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RESEARCH ARTICLE

Insecticidal potential of cinnamon oil against cigarette beetle, *Lasioderma serricorne* (Fabricius) and rice moth, *Corcyra cephalonica* (Stainton) infesting stored products

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Abstract

Grain storage leads to significant losses due to insect pests, degrades grain quality and increases the risk of mould infestations. The cigarette beetle (*Lasioderma serricorne*) and the rice moth (*Corcyra cephalonica*) are cosmopolitan pests that attack various dried plant products, including grains like rice, sorghum, maize and cotton seed. In organic grain storage, synthetic pesticides are prohibited due to their toxicity. As an alternative, essential oils from aromatic plants have shown promise. Cinnamon (*Cinnamomum* spp.) oil, particularly, has demonstrated insecticidal properties against stored insect pests. This study aimed to evaluate the efficacy of cinnamon oil against *L. serricorne* and *C. cephalonica* adults. Cinnamon oil was extracted from cinnamon bark and analyzed using GC–MS, identifying (E)-Cinnamaldehyde (51.16 %), acetic acid and cinnamyl ester (9.67 %) as the primary compounds. The contact toxicity of the cinnamon oil was tested against adult *L. serricorne* and *C. cephalonica* at concentrations ranging from 80 to 400 µL/cm^2. The results showed that higher oil concentrations and longer exposure durations significantly increased toxicity. The LC_{50} values for *L. serricorne* were 260.65, 149.15 and 98.67 µL/cm^2 after 24, 48 and 72 hrs, respectively. For *C. cephalonica*, the LC_{50} values were 285.60, 160.08 and 109.33 µL/cm^2 at the same time intervals. The LT_{50} values at 400 µL/cm^2 were 20.34 hrs for *L. serricorne* and 21.43 hrs for *C. cephalonica*. Cinnamon oil proved highly effective, suggesting its potential as a botanical insecticide for managing these pests with minimal environmental impact.

Keywords: cinnamon oil; *Corcyra cephalonica*; *Lasioderma serricorne*; lethal concentration; lethal time; mortality

Introduction

Stored product insects cause significant losses in both weight and quality of stored goods, with global damage estimated to range between 10 % and 40 % annually. Over 70 different insect pests infest food grains in farmers' storage facilities and public warehouses, often thriving due to unregulated environmental conditions and inadequate warehousing technologies (1). The cigarette beetle, *Lasioderma serricorne* (Fabricius) (Coleoptera: Anobiidae) is one of the most destructive pests of stored tobacco, leading to considerable damage and economic loss (2). Its impact extends beyond tobacco, as it can infest and destroy a wide range of stored products, such as wheat, flour, dried fruits, spices, herbs, rice and other dry food items including wheat, flour, dried fruits, herbs, spices, rice and other dry foods. Similarly, the rice moth (*Corcyra cephalonica*) is a widespread pest affecting stored food commodities. The larvae of this pest cause damage by feeding on stored grains such as rice and maize. Additionally, the larvae create durable silk webs and produce faecal material, leaving behind silk threads that contaminate the stored grains with frass, excreta and pupal cocoons (3).

Control measures for these pests have traditionally relied on synthetic insecticides and fumigants, leading to various problems, including environmental disruption, increased application costs, pest resurgence, pesticide resistance and negative impacts on non-target organisms and direct toxicity to users. Consequently, there is a growing need for safer alternatives in stored product pest control. Botanicals have been employed for centuries to protect stored products from common pests. Plant essential oils, in particular, are being explored as alternatives to conventional pesticides due to their low toxicity to non-target organisms (1). These essential oils consist of complex mixtures of volatile organic compounds extracted from seeds, stems, leaves, bark and flowers and offer considerable potential as fumigants. Essential oils such as clove (*Syzygium aromaticum*), cinnamon (*Cinnamomum zeylanicum*), rosemary (*Rosmarinus officinalis*), bergamot (*Citrus bergamia*), Japanese mint (*Mentha*

arvensis), peppermint (*Mentha piperita*), black pepper (*Piper nigrum*), sweet marjoram (*Origanum majorana*) and sweet flag (*Acorus calamus*) have been identified as substances capable of acting as contact insecticides, providing antifeedant or repellent effects and influencing various biological parameters, including lifespan, growth rate and reproduction (1, 3, 4).

Cinnamon is derived from the bark of trees in the *Cinnamomum* genus, which belongs to the Lauraceae family. The bark and leaves are commonly used as spices in cooking, while the essential oils, extracted through distillation, act as flavoring agents in the food and beverage industries. These oils are also incorporated into perfumes, soaps and toothpaste and are used in alcoholic beverages and dental care products (5). Beyond its culinary uses, cinnamon is recognized for its broad range of medicinal and pharmacological benefits, including antioxidant, antimicrobial, antidiabetic and antiallergic properties (6). The toxic effects of cinnamon essential oil are primarily due to its main constituents, including monoterpenes such as cinnamaldehyde, β-caryophyllene, linalool, ethyl cinnamate, methyl cinnamate, cinnamoyl chloride and allyl cinnamate. These highly volatile compounds exhibit strong fumigant and contact toxicities against stored insect pests (7). Considering the above-mentioned facts, the current study intended to evaluate the insecticidal effects of essential oil extracted from the bark of Cinnamomum spp. against the cigarette beetle (*L. serricorne*) and the rice moth (*C. cephalonica*)

Material and Methods

Insect cultures

Lasioderma serricorne

Approximately 600g of coriander seeds were placed in 1-liter plastic jars, into which about 50 pairs of freshly emerged adults were introduced. The rearing was conducted under controlled conditions at a temperature of 28 ± 2 °C and 65 ± 5 % relative humidity. After 30-40 days, the adults emerging from the culture were used for maintaining subcultures. Subculturing of the beetles was performed at weekly intervals to ensure a continuous supply of insects for the experiments (8).

Corcyra cephalonica

The eggs of *C. cephalonica* were obtained from the Department of Entomology at Tamil Nadu Agricultural University, Coimbatore, India. In a plastic tray, 2.5 kg of sorghum, 100 g of powdered groundnut kernels, 5 g of yeast, 5 g of sulfur and an antibiotic were thoroughly blended. Approximately 0.5 cc of eggs (equivalent to 16000 eggs) was then inoculated into the 2.5 kg of sorghum in each tray, which was covered with white cloth to ensure adequate ventilation. After 4-5 days, the eggs hatched and the larvae reached the pupal stage after 30-35 days. The adult moths emerged after 45-50 days and were transferred into a plastic cage with wire mesh for ventilation, with additional mesh at the bottom for egg collection. The adult moths were provided with a 10 % sucrose solution, delivered through cotton balls soaked in the solution and suspended inside the cage. The eggs laid by the moths were subsequently re-inoculated into the plastic trays containing the feed for the larvae, thus continuing the cycle (9).

Extraction of cinnamon oil

The cinnamon bark used for oil extraction was procured from the local market in Coimbatore. The sample was cleaned, washed and shade dried for two days. After drying, it was ground to the proper size and stored in polyethylene bags for further analysis. Cinnamon powder (30 g) was placed into the extraction thimble made of thick filter paper and then inserted into the main chamber of the Soxhlet extractor, with hexane used as the solvent for extraction. The round bottom flask containing boiling chips was weighed and then 300 mL of hexane was poured into the round bottom flask. The solvent was heated to reflux at temperatures exceeding 65 °C for 5 to 10 hrs. After the extraction, the products were collected and purified using a rotary vacuum evaporator set at a temperature of 50 °C. After evaporation, the samples were placed under a fume hood for one hr to ensure all hexane in the crude oil fully evaporated into the environment (10).

GC-MS analysis

Analysis of the extracted oil was carried out through gas chromatography (GC) coupled with a Shimadzu mass spectrometer (MS) (GC-MS-TQ8040 NX SHIMADZU, Shimadzu Corp., Tokyo, Japan) at the Centre of Excellence, Department of Plant Biotechnology, Tamil Nadu Agricultural University, Coimbatore. The GC system was fitted with a 30 m fused silica capillary column, Rix-5 Sil MS, with a 0.25 mm diameter and 0.25 µm film thickness. Cinnamon oil, diluted for the analysis, was infused in split mode (10:1), with a constant helium gas flow rate of 1 mL/min. The oven temperature was originally programmed to 70°C for one minute, then gradually increased to 225 °C, followed by a further rise to 300°C at a rate of 5 °C per minute, for a total runtime of 55 minutes. The injector port temperature was maintained at 280 °C and the ion source temperature was set to 230 °C. MS, based on comparison of mass spectra with those listed in the NIST library.

Contact toxicity bioassay

The insecticidal activity of cinnamon oil against *L. serricorne* and *C. cephalonica* adults was tested following filter paper assay method (11). A precise quantity of cinnamon oil was diluted in acetone to obtain each concentration to be tested. Five different concentrations ranging from 80 to 400 µL/cm^2 were prepared using acetone. 500 µl of each concentration was sprayed separately onto 9 cm-diameter petri plates. After allowing 15 minutes for the solvent to evaporate, twenty 1-2day old adults each of *L. serricorne* and *C. cephalonica* were introduced onto each plate, separately and covered with a lid. Every concentration was repeated four times. The control plates were treated with acetone alone. Vaseline was applied to the Petri plate lids to prevent the settling of insects. The number of dead insects was recorded at 24, 48 and 72 hrs after treatment. Insects were considered dead if their appendages remained immobile when gently touched with a camel hair brush. Mortality percentage was then calculated using the following Equation 1 formula.

$$\text{Mortality } \% = \frac{\text{no. of insects dead}}{\text{total no. of insects released}} \text{ X } 100 \quad \text{(Eqn. 1)}$$

Data analysis

The experiments were performed using a Completely Randomized Design (CRD). The data from each dose-response bioassay were analyzed using probit analysis to obtain the LC_{50}, LT_{50} and 95 % fiducial limits using the SPSS 28.0 software program (Statistical Package for Social Sciences, Armonk, NY) (12). All data were analyzed using one-way ANOVA and significant differences among treatment means were compared at 0.01 and 0.05 probability levels using Tukeys' HSD.

Results

GC-MS analysis of cinnamon oil

The chemical components of cinnamon essential oil, along with their retention times and the percentages of each component, are outlined in Table 1. A total of 28 components, accounting for 88.27 % of the cinnamon oil, were identified. The major compounds in the essential oil were, (E)-cinnamaldehyde (51.16 %), acetic acid, cinnamyl ester (9.67 %), Bis(2-ethylhexyl) phthalate (4.77 %), tributyl acetyl citrate (4.52 %) nonacosanal (2.70 %), (Z)-2-methoxycinnamaldehyde (2.62 %) and .gamma. Sitosterol (2.62 %).

Bioassay

In an evaluation of the effectiveness of cinnamon essential oil against *L. serricorne* and *C. cephalonica*, the results indicated that cinnamon essential oil was significantly effective, with the mortality rate being concentration-dependent. An increase in concentration exacerbated mortality. The mortality percentages due to cinnamon essential oil on *L. serricorne* are shown in Table 2. Among the different concentrations tested, the highest mean mortality was observed at 400 µL/cm² (62.50 %), followed by 320 µL/cm² (57.50 %), 240 µL/cm² (43.75 %), 160 µL/cm² (36.25 %) and 80 µL/cm² (22.50 %) (df =20, F=19.22, P<0.05) after 24 hrs of exposure. Mortality rates increased to 76.25 %, 66.25 %, 58.75 %, 52.50 % and 33.75 % after 48 hrs (df=20, F=51.91, P<0.01) and 95.00 %, 86.25 %, 83.75 %, 67.50 % and 46.25 % after 72 hrs (df=20, F=101.94, P<0.01), respectively. The insecticidal activity of cinnamon essential oil against *C. cephalonica* is presented in Table 3. Among the various concentrations tested, the highest mean mortality was observed at 400 µL/cm² (61.25 %), followed by 320 µL/cm² (55.00 %), 240 µL/cm² (42.50 %), 160 µL/cm² (33.75 %) and 80 µL/cm² (20.00 %) after 24 hrs of exposure (df=20, F=74.77, P<0.01). Mortality rates increased to 76.25 %, 66.25 %, 57.50 %, 51.25 % and 33.75 % after 48 hrs (df=20, F=49.84, P<0.01) and 92.50 %, 85.00 %, 82.50 %, 65.00 % and 43.75 % after 72 hrs of exposure (df=20, F=107.58, P<0.01).

Table 2. Contact toxicity of cinnamon essential oil against *Lasioderms serricorne* adults

Concentration (µL/cm²)	Time (h)		
	24	48	72
80	22.50 (28.04)[c]	33.75 (35.34)[c]	46.25 (42.84)[d]
160	36.25 (36.98)[b]	52.50 (46.45)[b]	67.50 (55.66)[c]
240	43.75 (41.37)[b]	58.75 (50.18)[b]	83.75 (66.41)[b]
320	57.50 (49.34)[a]	66.25 (54.55)[ab]	86.25 (68.44)[b]
400	62.50 (52.51)[a]	76.25 (61.44)[a]	95.00 (78.21)[a]
Control	0.00 (2.86)[d]	0.00 (2.86)[d]	1.25 (5.38)[e]
S. Ed.	3.61	4.18	4.05
C.D. (0.05)	7.60	8.78	8.51

*Figures in parentheses are arcsine transformed values. Means within columns followed by the same letter(s) are not significantly different (p=0.05) by LSD.

Table 1. Chemical constituents of the cinnamon essential oil

Peak No.	Compound	Retention time (min)	% of Area
1.	(Z)-3-Phenylacrylaldehyde	11.17	0.74
2	(E)-Cinnamaldehyde	13.11	51.16
3	Copaene	15.27	1.00
4	Caryophyllene	16.39	0.13
5	Acetic acid, cinnamyl ester	17.00	9.67
6	.alpha.-Muurolene	18.30	1.07
7	(Z)-2-Methoxycinnamaldehyde	19.06	2.62
8	Tetradecanal	20.91	0.50
9	tau.-Muurolol	21.71	0.67
10	l Hexadecanal	25.35	0.45
11	Palmitic acid vinyl ester	28.67	0.19
12	cis-13-Octadecenal	29.74	0.31
13	Phytol	31.03	0.34
14	Undec-10-ynoic acid, undec-2-en-1-yl ester	32.90	0.19
15	Tributyl acetyl citrate	33.67	4.52
16	5-Methyl-Z-5-decosene	34.72	0.85
17	(R,S)-5-Ethyl-6-methyl-3E-hepten-2-one	35.87	0.38
18	Cyclopentanemethanol, 2-nitro-.alpha.-(2-phenylethenyl)-, [1.alpha.(S*),2.alpha.]-	38.67	0.67
19	Bis(2-ethylhexyl) phthalate	39.86	4.77
20	1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	43.51	0.43
21	Squalene	44.63	0.25
22	Dotriacontane	46.00	0.38
23	Dotriacontane	47.42	0.22
24	Dotriacontane	48.79	0.73
25	Campestero	50.39	0.52
26	.gamma.-Sitosterol	51.70	2.62
27	Nonacosanal	52.19	0.19
28	Nonacosanal	53.99	2.70

Table 3. Contact toxicity of cinnamon essential oil against *Corcyra cephalonica* adults

Cocentration (µL/cm²)	Time (h)		
	24	48	72
80	20.00 (26.01)[a]	33.75 (35.34)[a]	43.75 (41.37)[c]
160	33.75 (35.48)[ab]	51.25 (45.74)[ab]	65.00 (54.21)[b]
240	42.50 (40.65)[bc]	57.50 (49.46)[b]	82.50 (65.55)[a]
320	55.00 (47.90)[c]	66.25 (54.55)[b]	85.00 (67.58)[a]
400	61.25 (51.79)[d]	76.25 (61.44)[c]	92.50 (74.32)[a]
Control	1.25 (5.38)[e]	2.50 (7.89)[d]	3.75 (10.40)[d]
S. Ed.	4.40	4.55	4.56
C.D. (0.05)	9.25	9.57	9.58

*Figures in parentheses are arcsine transformed values. Means within columns followed by the same letter(s) are not significantly different (p=0.05) by LSD.

The LC_{50} values of cinnamon oil decreased over time, measuring 260.65 µL/cm² at 24 hrs, 149.15 µL/cm² at 48 hrs and 98.67 µL/cm² at 72 hrs for *L. serricorne*. For *C. cephalonica*, the LC_{50} values were 285.60 µL/cm² at 24 hrs, 160.08 µL/cm² at 48 hrs and 109.33 µL/cm² at 72 hrs. As time increased, the LC_{50} values decreased (Table 4). Overall, the time needed for cinnamon essential oil to achieve 50 % mortality (LT_{50}) decreased as the concentration increased (Table 5). The contact toxicity of the essential oil against *L. serricorne* and *C. cephalonica* resulted in lethal times of 20.34 hrs and 21.43 hrs, respectively, at the highest tested concentration.

Table 4. LC_{50} values of cinnamon essential oil against *Lasioderma serricorne* and *Corcyra cephalonica* adults

Insects	[a]LC_{50} (µL/cm²)	95 % confidence limits		Regression equation	[b]χ^2
		Lower (µL/cm²)	Upper (µL/cm²)		
Lasioderma serricorne					
24	260.65	214.31	317.00	y=1.56x+1.22	0.69
48	149.15	119.95	185.45	y=1.56x+1.59	0.80
72	98.67	78.99	123.24	y=2.33x+0.32	3.81
Corcyra cephalonica					
24	285.60	235.49	346.37	y=1.66x+0.90	0.48
48	160.08	131.00	195.61	y=1.61x+1.45	0.91
72	109.33	89.00	134.30	y=2.24x+0.41	2.34

[a]Lethal concentration 50 -the concentration that causes 50 % mortality; [b]Chi square value

Discussion

Essential oils are secondary metabolites produced by plants that serve crucial functions in protecting against biotic and abiotic stresses, as well as in attracting pollinators. They are found in various plant organs and accumulate in specific structures such as glandular trichomes and secretory cavities. Composed mainly of monoterpenes and sesquiterpenes, essential oils are synthesized in the cytoplasm and plastids, providing cost-effective, safer and eco-friendly alternatives to synthetic insecticides (13). These oils can protect food products from insect pests by acting on multiple mechanisms, including functioning as Insect Growth Regulators (IGRs) by interacting with the regulation of juvenile hormones (JH), thereby interfering with insect metamorphosis and developmental processes. Many essential oils (EOs) exhibit repellency effects even without direct contact with insects, suggesting that their action on target sites occurs through the respiratory system, which is useful for deterring pests (14). The components of EOs, including terpenes, terpenoids and phenylpropanoids, interact with acetylcholinesterase (AChE), inhibiting its activity. This inhibition leads to the accumulation of acetylcholine at the synapses, increasing nerve activity and ultimately resulting in the insects' death. EOs can also act as fumigants, diffusing and penetrating pest habitats to disrupt vital biological functions, ultimately leading to pest death or elimination (15). EOs are a promising option because they specifically target insects while leaving non-target species unharmed.

Among the compounds detected in cinnamon oil, cinnamaldehyde is a key component with significant biological activity, particularly in its insecticidal properties (Fig. 1). cinnamaldehyde has been shown to effectively disrupt the metabolic processes of pests, making it a valuable natural insecticide. In addition to its role in pest control, cinnamaldehyde is also utilized in the production of edible antimicrobial films, particularly for fruits and vegetables, where it plays a crucial role in inactivating foodborne pathogens (16). Another notable compound found in cinnamon oil is cinnamic acid esters. These compounds have attracted significant attention from pharmacologists due to their promising therapeutic properties, such as anti-inflammatory and antimicrobial activities (17). The present study highlighted that varying levels of contact toxicity against *L. serricorne* and *C. cephalonica*, with toxicity influenced by both the dosage and the duration of exposure to cinnamon oil. The highest mortality rates were documented after 72 hrs of treatment with the highest doses of cinnamon oil, with *L. serricorne* adults exhibiting a 95.00 % mortality rate and *C. cephalonica* adults showing a slightly lower mortality rate of 92.50 %. These results suggest that *L. serricorne* adults were more sensitive to the oil compared to *C. cephalonica*, across all tested concentrations.

Table 5. LT_{50} values of cinnamon essential oil against *Lasioderma serricorne* and *Corcyra cephalonica* adults at highest concentration of 400 µL/cm²

Insects	[a]LT_{50} (h)	95 % confidence limits		Regression equation	[b]χ^2
		Lower (h)	Upper (h)		
Lasioderma serricorne	20.34	17.45	23.72	y=2.62x+1.55	4.07
Corcyra cephalonica	21.43	18.44	24.91	y=2.48x+1.68	2.35

[a] Lethal time 50-the time exposure that causes 50 % mortality; [b]Chi square value

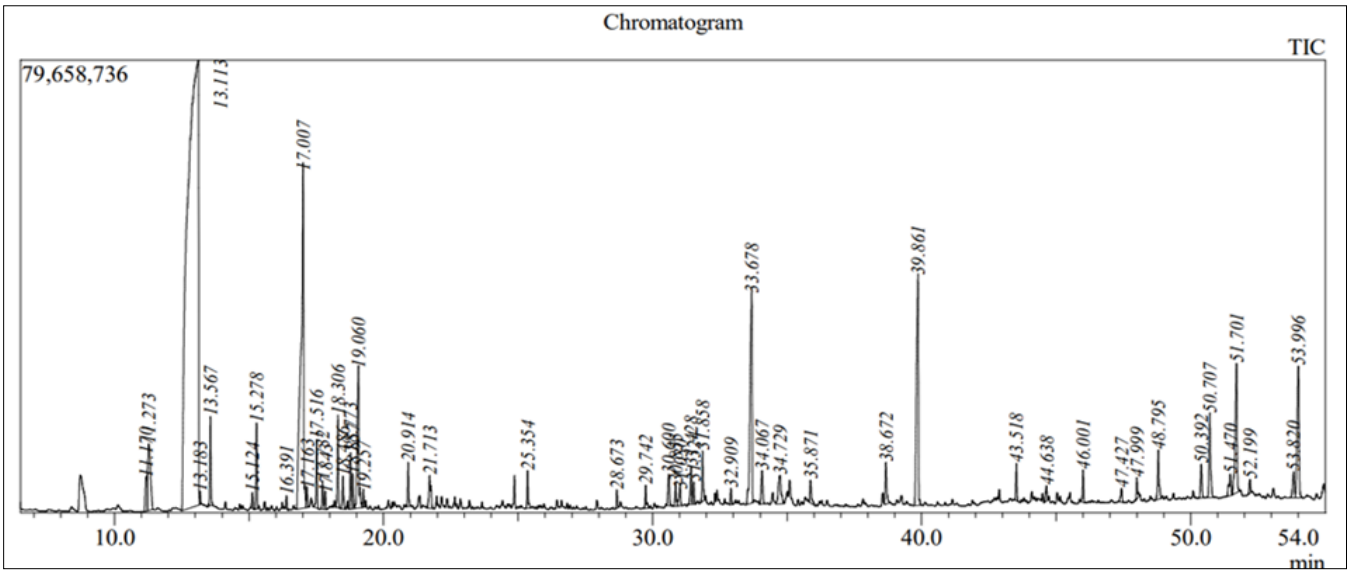

Fig. 1. Typical GC-MS TIC chromatogram for cinnamon essential oil. The numbers refer to those in Table 1.

The potent effectiveness of cinnamon oil against stored product pests can be attributed to the presence of compounds such as trans-cinnamaldehyde (32.1 %), 3,3-dimethylhexane (10.6 %) and 2,4-di-tert-butylphenol (7.9 %) (18). Several studies have demonstrated the efficacy of cinnamon oil against various pests, including *L. serricorne* and *C. cephalonica*. Studies conducted by (19) highlighted LC_{50} values of 18,303.78 ppm and 10,747.42 ppm, respectively, for trans-cinnamaldehyde, the primary component of cinnamon oil, against the grubs and adults of *L. serricorne* after 48 hrs of exposure. Similarly, the highest efficacy of cinnamon oil against adult *Callosobruchus maculatus*, with an LC_{50} of 0.186 %, was closely followed by cardamom (LC_{50} = 0.179 %) and nutmeg (LC_{50} = 0.214 %) (20). For instance, one study reported 98 % mortality in *C. maculatus* and 80 % mortality in *S. oryzae* adults with cinnamon oil at 1.2 mg/cm^2 after 24 hrs of treatment (7). Furthermore, *C. aurantium* oil resulted in 94.44 % mortality in adults of *C. maculatus* in a surface film bioassay, with LD_{50} values of 27.56 and 23.16 µg/cm^2 after 24 and 48 hrs of exposure, respectively. The corresponding regression equations were Y = 0.39 + 3.20x and Y = 1.25 + 2.75x (21).

Previous studies have demonstrated the effectiveness of several essential oils against various pests, including *L. serricorne* and *C. cephalonica*. Over 90 % mortality was reported in *L. serricorne* after three days of treatment with extracts from the rhizome of *Acorus calamus* var. *angustatus*, as well as cinnamon, horseradish and mustard oils at a concentration of 0.7 mg/cm^2 (18). Similarly, essential oils, including clove, cinnamon, lengukas, citronella and kaffir lime, exhibited contact toxicity against *C. maculatus* (22). A study by (23) reported that the LD_{50} values for the contact toxicity of essential oils from rosemary, geranium, citronella, basil and eucalyptus against *L. serricorne* adults were 3.60, 3.49, 8.90, 6.70 and 7.80 µL/L, respectively. These oils were more effective than pirimiphos-methyl (15.45 µL/L) and chlorantraniliprole (249.77 µL/L). Significant contact toxicity of *Elsholtzia densa* (L.) Benth essential oil was reported, with an LD_{50} of 24.29 mg/L against *L. serricorne* (24). Additionally, essential oil from *Artemisia lavandulaefolia* Wall. ex Besser demonstrated good contact toxicity with an LD_{50} of 13.51 µg/L against *L. serricorne* (25). Another investigation revealed that oils such as pine, eucalyptol and coriander were effective against adults of *Sitophilus oryzae* (L.), *Callosobruchus chinensis* (L.) and *C. cephalonica*, achieving around 90 % mortality after 72 hrs of treatment (26). However, a major criticism of using plant extracts and essential oils (EOs) as insecticides is their high volatility, which leads to low persistence. As a result, these characteristics necessitate continuous and repeated applications to maintain effective pest control. To address this challenge, there is a growing need for developing more stable formulations, such as microencapsulation or using carriers that can enhance plant-based insecticide persistence and overall effectiveness (15).

Conclusion

This study concludes that cinnamon oil is the most effective essential oil for managing the populations of *L. serricorne* and *C. cephalonica*. Botanicals have been used for centuries to ensure food safety by controlling insect populations in stored grain, but chemical insecticides have primarily supplanted them. Recent advancements in plant-based products and their application methods deserve further attention for controlling infestations in food commodities affected by stored insect pests. Many botanical formulations are farmer-friendly, as they can often be sourced from local flora. Therefore, using botanical insecticides is particularly advantageous in developing countries, where farmers may struggle to afford chemical alternatives. This study evaluated the effectiveness of bark-derived oil against *L. serricorne* and *C. cephalonica.* Therefore, large-scale validation of this oil will pave the way for designing a formulation that is easy to apply in storage conditions. The future of plant extracts and essential oils as natural insecticides depends on advancing their effectiveness, sustainability and safety through continuous technological innovation, in-depth scientific research and supportive regulatory frameworks. By focusing on these areas, plant-based insecticides can become a viable and sustainable alternative to synthetic pesticides for controlling storage pests, ultimately contributing to more eco-friendly and safe pest management practices.

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Authors' contributions

MS conducted the experiment and drafted the manuscript; SJ designed and edited the manuscript; MS and SJ interpreted the study results; AS, GP, DM and DJ helped with the statistical analysis and edited the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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