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RESEARCH ARTICLE

Fumigant toxicity and repellency of essential oils from cinnamon, thyme, and lavender against *Musca domestica* L.

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ABSTRACT

We evaluated the fumigant toxicity, behavioral, and ovipositional repellent properties of essential oils derived from cinnamon (*Cinnamomum zeylanicum* Blume), thyme (*Thymus vulgaris* L.), and lavender (*Lavandula officinalis* Chaix) against adults (aged 1-3 d old, undifferentiated by sex) of the housefly, *Musca domestica* L., under laboratory conditions. Adult specimens were obtained from cattle barns and subsequently maintained in controlled environments. Different concentrations of each essential oil were tested to assess their impact on housefly mortality and repellency. The main components in each oil included cinnamaldehyde (76.1%) in *C. zeylanicum*, thymol (37.9%) and *p*-cymol (21.09%) in *T. vulgaris*, linalool (31.06%), and linalyl anthranilate (21.9%) in *L. officinalis*. The bioassays indicated that essential oils of *T. vulgaris* (LC_{50} = 46.7 mL L^{-1} air) and *L. officinalis* (LC_{50} = 144.5 mL L^{-1} air) did not cause more than 50% mortality in fumigant activity against houseflies. In behavioral tests, houseflies treated with *C. zeylanicum* and *T. vulgaris* at 20% and *L. officinalis* at 20% and 40% concentration remained longer in the untreated or intermediate zones than in the treated areas. Lastly, in oviposition trials, *L. officinalis* showed no oviposition at any of the tested concentrations. These results suggest that essential oils from cinnamon, thyme, and lavender could be viable alternatives to traditional chemical insecticides for controlling houseflies in livestock and urban settings.

Key words: Botanical insecticides, *Cinnamomum zeylanicum, Lavandula officinalis, Thymus vulgaris,* veterinary terpenoids, urban pest.

INTRODUCTION

The synanthropic housefly (*Musca domestica* L.: Diptera: Muscidae) is a mechanical vector of pathogens, including bacteria, fungi, viruses, and parasites, some of which cause serious diseases in humans and domestic animals (Geden et al., 2021; Iqbal et al., 2024). Houseflies are found across many habitats. They are attracted to waste and feces and are commonly seen on farms. Because complete eradication is impossible, the goal is to reduce their numbers to acceptable levels (Bertelloni et al., 2023). In dairy facilities, flies can decrease feed intake and milk production. In high-rise layer barns, constant irritation from flies can cause stress in the birds, reduce feed intake, egg production, and hinder weight gain (Shah et al., 2016). Traditionally, controlling houseflies is typically done using chemical insecticides such as organophosphates and pyrethroids. However, the long-term use of these chemicals has been shown to have significant effects on human health and environmental pollution (Zhang et al., 2017). Furthermore, long-term chemical control routine can lead to the development of insecticide resistance. According to Geden et al. (2021), the estimated annual cost of

insecticides for fly control in the poultry industry is about US$30 million, with US$135 million and US$35 million for the dairy and swine industries, respectively. An alternative to synthetic insecticides is the use of essential oils (Isman, 2020). These compounds are neurotoxic because they inhibit neurotransmitters, such as acetylcholinesterase and octopamine, which regulate vital functions like movement, respiration, and heart rate (Jankowska et al., 2018). However, they are less harmful to biodiversity and human health. In controlling domestic flies, essential oils have demonstrated contact insecticidal and fumigant activity, as well as insectistatic, repellent, and feeding and oviposition inhibitory effects (Mossa, 2016; Villanueva-Pereira et al., 2025). For houseflies associated with livestock, there is evidence that essential oils from cinnamon, clove, turmeric, and citronella, among others, exhibit insecticidal and repellent activities (Showler et al., 2019). Therefore, this research aimed to assess, under laboratory conditions, the fumigant toxicity, behavioral, and ovipositional effects of essential oils of cinnamon, thyme, and lavender against adults of *M. domestica*.

MATERIALS AND METHODS

Insects

Adult houseflies (*Musca domestica* L.: Diptera: Muscidae) were field-collected using a sweep net from cattle-confined barns at the Facultad de Medicina Veterinaria of Universidad de Concepción in Chillán, Chile. Houseflies were managed by removing animal feces every 15 d and spraying the insecticide thiamethoxam (water-dispersible granules, 10 g ai kg^{-1}, AGITA 10WG, Elanco Animal Health, Indianapolis, Indiana, USA) at the start of summer. The collected insects were then transported to the laboratory and identified using the taxonomic key provided by De Carvalho and Mello-Patiu (2008), and reared under laboratory conditions according to Khater and Geden (2019) in a bioclimatic chamber (Memmert GmbH IPS 749, Schwabach, Germany) at 25 ± 5 °C, 65 ± 2% relative humidity (RH), and a photoperiod of 16:8 h (L:D). Adults were fed with a cotton swab soaked in 5.0 g milk powder, placed in a Petri dish, and replaced every 24 h. Eggs were collected daily and transferred to the rearing medium, which consisted of strips of absorbent paper stacked in layers moistened with a 2.0% milk and sugar solution inside a container with a lid until larval emergence.

Essential oils

The essential oils of *Thymus vulgaris* L., *Cinnamomum zeylanicum* Blume, and *Lavandula officinalis* Chaix were obtained from Now Essential Oils (Bloomingdale, Illinois, USA) with 99% purity. Chemical analysis was performed at the Laboratory of Natural Products, Department of Botany, Universidad de Concepcion in Concepcion city, using gas chromatography (GC) combined with mass spectrometry (GC-MS) and high-performance gas chromatography-mass spectrometry (HPGC-MS; series II 5890, Hewlett Packard, Palo Alto, California, USA), following the criteria of Adams (2007).

Bioassays

Fumigant activity. The essential oil of *C. zeylanicum* was not included in the experimental evaluations of this study, as Villanueva-Pereira et al. (2025) had previously conducted specific assays to analyze its activity. The essential oils from *T. vulgaris* and *L. officinalis* were tested against adults of *M. domestica* under laboratory conditions following the criteria of Villanueva-Pereira et al. (2025) and Oyarce et al. (2025). We used a 500 mL plastic container with a lid that had been modified to include two holes. A small test tube cap was inserted in each container and secured with fine mesh fabric, which also held an Eppendorf tube. A filter paper saturated with the respective essential oil was placed inside the tube. The mesh prevented flies from making direct contact with the treated paper but allowed the volatile compounds to disperse freely throughout the container. Inside, a cotton swab moistened with a 2% (w/v) sugar solution in distilled water provided sustenance for the flies. Each treatment involved five replicates, with twenty adult flies (aged 1-3 d, undifferentiated by sex) in each container. The tested concentrations were 2.5, 5.0, 10, 15, 20, and 40 mL L^{-1} air. Each treatment was replicated ten times, with a control using untreated filter paper. Mortality was recorded after 48 h exposure. The highest level of accepted mortality in the untreated control was 5%, and this was corrected in the other treatments using Abbott's formula (Abbott, 1925).

Behavioral bioassay. The behavioral effects of essential oils on *M. domestica* were assessed using the methodology of Baldacchino et al. (2013). A plastic box measuring 37.5 × 25.5 × 15.2 cm, with the lid replaced by anti-aphid mesh to allow air circulation, was used as a screen cage. The box was completely lined with white paper to reduce visual stimuli, with a yellow paper piece on each side. Two Petri dishes, each measuring 60 × 15 mm and containing oviposition substrate of wheat bran moistened with milk and 2.0% (w/v) sugar, were placed at the base. One dish was treated with an essential oil solution diluted in acetone, while the other remained untreated (Figure 1a). An adult female *M. domestica* (aged 1-3 d) was introduced and allowed to fly freely for 3 min, a period considered as a 'panic behavior' phase during which the insect exhibits unusual behaviors due to new or unexpected stimuli. Following this, behavioral observations were recorded via a 5 min video recording. The essential oils were tested at concentrations of 10%, 20%, and 40%, with each treatment replicated 50 times, using a different adult female in each replicate.

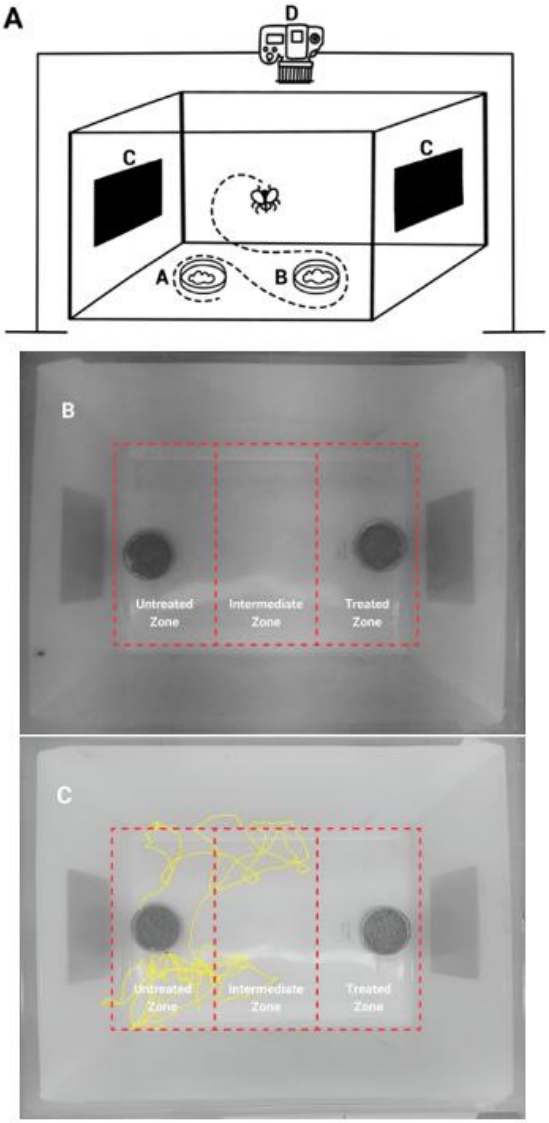

Figure 1. A. Behavioral bioassay dispositive, A: Untreated diet, B: treated diet, C: yellow paper, D: video camera. B. Aerial view of the system for spatial repellency bioassays. Cage was divided into three zones: Untreated, intermediate, and treated zones. C. Track showing the 3 min recording of a housefly.

Flight behavior analysis was performed by dividing the box into three equal-sized longitudinal sections, viewed from above. This division allowed for the measurement of the time spent in each sector during the assessment, distinguishing among treated, central, and untreated zones (Figure 1b). The flight was recorded using an EOS Rebel T6 camera (Canon, Tokyo, Japan), and the videos were converted to AVI format at a resolution of 640 × 480 pixels and 20 frames per second (FPS). They were then converted to grayscale and cropped to standardize video duration and framing for each repetition. The fly movement recordings were analyzed using ImageJ version 4.5.1 (National Institute of Mental Health, Bethesda, Maryland, USA; Schneider et al., 2012) and the animal tracker plugin, which is designed to examine the movement of objects on flat surfaces (Figure 1c). The parameter measured was the time spent in each demarcated area, considering 3 min of filming as 100%.

Oviposition repellency bioassay

In the oviposition test, a no-choice bioassay was conducted following the methodology described by Khan (2021). For this assay, a 3 L plastic cylindrical container was used, which was covered with anti-aphid mesh to allow for gas exchange while preventing the escape of flies. At the bottom of the container, a 60 × 15 mm Petri dish was placed, containing the oviposition substrate. This substrate was prepared by moistening wheat bran with milk and a 2.0% (w/v) sugar solution to provide suitable conditions for egg laying.

Then, 10 female flies, no older than 10 d, were introduced into the container. Every 24 h, the number of dead flies and eggs in each dish was recorded. The eggs were removed daily and transferred to a plastic container lined with absorbent paper moistened with a solution of powdered milk dissolved in distilled water, providing a suitable environment for larval development. The percentages of egg hatching, larval pupation, and emerging adults were evaluated. The tested concentrations were 0.5, 1.0, 2.0, and 4.0 µL in 1 mL acetone.

Experimental design and statistical analysis

All bioassays used a completely randomized design. For the fumigant toxicity bioassay, LC_{50} and LC_{90} values (with 95% confidence intervals) were estimated using a Probit model in SAS (Finney, 1971; SAS Institute, Cary, North Carolina, USA). Behavioral bioassay data were analyzed in RStudio (R version 4.5.1; RStudio 2025.09.0; Posit Software, PBC, Boston, Massachusetts, USA), with nonparametric tests applied due to assumptions not being met for ANOVA (Baldacchino et al., 2013). The Kruskal-Wallis test identified treatment differences, followed by Dunn's test with Bonferroni correction for post-hoc analysis (Okoye and Hosseini, 2024; Dinno, 2024). Fly zone preference was assessed using Chi-square tests for all culture-concentration combinations. Results were visualized with ggplot2 (Wickham, 2016). Oviposition bioassay data, after confirming normality and homoscedasticity with Shapiro-Wilk and Levene's tests, were analyzed using ANOVA and Tukey's test ($P \leq 0.05$).

RESULTS AND DISCUSSION

Chemical composition of essential oils

In the three essential oils, more than 90% of their components were identified (Table 1). The main components in each oil were cinnamaldehyde (76.1%) in *Cinnamomum zeylanicum*, thymol (37.9%) and *p*-cymol (21.09%) in *Thymus vulgaris,* and linalool (31.06%) and linalyl anthranilate (21.9%) in *Lavandula officinalis*. The high concentration of cinnamaldehyde aligns with Suriyagoda et al. (2021), who indicate that *C. zeylanicum*, commonly known as true cinnamon, contains at least 80.0% cinnamaldehyde. These essential oils are widely used to add cinnamon flavor to edible products, cosmetics, and perfumes. The essential oil and isolated cinnamaldehyde have shown insecticidal activity against larvae and adults of *M. domestica* (Gharib et al., 2024; Villanueva-Pereira et al., 2025). Thymol is the primary component of thyme (Saleih et al., 2018). These compounds are used in the food industry for their flavoring and preservative properties, in commercial mosquito repellents for their natural repellent effects, in aromatherapy, and in traditional medicine for treating headaches, coughs, and diarrhea (Marchese et al., 2016). According to Tian et al. (2024) and Yoon and Tak (2025), thyme essential oil demonstrated high toxicity against *M. domestica*. Regarding linalool, Senthoorraja et al. (2021) documented that this compound elicited a neuronal response in female adult *M. domestica*, including the induction of detoxifying enzymes carboxyl esterase (Car E) and glutathione *S*-transferases (GST). However, Yoon and Tak (2025) found that it did not cause lethality in adults of this species.

Table 1. Chemical composition of *Thymus vulgaris*, *Cinnamomum zeylanicum,* and *Lavandula officinalis* essential oils.

Compounds	Retention time	*Thymus vulgaris*	*Cinnamomum zeylanicum*	*Lavandula officinalis*
	min	%	%	%
1-Isopropyl-4-methylenebicyclo[3.1.0]hex-2-ene	5.65	2.07		
1*R*-α-Pinene	5.78	1.50		
Camphene	6.07	1.15		
(-)-β-Pinene	6.62	2.05		
3-octanone	6.84			0.75
α-Terpinen	6.90	2.05		2.69
p-Cymene	7.64	21.09		
β-Terpinyl acetate	7.66			0.93
Eucalyptol	7.72			1.00
1,3,6-Octatriene,3,7-dimethyl-,(*E*)-	7.83			9.59
γ-Terpinene	8.26	8.28		
Linalool	9.09	2.93		31.06
Octen-1-ol, acetate	9.28			0.79
2,4,6-Octatriene,2,6-dimethyl-,(*E*,*Z*)-	9.61			1.53
Benzeneethanol	9.82		0.38	
Camphor	9.97			0.45
Menthol	10.20	0.70		
Borneol	10.40	2.27		0.45
Terpineol	10.59	1.31		5.21
Hydrocinnamaldehyde	10.73		0.49	
p-Menth-1-en-8-ol	11.27			1.85
Thymyl methyl ether	11.58	0.51		
Pulegone	11.73	0.98		
Linalyl anthranilate	11.97			21.90
2-Anisaldehyde	12.22		0.23	
4-Hexen-1-ol,5-methyl-2-(1-methylethenyl)-acetate	12.53			5.10
Thymol	12.80	37.91		
Cinnamaldehyde	12.89		76.10	
Carvacrol	12.90	2.03		
Cinnamyl alcohol	13.32		0.26	
Nerolacetate	13.77			1.08
Geraniol acetate	14.09			1.40
Caryophyllene	14.75	4.11		5.75
(*Z*)-α-Farnesene	15.23			5.46
Cinnamyl alcohol acetate	15.57		5.97	
β-Cubebene	15.71			0.71
o-Methoxycinnamaldehyde	15.77		0.43	
γ-Cadinene	16.21	0.77		
Cadinene	16.32	0.87		
Tetradecamethylcycloheptasiloxane	16.23		0.59	
2-Methoxycinnamaldehyde	16.98		13.90	
Caryophyllene oxide	17.30	1.50		
T-Cadinol	18.10	0.42		
Total, %	-	92.50	98.40	97.30

Fumigant activity

The two essential oils tested did not cause more than 50% mortality in their fumigant activity against houseflies. Among them, *T. vulgaris* essential oil showed the highest toxicity, reaching a maximum of 43% mortality at a concentration of 40 mL L^{-1} air, with LC_{50} and LC_{90} values of 46.7 mL L^{-1} air and 528 mL L^{-1} air, respectively (Table 2). In comparison, *L. officinalis* essential oil resulted in a 31% mortality rate at the same concentration, with LC_{50} and LC_{90} values of 144.5 and 6574 mL L^{-1} air, respectively. Overall, there is limited background on using essential

oils as fumigants for adult housefly control, as most previous studies have focused on contact toxicity and repellency. The results for *T. vulgaris* align with those of Baz et al. (2023), who reported 36% adult housefly mortality at a concentration of 0.06%, corresponding to 60 mL L^{-1} air, a value higher than the concentrations evaluated in this study. Zhang et al. (2017) examined the fumigant activity of thymol and linalool (the main components of *T. vulgaris* and *L. officinalis* essential oils, respectively) against *M. domestica* adults. They found LC_{50} values of 1.60 mL L^{-1} air for thymol and 4.43 mL L^{-1} air for linalool, both lower than the values observed in this research. According to Isman (2020), such inconsistencies in the efficacy of botanical insecticides have contributed to their limited adoption on a large scale.

Table 2. Lethal concentrations 50% (LC_{50}) and 90% (LC_{90}), and slope (b) of essential oils of *Thymus vulgaris* and *Lavandula officinalis* by fumigant toxicity against adults of *Musca domestica*. [a]Number of treated insects. [b]Slope value. [c]Lethal concentration at 50% effect with 95% confidence limits. [d]Lethal concentration at 90% effect with 95% confidence limits. [e]Model fit to a straight line.

Essential oil	N[a]	b ± SE[b]	LC_{50} (LC_{95} %)[c]	LC_{90} (LC_{95} %)[d]	Pr > X^{2e}
			mL L^{-1} air	mL L^{-1} air	
Thymus vulgaris	200	1.21 ± 0.16	46.7 (33.7-77.8)	528 (239-2046)	< 0.0001
Lavandula officinalis	200	0.77 ± 0.15	144.5 (67.9-782.0)	6574 (1073-44 559)	0.025

Behavioral bioassay

In behavioral tests, houseflies spent more time in untreated areas than those treated with *C. zeylanicum* (20%), *T. vulgaris* (20% and 40%), or *L. officinalis* (20% and 40%) (Table 3, Figures 2 and 3). Other treatments showed nonsignificant differences (Kruskal-Wallis test, $p > 0.001$). Comparing treated *vs*. untreated zones, flies exposed to *T. vulgaris* at 10% and the above oils stayed significantly longer in the untreated area ($p \leq 0.05$). At 40%, *C. zeylanicum* and *T. vulgaris* showed nonsignificant effect, but 20% concentrations exhibited a repellent action, possibly due to insect intoxication. No mortality was recorded; however, houseflies treated at 40% exhibited erratic, neurotoxic behavior. Essential oils can trigger neurotoxic symptoms by inhibiting neurotransmitters that control movement and vital functions. The repellent effects observed contradict previous studies on *L. officinalis* and *C. zeylanicum.* The results for thyme differ from those of Tian et al. (2024), who found that its main component attracts houseflies at concentrations of up to 10%.

Table 3. Permanence in each zone by component and concentration, along with Kruskal-Wallis test results. Kruskal-Wallis test: *Significant differences ($p \leq 0.05$); **very significant differences ($p \leq 0.01$); ***highly significant differences ($p \leq 0.001$). Values followed by different letters differ significantly among zones according to Dunn's test ($p \leq 0.05$, Bonferroni).

Treatment	Concentration %	Permanence by zone (%)			Kruskal-Wallis (p)
		Treated	Intermediate	Untreated	
Cinnamomum zeylanicum	10	32.0[a]	25.6[a]	42.4[a]	0.1783
	20	21.9[a]	33.5[ab]	44.6[b]	0.0197*
	40	25.0[a]	39.0[a]	35.9[a]	0.1673
Lavandula officinalis	10	24.2[a]	37.5[a]	38.3[a]	0.1477
	20	23.3[a]	24.8[ab]	51.9[b]	0.0101*
	40	18.2[a]	32.3[ab]	49.5[b]	0.0397*
Thymus vulgaris	10	20.3[a]	33.0[a]	46.7[a]	0.1033
	20	26.1[a]	14.5[a]	59.5[b]	0.00053***
	40	41.0[a]	21.1[a]	37.9[a]	0.1997

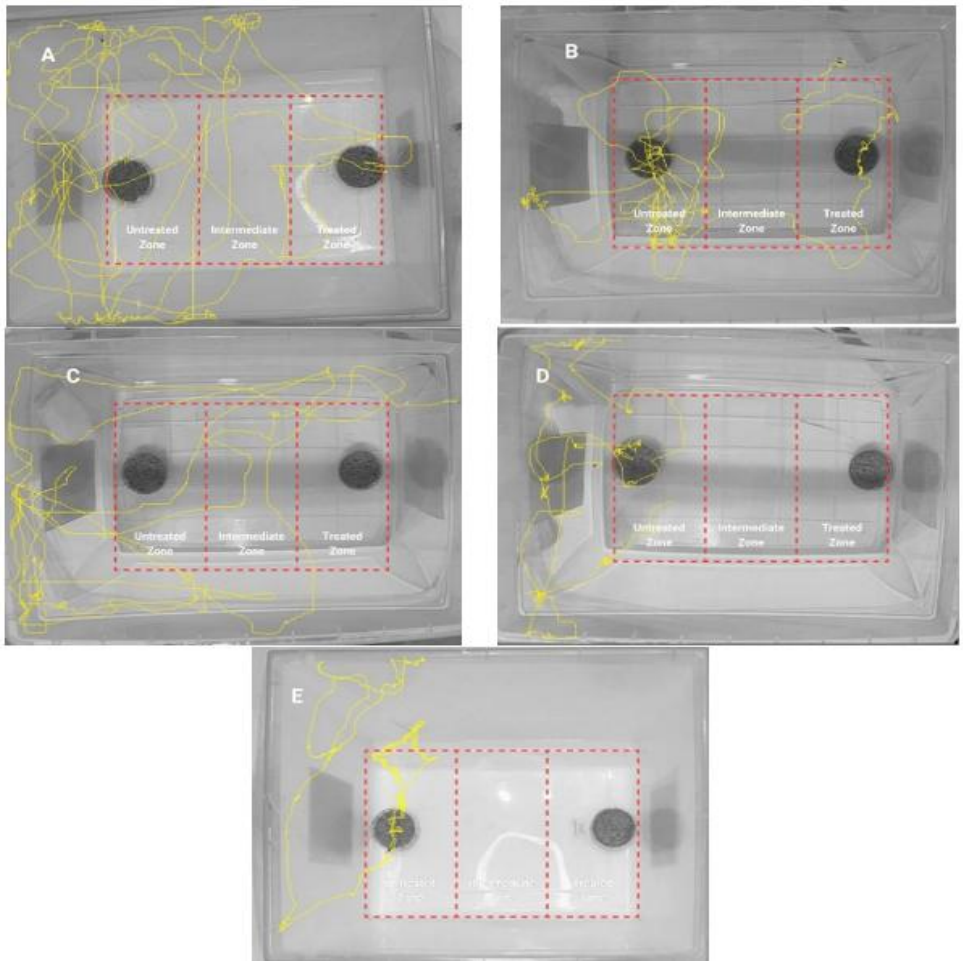

Figure 2. Analyzed tracks of *Thymus vulgaris* at 20% (A), *Thymus vulgaris* at 40% (B), *Lavandula officinalis* at 20% (C), *Lavandula officinalis* at 40% (D), and *Cinnamomum zeylanicum* at 20% (E).

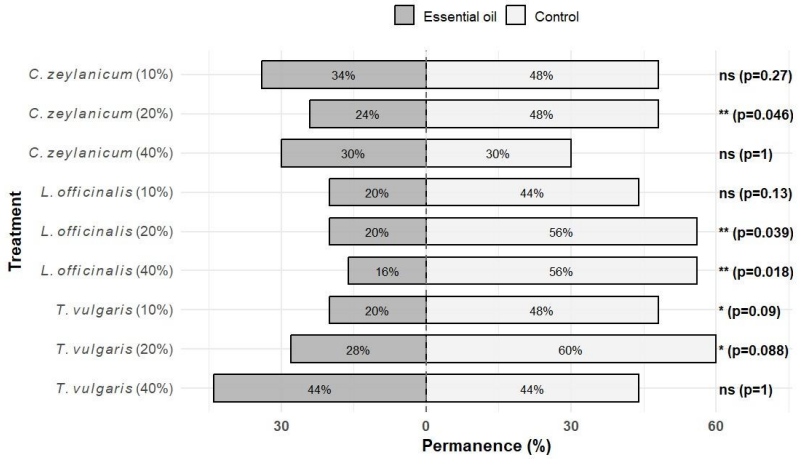

Figure 3. Permanence time (5 min = 100%) of an adult housefly in the chamber zone with oviposition substrate treated and untreated with essential oils of *Lavandula officinalis*, *Thymus vulgaris,* and *Cinnamomum zeylanicum*. The missing value to complete 100% corresponds to the insect's permanence time in the intermediate zone.

Oviposition bioassay

In the oviposition test, *L. officinalis* did not show oviposition at any evaluated concentration, while in *C. zeylanicum*, the control and the two lowest assessed concentrations (0.5 and 1.0 µL essential oil in 1 mL acetone) exhibited oviposition, laying 34, 18, and 1.8 eggs, respectively. However, the ovipositional rate with 1.0 µL essential oil in 1 mL acetone was significantly lower than that of the control. Experimental units treated with *T. vulgaris* showed no eggs at the highest concentration (4.0 µL essential oil in 1 mL acetone); however, all concentrations resulted in considerably fewer eggs compared to the control. The lower oviposition observed in *L. officinalis* treatments stands out from the other essential oils because, when analyzing mortality, it is not even 30% at the higher concentration of 4.0 µL essential oil in 1 mL acetone, unlike *T. vulgaris* and *C. zeylanicum,* which recorded 88.0% and 71% mortality at the same concentration, respectively (Table 4). Thus, the reduced number of eggs in these last two treatments may be associated with mortality, but not in *C. zeylanicum*. Only the untreated control group completed their biological cycle, with 97.8% of the adults emerging. Meanwhile, in *T. vulgaris*, concentrations of 0.5, 1.0, and 2.0 µL showed adult emergence without significant differences compared to the control (Table 4). Results with *L. officinalis* agreed with Sinthusiri and Soonwera (2014), who assessed 10% of *L. angustifolia* Mill. essential oil and obtained an oviposition inhibition of 88.14%. In the case of cinnamon, Alghamdi et al. (2025) found that higher doses significantly reduced egg-laying behavior in gravid females.

Table 4. Mortality, oviposition, egg hatching, pupation, and adult emergence of houseflies exposed to an oviposition medium treated with different concentrations of essential oil of *Lavandula officinalis*, *Thymus vulgaris*, and *Cinnamomum zeylanicum*. Means with a common letter are not significantly different according to Tukey test ($P > 0.05$).

Essential oil	Concentration	Mortality	Oviposition	Egg hatching	Pupation	Adult emergence
	µL oil mL^{-1} acetone	%	n	%	%	%
Lavandula officinalis	0.0	0.0^{c}	21.0	82.9	95.8	97.8
	0.5	2.5^{bc}	0.0	-	-	-
	1.0	4.2^{bc}	0.0	-	-	-
	2.0	8.3^{ab}	0.0	-	-	-
	4.0	29.2^{a}	0.0	-	-	-
Thymus vulgaris	0.0	0.0^{a}	75.0^{a}	92.3^{a}	95.5^{a}	90.6^{a}
	0.5	0.0^{a}	29.0^{b}	82.0^{ab}	95.8^{a}	87.8^{a}
	1.0	0.0^{a}	25.0^{b}	81.0^{ab}	94.7^{a}	78.8^{ab}
	2.0	8.3^{a}	18.0^{b}	40.5^{b}	50.0^{b}	43.8^{b}
	4.0	88.0^{b}	0.0^{b}	-	-	-
Cinnamomum zeylanicum	0.0	0.0^{b}	34.0^{a}	87.5^{a}	95.8^{a}	97.8
	0.5	4.2^{b}	18.0^{ab}	22.2^{b}	0.0^{b}	-
	1.0	4.2^{b}	2.8^{b}	0.0^{b}	-	-
	2.0	4.2^{b}	0.0^{b}	-	-	-
	4.0	71.0^{a}	0.0^{b}	-	-	-

CONCLUSIONS

The primary components identified in the essential oils were cinnamaldehyde from cinnamon (*Cinnamomum zeylanicum*), thymol and *p*-cymol in thyme (*Thymus vulgaris*), and linalool and linalyl anthranilate in lavender (*Lavandula officinalis*). Against adults of *Musca domestica*, thyme exhibited the highest toxicity, with up to 43% mortality at a concentration of 40 mL L^{-1} air. Lavender resulted in 31% mortality at the same concentration. Neither essential oil resulted in a mortality rate exceeding 50%. Houseflies treated with cinnamon and thyme at 20%, and lavender at 20% and 40%, remained longer in untreated areas, indicating a repellent effect. Higher concentrations caused erratic flight behavior, implying neurotoxicity. Lavender showed no effect on oviposition

at any level. Cinnamon and thyme reduced oviposition at higher concentrations, with notable mortality. The essential oils of cinnamon, thyme, and lavender demonstrated potential as alternatives to conventional insecticides, with thyme being the most toxic and lavender showing strong oviposition repellency. These oils can effectively repel house flies at specific concentrations, which could help lower fly populations in various settings. They could be incorporated into pest management strategies to reduce dependence on synthetic insecticides, thereby mitigating health and environmental risks.

Author contribution

Conceptualization: G.S., J.C.R., I.F. Methodology: G.S., M.R., J.C.R., C.B., G.O., J.L., P.L. Software: C.B., G.S., I.F., J.L. Validation: G.S., J.C.R., M.R. Formal analysis: G.S. J.C.R., M.R., I.F. Investigation: G.S., C.B., J.L., G.O., P.L. Resources: G.S., M.R., I.F., P.L. Data curation: C.B., J.L., G.O. Writing-original draft: G.S., J.C.R., C.B., I.F. Writing-review & editing: G.S., J.C.R., M.R. Visualization: C.B., G.S., M.R. Supervision: G.S., M.R., I.F. All co-authors reviewed the final version and approved the manuscript before submission.

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