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RESEARCH PAPER

Fumigant activity of three aromatic essential oils against fruit fly *Bactrocera carambolae*

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ABSTRACT

Essential oils have attracted considerable attention as environmentally friendly alternatives to synthetic insecticides because of their selective neurotoxicity, high volatility, and rapid biodegradability. This study investigated the chemical composition and fumigant toxicity of the essential oils of *Melaleuca cajuputi*, *Amomum cardamomum*, and *Myristica fragrans* against the fruit fly *Bactrocera carambolae*. The chemical constituents of each oil were characterized by gas chromatography–mass spectrometry (GC–MS), and their fumigant toxicity was evaluated by determining the median lethal concentration (LC_{50}) and 90% lethal concentration (LC_{90}). GC–MS analysis identified 27 compounds in *M. cajuputi* oil, with 1,8-cineole (34.88%), α-terpineol (10.52%), β-caryophyllene (10.44%), α-humulene (5.74%), and limonene (5.15%) as the major constituents. *A. cardamomum* oil contained 32 compounds and was dominated by 1,8-cineole (60.48%), followed by β-pinene (8.24%) and α-terpineol (5.35%). In contrast, *M. fragrans* oil contained 12 compounds, with sabinene (21.51%), α-pinene (17.34%), terpinen-4-ol (15.92%), β-pinene (15.10%), β-phellandrene (8.72%), and α-terpinene (5.95%) as the principal constituents. Among the three oils, *M. fragrans* exhibited the highest fumigant toxicity against *B. carambolae*, with LC_{50} and LC_{90} values of 0.05 and 0.48 µL/L, respectively, followed by *M. cajuputi* (LC_{50} = 0.82 µL/L; LC_{90} = 1.48 µL/L) and *A. cardamomum* (LC_{50} = 2.58 µL/L; LC_{90} = 3.43 µL/L). The superior fumigant toxicity of *M. fragrans* was associated with its characteristic mixture of monoterpene hydrocarbons and oxygenated monoterpenes, whereas the high proportion of 1,8-cineole in *A. cardamomum* alone did not result in greater toxicity. These findings demonstrate that *M. fragrans* essential oil is a promising botanical fumigant for the management of *B. carambolae* and highlight the importance of overall chemical composition rather than the abundance of a single constituent in determining fumigant efficacy.

Keywords: *Amomum cardamomum*, chemical composition, fumigant toxicity, *Melaleuca cajuputi, Myristica fragrans*

INTRODUCTION

Bactrocera carambolae is one of the most destructive pests of horticultural crops, particularly fruit trees, and its distribution has expanded widely across Indonesia and other tropical regions (Marchioro, 2016; Sudiarta et al., 2020; Setiawan et al., 2024). This highly polyphagous fruit fly attacks more than 270 host plant species, including starfruit, avocado, guava, lemon, mango, orange, papaya, and many other economically important crops (Vargas et al., 2015; Widihastuty et al., 2023). Under severe infestations, fruit losses may reach 60–100%, resulting in substantial reductions in both yield and market quality. Female flies oviposit beneath the fruit skin using their ovipositor, producing characteristic puncture marks that facilitate microbial infection and accelerate fruit decay (Koswanudin et al., 2018). Management of *B. carambolae* relies predominantly on synthetic insecticides. However, their intensive and indiscriminate use has raised serious concerns, including the development of insecticide resistance, pest resurgence, adverse effects on non-target organisms, and environmental contamination (Dey & Gupta, 2016). Consequently, environmentally friendly alternatives are needed for sustainable fruit fly management.

Plant essential oils have attracted increasing attention as promising botanical insecticides because they are biodegradable, relatively safe to non-target organisms, and contain diverse bioactive secondary metabolites. Extracted from various plant parts, including leaves, flowers, bark, seeds, and roots, essential oils are complex mixtures primarily composed of monoterpenes, sesquiterpenes, and their oxygenated derivatives, together with smaller amounts of aliphatic

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compounds such as aldehydes, ketones, alcohols, and acids (Dey & Gupta, 2016; Kasman et al., 2020). These compounds contribute to a wide range of biological activities, including antimicrobial, antioxidant, anti-inflammatory, and insecticidal properties (Khoa et al., 2024).

Some essential oils are known to possess diverse bioactivities against insect pests, including fumigant toxicity, contact toxicity, repellency, antifeedant activity, growth inhibition, and oviposition deterrence (Kumar et al., 2022). Similar repellent activity has also been demonstrated for celery essential oil against Spodoptera frugiperda under laboratory conditions (Alif & Wahidah, 2021). Their efficacy depends on several factors, including concentration, exposure duration, and chemical composition (Said-Al Ahl et al., 2017; Yakhlef et al., 2020). Among the bioactive constituents, 1,8-cineole, a major component of several *Myrtaceae* species such as *Melaleuca cajuputi*, has been reported to exhibit significant insecticidal activity (Pujiarti et al., 2013; Wang et al., 2015). Likewise, myristicin, the principal phenylpropanoid compound in *Myristica fragrans* essential oil, has shown potent contact and fumigant toxicity against several insect species (Warsito, 2021). These findings suggest that differences in chemical composition may substantially influence the insecticidal performance of essential oils.

The insecticidal activity of essential oils can be evaluated through either direct contact or fumigation bioassays. Previous studies have reported significant fumigant and contact toxicity of essential oils from various aromatic plants, including *Artemisia judaica, Citrus aurantifolia, Pinus longifolia, Eucalyptus obliqua, Coriandrum sativum, Ocimum basilicum, Mentha spicata, Mentha pulegium*, and *Ricinus communis* against a wide range of agricultural and stored-product insect pests (Abdelgaleil et al., 2015; Eliopoulos et al., 2015; Salem et al., 2017). Nevertheless, comparative information regarding the fumigant toxicity of Indonesian aromatic essential oils against *B. carambolae* remains limited, and the relationship between their chemical composition and insecticidal efficacy has not been thoroughly investigated.

To our knowledge, this is the first study to comparatively evaluate the fumigant toxicity of three commercially important Indonesian essential oils—*M. cajuputi*, *Amomum cardamomum*, and *M. fragrans*—against adult *B. carambolae* while simultaneously characterizing their chemical compositions. Therefore, this study aimed to evaluate the fumigant insecticidal activity of these essential oils against adult *B. carambolae* and to relate their insecticidal efficacy to their major chemical constituents.

MATERIALS AND METHODS

Research Site. This study was conducted at the Biomaterial Chemical Conversion Laboratory, Faculty of Forestry, Universitas Gadjah Mada and the Basic Entomology Laboratory, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia from May-August 2019. Fresh cajuput leaves (*Melaleuca cajuputi*) were collected from cajuput plantations managed by the Yogyakarta Forest Management Unit, Indonesia. Dried cardamom seeds (*Amomum cardamomum*) were obtained from Purworejo, Central Java, Indonesia, whereas dried nutmeg seeds (*Myristica fragrans*) were obtained from Cisaat District, Sukabumi Regency, West Java, Indonesia.

Plant Materials and Essential Oils Extraction. Fresh cajuput leaves (*M. cajuputi*) were collected from plantations managed by the Yogyakarta Forest Management Unit, Indonesia. Dried cardamom seeds (*A. cardamomum*; approximately 15% moisture content) were obtained from Purworejo, Central Java, Indonesia, while dried nutmeg seeds (*M. fragrans*; approximately 15% moisture content) were collected from Cisaat District, Sukabumi Regency, West Java, Indonesia. The moisture content of both seed samples was confirmed by oven drying at 60 ± 5 ºC until a constant weight was achieved.

Essential oils were extracted at the Biomaterial Chemical Conversion Laboratory, Faculty of Forestry, Universitas Gadjah Mada (UGM), Yogyakarta, Indonesia. Approximately 200 g of each plant material was subjected to hydrodistillation using a Clevenger-type apparatus for 4 hours at 100 ºC. This extraction period was selected to maximize essential oil recovery while minimizing thermal degradation of volatile constituents. After distillation, the oils were dried over anhydrous sodium sulfate to remove residual moisture, transferred into amber glass bottles, and stored at 4 ºC until further use.

The average essential oil yields were 1.2% (v/w) for *M. cajuputi* leaves, 3.8% (v/w) for *A. cardamomum* seeds, and 6.5% (v/w) for *M. fragrans* seeds.

GC-MS Analysis. The chemical compositions of the essential oils were determined using gas chromatography–mass spectrometry (GC–MS) (QP2010S, Shimadzu Co. Ltd., Kyoto, Japan) equipped with an HP-5MS capillary column (30 m). Helium was used as the carrier gas at a flow rate of 60 mL/min. Samples (1 µL) were injected in split mode, with an injector temperature of 310 ºC. Mass spectra were obtained by electron impact (EI) ionization at 70 eV.

The relative abundance of each compound was calculated from the percentage peak area of the total ion chromatogram. Chemical constituents were identified by comparing their mass spectra and retention times with those in the instrument library and published literature.

Insect Rearing. A laboratory colony of *B. carambolae* was established from pupae obtained from the Basic Entomology Laboratory, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia. The insects were maintained at 25 ± 2 ºC, 90% relative humidity (RH), and a 12:12 h (light) photoperiod.

After adult emergence, flies were provided with a diet consisting of yeast extract and granulated sugar (1:2, w/w). Eggs laid by 12-day-old females were collected every two days and transferred immediately onto larval diet.

The larval diet consisted of wheat bran (175 g), instant dry yeast (35 g), 3.5% HCl (20 mL), sodium benzoate (0.75 g), tissue paper (25 g), and distilled water (650 mL). The mixture was placed in plastic trays as both oviposition and larval development media. Each tray was surrounded with soft sawdust to facilitate pupation. Approximately 13 days after egg hatch, mature larvae exited the diet and pupated in the sawdust. Pupae were collected five days later by sieving, transferred into rearing cages, and maintained until adult emergence. Healthy adults were used for the fumigation bioassays.

Fumigant Toxicity Bioassay. The fumigant toxicity of *M. cajuputi, A. cardamomum,* and *M. fragrans* against *B. carambolae* essential oils was evaluated following the methods of Pujiarti et al. (2013) and Al-Sarar et al. (2014) with minor modifications.

Fifteen adult flies were introduced into each 3-L glass bottle. A circular filter paper (12 cm diameter) was placed inside the bottle and treated with the appropriate volume of essential oil solution prepared in acetone. For each essential oil, three concentrations were selected based on preliminary bioassays to produce mortality both below and above 50%.

The fumigant concentrations tested were: 1) *M. cajuputi*: 0.33, 0.67, and 1.00 µL/L air; 2) *M. fragrans*: 0.33, 0.67, and 1.00 µL/L air, 3) *A. cardamomum*: 1.17, 2.33, and 3.50 µL/L air.

After the acetone had evaporated (approximately 30 s), each bottle was sealed with spunbond nonwoven fabric and covered with a moist sponge to maintain humidity. A cotton wick soaked in sugar solution was provided as a food source throughout the experiment. Each treatment consisted of three independent replicates. Control bottles received acetone only without essential oil.

The bioassays were conducted under laboratory conditions (28 ± 2 ºC and 70 ± 5% RH). Insect mortality was assessed after 6, 12, 24, 36, and 48 hours of exposure. Flies were considered dead when they showed no movement after gentle stimulation with a fine brush.

Statistical Analysis. Mortality data were analyzed by one-way analysis of variance (ANOVA) using SPSS Statistics version 22.0 (IBM Corp., Armonk, NY, USA). Differences among treatment means were compared using Tukey's honestly significant difference (HSD) test at $P < 0.05$. Median lethal concentration (LC_{50}) and 90% lethal concentration (LC_{90}) values were estimated by probit analysis.

RESULTS AND DISCUSSION

Chemical Composition of Essential Oils. GC-MS analysis revealed distinct chemical profiles among the three essential oils (Table 1), reflecting differences in plant species and geographical origin. *M. cajuputi* oil contained 27 compounds, with 1,8-cineole (34.88%). as the dominant constituent, followed by α-terpineol (10.52%), β-caryophyllene (10.44%), α-humulene (5.74%), and limonene (5.15%). Compared to the previous study (Pujiarti et al. 2011), the main compounds of *M. cajuputi* oil in this study were almost similar, such as 1,8-cineole (44.76-60.19%), α-terpineol (5.93-12.45%), d (+)-limonene (4.45-8.85%), and β-caryophyllene (3.78-7.64%). This composition agrees with previous reports describing 1,8-cineole as the principal component of *M. cajuputi* and other *Melaleuca* species, although its relative abundance varies depending on genotype and environmental conditions (Siani et al., 2016; Pujiarti et al., 2011; Hayouni et al., 2008; Padalia et al., 2015).

A. cardamomum oil contained 32 identified compounds and was also dominated by 1,8-cineole (60.48%), together with β-pinene (8.24%) and α-terpineol (5.35%). The predominance of 1,8-cineole is consistent with previous studies on cardamom essential oil, although its proportion differs among growing regions and extraction conditions (Husain & Ali, 2014).

Table 1. Chemical composition of the essential oils of *M. cajuputi*, *A. cardamomum*, and *M. fragrans* by GC-MS

No	Retention time (m)	Component	Component percentages (%)		
			M. cajuputi	*A. cardamomum*	*M. fragrans*
		Monoterpene	***52.91***	***83.06***	***84.08***
1	4.287	Camphene	-	-	1.27
2	6.737	Sabinene	-	-	21.51
3	11.082	Ascaridole	-	0.07	-
4	11.391	α-Thujene	0.30	0.28	3.20
5	11.727	α-Pinene	2.13	2.81	17.34
6	13.255	β-Phellandrene	-	1.22	8.72
7	13.423	β-Pinene	1.53	8.24	15.10
8	13.538	β-Myrcene	0.76	-	-
9	14.247	α-Phellandrene	-	0.28	-
10	14.369	3-Carene	-	0.28	1.92
11	14.674	α-Terpinene	0.52	-	5.95
12	15.061	Limonene	5.15	4.42	-
13	15.209	Para cymene	1.07	3.67	1.97
14	15.504	1,8-Cineole	34.88	60.48	-
15	16.011	γ-Terpinene	3.22	-	-
16	16.065	Delta 3-Carene	-	0.08	-
17	17.038	α-Terpinolene	1.72	-	2.88
18	17.571	Trans Sabine Hydrate	-	1.07	-
19	18.806	Cis-sabinene- hydrate	-	0.07	-
20	22.398	Myrtenal	-	0.11	-
21	23.700	Myristicin	-	-	4.26
22	26.064	α-Terpinyl acetate	1.63	-	-
		Oxygenated monoterpene	***11.91***	***11.10***	***15.92***
23	13.560	Terpinene-4-ol	1.11	-	15.92
24	18.321	Linalool	0.28	2.22	-
25	18.830	Terpinen-1-ol	-	0.17	-
26	21.764	α-Terpineol	10.52	5.35	-
27	21.817	β-Fechyl Alcohol	-	3.29	-
28	24.467	Phenol,m-isopropyl	-	0.08	-
		Sesquiterpene	***30.64***	***3.86***	***-***
29	26.319	α-Ylangene	0.43	-	-
30	26.646	α-Cubebene	0.35	-	-
31	27.003	β-Elemene	0.41	-	-
32	27.574	Santalen	-	1.59	-
33	27.943	α-Bergamotene	-	0.46	-
34	28.186	Caryophyllene	10.44	-	-
35	28.233	α-Guaiene	-	0.75	-
36	29.065	Scyehellene	-	0.24	-
37	29.341	α-Humulene	5.74	-	-

Table 1. Continued. Chemical composition of the essential oils of *M. cajuputi*, *A. cardamomum*, and *M. fragrans* by GC-MS

No	Retention time (m)	Component	Component percentages (%)		
			M. cajuputi	*A. cardamomum*	*M. fragrans*
38	29.375	α-Patchoulene	-	0.13	-
39	29.519	α-Amorphene	1.8	-	-
40	29.712	α-Gurjunene	0.91	-	-
41	29.888	Cadinene	0.76	-	-
42	30.094	β-Bisabolene	-	0.12	-
43	30.125	Copaene	0.95	-	-
44	30.253	β-Selinene	-	0.36	-
45	30.365	β –Salinene	3.8	-	-
46	30.420	α-Salinene	4.35	-	-
47	30.473	Azulene	-	0.22	-
48	30.809	Δ-Cadinene	0.7	-	-
		Oxygenated sesquiterpene	***4.56***	***1.76***	***-***
49	29.667	Farnesol	-	0.10	-
50	32.063	Teresantalol	-	0.61	-
51	35.608	Viridiflorol	4.56	-	-
52	40.082	Patchaoli alcohol	-	1.05	-
		Boran and alkene	-	0.21	-
53	13.600	Trans-2-4-hexadienol	-	0.10	-
54	15.842	Hexaborane	-	0.13	-
		Total	100.00	99.99	100.00

Chemical constituents were identified by comparing their mass spectra and retention times with those in the Wiley 229 mass spectral library.

In contrast, *M. fragrans* oil contained only 12 major compounds but exhibited a chemically distinct profile dominated by sabinene (21.51%), α-pinene (17.34%), β-pinene (15.10%), terpinen-4-ol (15.92%), β-phellandrene (8.72%), and α-terpinene (5.95%). Similar compositions have been reported for nutmeg oils from Indonesia and other producing countries, although quantitative variation among constituents is common because of genetic and environmental factors (Pal et al., 2011; Seaforth, 1991).

Overall, the three essential oils differed not only in their dominant compounds but also in the relative proportions of monoterpene hydrocarbons, oxygenated monoterpenes, and sesquiterpenes, suggesting that differences in biological activity may be associated with their chemical composition.

Fumigant Toxicity Against *B. carambolae*. All three essential oils exhibited fumigant toxicity against adult *B. carambolae*, with mortality increasing significantly as both concentration and exposure time increased (Figures 1–4). No mortality was observed in the control treatment throughout the 48-hours exposure period.

Among the tested oils, *M. fragrans* showed the greatest insecticidal activity, producing 100% mortality at concentrations of 0.67 and 1.00 µL/L after 48 h. *M. cajuputi* showed intermediate activity, reaching 51.11% mortality at 1.00 µL/L, whereas *A. cardamomum* achieved complete mortality only at the highest concentration tested (3.50 µL/L).

The probit analysis further confirmed these differences. *M. fragrans* exhibited the lowest (LC_{50} (0.05 µL/L) and LC_{90} (0.48 µL/L), followed by *M. cajuputi* (LC_{50} = 0.82 µL/L; LC_{90} = 1.48 µL/L), and *A. cardamomum* (LC_{50} = 2.58 µL/L; LC_{90} = 3.43 µL/L). Lower LC values indicate greater fumigant toxicity, demonstrating that *M. fragrans* was considerably more effective than the other two oils.

Relationship Between Chemical Composition and Fumigant Activity. The three essential oils evaluated in this study exhibited significant fumigant toxicity against *B. carambolae*, although with markedly different levels of efficacy. Based on insect mortality and LC values, *M. fragrans* showed the highest insecticidal activity, followed by *M. cajuputi* and *A.*

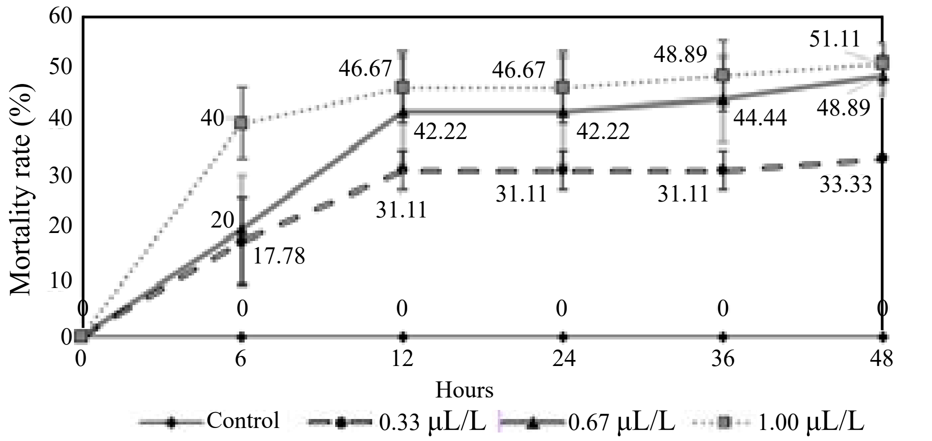

Figure 1. Mortality of *B. carambolae* adults exposed to different concentrations of *M. cajuputi* essential oil.

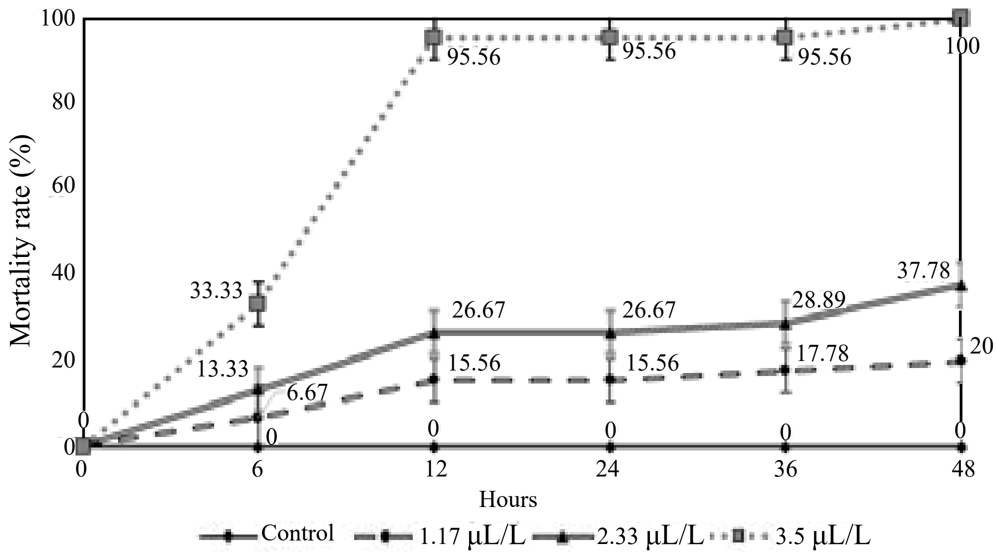

Figure 2. Mortality of *B. carambolae* adults exposed to different concentrations of *A. cardamomu*m essential oil.

cardamomum. These differences in fumigant toxicity are likely associated with variations in chemical composition and the synergistic interactions among essential oil constituents rather than the presence of a single dominant compound (Farag et al., 2024).

The superior fumigant activity of *M. fragrans* can be attributed to its distinctive chemical profile, characterized by relatively high proportions of sabinene (21.51%), α-pinene (17.34%), β-pinene (15.10%), and the oxygenated monoterpene terpinen-4-ol (15.92%). Oxygenated monoterpenes generally exhibit greater fumigant efficacy because of their higher volatility and improved penetration through the insect cuticle (Chaudhari et al., 2021). The neurotoxicity of essential oils has generally been attributed to interference with insect neurotransmission through inhibition of acetylcholinesterase (AChE), modulation of GABA-gated chloride channels, and interactions with octopamine receptors (Jankowska et al., 2017). Accordingly, terpinen-4-ol has been reported to modulate GABA-gated chloride channels, whereas α-pinene and β-pinene primarily inhibit acetylcholinesterase, disrupting neural transmission and causing paralysis and death (Miyazawa & Yamafuji, 2005; Langsi et al., 2020; Liu et al., 2021). The coexistence of these compounds may therefore generate complementary modes of action, resulting in stronger fumigant toxicity than oils dominated by a single class of compounds.

The simultaneous action of these compounds on multiple physiological targets likely explains the exceptionally low LC_{50} value (0.05 µL/L) obtained for *M. fragrans*. Previous studies have similarly demonstrated the strong insecticidal activity of *M. fragrans* essential oil against *Blattella germanica* (Lee et al., 2003). In addition, sabinene possesses fumigant and repellent activity against storage pests (Rani, 2012), while the high volatility of α-pinene and β-pinene further enhances their fumigant efficacy by facilitating penetration through the insect cuticle (Jaffar & Lu, 2022). Bioactive constituents such as myristicin may also contribute to the insecticidal activity of nutmeg

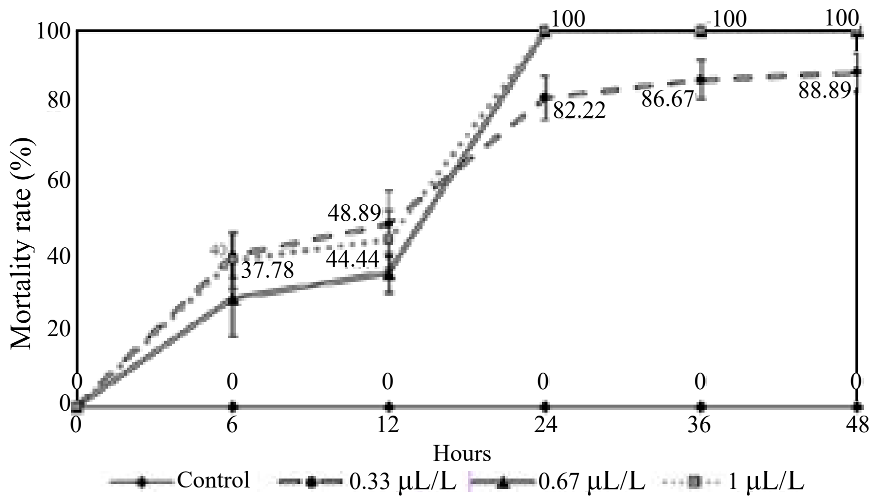

Figure 3. Mortality of *B. carambolae* adults exposed to different concentrations of *M. fragrans* essential oil.

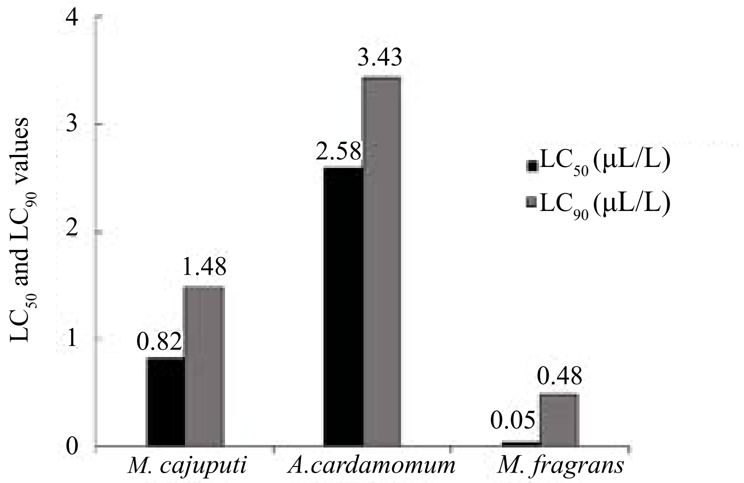

Figure 4. LC_{50} and LC_{90} values of the essential oils of *M. cajuputi, A. cardamomum*, and *M. fragrans* against *B. carambolae* adults.

oil, although their concentration varies depending on plant origin and extraction methods (Nowak et al., 2016).

Although *M. cajuputi* exhibited lower fumigant activity than *M. fragrans*, it still showed considerable fumigant activity against *B. carambolae.* Its insecticidal effect is likely associated with the presence of 1,8-cineole, α-terpineol, β-caryophyllene, and α-humulene. Both 1,8-cineole and α-terpineol have been widely reported to possess contact and fumigant toxicity against numerous agricultural and storage insect pests (Pujiarti et al., 2013; Langsi et al., 2020; Wandjou et al., 2022; Paul et al., 2024). However, the biological activity of an essential oil depends not only on the toxicity of individual constituents but also on synergistic interactions among compounds acting on different physiological targets, including acetylcholinesterase inhibition, disruption of neural transmission, and interference with respiratory metabolism (Pavela, 2015; Gaire et al., 2020; Purnawan et al., 2025). Consequently, the lower toxicity of *M. cajuputi* compared with *M. fragrans* is more likely related to differences in the overall chemical profile and constituent interactions than to the activity of individual compounds.

Interestingly, despite containing the highest proportion of 1,8-cineole (60.48%), *A. cardamomum* exhibited the lowest fumigant toxicity among the three essential oils. Besides 1,8-cineole, this oil contained β-pinene (8.24%) and α-terpineol (5.35%), both of which possess recognized insecticidal properties. Several monoterpenes, including 1,8-cineole, have been reported to inhibit acetylcholinesterase(AChE), thereby contributing to their fumigant toxicity (Abdelgaleil et al., 2009; Rants'o et al., 2022). However, the present results suggest that a high concentration of 1,8-cineole alone is insufficient to confer superior fumigant toxicity against *B. carambolae*. Instead, the overall insecticidal activity appears to depend on the chemical profile of the essential oil and the interactions among its constituents. Similar observations were reported by Nyamador et al. (2017), who found that differences in essential oil toxicity among plant species were determined primarily by the combined effects of multiple constituents rather than by a single dominant compound. Likewise, Tanoh et al. (2020) demonstrated that variations in the relative abundance of β-myrcene, β-caryophyllene, α-humulene, and citronellol influenced the insecticidal and repellent activities of *Zanthoxylum leprieurii* essential oils. These studies further support the importance of synergistic interactions among monoterpenes and sesquiterpenes play a critical role in determining the biological activity of essential oils (Gaire et al., 2020; Abdelgaleil et al., 2021). Similar findings have also been reported in clove leaf essential oil, which exhibited both larvicidal and antifeedant activities against Spodoptera litura, further confirming the potential of essential oils as environmentally friendly botanical insecticides (Fateha et al., 2021).

From a broader perspective, the fumigant toxicity of Indonesian *M. fragrans* essential oil against *B. carambolae* is remarkably high compared with previously reported botanical oils for other tephritid fruit flies. Hossain et al. (2025) reported LC_{50} values of 3.29 µL/L for aniseed oil and 4.95 µL/L for peppermint oil against *B. tryoni*, whereas eucalyptus oil, which is rich in 1,8-cineole, exhibited an LC_{50} of 18.1 µL/L against *Musca domestica* (Oyarce et al., 2025). The substantially lower LC_{50} obtained in the present study highlights the considerable potential of Indonesian *M. fragrans* essential oil as a botanical fumigant for fruit fly management. Nevertheless, further investigations under semi-field and field conditions, together with studies on formulation stability, persistence, and safety toward non-target organisms, are required before practical application can be recommended.

CONCLUSION

The present study demonstrated that the essential oils of *Melaleuca cajuputi*, *Amomum cardamomum*, and *Myristica fragrans* possess significant fumigant toxicity against the fruit fly *Bactrocera carambolae*. Among the three oils, *M. fragrans* exhibited the highest fumigant toxicity, followed by *M. cajuputi* and *A. cardamomum*, as indicated by their LC_{50} and LC_{90} values. The superior efficacy of *M. fragrans* is likely associated with its distinctive chemical composition, particularly the combination of monoterpene hydrocarbons and oxygenated monoterpenes, which may act synergistically to enhance fumigant toxicity. These findings highlight the potential of *M. fragrans* essential oil as a promising botanical fumigant for the management of *B. carambolae*. Further studies are needed to investigate the synergistic interactions among its bioactive constituents and to evaluate its efficacy, formulation stability, and safety under semi-field and field conditions.

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AUTHORS' CONTRIBUTIONS

RP conceived and designed the study, supervised the research, and drafted the manuscript. AT contributed to data interpretation and analysis of the fumigant toxicity of the essential oils against Bactrocera carambolae. S conducted insect rearing and performed the fumigation bioassays. BAVP assisted with essential oil extraction, GC–MS analysis, data processing, and figure preparation. All authors contributed to data interpretation, critically revised the manuscript, and approved the final version.

COMPETING INTEREST

The authors declare that they have no competing financial or personal interests that could have influenced the work reported in this paper.

REFERENCES

Abdelgaleil SAM, Badawy MEI, Shawir MS, & Mohamed MIE. 2015. Chemical composition, fumigant and contact toxicities of essential oils isolated from Egyptian plants against the stored grain insects: *Sitophilus oryzae* L. and *Tribolium castaneum* (Herbst). *Egypt. J. Biol. Pest Control*.

25(3): 639–647.

Abdelgaleil SAM, Mohamed MIE, Badawy MEI, & El-arami SAA. 2009. Fumigant and contact toxicities of monoterpenes to *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst) and their inhibitory effects on acetylcholinesterase activity. *J. Chem. Ecol*. 35(5): 518–525. https://doi.org/10.1007/s10886-009-9635-3

Abdelgaleil SAM, Gad HA, Ramadan GRM, El-Bakry AM, & El-Sabrout AM. 2024. Monoterpenes: chemistry, insecticidal activity against stored product insects and modes of action—a review. *Int. J. Pest Manag*. 70(3): 267–289. https://doi.org/10.1080/09670874.2021.1982067

Alif T & Wahidah FF. 2021. Repellency of celery essential oils (*Apium graveolens* L.) against *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the laboratory. *J. Trop. Plant Pests Dis*. 21(2): 91–96. https://doi.org/10.23960/jhptt.22191-96

Al-Sarar AS, Hussein HI, Abobakr Y, Bayoumi AE, & Al-Otaibi MT. 2014. Fumigant toxicity and antiacetylcholinesterase activity of Saudi *Mentha longifolia* and *Lavandula dentata* species against *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae). *Turk. Entomol. Derg*. 38(1): 11–18. https://doi.org/10.16970/ted.10646

Chaudhari AK, Singh VK, Kedia A, Das S, & Dubey NK. 2021. Essential oils and their bioactive compounds as eco-friendly novel green pesticides for management of storage insect pests: prospects and retrospects. *Environ. Sci. Pollut. Res*. 28(15): 18918–18940. https://doi.org/10.1007/s11356-021-12841-w

Dey D & Gupta MK. 2016. Use of essential oils for insect pest management–A review. *Innovative Farming*. 1(2): 21–29.

Eliopoulos PA, Hassiotis CN, Andreadis SS, & Porichi AE. 2015. Fumigant toxicity of essential oils from basil and spearmint against two major pyralid pests of stored products. *J. Econ. Entomol.* 108(2): 805–810. https://doi.org/10.1093/jee/tov029

Farag SM, Moustafa MAM, Fónagy A, Kamel OMHM, & Abdel-Haleem DR. 2024. Chemical composition of four essential oils and their adulticidal, repellence, and field oviposition deterrence activities against *Culex pipiens* L. (Diptera: Culicidae). *Parasitol. Res.* 123(1): 110. https://doi.org/10.1007/s00436-024-08118-z

Fateha RN, Grasela M, Ichwan MN, Purwanti EW, & Kurniasari I. 2020. Larvacidal and antifeedant activities of clove leaf oil against *Spodoptera litura* (F.) on soybean. *J. Trop. Plant Pests Dis.* 21(1): 20–25. https://doi.org/10.23960/jhptt.12120-25

Gaire S, Scharf ME, & Gondhalekar AD. 2020. Synergistic toxicity interactions between plant essential oil components against the common bed bug (*Cimex lectularius* L.). *Insects*. 11(2): 133. https://doi.org/10.3390/insects11020133

Hayouni A, Bouix M, Abedrabba M, Leveau JY, & Hamdi M. 2008. Mechanism of action of *Melaleuca armillaris* (Sol. Ex Gaertu) Sm. essential oil on six LAB strains as assessed by multiparametric flow cytometry and automated microtiter-based assay. *Food Chem*. 111(3): 707–718. https://doi.org/10.1016/j.foodchem.2008.04.044

Hossain MdS, Akter S, Hossain MdF, Rizvi SZ, Mendez V, Taylor P, & Park SJ. 2025. Essential oils as potential insecticides and behavior-modifying agents against *Bactrocera tryoni* (Diptera: Tephritidae). *J. Insect Sci*. 25(5): ieaf073. http://doi.org/10.1093/jisesa/ieaf073

Husain SS & Ali M. 2014. Analysis of volatile oil of the fruits of *Elettaria cardamomum* (L.) Maton and its antimicrobial activity. *World J. Pharm. Pharm. Sci.* 3(2): 1798–1808.

Jaffar S & Lu Y. 2022. Toxicity of some essential oils constituents against oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae). *Insects*. 13(10): 954. https://doi.org/10.3390/insects13100954

Jankowska M, Rogalska J, Wyszkowska J, & Stankiewicz M. 2017. Molecular targets for components of essential oils in the insect nervous system—A review. *Molecules*. 23(1): 34. https://doi.org/10.3390/molecules23010034

Kasman, Ishak NI, Hastutiek P, Suprihati E, & Mallongi A. 2020. Identification of active compounds of ethanol extract of *Citrus amblycarpa* leaves by analysis of thin-layer chromatography and gas chromatography-mass spectrometry as bioinsecticide candidates for mosquitoes. *J. Med. Sci*. 8(T2): 1–6. https://doi.org/10.3889/

oamjms.2020.5207

Khoa VV, Dai DN, Huong LT, & Thinh BB. 2024. Sesquiterpene hydrocarbon-rich essential oil from *Teucrium viscidum* blume and its antimicrobial and mosquito larvicidal activities. *Nat. Prod. Commun.* 19(11): 1–9. https://doi.org/10.1177/1934578X241299995

Koswanudin D, Basukriadi A, Samudra IM, & Ubaidillah R. 2018. Host preference fruit flies *Bactrocera carambolae* (Drew & Hancock) and *Bactrocera dorsalis* (Drew and Hancock) (Diptera: Tephritidae). *Jurnal Entomologi Indonesia.* 15(1): 40–49. https://doi.org/10.5994/jei.15.1.40

Kumar S, Mahapatro GK, Yadav DK, Tripathi K, Koli P, Kaushik P, Sharma K, & Nebapure S. 2022. Essential oils as green pesticides: An overview. *Indian J. Agric. Sci.* 92(11): 1298–1305. https://doi.org/10.56093/ijas.v92i11.122746

Langsi JD, Nukenine EN, Oumarou KM, Moktar H, Fokunang CN, & Mbata GN. 2020. Evaluation of the insecticidal activities of α-pinene and 3-carene on *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae). *Insects*. 11(8): 540. https://doi.org/10.3390/insects11080540

Lee S, Peterson CJ, & Coats JR. 2003. Fumigation toxicity of monoterpenoids to several stored product insects and *Blattella germanica. J. Stored Prod. Res.* 39(1): 77–85. https://doi.org/10.1016/S0022-474X(02)00020-6

Liu J, Hua J, Qu B, Guo X, Wang Y, Shao M, & Luo S. 2021. Insecticidal terpenes from the essential oils of *Artemisia nakaii* and their inhibitory effects on acetylcholinesterase. *Front. Plant Sci.* 12: 720816. https://doi.org/10.3389/fpls.2021.720816

Marchioro CA. 2016. Global potential distribution of *Bactrocera carambolae* and the risks for fruit production in Brazil. *PLoS One*. 11(11): e0166142. https://doi.org/10.1371/journal.pone.0166142

Miyazawa M & Yamafuji C. 2005. Inhibition of acetylcholinesterase activity by bicyclic monoterpenoids. *J. Agric. Food Chem*. 53(5): 1765–1768. https://doi.org/10.1021/jf040019b

Nowak J, Woźniakiewicz M, Gładysz M, Sowa A, & Kościelniak P. 2016. Development of advanced extraction methods for the extraction of myristicin from *Myristica fragrans. Food Anal. Methods.* 9(5): 1246–1253. https://doi.org/10.1007/s12161-015-0300-x

Nyamador SW, Mondédji AD, Kasseney BD, Ketoh GK, Koumaglo HK, & Glitho IA. 2017. Insecticidal activity of four essential oils on the survival and oviposition of two sympatric bruchid species: *Callosobruchus maculatus* F. and *Callosobruchus subinnotatus* Pic. (Coleoptera: Chrysomelidae: Bruchinae). *J. Stored Prod. Postharvest Res*. 8(9): 103–112. https://doi.org/10.5897/JSPPR2017.0240

Oyarce GA, Loyola P, Iubini-Aravena M, Romero A, Rodriguez-Maciel JC, Becerra J, & Silva-Aguayo G. 2025. Adulticidal and repellent activity of essential oils from three cultivated aromatic plants against *Musca domestica* L. *Insects*. 16(5): 542. https://doi.org/10.3390/insects16050542

Padalia RC, Verma RS, Chauhan A, Goswami P, Verma SK, & Darokar MP. 2015. Chemical composition of *Melaleuca linarrifolia* Sm. from India: A potential source of 1,8-cineole. *Ind. Crops Prod.* 63: 264–268. https://doi.org/10.1016/j.indcrop.2014.09.039

Pal M, Srivastava M, Soni DK, Kumar A, & Tewari SK. 2011. Composition and anti-microbial activity of essential oil of *Myristica fragrans* from Andaman Nicobar Island. *Int. J. Pharm. & Life Sci*. 2(10): 1115–1117.

Paul A, Visakh NU, Pathrose B, Mori N, Baeshen RS, & Shawer R. 2024. Exploring the chemical characterization and insecticidal activities of *Curcuma angustifolia* roxb. leaf essential oils against three major stored product insects. *Saudi J. Biol. Sci.* 31(6): 103986. https://doi.org/10.1016/j.sjbs.2024.103986

Pavela R. 2015. Essential oils for the development of eco-friendly mosquito larvicides: A review. *Ind. Crops Prod.* 76: 174–187. https://doi.org/10.1016/j.indcrop.2015.06.050

Pujiarti R, Ohtani Y, & Ichiura H. 2011. Physicochemical properties and chemical compositions of *Melaleuca leucadendron* leaf oils taken from the plantations in Java, Indonesia. *J. Wood Sci.* 57(5): 446–451. https://doi.org/10.1007/s10086-011-1183-0

Pujiarti R, Ohtani Y, Ichiura H, & Nishimura Y. 2013.

Insecticidal activity of *Melaleuca leucadendron* oil against greenhouse whitefly *Trialeurodes vaporium*. In: Suwinarti W, Sari NM, Kiswanto, Kusuma IW, Erwin, & Ismail (Eds.). Utilization of Renewable Natural Resources Towards Welfare and Environmental Sustainability. *Proc. 5th Int. Symp. Indones. Wood Res. Soc. Indonesian Wood Research Society (IWoRS)*. pp. 65–70. Balikpapan.

Purnawan P, Hidayat Y, & Dono D. 2025. Controlling *Bactrocera* spp. fruit flies using several essential oils from clove, lemongrass, citronella grass and eucalyptus plants on chili plants (*Capsicum annuum* L.). *Cropsaver J. Plant Prot*. 8(1): 7–18. https://doi.org/10.24198/cropsaver.v8i1.62092

Rani PU. 2012. Fumigant and contact toxic potential of essential oils from plant extracts against stored product pests. *J. Biopestic*. 5(2): 120–128. https://doi.org/10.57182/jbiopestic.5.2.120-128

Rants'o TA, Koekemoer LL, Panayides JL, & van Zyl RL. 2022. Potential of essential oil-based anticholinesterase insecticides against *Anopheles* vectors: A review. *Molecules*. 27(20): 7026. https://doi.org/10.3390/molecules27207026

Said-Al AHAH, Hikal WM, & Tkachenko KG. 2017. Essential oils with potential as insecticidal agents: A review. *Int. J. Environ. Plan. Manag*. 3(4): 23–33.

Salem N, Bachrouch O, Sriti J, Msaada K, Khammassi S, Hammami M, Selmis S, Boushih E, Koorani S, Abderraba M, Marzouk B, Limam F, & Jemaa JMB. 2017. Fumigant and repellent potentials of *Ricinus communis* and *Mentha pulegium* essential oils against *Tribolium castaneum* and *Lasioderma serricorne. Int. J. Food Prop.* 20(sup3): S2899–S2913. https://doi.org/10.1080/10942912.2017.1382508

Seaforth CE. 1991. *Natural Products in Caribbean Folk Medicine.* University of the West Indies, Jamaica.

Setiawan Y, Hamdoen FM, Muhammad FN, Hata K, Tarno H, & Wang J. 2024. Species composition of *Bactrocera* fruit flies (Diptera: Tephritidae) and their parasitoids on horticultural commodities in Batu City and Malang District, East Java, Indonesia. *Biodiversitas*. 25(1): 305–311. https://doi.org/10.13057/biodiv/d250135

Siani AC, Nakamura MJ, Neves GPd, Monteiro SdS, & Ramos MFS. 2016. Leaf essential oil from three exotic mytaceae species growing in the botanical garden of Rio de Janeiro, Brazil. *Am. J. Plant Sci.* 7(6): 834–840. https://doi.org/10.4236/ajps.2016.76079

Sudiarta IP, Wijayanti FE, Temaja IGRM, Wirya GNAS, Sumiartha K, & Selangga DGW. 2020. Present status of fruit fly *Bactrocera carambolae* Drew & Hancock in Bali Island, Indonesia. *Proceedings of the International Conference on Climate Change and Environmental Sustainability (ICCESI 2019).* pp. 101–106. https://doi.org/10.2991/absr.k.200513.017

Tanoh EA, Boué GB, Nea F, Genva M, Wognin EL, Ledoux A, Martin H, Tonzibo ZF, Frederich M, & Fauconnier ML. 2020. Seasonal effect on the chemical composition, insecticidal properties and other biological activities of *Zanthoxylum leprieurii* Guill. & Perr. essential oils. *Foods*. 9(5): 550. https://doi.org/10.3390/foods9050550

Vargas RI, Piñero JC, & Leblanc L. 2015. An overview of pest species of *Bactrocera* fruit flies (Diptera: Tephritidae) and the integration of biopesticides with other biological approaches for their management with a focus on the pacific region. *Insects*. 6(2): 297–318. https://doi.org/10.3390/insects6020297

Wandjou JGN, Baldassarri C, Ferrati M, Maggi F, Pavela R, Tsabang N, Petrelli R, Ricciardi R, Desneux N, & Benelli G. 2022. Essential oils from Cameroonian aromatic plants as effective insecticides against mosquitoes, houseflies, and moths. *Plants*. 11(18): 2353. https://doi.org/10.3390/plants11182353

Wang DC, Sun SH, Shi LN, Qiu DR, Li X, Wei DS, Zhang YM, & Qin JC. 2015. Chemical composition, antibacterial, and antioxidant activity of the essential oils of *Metaplexis japonica* and their antibacterial components. *Int. J. Food Sci. Tech.* 50(2): 449–457. https://doi.org/10.1111/ijfs.12645

Warsito MF. 2021. A review on chemical composition, bioactivity, and toxicity of *Myristica fragrans* Houtt. essential oil. *Indonesian. J. Pharm.* 32(3):

304–313. https://doi.org/10.22146/ijp.1271

Widihastuty, Utami S, Munar A, Ardilla D, & Rangkuti K. 2023. Fruit fly *Bactrocera* spp. responses to odour of curry leaves, *Murraya koenigii* L. Spreng. *Serangga*. 28(2): 99–108.

Yakhlef G, Hambaba L, Pinto DCGA, & Silva AMS. 2020. Chemical composition and insecticidal, repellent and antifungal activities of essential oil of *Mentha rotundifolia* (L.) from Algeria. *Ind. Crops Prod.* 158(22): 112988. https://doi.org/10.1016/j.indcrop.2020.112988