Toxicity of Phytochemical Monoterpenes against the Rice Weevil (Coleoptera: Curculionidae)[1]

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J. Entomol. Sci. 60(4): 000–000 (Month 2025)
DOI: 10.18474/JES24-74

Abstract Postharvest insect pests pose a significant threat during product storage, diminishing both the quantity and quality of stored goods. Recently, plant-based pesticides have emerged as a promising alternative for managing storage pests. Plant essential oils are rich in biologically active monoterpenes, which have shown considerable potential as pest control agents due to their toxicity to insects. The purpose of the study was to assess the toxicity of six monoterpene compounds (citral, β-citronellol, eucalyptol, geraniol, β-myrcene, and thymol) against rice weevil, *Sitophilus oryzae* L. (Coleoptera: Curculionidae). Among the tested monoterpenes, thymol and geraniol exhibited the highest contact toxicity, with 50% lethal concentration (LC_{50}) values of 63.16 and 70.77 μl/cm^2 against *S. oryzae*, respectively, at 72 h after treatment, followed by β-citronellol and citral. The fumigant activity of the compounds tested at concentrations ranging between 20.0 and 100.0 μl/ml of air was highest with β-citronellol (LC_{50} of 22.12 μl/ml of air), followed by citral (LC_{50} of 32.23 μl/ml of air) at 72 h after exposure. β-Myrcene and geraniol also exhibited fumigant toxicity but at levels lower than β-citronellol or citral. Among the six monoterpenes, geraniol showed highest repellent activity of 90.00% ± 1.44%, followed by β-citronellol (75.00% ± 2.88%) and citral (71.75% ± 1.25%) at 4 h of exposure at 7.5 μl/cm^2. In sum, the six tested monoterpenes exhibited moderate to high toxicity against *S. oryzae*, suggesting that they have the potential to be developed and used as effective alternatives for managing *S. oryzae* in stored products.

Key Words monoterpenes, *Sitophilus oryzae*, contact toxicity, fumigant toxicity, repellent activity

Grain losses caused by stored product pests have been estimated as 5% to 10% worldwide, and up to 40% in developing countries (Cao et al. 2019). Stored grains are attacked by several insect pests, including the rice weevil, *Sitophilus oryzae* L. (Coleoptera: Curculionidae), a cosmopolitan and destructive pest of stored grains. This insect attacks a wide range of grains and cereal products, including wheat, corn, rice, oats, rye, barley, dried beans, sorghum, and macaroni

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(Khani et al. 2012). Heavy infestations lead to secondary infestations, heat, and moisture, leading to colonization by molds and mites (Tyagi et al. 2019).

Generally, nonchemical treatments, except heat, require more treatment time or fail to achieve 100% insect mortality. Despite the problems of development of insect resistance to insecticides, environmental issues, and residue problems, chemical control is inevitable and continues to be the most effective and rapid control method. There are limited options with respect to alternative fumigants, and the alternatives have constraints regarding environmental and health concerns, cost, and other logistics (Lee et al. 2003). These drawbacks of synthetic insecticides have created a need to use alternate, safe, and natural plant products to meet the growing demand for healthy and safe food grains (Yıldırım et al. 2013). Keeping this in mind, focus has been placed on the use of botanicals or biopesticides as safer alternatives.

Monoterpenes are common secondary metabolites in plants. These compounds contribute to the specific essence and scent of many plants. Monoterpenoids are synthesized in the cytoplasm (Lee et al. 2003) and plastids of the plant cell through two distinct pathways: mevalonate and methyl erythritol phosphate. More than 1,000 naturally occurring monoterpenoids, including myrcene, citral, linalool, limonene, thymol, menthol, carvone, citronellol, geraniol, cuminaldehyde, eugenol, eucalyptol, α-thujone, and borneol, have been isolated from essential oils of major botanical families, including Verbenaceae, Lauraceae, Poaceae, Apiaceae, Rutaceae, Lamiaceae, Myrtaceae, Asteraceae, Zingiberaceae, Hyperaceae, Pinaceae, Meliaceae, Rubiaceae, and Solanaceae (Abdelgaleil et al. 2009).

Monoterpenes are lipophilic liquids with high volatility and are utilized in a wide range of biological activities such as in food chemistry, chemical ecology, and pharmaceutical industry applications (Peixoto et al. 2015). They also have been reported to possess exceptional pesticidal activities, including insecticidal, herbicidal, fungicidal, and bactericidal properties (Saad et al. 2018). Many monoterpenoids have been demonstrated to be effective against several postharvest insect pests, with acute contact and fumigant toxicity, as well as repellent properties, antifeedant activity, and inhibitory effects on insect development and growth (Hough-Goldstein 1990, Watanabe et al. 1993). We therefore undertook this study to identify a suitable phytomolecule/monoterpene that could be used for managing stored product pests. We specifically assessed the contact toxicity, fumigant toxicity, and repellent effects of six monoterpene compounds against the rice weevil, *S. oryzae*, in laboratory assays.

Materials and Methods

Insect culture. Our colony of *S. oryzae* was initially obtained from the Department of Seed Technology, Tamil Nadu Agricultural University, Coimbatore. *Sitophilus oryzae* was mass-reared on rice grains. Weevils were sexed on the basis of body size, and 25 pairs of 1- to 2-d-old adults were placed in a jar containing the rice grains (0.5 kg). The plastic jars were wrapped with a delicate khada fabric for aeration and secured with a rubber band to prevent the adults from escaping. The jars were sealed for a maximum period of 7 d to facilitate mating and egg deposition. After 25 to 30 d, emerging adults from the culture were collected and utilized for the maintenance of subcultures. From this culture, 7- to 10-d-old adults were used for the laboratory assays (Saad et al. 2018).

Monoterpenes. On the basis of literature reports, six monoterpenes (e.g., citral [95%], β-citronellol [95%), eucalyptol [99%], geraniol [98%], β-myrcene [98%], and thymol [99%]) were selected for the study and purchased from Sigma-Aldrich Chemical Co. (Mumbai, India). Each monoterpene was assayed at five concentrations against *S. oryzae* adults.

Contact toxicity assay. Contact toxicity of the monoterpenes was determined in concentration–mortality assays against *S. oryzae* adults by a surface coating method described by Broussalis et al. (1999). Acetone was used to prepare a series of concentrations (10,000, 20,000, 30,000, 40,000, and 50,000 parts per million) of each compound; 500 μl of each concentration was sprayed on the inner surface of 9-cm-diameter Petri plates to create surface concentrations of 80, 160, 240, 320, and 400 $\mu l/cm^2$ for the respective concentrations. The control plates were treated with acetone alone. After the solvent was evaporated (15 min), 20 adults were introduced onto each Petri plate, allowed to crawl over the treated surface, and then covered with a lid. Each chemical concentration was replicated four times in a completely randomized design (CRD). Petri plate lids were applied with Vaseline to arrest the settling of insects. Mortality percentages were assessed after 24, 48, and 72 h of exposure. Test insects were considered dead if their appendages did not move when prodded with a camel-hair brush.

Fumigant toxicity assay. The six monoterpene treatments were dissolved in acetone and diluted to working concentrations of 100, 80, 60, 40 and 20 μl/ml of air. Fumigant toxicity of the monoterpenes was evaluated by the method of Rani and Rajasekharreddy (2010). A 250-ml plastic jar served as a fumigation chamber. Circular filter paper discs were made to fit the open end of the plastic jar. These circular discs were each treated with 500 μl of the respective chemical concentrations and affixed to the underside of the jar lid. Acetone was used as control. A nylon 60-mesh wrapped diet cup (3.0×1.5 cm) containing 20 insects was placed on the inner bottom of each jar, after which the jar was sealed with a lid that had the phytochemical compound applied to its inner surface. This method eliminated direct contact between the test adults and the monoterpene compound. Each monoterpene concentration was replicated four times in a CRD at room temperature without disturbance. Insect mortality was determined as previously described at 24, 48, and 72 h after initial exposure.

Repellent activity assay. The behavioral response of *S*. *oryzae* adults to different monoterpenes was performed using the area preference method of Lü and Liu (2016). All test monoterpenes were dissolved in acetone and diluted to working concentrations of 1.5, 3, 4.5, 6, and 7.5 $\mu l/cm^2$. Each experimental unit consisted of a Petri plate (9-cm-diameter) containing 20 unsexed adults of *S*. *oryzae*. A 9-cm-diameter Whatman No. 1 filter paper disc was cut into two halves. One of the halves was treated with 0.5 ml of the appropriate monoterpene concentration using a micropipette; the remaining half was treated with acetone as the control. Chemically treated and control half-discs were air dried for 10 min to evaporate the solvent completely. A treated half-disc was attached to an untreated half-disc using gum. Each reconstructed filter paper disc was then placed into an individual Petri plate, after which 20 adult insects were released in the center of each plate. The Petri plates

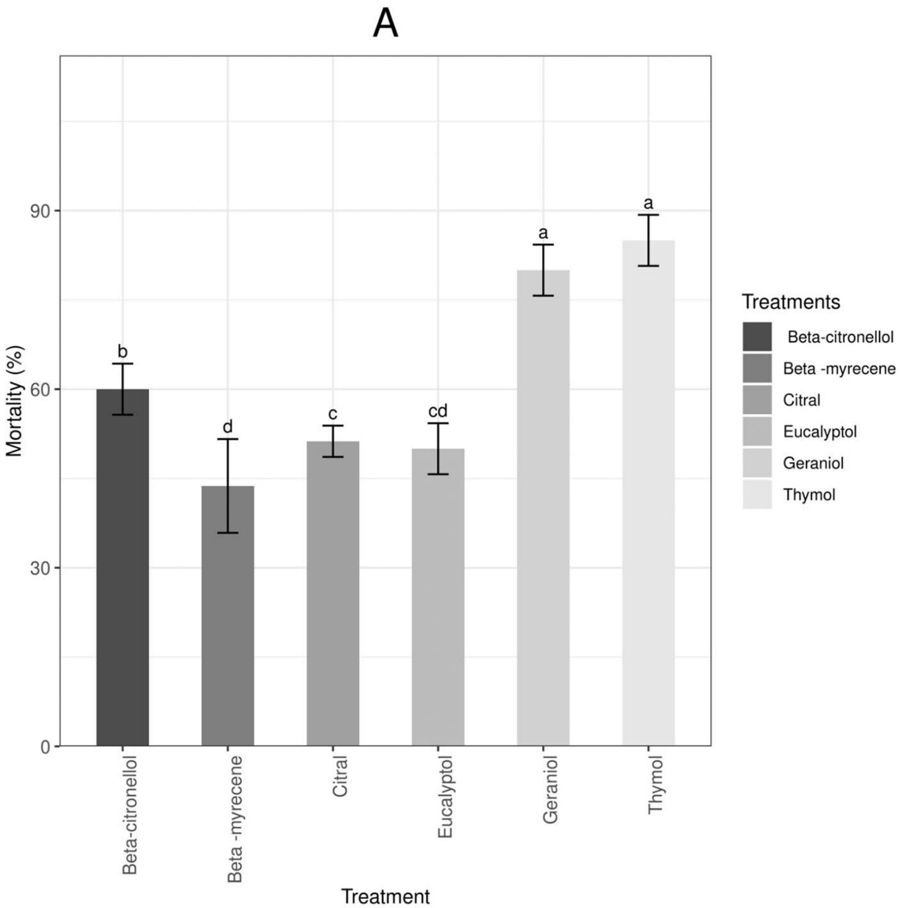
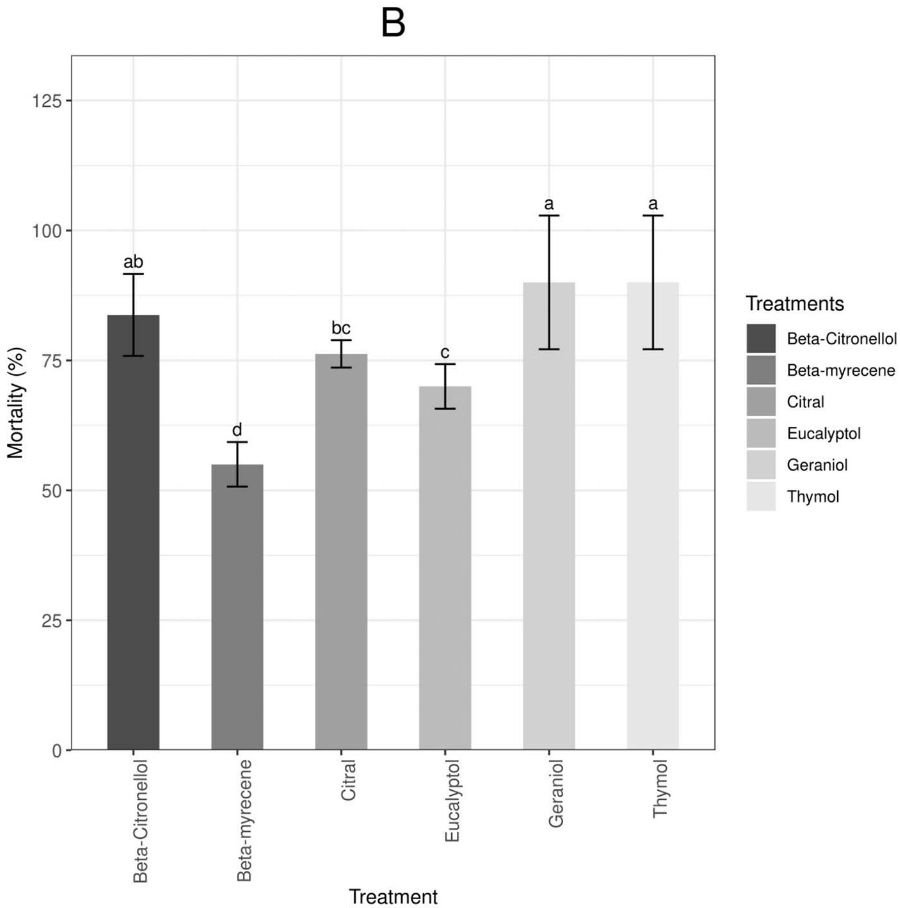


Fig. 1. Contact toxicity of monoterpenes at 400 µl/cm^2 after (A) 24 h, (B) 48 h, and (C) 72 h of exposure against *Sitophilus oryzae*. Vertical bars indicate standard errors of the mean (*n* = 4 independent replicates); different lowercase letters above the bars indicate that the means are significantly different between the control and the chemical ($P \leq 0.05$).

were subsequently covered with lids. Each monoterpene/concentration treatment was replicated four times in a CRD. The numbers of insects present on the control (N_c) and treated (N_t) half-discs were recorded at 2, 4, 8, and 24 h after exposure. Repellent percentage (RP) rates were computed with the formula RP $= ([N_c - N_t]/[N_c + N_t]) \times 100$.

Statistical analyses. In the contact toxicity assays and fumigant toxicity assays, corrected mortality percentages were calculated using Abbott's formula (Abbott 1925) when mortality in the control ranged between 5% and 20%. Mortality levels in these assays were subjected to probit analysis (Finney 1971) to yield concentration/mortality and time/mortality responses using the SPSS (Statistical



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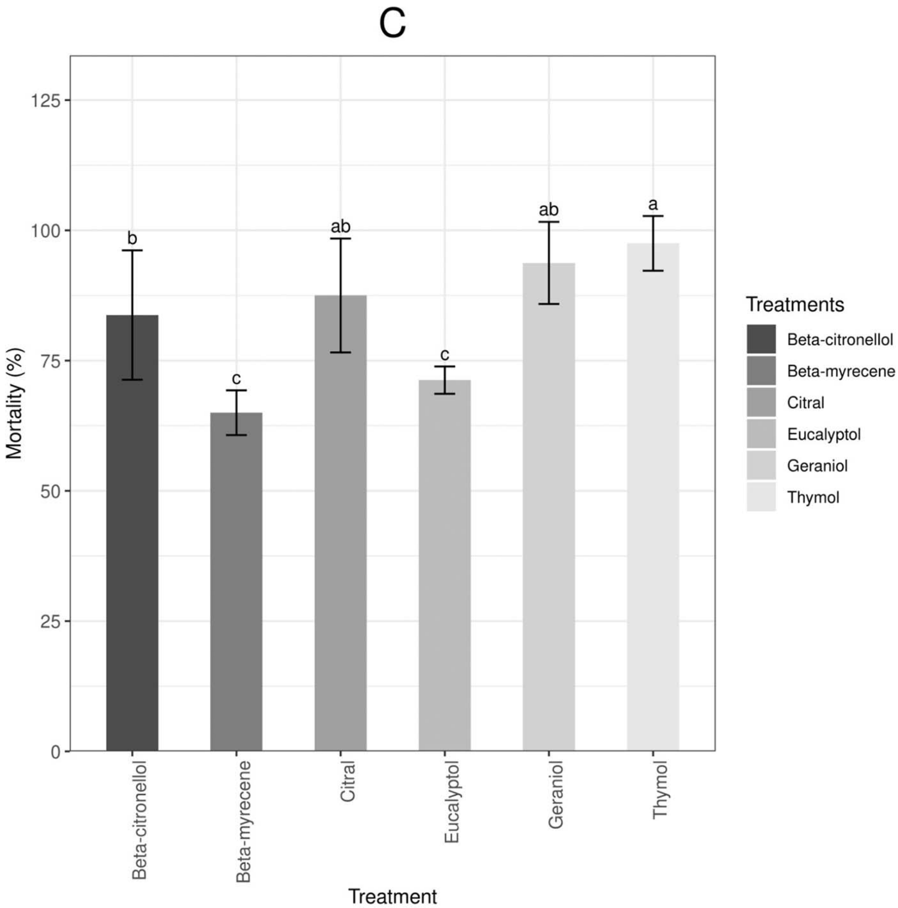
Package for the Social Sciences, Version 28.0, Armonk, NY). All data were subjected to one-way analysis of variance, and significant differences among treatment means were compared at 0.01 and 0.05 probability levels using Tukey's honestly significant difference.

Results and Discussion

Contact toxicity. The contact assay indicated that the mortality of *S. oryzae* was dependent on both time (24, 48, and 72 h) and concentration (80, 160, 240, 320, and 400 $\mu l/cm^2$). Among the tested monoterpenes after 24 h of exposure, the highest mortality of *S. oryzae* was observed with geraniol, with a mean ($\pm$SD) of 87.00% $\pm$ 2.39%, followed by thymol with 85.70% $\pm$ 2.88%, β-citronellol with 79.50% $\pm$ 1.44%, and citral with 70.40% $\pm$ 1.44% (Fig. 1A). The lowest mortality was observed with β-myrcene (41.60% $\pm$ 1.25%), followed by eucalyptol



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(45.25% ± 1.25%) after 24 h of exposure at 400 μl/cm^2 ($F = 145.39$; df = 7, 14; $P < 0.05$) (Fig. 1A). The median lethal concentration (LC_{50}) was 138.49 μl/cm^2 for thymol, followed by 147.31 μl/cm^2 for geraniol (Table 1). The β-myrcene, with an LC_{50} of 486.51 μl/cm^2, was the least effective monoterpene (Table 1).

After 48 h of exposure, a maximum mortality of 90.00% ± 1.25% was recorded with geraniol, followed by thymol (89.20% ± 1.25%), β-citronellol (83.7 5%± 4.09%), and citral (81.90% ± 1.25%), whereas the minimum mortality was recorded with β-myrcene (50.40% ± 3.75%), followed by eucalyptol (63.75% ± 2.39%) at 400 μl/cm^2 ($F = 26.25$; df = 7, 14; $P < 0.05$) (Fig. 1B). The LC_{50} values were 95.45 μl/cm^2 for thymol, followed by 120.09 μl/cm^2 for geraniol (Table 1). β-Myrcene, with an LC_{50} of 452.88 μl/cm^2, was the least effective (Table 1).

The tested monoterpenes significantly affected *S. oryzae* mortality after 72 h of exposure (Fig. 1C). Mortality was higher in thymol, with 97.50% ± 1.44%, followed by geraniol with 92.80% ± 3.75%, whereas β-citronellol with 88.40% ± 2.39%

Table 1. Concentration–mortality response of *Sitophilus oryzae* to monoterpenes by contact toxicity assay.

Time (h)	Monoterpen	LC_{50}* (µl/cm^2)	Fiducial Limits 95% (µl/cm^2) Lower	Upper	χ^2	*P***	Slope ± SE†
24	Citral	283.10	239.11	335.20	1.19	0.041	1.95 ± 0.28
	β-Citronellol	213.27	181.96	249.96	1.29	0.044	1.87 ± 0.39
	Eucalyptol	466.51	359.35	605.62	5.63	0.028	1.87 ± 0.38
	Geraniol	147.31	127.53	170.15	1.71	0.045	2.44 ± 0.28
	β-myrcene	486.17	396.39	596.28	1.42	0.039	2.83 ± 0.40
	Thymol	138.49	118.75	161.52	0.91	0.044	2.37 ± 0.28
48	Citral	197.95	170.11	230.34	1.34	0.014	1.94 ± 0.21
	β-Citronellol	157.94	134.92	184.89	1.87	0.052	2.13 ± 0.27
	Eucalyptol	362.08	302.47	433.43	9.31	0.027	2.09 ± 0.82
	Geraniol	120.09	100.23	143.88	1.72	0.015	2.25 ± 0.88
	β-Myrcene	452.88	364.54	562.62	4.18	0.043	2.23 ± 0.52
	Thymol	95.45	74.63	122.09	0.15	0.044	1.99 ± 0.39
72	Citral	107.07	79.16	144.81	2.81	0.044	1.51 ± 0.28
	β-Citronellol	87.26	60.88	125.06	2.59	0.045	1.50 ± 0.38
	Eucalyptol	316.45	258.79	386.95	1.95	0.010	1.70 ± 0.54
	Geraniol	70.77	48.45	103.36	2.19	0.043	1.75 ± 0.22
	β-Myrcene	368.53	307.06	442.30	2.7	0.022	2.10 ± 0.10
	Thymol	63.16	42.22	94.47	1.06	0.048	1.99 ± 0.37

* Median lethal concentration.
** $P \leq 0.05$ indicates a significant fit between the observed and expected regression lines in a probit analysis.
† Slope of the concentration–mortality regression line ± standard error.

and citral with 87.50% ± 1.25% elicited moderate levels of contact toxicity at 72 h of exposure ($F = 24.55$; df = 7, 14; $P < 0.05$) (Fig. 1C). Mortality over all concentrations of tested monoterpenes was significantly greater than that of the control ($P < 0.05$). In addition, the LC_{50}s of tested monoterpenes against *S. oryzae* adults at 72 h after treatment showed that thymol ($LC_{50} = 63.16$ µl/cm^2) and geraniol ($LC_{50} = 70.77$ µl/cm^2) had potent contact toxicities, followed by β-citronellol ($LC_{50} = 87.26$ µl/cm^2) and citral ($LC_{50} = 107.07$ µl/cm^2) (Table 1).

All six monoterpenes demonstrated significantly overlapping toxicity against *S. oryzae*; however, when comparing median lethal time (LT_{50}) values at the highest test concentration (400 µl/cm^2), thymol outperformed the other monoterpenes, with the lowest LT_{50} of 15.44 h, followed by geraniol at 16.14 h (Table 2). Moutassem et al. (2024) previously demonstrated that the essential oils of *Thymus pallescens* de Noé and *Cymbopogon citratus* (de Candolle) Stapf containing thymol and geraniol exhibited 97.50% and 86.25% mortality, with the LC_{50}s of 12.61 and 9.31 µl/ml, respectively, against *Sitophilus granarius* (L.). The lower concentration of β-myrcene

Table 2. Time–mortality response of *Sitophilus oryzae* to monoterpenes.

Monoterpene	LT_{50}* (h)	Fiducial Limits 95% (h)		χ^2	*P***	Slope ± SE†
		Lower	Upper			
Contact Toxicity (400 μl/cm^2)						
Citral	27.20	24.53	30.17	3.17	0.850	3.50 ± 0.68
β-Citronellol	22.99	20.10	26.30	1.21	0.155	2.58 ± 0.77
Eucalyptol	31.31	24.55	39.92	4.25	0.0002	1.17 ± 0.15
Geraniol	16.14	13.73	18.97	1.32	0.096	2.53 ± 0.82
β-Myrecene	48.52	41.14	57.22	2.12	0.808	2.98 ± 1.19
Thymol	15.44	13.75	17.33	1.42	0.020	3.01 ± 0.40
Fumigant Toxicity (100 μl/ml of air)						
Citral	28.97	25.18	33.33	1.00	0.016	2.60 ± 0.25
β-Citronellol	26.16	22.56	30.33	0.13	0.0009	2.56 ± 0.10
Eucalyptol	66.91	51.02	87.76	1.57	0.042	2.07 ± 0.34
Geraniol	45.25	38.91	52.63	0.08	0.001	2.54 ± 0.07
β-Myrcene	43.85	37.78	50.90	0.95	0.047	2.49 ± 0.28
Thymol	52.20	43.71	62.35	3.13	0.133	2.34 ± 0.46

* Median lethal time.
** $P \leq 0.05$ indicates a significant fit between the observed and expected regression lines in a probit analysis.
† Slope of the time exposure–mortality regression line ± standard error.

showed no significant difference compared with the control. Our results agree with the reports of Abdelgaleil et al. (2009), wherein they reported that the myrecene had weak activity against *S. oryzae* and *Tribolium castaneum* (Herbst). Additionally, our findings indicate that β-citronellol is a stronger contact toxicant than β-myrcene, corroborating the results of Yıldırım et al. (2013).

Fumigant toxicity. The effect of the tested monoterpenes on the survival of *S. oryzae* adults was concentration dependent. Among the six tested monoterpenes, the highest mortality of *S. oryzae* was observed with β-citronellol (48.10% ± 1.66%), followed by citral (40.70% ± 3.75%), β-myrcene (28.80% ± 1.66%), and geraniol with 27.10% ± 1.66% mortality at a concentration of 100 μl/ml of air (Fig. 2A). The lowest mortality was observed with eucalyptol, followed by thymol after 24 h of exposure ($F = 34.43$; df = 7, 14; $P < 0.05$) (Fig. 2A). The LC_{50}s were 104.06 μl/ml of air for β-citronellol, followed by 143.22 μl/ml of air for citral (Table 3). The geraniol, with a LC_{50} of 264.34 μl/cm^2, was the least effective in causing mortality (Table 3).

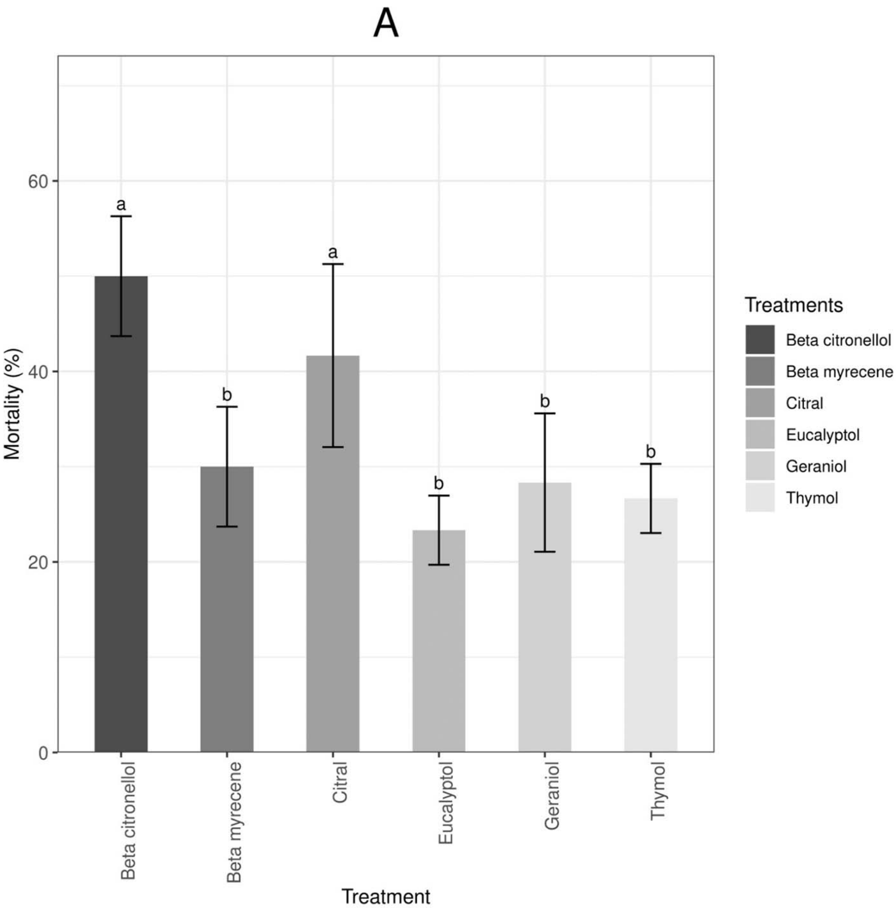
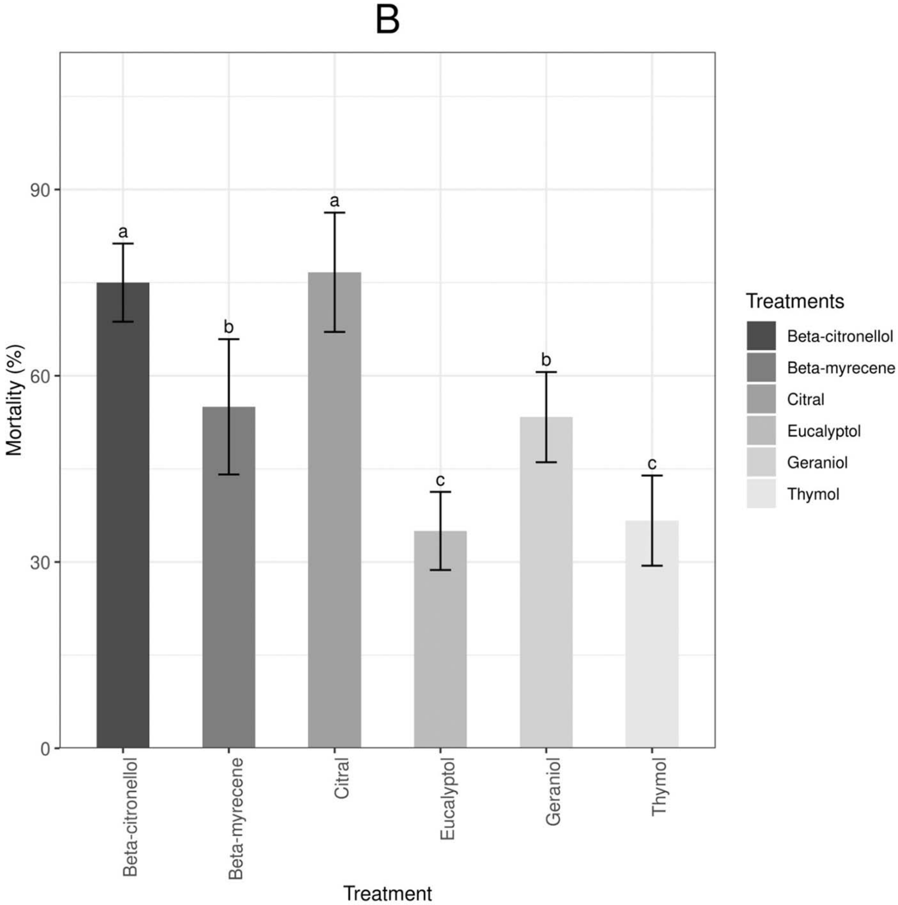


Fig. 2. Fumigant toxicity of six monoterpenes at 100 μl/ml of air after (A) 24 h, (B) 48 h, and (C) 72 h of exposure against *Sitophilus oryzae*. Vertical bars indicate standard errors of the mean (*n* = 4 independent replicates); different lowercase letters above the bars indicate that the means are significantly different between the control and the chemical ($P \leq 0.05$).

After 48 h of exposure, maximum mortality of 75.90% ± 1.66% was recorded with citral, followed by β-citronellol, β-myrecene, and geraniol, whereas minimal mortality was recorded with eucalyptol (32.80% ± 3.75%), followed by thymol ($F = 49.83$; df = 7, 14; $P < 0.05$) (Fig. 2B). The LC_{50}s were 45.90 μl/ml of air for β-citronellol, followed by 47.33 μl/ml of air for citral (Table 3). Thymol was found to be the least effective (Table 3).

The monoterpenes also had a significant effect after 72 h of exposure ($F = 36.76$; df = 7, 14; $P < 0.05$) (Fig. 2C). β-Citronellol caused the highest mortality at 87.70 ± 1.25%, followed by citral and β-myrcene (Fig. 2C). In contrast, the



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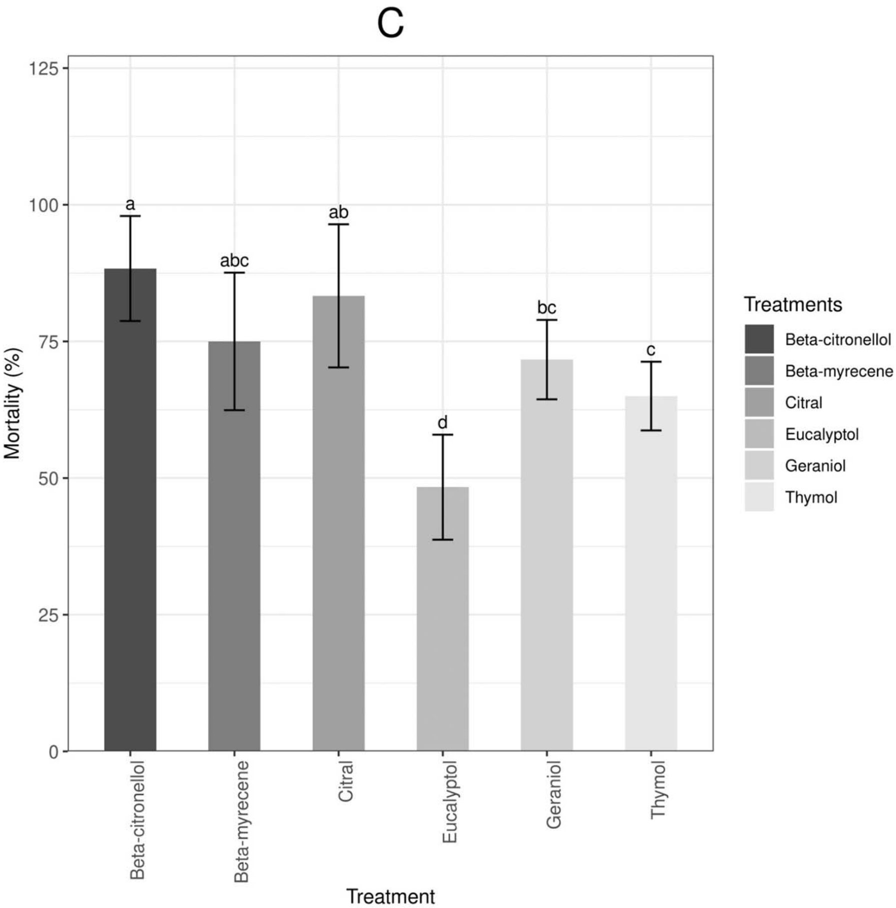
percent mortality for eucalyptol did not exceed 50% at any of the tested concentrations (Fig. 2C). The LC_{50}s against *S. oryzae* were 22.12 μl/ml of air for β-citronellol, 32.23 μl/ml for citral, 41.84 μl/ml for geraniol, 45.55 μl/ml for β-myrcene, 70.34 μl/ml for thymol, and 136.65 μl/ml for eucalyptol (Table 3).

The effectiveness of the six monoterpenes as fumigants against *S. oryzae* overlapped; however, in terms of LT_{50}s, β-citronellol exhibited the highest fumigant toxicity among the tested monoterpenes, with a LT_{50} of 26.16 h, followed by geraniol at 28.97 h (Table 2). Similarly, Nishchala et al. (2021) in their study of contact and fumigant toxicity of transcinnamaldehyde, geraniol, thymol, β-citronellol, citral, eucalyptol, and β-myrcene against *Lasioderma serricorne* (F.) adults concluded that transcinnamaldehyde, β-citronellol, and geraniol were the more potent contact toxicants, whereas transcinnamaldehyde, β-citronellol, and β-myrcene were the more effective fumigant toxicants. Oyedeji et al. (2020) reported fumigant toxicity of citral against *Callosobruchus maculatus* (F.) and *Sitophilus zeamais* (Motschulsky),



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with LC_{50}s of 0.19 and 2.02 μl/l of air at 24 h after exposure, respectively. We also observed differential actions of monoterpenes on the basis of the assay method. For instance, β-myrcene (73.70%) had pronounced fumigant toxicity toward *S. oryzae*, but was a weak contact toxicant (59.40%). In contrast, geraniol (92.80%) was an effective contact toxicant but was a weak fumigant (70.20%). Similar results were documented by Prates et al. (1998) and Park et al. (2003) regarding the insecticidal activity of monoterpenes against stored product insects.

Repellency activity. The repellent effect of the six monoterpenes against *S. oryzae* also increased with the concentration of monoterpenes but decreased with longer exposure times. Repellent activity was observed up to 4 h after initial exposure and declined thereafter for most of the tested monoterpenes. Notably, geraniol exhibited strong repellency toward *S. oryzae* adults at all tested concentrations up to 8 h of exposure (Table 4). Geraniol exhibited the highest repellent effect among the tested monoterpenes, showing 32.50% ± 2.50% at the lowest test concentration

Table 3. Concentration–mortality response of *Sitophilus oryzae* to monoterpenes by fumigant assay.

Time (h)	Monoterpene	LC_{50}* (µl/ml of air)	Fiducial Limits 95% (µl/ml of air) Lower	Upper	χ^2	*P***	Slope ± SE†
24	Citral	143.22	76.63	267.64	0.56	0.050	1.14 ± 0.09
	β-Citronellol	104.06	68.63	157.77	0.36	0.045	1.28 ± 0.12
	Eucalyptol	228.80	115.09	454.86	0.38	0.043	2.02 ± 0.32
	Geraniol	264.34	112.33	622.03	0.44	0.005	1.47 ± 0.06
	β-Myrcene	193.38	111.83	334.38	1.19	0.028	1.84 ± 0.46
	Thymol	242.96	113.81	518.63	0.03	0.007	1.68 ± 0.06
48	Citral	47.33	39.33	56.95	0.87	0.045	1.89 ± 0.25
	β-Citronellol	45.90	36.99	56.96	0.23	0.041	1.60 ± 0.23
	Eucalyptol	186.91	104.34	334.81	0.06	0.017	1.68 ± 0.10
	Geraniol	93.63	69.76	125.67	0.08	0.044	1.62 ± 0.10
	β-Myrcene	88.80	67.01	117.68	0.14	0.014	1.60 ± 0.07
	Thymol	187.52	99.42	353.71	0.19	0.035	1.50 ± 0.11
72	Citral	32.23	25.01	41.53	1.03	0.021	1.72 ± 0.13
	β-Citronellol	22.12	15.59	31.37	0.03	0.001	0.99 ± 0.23
	Eucalyptol	136.65	86.89	214.62	0.04	0.020	1.32 ± 0.28
	Geraniol	41.84	31.60	55.38	0.31	0.025	1.26 ± 0.11
	β-Myrcene	45.55	36.85	56.30	0.01	0.027	1.70 ± 0.23
	Thymol	70.34	55.76	88.74	0.39	0.045	0.94 ± 0.53

* Median lethal concentration.
** $P \leq 0.05$ indicates a significant fit between the observed and expected regression lines in a probit analysis.
† Slope of the concentration–mortality regression line ± standard error.

(1.5 µl/cm²) and 69.00% ± 2.04% at 7.5 µl/cm² after 2 h of exposure ($F = 27.55$; df = 5, 10; $P < 0.01$) (Table 4). The RP increased up to 4 h of exposure ($F = 19.46$; df = 5, 10; $P < 0.01$), reaching 62.50% ± 2.50% at 1.5 µl/cm² and 90.00% ± 1.44% at 7.5 µl/cm², and decreased after 24 h of exposure (Table 4). Citral ($F = 53.93$; df = 5, 10; $P < 0.01$), β-citronellol ($F = 40.62$; df = 5, 10; $P = 0.01$), and thymol ($F = 114.57$; df = 5, 10; $P < 0.01$) showed RPs of 55.25% ± 1.25%, 53.25% ± 1.44%, and 45.00% ± 3.75% at 2 h of exposure, respectively, and 71.75% ± 1.25% ($F = 77.18$; df = 5, 10; $P < 0.01$), 75.00% ± 2.88% ($F = 53.25$; df = 5, 10; $P < 0.05$), and 65.00% ± 4.08% ($F = 175.90$; df = 5, 10; $P < 0.05$) at 4 h of exposure (Table 4). In contrast, eucalyptol (40.00% ± 2.04%) ($F = 80.78$; df = 5, 10; $P > 0.05$) and

Table 4. Repellent activity of monoterpenes to *Sitophilus oryzae* adults.

Monoterpene	Concentration (μl/cm²)	Repellency Percentage (% ± SE)*			
		2 h	4 h	8 h	24 h
Citral	1.5	25.25 ± 2.39c	38.75 ± 1.25d	10.00 ± 2.04d	−1.25 ± 1.25c
	3.0	32.00 ± 2.04bc	45.00 ± 2.04c	20.00 ± 1.250c	3.75 ± 2.39c
	4.5	39.50 ± 1.44b	55.00 ± 2.04b	25.00 ± 3.75b	10.00 ± 2.04b
	6.0	43.25 ± 1.25b	67.75 ± 2.39b	30.00 ± 2.04ab	16.25 ± 1.25a
	7.5	55.25 ± 1.25a	71.75 ± 1.25a	46.25 ± 1.25a	24.00 ± 1.25a
β-Citronellol	1.5	30.50 ± 2.50d	40.50 ± 2.50bd	6.25 ± 1.25d	−5.00 ± 2.04bc
	3.0	35.50 ± 2.88cd	49.00 ± 2.88cd	12.50 ± 1.44bc	−1.25 ± 2.39d
	4.5	40.00 ± 2.04c	58.25 ± 4.08c	40.00 ± 4.08b	18.75 ± 1.25c
	6.0	49.25 ± 1.25b	62.25 ± 2.88b	65.00 ± 2.88a	20.00 ± 2.88bc
	7.5	53.25 ± 1.44a	75.00 ± 2.88a	25.00 ± 1.25e	10.00 ± 1.44e
Eucalyptol	1.5	−2.50 ± 1.44d	−2.50 ± 2.50d	−10.50 ± 4.08c	−20.00 ± 1.44d
	3.0	1.25 ± 2.04c	−1.25 ± 2.39cd	10.00 ± 1.25bc	−10.00 ± 3.75cd
	4.5	2.50 ± 1.44c	−2.50 ± 4.78c	12.00 ± 2.88bc	−7.50 ± 2.88c
	6.0	12.50 ± 2.50b	17.50 ± 1.44b	13.75 ± 2.39ab	2.50 ± 1.44b
	7.5	40.00 ± 2.04a	23.75 ± 1.25a	10.00 ± 1.25a	35.00 ± 2.04a
Geraniol	1.5	32.50 ± 2.50c	62.50 ± 2.50c	37.50 ± 4.78d	23.75 ± 3.75b
	3.0	42.00 ± 1.25c	75.00 ± 2.88bc	40.00 ± 2.04d	35.00 ± 2.39a
	4.5	59.25 ± 2.39b	77.50 ± 2.50b	41.25 ± 2.50c	36.00 ± 2.04a
	6.0	65.00 ± 2.50ab	81.25 ± 2.39ab	46.25 ± 4.08b	37.50 ± 1.14a
	7.5	69.00 ± 2.04a	90.00 ± 1.44a	51.25 ± 2.50a	45.00 ± 2.04a
β-Myrcene	1.5	5.00 ± 2.39c	−1.25 ± 1.25c	−10.00 ± 1.25c	−35.00 ± 2.39d
	3.0	20.00 ± 2.39b	2.50 ± 2.50bc	−2.50 ± 1.25b	−40.00 ± 1.25de
	4.5	22.50 ± 2.80b	12.50 ± 2.50b	5.00 ± 1.44a	−20.00 ± 1.25c
	6.0	20.00 ± 4.08b	12.50 ± 1.39b	6.00 ± 2.04a	8.00 ± 1.25a
	7.5	32.50 ± 1.25a	27.50 ± 2.50a	8.00 ± 1.25a	−2.50 ± 2.04b
Thymol	1.5	11.25 ± 1.25d	17.50 ± 1.44c	8.75 ± 1.25e	−1.25 ± 1.25b
	3.0	23.75 ± 1.25cd	25.00 ± 2.04c	12.50 ± 1.44bc	2.25 ± 4.08d
	4.5	32.50 ± 1.25c	35.00 ± 1.44d	26.25 ± 1.25b	10.00 ± 3.75b
	6.0	36.25 ± 1.25f	47.50 ± 1.44b	35.00 ± 3.75c	16.25 ± 1.25b
	7.5	45.00 ± 3.75c	65.00 ± 4.08bc	39.00 ± 2.39d	26.35 ± 1.25c

* Means (repellency percentage ± standard error) in the same column followed by the same letters do not differ significantly ($P = 0.05$) in analysis of variance (ANOVA) tests. Repellency percentage was subjected to arcsine square-root transformation before ANOVA.

β-myrcene (32.50% ± 1.25%) ($F = 1.33$; df = 5, 10; $P = 0.60$) showed poor efficacy at 2 h of exposure (Table 4). Unlike other monoterpenes, eucalyptol and β-myrcene exhibited reduced repellency after 2 h of exposure. These results indicate, however, that eucalyptol at lower concentrations and β-myrcene were not statistically significant from the control ($P > 0.05$).

Our findings are similar to the findings of Peixoto et al. (2015), who reported moderate repellent activity of citral against *S. oryzae* and *T. castaneum*. Our results are also consistent with those of Brari and Kumar (2020), who reported that citronellol had 56.61% and geraniol had 50.56% repellency effect against *S. oryzae*. We further postulate that the central nervous system decodes chemical messages in response to odor molecules perceived by insects. Plant compounds, such as hydrocarbons and particularly monoterpenes and oxygenated chemicals such as phenols and esters, have a repelling effect on insects. These volatile ingredients stimulate the insect's olfactory receptors, causing olfaction-induced changes in insect behavior.

In conclusion, the identification and development of natural insecticides could help decrease the adverse effects of synthetic insecticides such as residues, insect resistance, and environmental pollution. Natural insecticides may also be effective, selective, biodegradable, and less harmful to the environment. The present study indicated significant contact toxicity, fumigant toxicity, and repellent activity of monoterpenes against *S*. *oryzae*. On the basis of these findings, the monoterpenes may serve as a viable alternative to synthetic insecticides. Future research should focus on improving monoterpenoid formulations, field doses, and their integration into integrated pest management programs.

Acknowledgments

The authors thank the Department of Entomology, Tamil Nadu Agricultural University for furnishing all the necessary resources for the research. M.S. gratefully acknowledges the financial assistance provided by the Tamil Nadu Agricultural University, Coimbatore for the research program.

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