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**Repellent, Fumigant, and Antifeedant Activities of 50 Plant Essential
Oils Against the Sweet potato Weevil, *Cylas formicarius* (Coleoptera:
Brentidae)**

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Abstract

The sweet potato weevil, (*Cylas formicarius*), is a major constraint to global sweet potato production. Conventional chemical control faces challenges such as insecticide resistance and environmental pollution. Plant essential oils, characterized by low toxicity, rapid degradation, and multi-target mechanisms, represent promising alternatives to synthetic pesticides. In this study, Y-tube olfactometry, sealed jar fumigation assays, and tuber coating tests were employed to systematically evaluate the repellent, fumigant, and antifeedant activities of 50 plant-derived essential oils against *C. formicarius*. Repellency bioassays indicated that adults exhibited the highest repellency rates toward essential oils of *Camphora officinarum* (82.8%), *Camellia sinensis* (78.3%), and *Allium sativum* (73.5%). Conversely, significant attractancy was observed for *Perilla frutescens* (-53.7%) and *Citrus × limon* (-43.6%). Sex-specific analysis revealed that males were most sensitive to *Myristica fragrans* (88.4%), while females showed strongest repellency toward *C. officinarum* (86.5%) and *A. sativum* (82.1%). Notably, *Cymbopogon citratus* (-43.3%) demonstrated potential for female-specific attraction. In fumigation assays, essential oils of *C. officinarum*, *C. sinensis*, and *A. sativum* achieved corrected mortalities exceeding 90% after 24 h at a concentration of 150 µL/L. Reducing the dosage by 25% compared to the 200 µL/L treatment resulted in less than a 10% decrease in efficacy, highlighting their high efficiency and cost-effectiveness. Antifeedant assays confirmed significant feeding deterrence across all three oils; *C. officinarum* oil exhibited the highest mean antifeedant rate (96.3%), whereas *A. sativum* oil displayed superior persistence, with a

minimal daily decline rate of 0.78%, significantly outperforming *C. sinensis* (3.8%). In conclusion, essential oils derived from *C. officinarum*, *C. sinensis*, and *A. sativum* possess potent repellent, fumigant, and antifeedant properties against *C. formicarius*. These findings suggest their candidacy as green pesticides for integrated pest management programs, providing technical support for eco-friendly cultivation and post-harvest pest control of sweet potato.

Keywords

Cylas formicarius; essential oils; repellency; fumigation; antifeedant activity

Introduction

The sweet potato weevil, *Cylas formicarius* (Coleoptera: Brentidae), is an insect pest of significant economic importance, inflicting damage throughout both the production and storage phases of sweet potato^[1]. In tropical regions, infestation by *C. formicarius* frequently leads to severe yield losses due to larval boring^[2]. The larvae bore into tubers to feed, creating black or brown tunnels within the flesh and inducing a bitter taste that renders the crop unmarketable^[3]. Adults inflict further damage by feeding on foliage, stems, and tubers, typically reducing yields by 5%–20%; however, losses can reach up to 100% in local Indonesian varieties^[4]. Consequently, this pest severely compromises sweet potato yield, quality, and commercial value.

Plant essential oils, as natural botanical extracts, exhibit multiple modes of action against pests, including contact toxicity, repellency, attraction, fumigation, antifeedant effects, and growth inhibition^[5]. These oils are characterized by broad-spectrum activity, multi-target mechanisms, a reduced likelihood of target organisms developing

70 resistance, favorable safety profiles for non-target organisms, environmental
71 friendliness, and biodegradability^[6–7]. Therefore, considering factors such as biosafety,
72 pest resistance management, target specificity, and environmental impact, the
73 application of plant essential oils for pest control aligns with the current developmental
74 paradigm of "green agriculture"^[8] and holds considerable promise for widespread
75 application.

76 Current research on essential oil-based control of *C. formicarius* largely remains
77 limited to the screening of single or small numbers of oils^[9–10]. There is a notable
78 absence of large-scale, horizontal screenings comparing diverse oils. Given that
79 essential oils derived from different families and genera exhibit compositional diversity,
80 variations in these phytochemical constituents likely result in distinct repellent
81 mechanisms. In this study, 50 widely sourced essential oils with diverse compositions
82 were evaluated. Using a Y-tube olfactometer, we assessed the repellent responses of *C.*
83 *formicarius* to identify oils with superior activity. This work aims to provide empirical
84 data to support the future development of essential oil-based active ingredients and
85 advance green control strategies against the sweet potato weevil.

86 **Materials and Methods**

87 **Test Insects**

88 Adult *C. formicarius* were collected from sweet potato fields within the campus
89 of Guangdong Ocean University. Upon collection, the weevils were transferred to the
90 laboratory and maintained in rearing cages (50 cm × 50 cm × 50 cm) at 25 ± 3 °C and
91 65 ± 5% relative humidity^[7]. The colony was continuously reared on fresh sweet potato

tubers for multiple generations prior to experimentation^[11].

Test EOs and Apparatus

A total of 50 plant-derived essential oils (EOs) were commercially purchased from three certified suppliers in China and stored at room temperature in the dark prior to use. Detailed supplier information is as follows:

Caiyuan Vegetable Oil Co., Ltd. (Ji'an, China): *Cupressus funebris* (Cedarwood), *Perilla frutescens* (Perilla), *Acorus calamus* (Calamus), *Artemisia argyi* (Mugwort), *Myristica fragrans* (Nutmeg), *Zingiber officinale* (Ginger), *Allium sativum* (Garlic), and *Piper nigrum* (Black Pepper).

Ji'an Huashuo Spice Co., Ltd. (Ji'an, China): *Camphora officinarum* (Camphor), *Eucalyptus robusta* (Eucalyptus), *Cymbopogon citratus* (Lemongrass), *Citrus × limon* (Lemon), *Camellia sinensis* (Tea tree), *Litsea cubeba* (May chang), *Mentha spicata* (Spearmint), *Cedrus deodara* (Cedarwood), *Cinnamomum cassia* (Cinnamon), *Rhodomyrtus tomentosa* (Myrtle), *Myrtus communis* (Myrtle), and *Melia azedarach* (Neem).

Ji'an Qingyuan District Haoyu Plant Spice Oil Co., Ltd. (Ji'an, China): *Artemisia caruifolia* (Sweet wormwood), *Citrus medica* (Bergamot), *Matricaria chamomilla* (Chamomile), *Citrus sinensis* (Sweet orange), *Gardenia jasminoides* (Gardenia), *Citrus × aurantium* (Grapefruit), *Jasminum sambac* (Jasmine), *Pogostemon cablin* (Patchouli), *Mentha canadensis* (Peppermint), *Origanum majorana* (Marjoram), *Thymus mongolicus* (Thyme), *Ligusticum sinense* (Szechuan lovage), *Commiphora myrrha* (Myrrh), *Citrus × aurantifolia* (Lime), *Keteleeria fortunei* (Juniper berry),

Pelargonium × *hortorum* (Geranium), *Eucalyptus globulus* (Blue gum), *Rosa chinensis* (Rose), *Rosmarinus officinalis* (Rosemary), *Yulania liliflora* (Magnolia flower), *Lavandula angustifolia* (Lavender), *Santalum album* (Sandalwood), *Platycladus orientalis* (Oriental arborvitae leaf), *Osmanthus fragrans* (Sweet osmanthus), *Cananga odorata* (Ylang-ylang), *Melaleuca cajuputi* (Cajeput), *Lonicera japonica* (Honeysuckle), *Xerochrysum bractatum* (Immortelle), and *Nelumbo nucifera* (Lotus).

All essential oils were commercially purchased standardized products; therefore, no voucher specimens were deposited in an herbarium. The authenticity of the plant species from which the oils were derived is certified by the respective suppliers, and the chemical composition of each oil was independently verified by GC-MS analysis (see Section 2.6).

A Y-tube olfactometer was obtained from Nanjing Snowley Bio-Tech Co., Ltd. (Nanjing, China). The test sweetpotato variety 'Pushu 32' was purchased from Shenzhen Xinlihe Technology Co., Ltd. (Shenzhen, China).

Response of *Cylas formicarius* to EOs

A Y-tube olfactometer was employed to assess the behavioral responses of *C. formicarius* to volatile compounds emitted from various EOs^[12–13]. By comparing the selective preferences of the weevils for different oil types, the correlation between olfactory preference and the insecticidal efficacy of these volatiles was determined^[14].

Prior to bioassays, adult weevils of each sex were segregated and starved in darkness for 24 h^[15]. One milliliter of essential oil was evenly applied onto filter paper placed inside the odor chambers. Filtered air was pumped through the system at a flow

rate of 300 mL/min per arm of the Y-tube^[16]. Twenty pre-conditioned weevils of a single sex were introduced into the base tube of the olfactometer. After a 30-minute observation period under dark conditions, the position of each insect was recorded. The response criteria were defined as follows: a positive choice was recorded if a weevil entered one of the Y-tube arms and remained there for at least 1 min; conversely, individuals that failed to make a choice or remained stationary after 30 min were classified as "no response." Each treatment was replicated three times. To eliminate residual odors, the olfactometer was thoroughly cleaned with 95% ethanol and dried with heated air between replicates. The selection rate and repellency rate were calculated according to formulas (1) and (2), respectively.

Formula (1): Selection Rate

$$\text{Selection rate (\%)} = \frac{\sum N_i}{N_t} \times 100\%$$

where $\sum N_i$ is the total number of tested insects recovered from the two collecting arms of the Y-tube olfactometer, and N_t is the total number of insects released (excluding "no response" individuals).

Formula (2): Repellency Rate

$$\text{Repellency Rate (\%)} = \frac{N_c}{\sum N_i} \times 100\%$$

where N_c is the number of insects recovered from the control (blank) arm (i.e., the arm paired with a blank filter paper only), and $\sum N_i$ is defined as in Formula (1).

Fumigant Activity Assay of EOs Against *Cylas formicarius*

A sealed jar fumigation assay was employed^[17]. Adult *C. formicarius* were collected and placed into 500 mL glass jars at a density of 10 individuals per jar. The

three essential oils exhibiting the highest repellency in Response of *C. formicarius*—*C. officinarum* (camphor), *C. sinensis* (tea tree), and *A. sativum* (garlic)—were diluted with acetone to final concentrations of 50, 100, 125, 150, and 200 $\mu\text{L/L}$ relative to the headspace volume (gas-phase space) of the jars. Subsequently, 25 μL of each dilution was pipetted onto the front end of a 2 cm $\times$ 10 cm filter paper strip. After allowing 30 s for complete acetone evaporation, the filter paper strip was placed inside the jar, which was then sealed tightly with a glass lid. Acetone alone served as the blank control. Mortality of the weevils was recorded at 1, 2, 4, 6, 8, 12, and 24 h post-treatment. Each treatment was replicated five times^[18–19]. The corrected mortality was calculated according to Formula (3).

$$\text{Corrected mortality (\%)} = \frac{N_{d,t} - N_{d,c}}{N_{t,t}} \times 100\%$$

where $N_{d,t}$ is the number of dead weevils in the essential oil-treated groups, $N_{d,c}$ is the number of dead weevils in the acetone blank control group, and $N_{t,t}$ is the total number of weevils initially placed in each treated jar.

Antifeedant Activity Assay of EOs Against *Cylas formicarius*

The three EOs exhibiting the highest repellency in response of *C. formicarius*—*C. officinarum* (camphor), *C. sinensis* (tea tree), and *A. sativum* (garlic)—were diluted with acetone to a final concentration of 100 $\mu\text{L/L}$, loaded into small handheld spray bottles, and evenly sprayed onto the surface of intact small sweet potato tubers.

For the choice assay, three tubers coated with the same EO were placed in three separate corners of a 50 cm $\times$ 50 cm $\times$ 50 cm rearing cage, while the remaining corner held tubers sprayed only with acetone as the blank control. For the non-choice assay,

three tubers coated with the same essential oil were placed in three separate corners of the cage, leaving the remaining corner empty(i.e., no food source provided). Additionally, a separate control cage was established, in which all three corners were occupied by tubers sprayed solely with acetone.

Ten *C. formicarius* adults that had been starved for 24 h in darkness were introduced into each cage. All cages were maintained under dark conditions, and the number of feeding punctures on the tubers was recorded at 1, 3, 5, and 7 d post-treatment. Each treatment was replicated three times. The choice and non-choice antifeedant rates were calculated according to Formulas (4) and (5), respectively [20–21].

Formula (4): Choice Antifeedant Rate

$$\text{Choice antifeedant rate (\%)} = \frac{N_{cc} - N_{ct}}{N_{cc}} \times 100\%$$

where N_{cc} is total feeding punctures on the acetone-treated control tuber in a single choice-assay cage, N_{ct} is total feeding punctures on the three same-type essential oil-treated tubers in the same cage.

Formula (5): Non-choice Antifeedant Rate

$$\text{Non-choice antifeedant rate (\%)} = \frac{N_{nc} - N_{nt}}{N_{nc}} \times 100\%$$

where N_{nc} is total feeding punctures on all acetone-treated control tubers across non-choice assay replicates (separate cages for controls), N_{nt} is total feeding punctures on all essential oil-treated tubers across non-choice assay replicates (separate cages for treatments).

GC-MS Analysis of the Three Selected EOs

The chemical composition of the three essential oils was analyzed using an Agilent

7000E triple quadrupole gas chromatograph-mass spectrometer (GC-QQQ-MS) equipped with an HP-5MS capillary column (30 m × 0.25 mm, 0.25 µm film thickness). High-purity helium was used as the carrier gas. The oven temperature was programmed from 50 °C to 250 °C, and samples were injected in splitless mode. Mass spectrometric detection was performed using an electron impact (EI) ionization source at 70 eV, with data acquired in full-scan mode over the mass range of m/z 50–550. Prior to analysis, samples were diluted 50-fold with n-hexane. Compound identification was achieved by matching mass spectra against the NIST 20 mass spectral library and confirmed using retention indices (RIs). The relative content of each constituent was calculated using the peak area normalization method (relative peak area, %_T) [22–24].

Data Analysis

Data were statistically processed and analyzed using Microsoft Excel. Statistical comparisons were performed using IBM SPSS Statistics 27, with significance determined via Duncan's multiple range test (DMRT). Visualization of the analytical results was conducted using GraphPad Prism 9 [25–27].

Results

Selection Responses of *Cylas formicarius* to EOs

Selection responses of *Cylas formicarius* to the 50 tested EOs were evaluated using a Y-tube olfactometer, with results summarized in Table 1. The data indicated that the selection rate exceeded 50% for all candidate oils. Excluding *M. azedarach* (neem), *R. tomentosa* (myrtle), and *C. sinensis* (tea tree), the remaining 47 essential oils all yielded selection rates above 75%. Notably, selection rates surpassed 95% for *A.*

224 *calamus* (calamus), *M. spicata* (spearmint), *T. mongolicus* (thyme), *L. japonica*
 225 (honeysuckle), and *C. sinensis* (sweet orange), identifying these five oils as the most
 226 potent modulators of selection behavior in *C. formicarius* among all tested samples.
 227 Additional observations revealed that these top-performing oils also exhibited high
 228 efficacy in terminating thanatosis (death-feigning behavior) in adult weevils.

229

230

231 **Table 1.** Selection responses of the *Cylas formicarius* to 50 EOs

Family	Essential oil	Number of selections	Selection rate
Cupressaceae	<i>Cupressus funebris</i>	100	83.33%
	<i>Platycladus orientalis</i>	111	92.50%
Acoraceae	<i>Acorus calamus</i>	119	99.17%
Lamiaceae	<i>Perilla frutescens</i>	99	82.50%
	<i>Mentha spicata</i>	114	95.00%
	<i>Mentha canadensis</i>	110	91.67%
	<i>Pogostemon cablin</i>	100	83.33%
	<i>Origanum majorana</i>	112	93.33%
	<i>Thymus mongolicus</i>	114	95.00%
	<i>Rosmarinus officinalis</i>	108	90.00%
Annonaceae	<i>Lavandula angustifolia</i>	111	92.50%
	<i>Cananga odorata</i>	109	90.83%
Burseraceae	<i>Commiphora myrrha</i>	101	84.17%

Poaceae	<i>Cymbopogon citratus</i>	101	84.17%
Piperaceae	<i>Piper nigrum</i>	109	90.83%
Zingiberaceae	<i>Zingiber officinale</i>	103	85.83%
Asteraceae	<i>Artemisia argyi</i>	90	75.00%
	<i>Artemisia caruifolia</i>	106	88.33%
	<i>Matricaria chamomilla</i>	109	90.83%
	<i>Xerochrysum bracteatum</i>	110	91.67%
Nelumbonaceae	<i>Nelumbo nucifera</i>	105	87.50%
Meliaceae	<i>Melia azedarach</i>	78	65.00%
Geraniaceae	<i>Pelargonium</i> × <i>hortorum</i>	89	74.17%
Magnoliaceae	<i>Yulania liliiflora</i>	104	86.67%
Oleaceae	<i>Jasminum sambac</i>	103	85.83%
	<i>Osmanthus fragrans</i>	110	91.67%
Rubiaceae	<i>Gardenia jasminoides</i>	113	94.17%
Rosaceae	<i>Rosa chinensis</i>	100	83.33%
Solanaceae	<i>Capsicum annuum</i>	109	90.83%
Caprifoliaceae	<i>Lonicera japonica</i>	115	95.83%
Myristicaceae	<i>Myristica fragrans</i>	101	84.17%
Apiaceae	<i>Ligusticum sinense</i>	105	87.50%
Theaceae	<i>Camellia sinensis</i>	83	69.17%
Amaryllidaceae	<i>Allium sativum</i>	113	94.17%
Pinaceae	<i>Cedrus deodara</i>	113	94.17%

	<i>Keteleeria fortunei</i>	98	81.67%
Santalaceae	<i>Santalum album</i>	118	98.33%
Myrtaceae	<i>Rhodomyrtus tomentosa</i>	81	67.50%
	<i>Myrtus communis</i>	99	82.50%
	<i>Eucalyptus robusta</i>	92	76.67%
	<i>Eucalyptus globulus</i>	97	80.83%
	<i>Melaleuca cajuputi</i>	107	89.17%
Rutaceae	<i>Citrus × limon</i>	97	80.83%
	<i>Citrus medica</i>	97	80.83%
	<i>Citrus sinensis</i>	117	97.50%
	<i>Citrus × aurantium</i>	98	81.67%
	<i>Citrus × aurantiifolia</i>	108	90.00%
Lauraceae	<i>Camphora officinarum</i>	93	77.50%
	<i>Cinnamomum cassia</i>	102	85.00%
	<i>Litsea cubeba</i>	106	88.33%

232

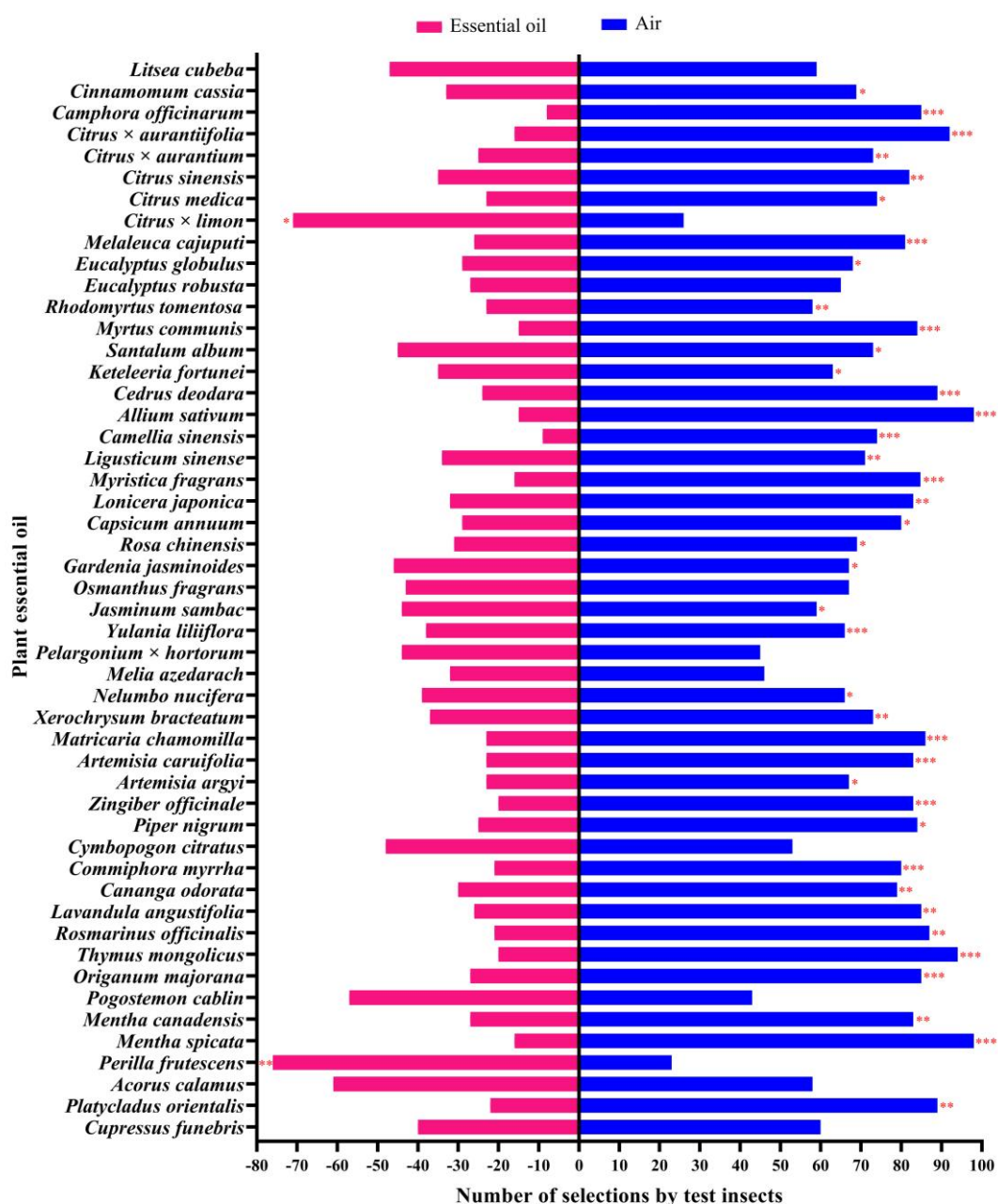
233 **Repellent Activity of EOs Against *Cylas formicarius***

234 Among *C. formicarius* adults that made a definitive choice (Figure 1), highly
235 significant repellency ($p < 0.01$) was observed toward EOs of *M. spicata* (spearmint),
236 *O. majorana* (marjoram), *T. mongolicus* (thyme), *C. myrrha* (myrrh), *Z. officinale*
237 (ginger), *A. caruifolia* (sweet wormwood), *M. chamomilla* (chamomile), *Y. liliiflora*
238 (magnolia flower), *M. fragrans* (nutmeg), *C. sinensis* (tea tree), *A. sativum* (garlic), *C.*

239 *deodara* (cedarwood), *R. tomentosa* (myrtle), *M. cajuputi* (cajeput), *C. ×*
 240 *aurantiifolia* (lime), and *C. officinarum* (camphor). Significant repellency ($0.01 \leq p <$
 241 0.05) was detected toward oils of *P. orientalis* (oriental arborvitae leaf), *M. canadensis*
 242 (peppermint), *R. officinalis* (rosemary), *L. angustifolia* (lavender), *C. odorata* (ylang-
 243 ylang), *X. bracteatum* (immortelle), *L. japonica* (honeysuckle), *L. sinense* (Szechuan
 244 lovage), *R. tomentosa* (myrtle), *C. sinensis* (sweet orange), and *C. × aurantium*
 245 (grapefruit). Marginally significant repellency ($0.05 \leq p < 0.1$) was recorded for oils
 246 of *P. nigrum* (black pepper), *A. argyi* (mugwort), *N. nucifera* (lotus), *J. sambac* (jasmine),
 247 *G. jasminoides* (gardenia), *R. chinensis* (rose), *C. annuum* (chili pepper), *K. fortune*
 248 (juniper berry), *S. album* (sandalwood), *E. globulus* (blue gum), *C. medicacv*
 249 (bergamot), and *C. cassia* (cinnamon).

250 Notably, *C. formicarius* was significantly attracted to *P. frutescens* (perilla)
 251 essential oil, and showed marginally significant attraction toward *C. × limon* (lemon)
 252 essential oil. No significant repellency or attraction was observed for oils of *C. funebris*
 253 (cedarwood), *A. calamus* (calamus), *P. cablin* (patchouli), *C. citratus* (lemongrass), *M.*
 254 *azedarach* (neem), *P. × hortorum* (geranium), *O. fragrans* (sweet osmanthus), *E.*
 255 *robusta* (eucalyptus), and *L. cubeba* (may chang). This lack of directional response was
 256 attributed either to excessive inter-replicate variance or to probabilities of selecting
 257 treated versus control arms approximating random choice.

258



259 **Figure 1.** Repellent behaviour of *C. formicarius* towards EOs

260 **Correlation Analysis of Repellency Rates of *Cylas formicarius* to EOs**

261 Analysis of repellency rate data for pooled-sex *C. formicarius* adults (Figure 2)

262 revealed that *C. officinarum* (camphor) exhibited the highest repellency activity, with a

263 mean repellency rate of 82.8% that differed significantly from those of all other tested

oils. Other oils with notably high repellency included *C. sinensis* (tea tree) (78.3%), *A. sativum* (garlic) (73.5%), *M. spicata* (spearmint) (71.8%), *C. × aurantiifolia* (lime) (70.2%), *M. fragrans* (nutmeg) (70.5%), and *M. communis* (myrtle) (69.7%). Notably, *C. sinensis*, *M. fragrans*, and *M. communis* achieved 100% repellency at maximum, warranting further investigation into their chemical composition and potential for practical development. In contrast, *P. frutescens* (Perilla) (-53.7%) and *C. × limon* (lemon) (-43.6%) exerted significant attractive effects on pooled-sex adults, with maximum attraction rates reaching 88% for both. These oils hold promise for use as attractant components in lure formulations, which could be combined with pheromones to improve trapping efficiency against *C. formicarius*.

Analysis of repellency rate data for male *C. formicarius* adults (Figure 3) showed that *M. fragrans* (nutmeg) had the most pronounced repellency activity, with a mean rate of 88.4%—distinct from *C. officinarum*, which exhibited the highest repellency in pooled-sex and female cohorts. Other oils with significant male-specific repellency included *C. sinensis* (tea tree) (87.9%), *M. spicata* (spearmint) (82.0%), and *C. officinarum* (camphor) (79.1%), with repellency rates comparable to those observed in pooled-sex trials. Furthermore, *P. nigrum* (black pepper) (77.7%) and *Z. officinale* (ginger) (74.4%) exhibited relatively stable inter-replicate data in male repellency assays, with standard deviations of 0.0124 and 0.0096, respectively. Based on these results, it can be inferred that male *C. formicarius* are more sensitive to these two essential oils.

Analysis of repellency rate data for female *C. formicarius* adults (Figure 4)

286 identified the most potent repellents as *C. officinarum* (camphor) (86.5%), *A. sativum*
287 (garlic) (82.1%), *P. orientalis* (oriental arborvitae leaf) (77.8%), *M. communis* (myrtle)
288 (69.7%), *M. canadensis* (peppermint) (69.4%), and *C. sinensis* (tea tree) (68.8%). Three
289 oils showed significant attractive activity toward females: *P. frutescens* (Perilla) (-
290 55.3%), *C. citratus* (lemongrass) (-43.3%), and *C. × limon* (lemon) (-42.6%), all with
291 maximum attraction rates exceeding 70%. Notably, *C. citratus* induced complete
292 attraction across all experimental replicates for females, a response pattern distinct from
293 that of males, which exhibited mixed attractive and repellent behaviors toward these
294 oils. This suggests *C. citratus* has potential for development as a female-specific
295 attractant essential oil. In addition, while the mean repellency rate of males to all 50
296 tested oils was 42.9%, the corresponding rate for females was only 35.2%, indicating
297 that female *C. formicarius* are less sensitive to essential oils and less prone to repellency
298 in their presence.

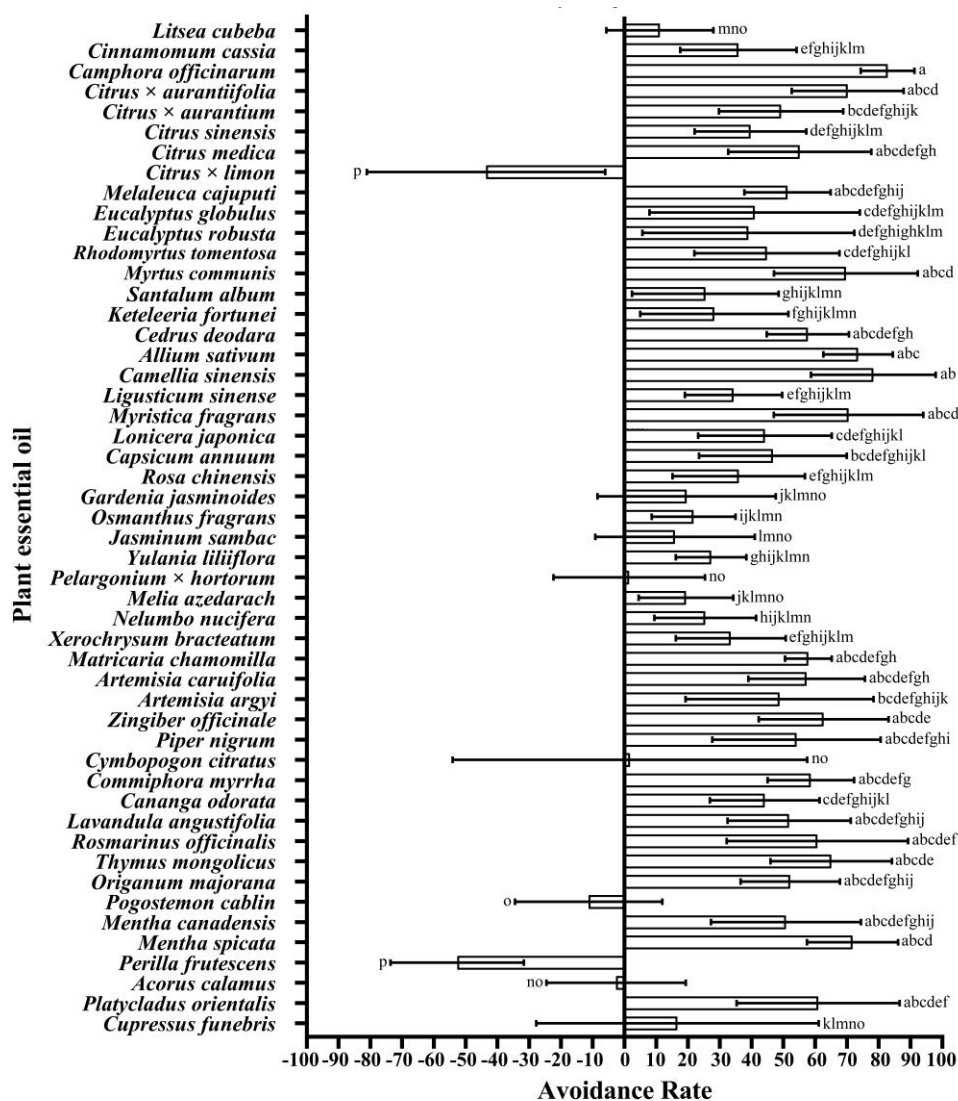


Figure 2. Total repellency of *C. formicarius* to EOs

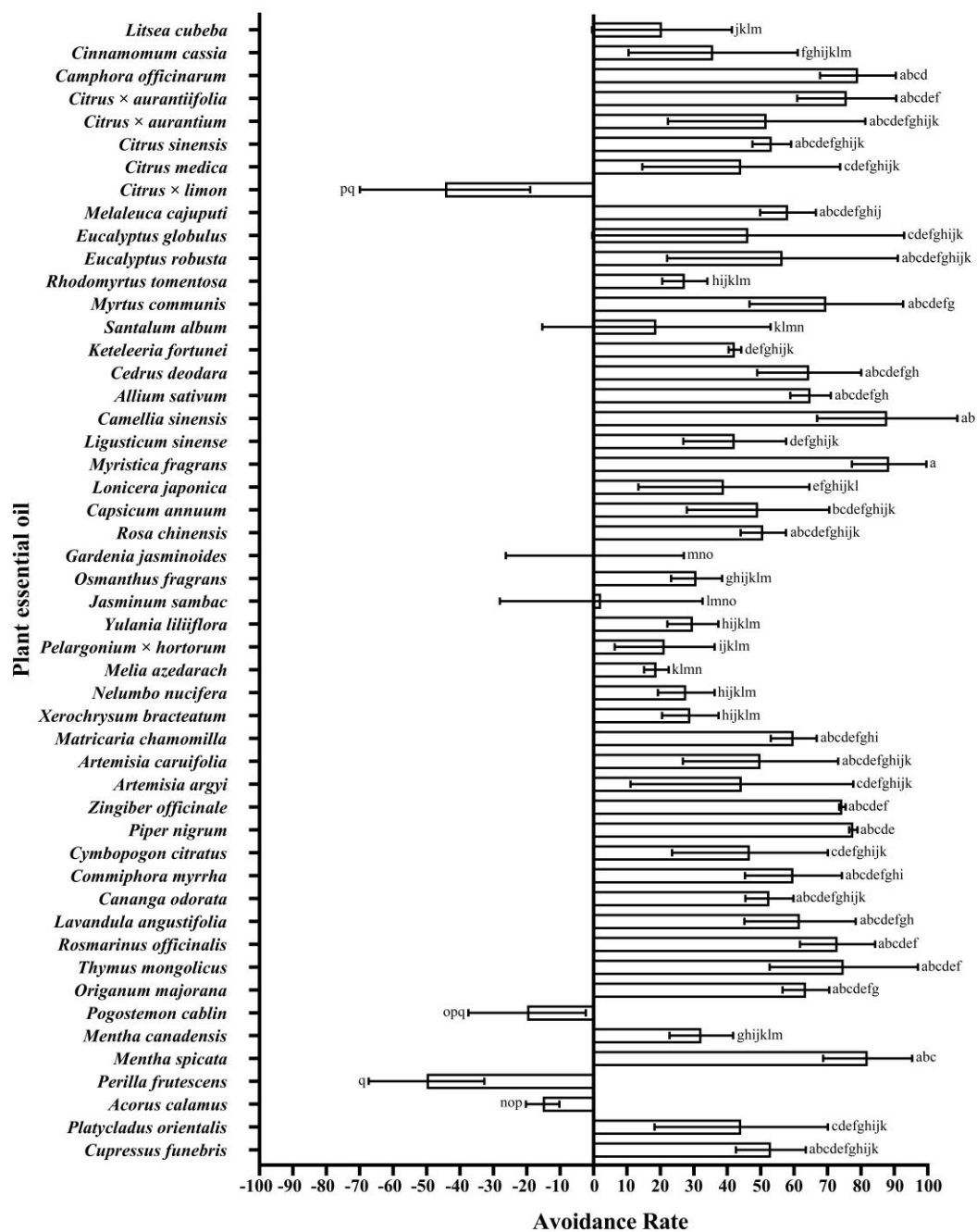


Figure 3. Repellency of male *C. formicarius* to EOs

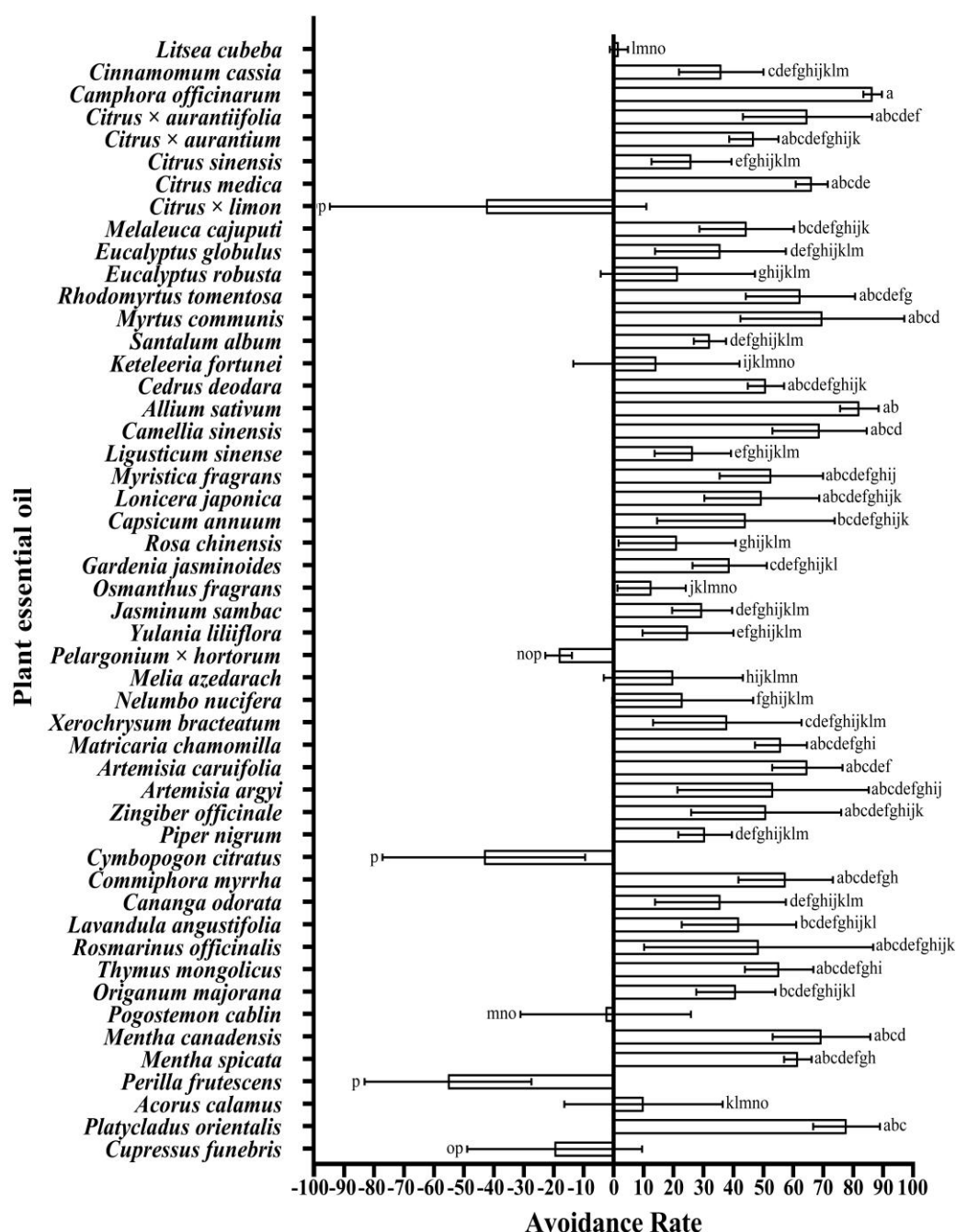


Figure 4. Repellency of female *C. formicarius* to EOs

Fumigant Activity of EOs Against *Cylas formicarius*

Fumigant efficacy assays of the three selected EOs revealed that all achieved 100% mortality of *C. formicarius* adults in sealed jars at a concentration of 200 μ L/L. *C. sinensis* (tea tree) oil (Figure 5A) required only 4 h of exposure to reach a mean

corrected mortality exceeding 90% at this concentration. *C. officinarum* (camphor) oil (Figure 5B) achieved the same 90% mortality benchmark after 6 h of exposure. In contrast, *A. sativum* (garlic) oil (Figure 5C) performed relatively poorly: even after 12 h of exposure at 200 $\mu\text{L/L}$, corrected mortality remained below 90%. Linear regression modeling predicted that 17 h of exposure would be required for *A. sativum* oil to reach 90% corrected mortality.

At a reduced concentration of 150 $\mu\text{L/L}$, all three oils achieved 24 h corrected mortality rates above 90%. This 25% dosage reduction relative to the 200 $\mu\text{L/L}$ treatment resulted in less than a 10% decrease in insecticidal efficacy: specifically, 24 h corrected mortalities for *C. sinensis* and *A. sativum* oils were 94% (a 6% reduction from the 200 $\mu\text{L/L}$ treatment), while that for *C. officinarum* oil reached 96% (only a 4% reduction). Thus, 150 $\mu\text{L/L}$ represents an optimal concentration balancing high insecticidal efficacy and cost-effectiveness, and is recommended for practical application in post-harvest warehouse fumigation targeting *C. formicarius*.

Data analysis revealed that the 24 h corrected mortality of *C. sinensis* and *C. officinarum* oils did not increase linearly across the three equidistant concentrations of 100, 125, and 150 $\mu\text{L/L}$. For *C. sinensis* oil, corrected mortality rose by 36 percentage points from 50% at 100 $\mu\text{L/L}$ to 86% at 125 $\mu\text{L/L}$, but increased by only 8 percentage points from 125 $\mu\text{L/L}$ (86%) to 150 $\mu\text{L/L}$ (94%). This suggests the existence of a fumigant efficacy threshold for *C. sinensis* oil between 100 and 125 $\mu\text{L/L}$. For *C. officinarum* oil, corrected mortality increased by 20 percentage points from 42% at 100 $\mu\text{L/L}$ to 62% at 125 $\mu\text{L/L}$, followed by a 34-percentage-point rise to 96% at 150 $\mu\text{L/L}$,

indicating a threshold concentration between 125 and 150 $\mu\text{L/L}$.

In contrast, *A. sativum* oil exhibited a strictly linear dose-response relationship with no observed efficacy threshold across the tested concentration range. Corrected mortality increased by 20 percentage points from 56% at 100 $\mu\text{L/L}$ to 76% at 125 $\mu\text{L/L}$, and by a further 18 percentage points to 94% at 150 $\mu\text{L/L}$, aligning precisely with the equidistant concentration gradient. This linear trend extended to lower concentrations: mortality rose by 42 percentage points from 14% at 50 $\mu\text{L/L}$ to 56% at 100 $\mu\text{L/L}$, and by 38 percentage points from 100 $\mu\text{L/L}$ to 150 $\mu\text{L/L}$. These results confirm a positive linear correlation between *A. sativum* oil concentration and fumigant-induced mortality.

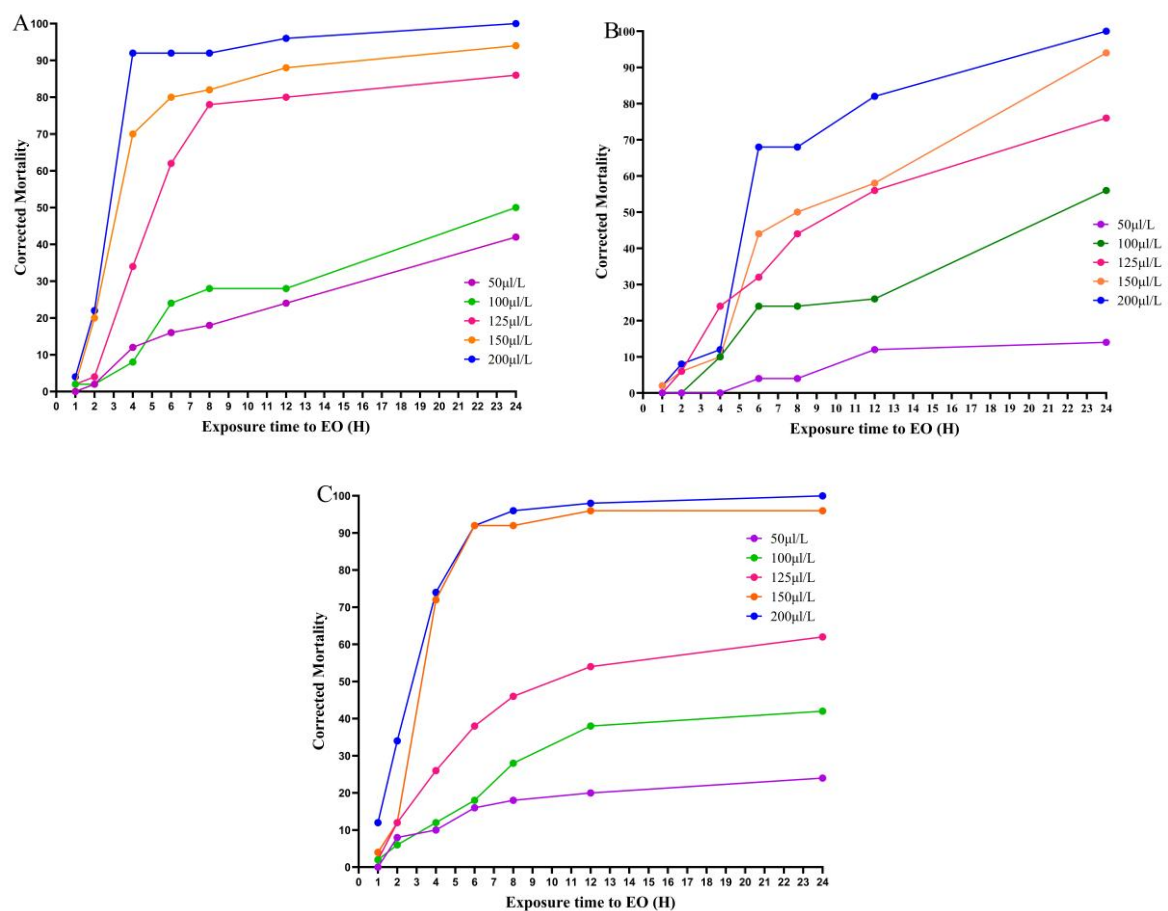


Figure 5. Corrected mortality of *C. formicarius* under EOs fumigation over time.

Note: A: *C. sinensis* EO; B: *C. officinarum* EO; C: *A. sativum* EO.

Antifeedant Activity of EOs Against *Cylas formicarius*

Results showed that both the choice and non-choice antifeedant rates of *C. formicarius* toward sweet potato tubers coated with the three tested essential oils exceeded 80%, confirming the potent overall antifeedant efficacy of all three oils against the pest.

For non-choice assays, significant differences in antifeedant rates were detected between each treatment group and the blank control, whereas no significant inter-treatment differences were observed (Figure 6A). Trend analysis of the non-choice antifeedant rate curves (Figure 6B) revealed that *A. sativum* (garlic) oil exhibited a marginally positive slope ($k = 0.0023$) over time; overall goodness-of-fit analysis ($R^2 = 0.0259$) confirmed its sustained antifeedant activity, with no significant decline over the 7-day experimental period, representing the optimal non-choice performance among the three tested oils. Both *C. sinensis* (tea tree) and *C. officinarum* (camphor) oils showed a slow, progressive decline in non-choice antifeedant rates over time, with comparable declining slopes; the mean non-choice antifeedant rate of *C. officinarum* oil was 3.3 percentage points higher than that of *C. sinensis* oil.

For choice assays, significant differences in antifeedant rates were detected between each treatment group and the blank control across all sampling dates, except for day 3, when no significant inter-treatment differences were observed (Figure 6C). Trend analysis of the choice antifeedant rate curves (Figure 6D) showed that all three oils exhibited a declining trend in choice antifeedant rates over time. *C. sinensis* oil had the steepest daily decline, with an average reduction of 3.8 percentage points per day,

whereas *A. sativum* oil showed the gentlest slope, with a mere 0.78 percentage point daily decrease. Among the three oils, *C. officinarum* oil delivered the best performance in choice assays, with a mean choice antifeedant rate of 96.3%.

In summary, all three essential oils exhibited high overall antifeedant efficacy against *C. formicarius*. *A. sativum* oil provided the most durable antifeedant activity, while *C. officinarum* oil achieved the highest overall antifeedant rate. These two oils show strong potential for development into post-harvest anti-pest sprays for direct application on sweet potato tuber surfaces.

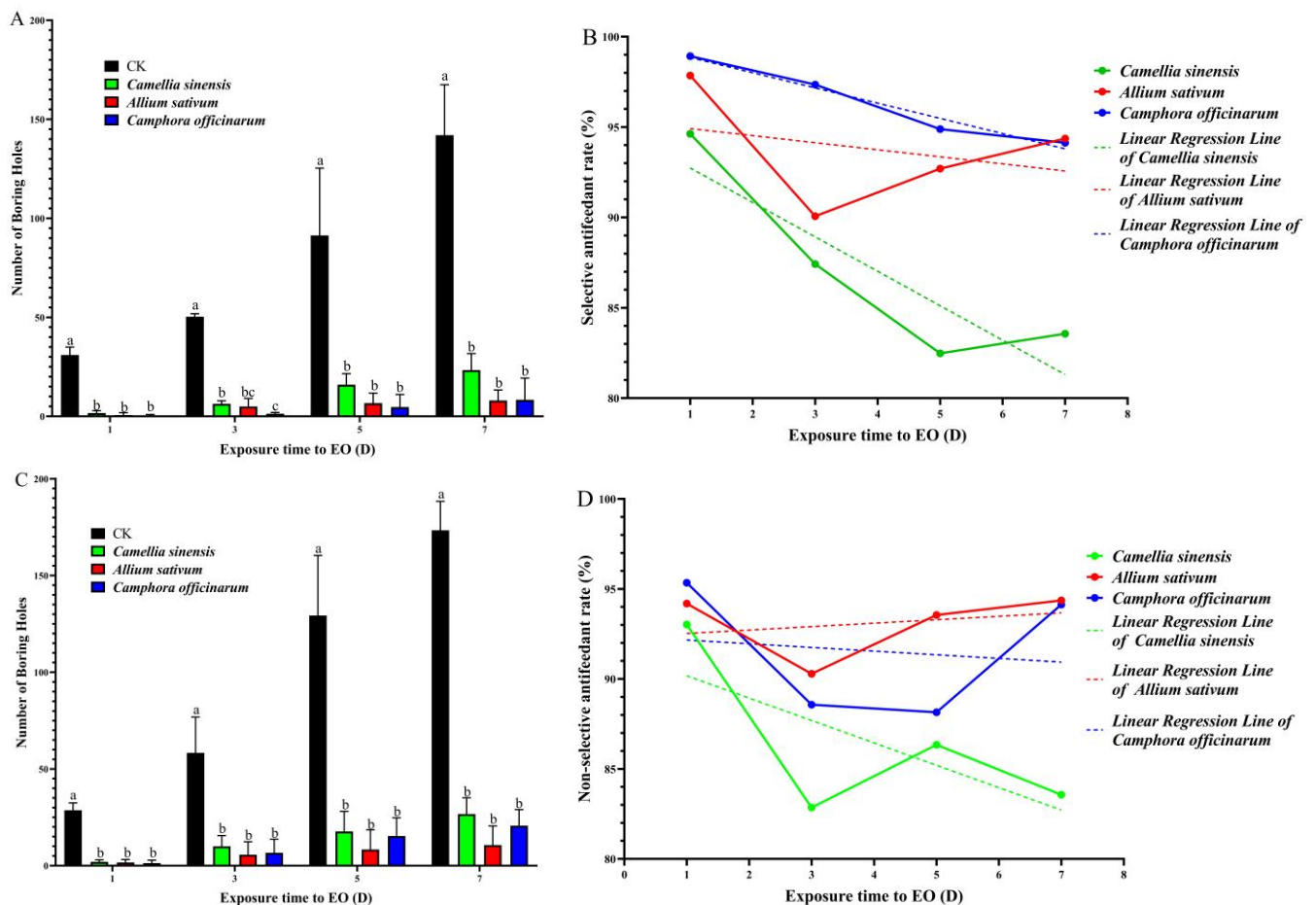


Figure 6. Antifeedant activity of *C. formicarius* towards EOs under choice and non-choice assays.

Note: A: Choice antifeedant number among different EOs; B: Choice antifeedant rate among different EOs; C: Non-choice antifeedant number among different EOs; D: Non-choice antifeedant rate among different EOs.

Chemical Composition of the Three Selected EOs

Gas chromatography-mass spectrometry (GC-MS) was employed to separate and identify the volatile constituents of *C. officinarum* (camphor), *A. sativum* (garlic), and *C. sinensis* (tea tree) EOs. The relative percentage content of each component was calculated using the peak area normalization method. The analytical results are summarized in Tables 2–4.

A total of 45 constituents were identified in *C. officinarum* EO, accounting for 99.99% of the total peak area. These compounds encompassed monoterpenes, monoterpenoid oxides, sesquiterpenes, and phenylpropanoids. The predominant constituents were (+)-2-Bornanone (23.92%, Fig.7A-1), alpha-Terpineol (15.86%, Fig.7A-2), Eucalyptol (13.11%, Fig.7A-3), and Safrole (10.07%, Fig.7A-4), which collectively represented 62.95% of the total content. Additionally, notable proportions of D-Limonene (4.10%), Linalool (3.08%), and 1,6,10-Dodecatrien-3-ol, 3,7,11-trimethyl-, (E)- (5.58%) were also detected.

The chemical profile of *A. sativum* EO was highly specific, with 12 identified constituents—all classified as sulfur-containing compounds—accounting for 99.99% of the total peak area. Trisulfide, di-2-propenyl (51.99%, Fig.7B-5) and Diallyl disulphide (31.18%, Fig.7B-6) were the most abundant components, together comprising 83.01% of the total content. The remaining constituents included

Tetrasulfide, di-2-propenyl (8.37%, Fig.7B-7), 1-Allyl-3-(2-(allylthio)propyl)trisulfane (2.18%), and Diallyl sulfide (2.08%).

In *C. sinensis* EO, 34 compounds were identified, representing 99.99% of the total chromatographic peak area. The main components were monoterpenes and their oxygenated derivatives. The five most abundant compounds were 3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-, (R)- (17.62%, Fig.7C-8), gamma-Terpinene (12.97%, Fig.7C-9), p-Cymene (9.65%, Fig.7C-10), (+)-4-Carene (9.22%, Fig.7C-11), and D-Limonene (8.86%, Fig.7C-12). These five constituents collectively accounted for 58.32% of the total content, forming the primary aromatic profile of the tea tree oil. Furthermore, oxygenated compounds such as Eucalyptol (4.33%) and trans-Ocimenol (7.66%) also contributed significantly to the overall chemical composition.

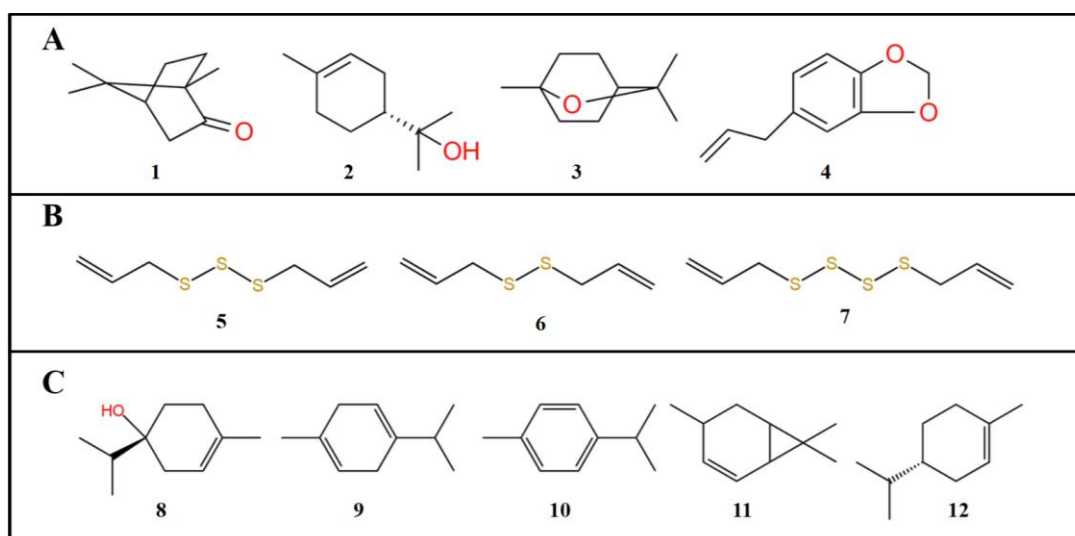


Figure 7. Chemical structures of the major constituents of the three screened EOs.

Panel arrangements correspond to the oil sources, showcasing the primary volatile frameworks identified by GC-MS analysis.

413 **Table 2.** Main chemical constituents of the *C. officinarum* EO identified by GC-
 414 MS

No	RT (min)	Compound name	CAS registry number	Relative content (%)
1	6.7553	.alpha.-Phellandrene	99-83-2	0.2
2	6.9371	(1R)-2,6,6-Trimethylbicyclo[3.1.1]hept-2-ene	7785-70-8	2.29
3	7.3435	Bicyclo[2.2.1]heptane,2,2-dimethyl-3-methylene-, (1S)-	5794-04-7	1.12
4	8.0503	.beta.-Phellandrene	555-10-2	1.91
5	8.1327	.beta.-Pinene	127-91-3	1.16
6	8.5567	Bicyclo[3.1.1]heptane,6,6-dimethyl-2-methylene-, (1S)-	18172-67-3	0.73
7	8.9360	.alpha.-Phellandrene	99-83-2	0.28
8	9.2931	1,3-Cyclohexadiene, 1-methyl-4-(1-methylethyl)-	99-86-5	0.3
9	9.5320	o-Cymene	527-84-4	1.19
10	9.6490	D-Limonene	5989-27-5	4.1
11	9.7138	Eucalyptol	470-82-6	13.11
12	10.5448	.gamma.-Terpinene	99-85-4	0.41
13	10.5524	Benzene, (2-methylpropyl)-	538-93-2	0.09
14	11.4173	Cyclohexene, 1-methyl-4-(1-methylethylidene)-	586-62-9	0.36
15	11.8851	Linalool	78-70-6	3.08
16	13.0752	(+)-2-Bornanone	464-49-3	23.92
17	13.9223	Cyclohexanemethanol,.alpha.,.alpha.-dimethyl-4-methylene-	7299-42-5	1.65
18	13.9230	1H-Imidazole, 2-ethyl-	1072-62-4	0.39
19	14.0935	3-Cyclohexen-1-ol,4-methyl-1-(1-methylethyl)-,(R)-	20126-76-5	2.4
20	14.5987	.alpha.-Terpineol	98-55-5	15.86
21	14.6878	2-Cyclohexen-1-one	930-68-7	0.05
22	17.1651	Safrole	94-59-7	10.07
23	17.6687	1,2-Ethanediol, monoacetate	542-59-6	0.06
24	17.6753	Triacetin	102-76-1	0.42
25	18.8534	Phenol, 2-ethoxy-	94-71-3	0.04
26	19.5127	.alpha.-Cubebene	17699-14-8	0.72
27	19.9324	Cyclohexane,1-ethenyl-1-methyl-2,4-bis(1-methylethenyl)-, [1S-(1.alpha.,2.beta.,4.beta.)]-	515-13-9	0.16
28	20.2231	Methyleugenol	93-15-2	0.16
29	20.6376	Tricyclo[2.2.1.0(2,6)]heptane,1,7-dimethyl-7-(4-methyl-3- pentenyl)-, (-)-	512-61-8	1.87
30	21.0193	cis-.alpha.-Bergamotene	18252-46-5	0.59
31	21.3244	Bicyclo[2.2.1]hept-2-ene, 2,3-dimethyl-	529-16-8	0.05
32	21.5191	Humulene	6753-98-6	0.39
33	21.6505	Bicyclo[2.2.1]heptane,2-methyl-3-methylene-2-(4-methyl-3- pentenyl)-, (1S-exo)-	511-59-1	0.64
34	22.1954	2-Phenylacetamide, N-(1-phenyl-2-propyl)-	1000223-70-1	0.21

35	22.8244	.beta.-Bisabolene	495-61-4	0.13
36	23.2053	Naphthalene,1,2,3,5,6,8a-hexahydro-4,7-dimethyl-1-(1-methylethyl)-, (1S-cis)-	483-76-1	0.62
37	24.3386	1,6,10-Dodecatrien-3-ol, 3,7,11-trimethyl-, (E)-	40716-66-3	5.58
38	25.3123	Cyclohexane, 1,1'-ethylidenebis-	2319-61-1	0.07
39	25.4117	1,4-Methanobenzocyclodecene, 1,2,3,4,4a,5,8,9,12,12a-decahydro-	74708-73-9	0.48
40	26.9973	Isopsoralen	523-50-2	0.19
41	27.6072	3-Methylbut-2-enoic acid, 4-nitrophenyl ester	1000307-59-8	0.19
42	29.2229	Propanoic acid, 2-methyl-, anhydride	97-72-3	0.28
43	29.2518	Octa-3,5-diene-2,7-dione, 4,5-dihydroxy-	1000266-61-0	0.32
44	29.2519	Docosane	629-97-0	1.74
45	29.9274	2-Propenoic acid, 2-methyl-, (tetrahydro-2-furanyl) methyl ester	2455-24-5	0.4

415

416 **Table 3.** Main chemical constituents of the *A. sativum* EO identified by GC-MS

No.	RT (min)	Compound name	CAS registry number	Relative content (%)
1	5.0630	Diallyl sulfide	592-88-1	2.08
2	7.5845	3H-1,2-Dithiole	288-26-6	0.76
3	7.5854	Nonanoic acid, 2-phenylethyl ester	57943-67-6	0.54
4	11.1544	Diallyl disulphide	2179-57-9	31.19
5	13.3175	4-Methyl-1,2,3-trithiolane	116664-29-0	1.82
6	15.0182	3-Vinyl-1,2-dithiacyclohex-5-ene	62488-53-3	0.72
7	17.4800	Trisulfide, di-2-propenyl	2050-87-5	51.99
8	23.6043	Tetrasulfide, di-2-propenyl	2444-49-7	8.37
9	24.6536	Disulfide, 1-(1-propenylthio)propyl propyl	143193-11-7	0.16
10	24.8859	3,5-Dihydroxy-2H-1,2,4-oxadiazine	1000214-68-3	0.18
11	28.5087	1-Allyl-3-(2-(allylthio)propyl)trisulfane	193625-59-1	2.18

417

418 **Table 4.** Main chemical constituents of the *C. sinensis* EO identified by GC-MS

No.	RT (min)	Compound name	CAS registry number	Relative content (%)
1	6.9485	(1R)-2,6,6-Trimethylbicyclo[3.1.1]hept-2-ene	7785-70-8	4.44
2	7.3576	Camphene	79-92-5	0.4
3	7.9125	Bicyclo[3.1.1]heptane,2,6,6-trimethyl-, (1.alpha.,2.beta.,5.alpha.)-	6876-13-7	0.28
4	8.1023	Cyclohexane, 1-methyl-4-(1-methylethyl)-, trans-	1678-82-6	0.15
5	8.1025	m-Menthane, (1S,3S)-(+)-	13837-67-7	0.13

6	8.2235	Bicyclo[3.1.1]heptane, 2,6,6-trimethyl-	473-55-2	0.36
7	8.3567	Cyclohexene, 3-methyl-6-(1-methylethyl)-	5256-65-5	0.32
8	8.5762	.beta.-Myrcene	123-35-3	0.15
9	8.7864	Cyclohexene, 3-methyl-6-(1-methylethyl)-	5256-65-5	0.19
10	8.9479	.alpha.-Phellandrene	99-83-2	0.84
11	9.1127	3-Carene	13466-78-9	1.18
12	9.1214	Decahydronaphtho[2,3-b]furan-2-one,3-[(4-methoxybenzylamino)methyl]-8a-methyl-5-methylene-	1010302-53-3	0.17
13	9.2600	7-Oxabicyclo[2.2.1]heptane,1-methyl-4-(1-methylethyl)-	470-67-7	2.51
14	9.3075	1,3-Cyclohexadiene, 1-methyl-4-(1-methylethyl)-	99-86-5	5.51
15	9.5457	p-Cymene	99-87-6	9.65
16	9.6631	D-Limonene	5989-27-5	8.86
17	9.6666	Cyclohexene, 4-methyl-1-(1-methylethyl)-, (R)-	619-52-3	2.66
18	9.7259	Eucalyptol	470-82-6	4.33
19	9.7290	2,5-Pyrrolidinedione,3-(1-aminoethylidene)-4-methyl-	58467-29-1	0.82
20	10.5591	.gamma.-Terpinene	99-85-4	12.97
21	10.5623	Glutaric acid, di(1-phenylethyl) ester	1000377-51-8	2.45
22	10.5659	2-Propanamine	75-31-0	0.09
23	11.4302	(+)-4-Carene	29050-33-7	9.22
24	11.4326	Butanenitrile, 2,3-bis(benzoyloxyimino)-	1000269-66-6	1.29
25	11.4675	Benzene, 4-ethenyl-1,2-dimethyl-	27831-13-6	0.22
26	14.0741	3-Cyclohexen-1-ol,4-methyl-1-(1-methylethyl)-, (R)-	20126-76-5	17.62
27	14.1614	2-Propenoic acid,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-pentadecafluorooctyl ester	307-98-2	0.06
28	14.5580	2-Propenamide	79-06-1	0.12
29	14.5724	trans-Ocimenol	7643-60-9	7.66
30	14.5730	5-Chlorovaleric acid, 4-isopropylphenyl ester	1000331-37-8	1.83
31	14.5796	Guanidine carbonate	593-85-1	1.04
32	14.5988	Ethane, (chloromethoxy)-	3188-13-4	1.39
33	14.6197	2H-Pyran-6-carboxamide, 2-oxo-	1010266-46-5	0.82
34	21.1596	1H-Cycloprop[e]azulene,decahydro-1,1,7-trimethyl-4-methylene-	72747-25-2	0.26

Discussion

In recent years, numerous studies have focused on the application of plant essential oils for pest control. For instance, Chantarapitak identified that *Syzygium aromaticum* and *Cinnamomum zeylanicum* essential oils exerted potent insecticidal toxicity against Termites^[28]; Gillij reported that *Baccharis spartioides*, *Rosmarinus officinalis*, and *Aloysia citriodora* essential oils exhibited significant repellency against *Aedes*

425 *aegypti*^[29]. In the present study, three essential oils with high repellency against *Cylas*
 426 *formicarius* were screened: *C. officinarum* (camphor), *C. sinensis* (tea tree), and *A.*
 427 *sativum* (garlic). Their core repellent mechanisms may be associated with olfactory
 428 interference effects mediated by specific volatile components^[30–31].

429 From the perspective of chemical composition, the GC-MS results of this study
 430 revealed that (+)-2-Bornanone (23.92%) and Eucalyptol (13.11%) were the
 431 predominant components in *C. officinarum* EO, collectively accounting for 36.03%. Fu
 432 et al^[32]. also confirmed that camphor and cineole were the dominant constituents of
 433 camphor EO (accounting for 36.61% and 30.05%, respectively), and the fumigant
 434 toxicity of this oil against minor workers of the red imported fire ant (*Solenopsis invicta*)
 435 was significantly higher than that against major workers^[33]. This indicates that both
 436 camphor and cineole, two monoterpenoid compounds, possess strong insecticidal
 437 activity, and their toxic effects on minor workers are superior to those on major workers.
 438 In the present study, *C. officinarum* EO exhibited the optimal repellency and antifeedant
 439 activities against *C. formicarius*, and this chemical basis likely originates from these
 440 two highly abundant active monoterpenes.

441 The primary insecticidal active component in *C. sinensis* EO is terpinen-4-ol (i.e.,
 442 3-Cyclohexen-1-ol,4-methyl-1-(1-methylethyl)-, (R)-, 17.62%). Using *Aedes aegypti*
 443 as a model, Chen et al^[34]. elucidated the molecular mechanism: the spatial repellency
 444 and oviposition deterrence against adults, as well as the repellency against larvae, of
 445 tea tree oil are all attributed to terpinen-4-ol. Furthermore, an antenna-biased odorant
 446 receptor, AaOr96, was identified, which interacts with terpinen-4-ol via van der Waals

forces involving five key residues. Knockout of AaOr96 significantly reduced the spatial repellency and oviposition deterrence of both tea tree oil and terpinen-4-ol against *Ae. aegypti*. This odorant receptor-level evidence provides a mechanistic explanation for the high repellency of tea tree oil against *C. formicarius* observed in this study.

A. sativum EO is a highly specific combination of sulfur-containing compounds, with diallyl trisulfide (51.99%) and diallyl disulfide (31.18%) as the main components, collectively accounting for 83.01%. Muturi et al^[35]. systematically evaluated the activity of garlic oil against the entire life cycle of *Culex pipiens Linnaeus*, finding that garlic oil exhibited broad-spectrum bioactivity against eggs, larvae, pupae, and adults. Among these, allyl disulfide significantly inhibited egg hatching, and the diallyl polysulfide mixture showed stronger insecticidal activity than a single sulfide. These studies collectively indicate that the high proportion of organic sulfides in garlic EO is the material basis for its strong fumigant and antifeedant activities.

In summary, the highly active components in the three EOs, such as (+)-2-Bornanone, terpinen-4-ol, and diallyl trisulfide, can be purified or used as formulation cores to develop green and efficient plant protection agents. With the intensification of synthetic pesticide resistance and environmental pollution, botanical pesticides based on plant EOs have become highly promising alternatives in integrated pest management (IPM) due to their rapid degradation and relative safety to non-target organisms. They hold high development value for post-harvest warehouse protection of sweetpotato and field repellency applications in the future.

Conclusion

This study revealed that *C. officinarum*, *C. sinensis*, and *A. sativum* EOs possess the potential to serve as stored-product insect repellents for managing *C. formicarius*. However, the specific active constituents responsible for the repellency have not been clearly identified and warrant further investigation. Additionally, this study only evaluated the laboratory efficacy of the 50 EOs against *C. formicarius*; their protective effects in actual storage settings and their safety to sweetpotato require further experimentation. Building upon these findings, the results of this study demonstrate that adult *C. formicarius* exhibit strong repellency toward *C. officinarum*, *C. sinensis*, and *A. sativum* EOs, highlighting their promising potential for development into targeted repellents for *C. formicarius* management.

Declarations

Abbreviations

CAS—Chemical Abstracts Service

EO—Essential oil

GC-MS—Gas Chromatography-Tandem Mass Spectrometry

GC-QQQ-MS—Gas Chromatography-Triple Quadrupole Mass Spectrometry

NIST—National Institute of Standards and Technology

RT—Retention Time

Ethics of approval and consent of participation

Not applicable.

Consent for publication

491 All authors consent for publication.

492 **Availability of data and materials**

493 All relevant data are included in the manuscript; further inquiries can be directed to the
494 corresponding authors.

495 **Competing interests**

496 The authors declare no competing interests.

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501 **Authors' contributions**

502 W.Z. wrote the main manuscript text. F.C., Z.W. (Zhiying Wu) and Q.Z. performed the
503 repellency, antifeedant, and fumigant bioassays, and collected the experimental data. S.Y. conducted
504 the statistical analysis and interpreted the results. X.L.prepared the essential oil samples and
505 provided technical support for the experiments. Z.W. (Zhengwei Wu) conceived and designed the
506 experiments, supervised the project, and reviewed and edited the manuscript. All authors reviewed
507 the manuscript.

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