techniques, identify and quantify the key active constituents and evaluate the long-term stability of plant extracts during storage conditions relevant to grain protection.

Future research should further examine potential synergistic interactions between plant extracts, optimize formulation types such as emulsions, powders, or microencapsulated systems and assess their performance under field or semi-field conditions. Ensuring the safety of these treatments for consumers, applicators and grain quality remains essential for successful adoption and regulatory acceptance[27,35].

Overall, the present findings reinforce the potential of medicinal plant extracts as sustainable, eco-friendly alternatives for managing *S. oryzae* in stored grains, offering considerable opportunities for future refinement and integration into broader pest management programs.

CONCLUSION

This study demonstrated that selected medicinal plant extracts possess strong potential as botanical agents for controlling the rice weevil, *Sitophilus oryzae*. From an initial screening of 21 species, four plants produced >50% adult mortality, with tobacco leaf extract showing the highest insecticidal efficacy. The 15% extract prepared with 70% ethanol caused 93.32% mortality, while the distilled-water extract resulted in complete mortality, indicating that key bioactive compounds in tobacco are effective across solvent systems. Clove flower extract exhibited the strongest repellent activity, achieving 100% repellency when extracted with 70% ethanol and 92.22% with distilled water. These findings highlight the value of tobacco- and clove-derived compounds as promising, low-toxicity alternatives for the management of *S. oryzae* in stored grains.

Future work should incorporate chemotypic variation by collecting plant materials from multiple geographic regions, as phytochemical profiles may influence bioefficacy. Additionally, although this study focused on *S. oryzae*, some extracts may have broader potential against other stored-product pests. Expanding bioassays to a wider range of pest species and assessing persistence, mode of action and compatibility with existing IPM practices will support the development of robust, field-ready botanical control strategies.

SIGNIFICANCE STATEMENT

This study highlights the potential of medicinal plant extracts as eco-friendly alternatives to synthetic pesticides for the management of rice weevils *Sitophilus oryzae* (L.). Among the screened plants, tobacco extracts exhibited strong insecticidal activity with rapid and high mortality, while clover extracts demonstrated consistent repellency across different solvents. The findings further emphasize that extraction solvent significantly influences the efficacy of plant-derived bioactive compounds. These results contribute to the development of sustainable, environmentally safer pest management strategies for stored grain protection.

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