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Sustainable pest management with citronella oil for eco-friendly control of *Aphis gossypii* in chili plants

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ABSTRACT

BACKGROUND AND OBJECTIVES: Chili is a key agricultural commodity in Indonesia, yet its productivity remains low, primarily due to pest and disease infestations. One of the most detrimental pests to chili plants is *Aphis gossypii*. While insecticides are effective in managing these pests, their environmental impact raises concern, making it essential to explore eco-friendly options. Citronella oil, a potential natural pesticide, warrants further investigation. This study was conducted in both laboratory and field settings. In the laboratory, the efficacy of citronella oil in controlling *Aphis gossypii* was assessed in terms of its toxicity and repellent effects. This study focused on analyzing the efficacy of citronella oil in regulating the populations of *Aphis gossypii* on chili plants.

METHODS: Laboratory and field experiments employed a Randomized Block Design. In the laboratory, citronella oil concentrations were tested against a control, and both mortality and repellent effects were monitored. In the field study, four treatments were implemented: the use of citronella oil, rotation with synthetic insecticides, and a control condition. The *Aphis gossypii* population was assessed weekly for a duration of ten weeks.

FINDINGS: The results revealed that citronella oil effectively reduced *Aphis gossypii* populations, demonstrating repellent (18.6 percent) and toxic (89.1 percent) effects. Citronella oil demonstrated a reduction in *Aphis gossypii* populations under field conditions, both when utilized on its own and when rotation with synthetic insecticides. At the end of the observation period, a single application of citronella oil resulted in a 91 percent reduction in *Aphis gossypii* populations. Citronella oil stands out as a sustainable and efficient method for controlling *Aphis gossypii*, making it a promising substitute for conventional insecticides in the management of pests affecting chili plants.

CONCLUSION: This study demonstrates that citronella oil effectively reduces *Aphis gossypii* infestations on chili plants by repelling and intoxicating the pests acting as a natural pesticide, citronella oil presents a safer alternative to synthetic chemicals, thereby decreasing environmental pollution and protecting beneficial organisms. Its integration into pest management strategies has the potential to promote sustainable agricultural practices. However, further research is needed to validate its effectiveness across different locations and assess its broader ecological impact.

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INTRODUCTION

Chili is a key agricultural commodity within Indonesia's horticulture subsector, playing a vital role in supporting the national economy, particularly through its contribution to increasing household income. The average chili production across the nation in 2022 was 7.2 tons per hectare, a figure that falls well short of the potential yield range of 15 to 20 tons per hectare (ha) (BPS, 2023). One of the main causes of this yield gap is the infestation of plant pests and diseases. The primary pests affecting chili plants are fruit flies (*Bactrocera s* Macquart (Diptera: Tephritidae) (Jamaluddin *et al.,* 2020), aphids (*Aphis gossypii* Glover (Hemiptera: Aphididae)) (Jamaluddin *et al.,* 2020) and silverleaf whitefly (*Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) (Saad *et al.,* 2017). *Aphis gossypii* is a pest and disease vector in chili plants (Cocuzza, 2024). The viruses transmitted by this insect are cucumber mosaic virus (CMV) and potato virus Y (PVY) (Thangjam *et al.,* 2023; Milonas *et al.,* 2023). Many farmers utilize synthetic chemical pesticides as their primary strategy for pest control (Agarwal and Verma, 2021), yet these substances are often used in ways that are misguided and. These inaccuracies span across factors such as dosage, concentration, application timing, and frequency, all of which lead to negative consequences, including the development of pest resistance (Özkara *et al.,* 2016; Siddiqui *et al.,* 2023), loss of beneficial insects (Siviter and Muth, 2020), environmental pollution and health problems (Pathak *et al.,* 2022). As resistance develops, there is a corresponding rise in the amount of insecticide used, since the recommended levels no longer succeed in controlling pests (Sarwar and Salman, 2015). Since synthetic insecticides are the main approach for managing Aphis gossypii in chili plants, it is essential to mitigate the adverse effects linked to their regular application. Efforts should focus on minimizing synthetic insecticide applications. This goal can be accomplished by implementing cutting-edge research methods to create a comprehensive insecticide application model that merges synthetic pesticides with plant-based alternatives (Wiratno *et al.,* 2025). The key component of this model is the use of citronella oil as a botanical pesticide, which aims to reduce reliance on synthetic chemicals while maintaining effective pest control. Citronella oil was chosen as a botanical pesticide due to previous studies showing that essential oils, including citronella, have harmful effects on insect pests (Istianto and Emilda, 2021); (Wicaksono *et al.,* 2023). Citronella oil in suppressing pest populations, functions as an insecticide (Saad *et al.,* 2017) egg-laying inhibitor, anti-feedant (Saleh *et al.,* 2023), and insect repellent (Saad *et al.,* 2017; Fouda *et al.,* 2017). The results of this study are anticipated to create avenues for the integration of plant-based materials into pest management strategies, thereby fostering more environmentally sustainable control practices. This study was carried out in both laboratory and field settings. In the laboratory, the efficacy of citronella oil in controlling *Aphis gossypii* was assessed in terms of its toxicity and repellent effects at Brawijaya University in Malang, East Java, Indonesia. The objective of this research was to assess the effectiveness of citronella oil in managing *A. gossypii* on chili plants while decreasing dependence on chemical pesticides. In Indonesia, the application of citronella oil as a botanical pesticide remains limited. Therefore, assessing its effectiveness and mode of action against this pest is essential. This study has been carried out in Tlekung Village, Batu City, Indonesia in 2023.

MATERIALS AND METHODS

Location and Time

Field research was conducted on chili plantations located on farmers' land in Tlekung Village, Batu City, 950 meters above sea level (masl) 7°54'19.5" south (S), 112°32'07.6" east (E) (Fig. 1). The climate conditions of Batu City include an average relative humidity of 77%, an average temperature of 24 degrees Celsius (°C), and average rainfall of 170 cubic meters (mm^3). The soil type in this area is andosol.

Analysis of compounds contained in citronella oil

For the testing, the citronella oil was procured from a supplier based in in Batusangkar, West Sumatra. Gas chromatography–mass spectrometry (GC-MS) analysis of the essential oil was conducted using a Shimadzu GC-2010 Plus gas chromatograph at the Instrumentation Laboratory of the Chemistry Department, FMIPA, Brawijaya University, Malang, East Java. The analysis was performed over a 50-minute period. A TG-5MS capillary column as 30 meters (m) length, 0.2 millimeters (mm) inner diameter, 0.25 micrometers (µm) film thickness, was used. A total of 2 microliters (µL) of the essential oil was injected into the GC apparatus.

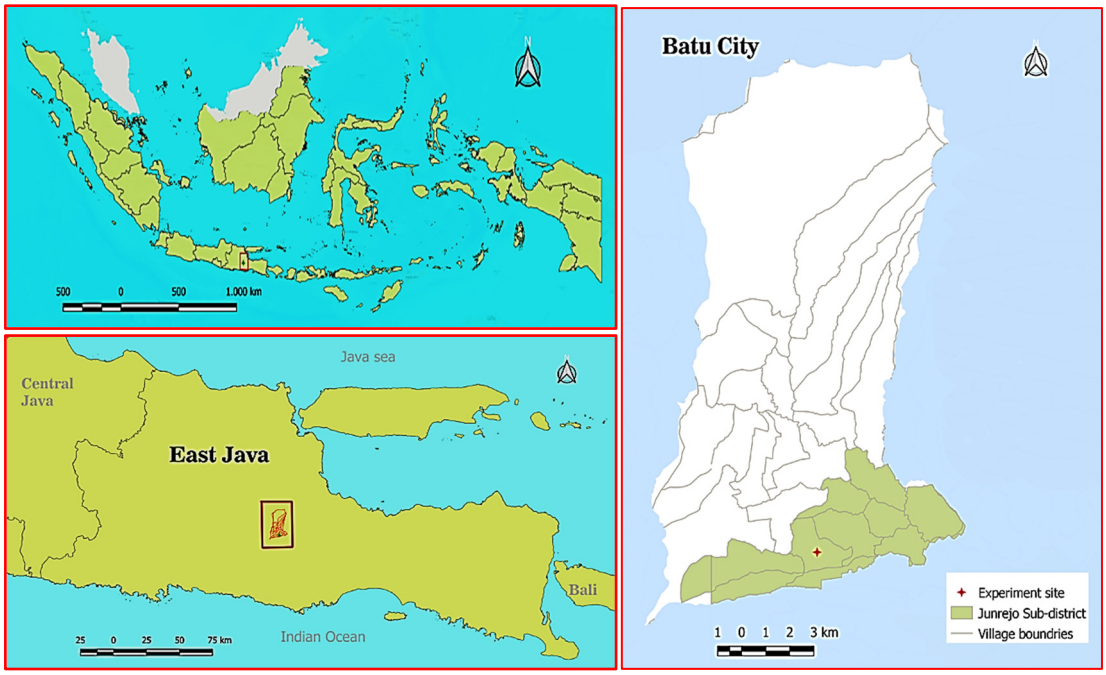

Fig. 1: Geographical location of the study area in the Brawijaya University in Malang, Indonesia

Laboratory study

The objective of the laboratory study was to assess how effective citronella oil is in managing *A. gossypii*. This study concentrated on analyzing the toxic and repellent characteristics of citronella oil, identifying them as the primary methods of combating this insect.

Tests on citronella oils toxicity against A. gossypii

In this test, the applied treatments were concentrations of pure citronella oil of (a) 1 milliliter per liter (mL/L), (b) 2 mL/L, (c) 3 mL/L, (d) positive control (abamectin insecticide), and (e) negative control (water, emulsifier). To improve the oil's dissolution in the water, an emulsifier was introduced at a concentration of 1 mL/L. Each treatment was repeated six times. A randomized block design (RBD) was applied, with treatment time serving as the block or replication. The population of *Aphis gossypii* per sample unit was set at 20 individuals. The study began by collecting shoot clusters or young leaves of chili, which were then hand-sprayed with a 3 milliliters (mL) treatment solution. Once the leaves had been sprayed, they were allowed to dry and then transferred into 2 mL glass bottles containing water, making sure that the leafstalks were immersed. To ensure the leaves remained fresh, a soaking procedure was carried out. The glass bottles with the leaves were then placed into 100 mL plastic vials for additional examination. The leaves function as food for *A. gossypii* (Nindatu *et al.,* 2018). A total of 20 *A. gossypii* imagoes were placed into each plastic vial, which were then sealed with ventilated lids covered in gauze. The vials were equipped with a layer of filter paper at the bottom, which was saturated with the treatment solution based on the test concentration. This setup ensured that the pests maintained contact with the test material even when they were not on the leaves. The setup for the toxicity test is illustrated in Fig. 2. Observations were made on the number of insect individuals that died at the following time intervals: 1, 2, 3, 6, 12, 24, and 48 hours (h) post-application.

The mortality percentage of the *A. gossypii* was calculated using Eq. 1 (Hidayati *et al.,* 2013):

$$Po = a/b \times 100\% \quad (1)$$

Where,

Po= mortality percentage; a = number of dead *A. gossypii*; b = number of *A. gossypii* in the treatment

If mortality occurs in the control group, the

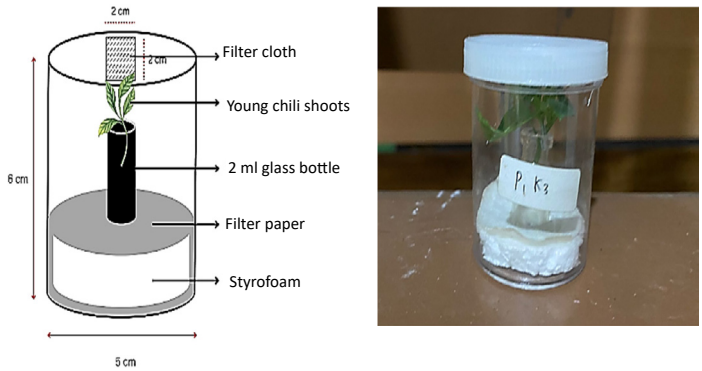

Fig. 2: Container for toxicity test

mortality percentage must be corrected. If the mortality in the control exceeds 20%, the test must be repeated (Matsumura, 2012). The corrected mortality percentage is calculated using Eq. 2 (Abbott, 1925):

$$E = C\text{-}T/C \times 100\% \quad (2)$$

Where,
E= mortality percentage; C= Quantity of insects that survived under the control; T= quantity of insects that survived the treatment.

Tests of citronella oils repellence against A. gossypii

The repellence test used the Petri Dish Olfactometer (Ikawati *et al.,* 2017). The olfactometer was modified by using 9 centimeters (cm) diameter Petri dishes, each with two vials attached to the bottom. Two holes, each measuring 2.5 cm in diameter to correspond with the size of the vials, were created in the Petri dishes. The holes were spaced approximately 3 cm apart, with the distance from the bottle hole to the rim of the dish being 1 cm. The vials, made of plastic, had a height of 3.5 cm. The Petri dish lids were altered to include a 2 cm diameter opening, which was covered with gauze to ensure that the insects could not escape. This configuration is depicted in Fig. 3.

This study began by selecting two clusters of chili shoots or young leaves. One cluster was treated with a solution of citronella oil, which included water, essential oil, and an emulsifier, while the other cluster received only water as a control treatment. The citronella oil concentrations tested were 1 mL/L, 2 mL/L, and 3 mL/L. The experimental design was a randomized block design, with treatment time serving as the block or replication. Each treatment was repeated seven times. After being sprayed, the clusters were air-dried for three minutes before being placed into separate vials. These vials were then affixed to the bottoms of Petri dishes. For each iteration, 20 adult *A. gossypii* were placed in the center of the Petri dishes, and the dishes were sealed. The number of *A. gossypii* adults entering vials with either citronella oil-treated or control clusters of shoots or young leaves was recorded at1, 2, and 3 hours post-application. In the repellence test, the number of *A. gossypii* entering the treated vials was compared to the number entering the control vials, using Eq. 3 (Pascual-Villalobos and Robledo's (1998):

$$R.I. = (C-T/C+T) \times 100 \quad (3)$$

Where,
RI: repellence index (%); C: quantity of insects in the control; T: quantity of insects in the treatment

In assessing the repellency properties, Pascual-Villalobos and Robledo (1998) stated that positive IR values indicate repellent properties, while negative IR values suggest attractant properties. The assessment of repellency is conducted according to the criteria presented in Table 1.

The data obtained were analyzed using analysis of variance (ANOVA) with Minitab 17. When substantial differences were identified among treatments, post hoc comparisons were performed using the Tukey test. A treatment difference was considered statistically significant when the p-value was 0.05 or lower

Field study

The purpose of the field study was to evaluate the

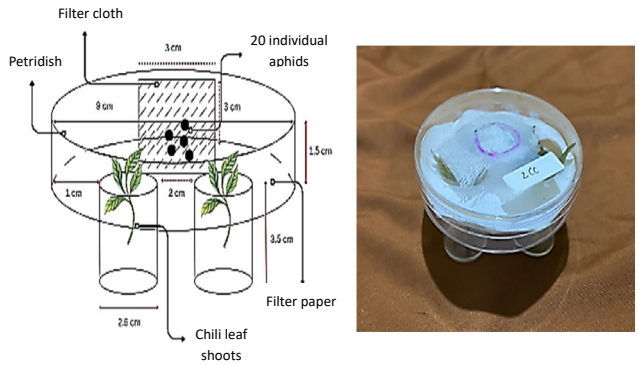

Fig. 3: Container for repellence test of *A. gossypii*

Table 1: Repellence level criteria

Repellence class	Repellence level	Repellence index (%)
0	Weak	<0.1
I	Moderately weak	0.1-20
II	Medium	20.1-40
III	Moderately strong	40.1 -60
IV	Strong	60.1-80
V	Very strong	80.1-100

effectiveness of a rotation pattern using citronella oil and synthetic insecticides in controlling *Aphis gossypii* on chili plants. The interventions were as follows: (a) a weekly application of citronella oil, (b) a weekly rotation between citronella oil and synthetic insecticides, (c) a weekly application of synthetic insecticides, and (d) a control group that received no treatment. The first application of treatments was conducted one week after planting. A randomized block design was used as the experimental design. The concentration of citronella oil was set at 2 mL/L, based on findings from previous studies (Istianto and Emilda, 2021). Pure citronella oil was used, and an emulsifier (Alkylaryl polyglycol ether, 400 grams per liter (g/L) active ingredient) was added to ensure proper dissolution in water, with a concentration of 1 mL/L of water. Abamectin, a synthetic pesticide, was employed at a dosage of 1 mL/L of active ingredient. Each treatment was replicated four times. Over a span of ten weeks, weekly evaluations of the *A. gossypii* population on each chili plant were performed. These evaluations were conducted the day before pesticide treatments were applied.

RESULTS AND DISCUSSION

This study points out that the field experiments, which were performed in one region with specific climate conditions and for a limited time, might not completely represent long-term and seasonal fluctuations. Thus, it is important to implement trials in various locations and across different seasons to ensure broader validation.

Compounds present in the scented oil of citronella oil

GC-MS analysis identified several bioactive compounds in citronella oil. The main compounds contained in citronella oil were alpha terpinolene, citronella, citronellyl acetate, Cyclohexane, 1-ethenyl-1-methyl-2,4-bis(1-methylethenyl)-, Cyclohexene, 1-methyl-4-(1-methylethenyl), E-citral, geranyl acetate, germacrene D, trans-caryophyllene, and Z-citral The analysis's findings are displayed in Fig. 4 and Table 2. The insecticidal and repellent characteristics of citronella oil are attributed to these compounds. Previous studies have confirmed that citronellal and citronellol disrupt insect nervous systems, leading to paralysis and mortality (Ken *et al.,* 2005). On a molecular level, the bioactive substances found in citronella oil hinder neurotransmission and metabolic activities, which results in diminished feeding behavior and eventual mortality in insect pest (Chaudhari *et al.,* 2021). Additionally, geranyl

acetate has been shown to interfere with insect respiration and feeding behavior (Angelica *et al.,* 2020). Compared to many synthetic pesticides, citronella oil has a lower toxicity level for beneficial insects. Nonetheless, more comparative studies involving other natural products are required to thoroughly understand its selectivity and ecological consequences (Nerio *et al.,* 2010). The presence of these compounds highlights citronella oil's potential as a natural pesticide with multiple modes of action. Citronella oil's effectiveness as a repellent and its toxic characteristics stem from several key bioactive compounds, including citronellal, citronellol, geranyl acetate, and limonene. These substances interfere with neural signaling and olfactory perception in *Aphis gossypii* (Popescu *et al.,* 2024). The dual repellent and insecticidal actions of citronella oil effectively reduce pest populations and may offer long-term benefits by delaying resistance development, thereby supporting sustainable pest management (Rattan, 2000). Prolonged and repeated use of citronella oil could impact the health of chili plants, the composition of soil microbial communities, and non-target organisms. Therefore, additional multi-season research is required to assess any potential phytotoxic and ecological consequences (Lahlali *et al.,* 2022). The findings of this study demonstrate that citronella oil has a detrimental effect on *Aphis gossypii*, both killing and repelling the pests, thereby reducing their population in the field. This observation aligns with previous studies that have shown citronella oil's efficacy in causing mortality in other pests, such as *Aedes aegypti*. These reliable results underscore the potential of citronella oil as an effective agent for pest management, specifically targeting (Cansian *et al.,* 2023; Cansian, 2021), *Oryzaephilus surinamensis* (Gharsan *et al.,* 2022) and *Spodoptera frugiperda* (Saleh *et al.,* 2023). Likewise, the repellent properties

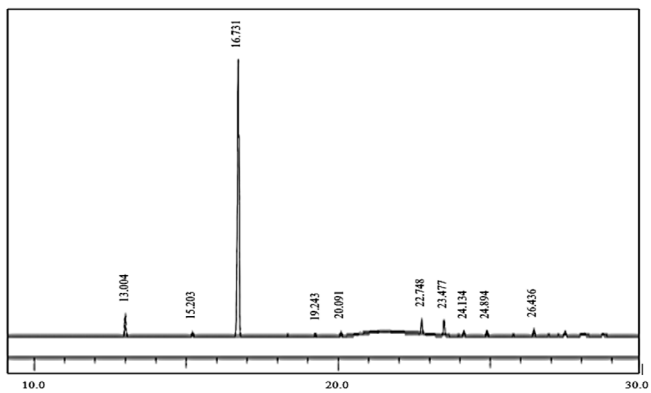

Fig. 4: Results of compound identification analysis in citronella oil using GC-MS

Table 2: The substances found in citronella oil

No.	Substances	R. Time	m/z	Area	Height	Conc.	UnitR	Index
1	Alpha terpinolene	15.203	43.00	80550	20613	0.582	%	0
2	Citronella	16.731	41.00	11934500	2967389	86.206	%	0
3	Citronellyl acetate	22.748	43.00	316898	102373	2.289	%	0
4	Cyclohexane, 1-ethenyl-1-methyl-2,4-bis(1-methylethenyl)-	24.134	41.00	42581	15675	0.308	%	0
5	Cyclohexene, 1-methyl-4-(1-methylethenyl)-	13.004	68.00	538175	181666	3.887	%	0
6	E-Citral	20.091	41.00	171085	52632	1.236	%	0
7	Geranyl acetate	23.477	69.00	462168	145319	3.338	%	0
8	Germacrene D	26.436	41.00	104461	29957	0.755	%	0
9	trans-Caryophyllene	24.894	41.00	107077	33742	0.773	%	0
10	Z-Citral	19.243	41.00	86637	27960	0.626	%	0

of citronella oil were also seen when it was tested on other pests such as *Bemisia tabaci* (Saad *et al.,* 2017), *Ceratitis* capitata (Gonzaga *et al.,* 2023) and Arthropoda (Lee, 2018).

Population dynamics of A. gossypii in the treatments of citronella oil and insecticide application

Findings from the study reveal that the application of citronella oil, either alone or in conjunction with synthetic insecticides on a weekly schedule, significantly reduces the Aphis gossypii population more effectively than the control group that received no treatment. The control treatment was included to monitor the natural presence and population dynamics of the pest in the absence of any control measures. Each treatment demonstrates varying levels of effectiveness in controlling the population of *Aphis gossypii*. Under field conditions, citronella oil deteriorates fairly quickly, making it essential to reapply it on a weekly basis to ensure ongoing effectiveness in pest management (Isman, 2006). Table 3 presents the results of ANOVA, which was conducted to assess the efficacy of each treatment in reducing the insect population.

In the second week of observation, following two applications, a marked difference was noted in the ability of the sole citronella oil treatment (P4) to suppress the *A. gossypii* population compared to the control group. This contrasts with other treatments, where a noticeable reduction in pest numbers compared to the control was achieved in the fifth week for the P2 treatment and in the third week for the K+ treatment. In subsequent weeks, the pesticide application treatments (P2, P4, and K+) continued to effectively suppress the pest population until the tenth week. Trials conducted in the field revealed that citronella oil significantly controls the populations of *A. gossypii*. The sole application of citronella oil (P4) led to a 91% reduction in aphid populations by the tenth week, comparable to the synthetic insecticide treatment (K+). This aligns with findings from Saad *et al.* (2017), who reported significant pest reduction when citronella oil was applied to whitefly populations. The treatment that combined citronella oil with synthetic insecticides (P2) showed superior effectiveness in lowering aphid populations compared to using synthetic insecticides by themselves. The data indicate that the integration of citronella oil into IPM can enhance crop yield and quality by reducing pest-related damage, though additional comparative analyses are necessary (Istianto and Emilda, 2021). Early analyses of synergy reveal that citronella oil can be effectively paired with other botanical pesticides and biological control agents, which may enhance pest management efforts and lessen the reliance on synthetic chemical solutions (Dassanayake *et al.,* 2021). This suggests that integrating citronella oil into pest management programs can enhance overall control while potentially reducing chemical pesticide use and associated environmental risks. By merging citronella oil with synthetic insecticides, the effectiveness of pest control is heightened through the integration of complementary action modes, which also helps to lower the selection pressure that can lead to resistance in insect pest (Isman, 2006). Overall, the sole citronella oil application (P4) is quite effective in suppressing the population of *A. gossypii*. The capacity to prevent *A. gossypii* population growth was comparable to that of synthetic insecticides (K+). The same pattern also occurred in the by-turn application of synthetic insecticides and citronella oil (P2). At the last observation showed that sole citronella application (P4) could decrease 91% population of *A. gossypii* when it compared with population of *A. gossypii* at K- treatment. When citronella oil was combined with insecticide (P2), there was a significant reduction in the *A. gossypii* population, in contrast to the population observed with only insecticide (K+). This result demonstrates the potential of citronella oil as an effective botanical insecticide. It has been observed that applying treatments weekly is essential, as studies on pests affecting cabbage, mangosteen, and citrus reveal that intervals longer than one week do not significantly reduce pest populations. Therefore, the efficacy of citronella oil is believed to last for no more than one week. Wahba *et al.* (2024) reported that a 10-day application interval for peppermint and eucalyptus essential oils was still effective in controlling *Bemisia tabaci*. Additionally, weather conditions play a significant role in determining the effectiveness of essential oils. Increasing temperature, humidity, and wind speed will increase the effectiveness of peppermint and eucalyptus essential oils in controlling *Bemisia tabaci* pests (Wahba *et al.,* 2024).

Tests of citronella oils toxicity against A. gossypii adult

2. Field test findings suggest that citronella oil

Table 3: Differences in the ability of each pesticide application treatment to suppress the population of *A. gossypii* on chili plants in the field (pest/plant)

Treatment	Observation week ± Standard error (SE)									
	I	II	III	IV	V	VI	VII	VIII	IX	X
P2	31.8 ± 4.2 a	37.3 ± 6.3 b	33.4 ± 5.9 bc	19.8 ± 8.5 b	17.4 ± 1.5 b	1.9 ± 0.2 a	3.1 ± 0.2 a	0.3 ± 0.2 a	1.6 ± 0.3 a	1.2 ± 0.2 a
P4	36.7 ± 7.7 a	22.2 ± 3.3 a	20.2 ± 6.8 a	16.2 ± 10.1 ab	11.8 ± 2.8 a	6.4 ± 1.5 c	3.3 ± 0.2 a	2.7 ± 1.1 b	2.3 ± 0.4 a	2.5 ± 1.0 b
K+	65.4 ±11.6 b	40.2 ± 6.7 b	25.2 ± 3.6 ab	7.6 ± 1.3 a	18.9 ± 1.5 b	3.7 ± 0.3 b	3.9 ± 0.1 b	1.0 ± 0.5 a	2.0 ± 0.2 a	1.9 ± 0.3 b
K-	41.7 ± 8.9 a	38.1 ± 4.5 b	37.7 ± 5.2 c	24.4 ± 13.8 b	24.8 ± 1.3 c	23.5 ± 4.8 d	26.1 ± 1.5 c	24.4 ± 9.8 c	23.5 ± 3.5 b	26.9 ± 5.7 c

Table 4: Average values of the percentage of mortality of *Aphis gossypii* at various concentrations of citronella oil

Treatment	Average value of mortality rate (%)*						
	1 HAA	2 HAA	3 HAA	6 HAA	12 HAA	24 HAA	48 HAA
Control (+)	13.33 a	29.17 b	41.67 c	69.17 c	85.83 c	96.53 d	100.00 d
1 mL/L	4.17 a	7.50 a	13.33 a	19.17 a	24.17 a	31.49 a	38.25 a
2 mL/L	7.50 a	19.17 b	25.83 b	38.33 b	44.17 b	47.81 b	61.84 b
3 mL/L	10.83 a	20.83 b	34.17 bc	42.50 b	53.33 b	60.66 c	89.08 c

*Significant differences are indicated by the numbers in the same column that are followed by different letters according to Tukey's test at a 5% error level. HAA is hours after application and Control + is the abamectin treatment. The data were transformed into $\sqrt{x + 0{,}5}$ data analysis purposes.

could effectively lower the population of A. gossypii. To explore this further, a laboratory experiment was carried out to examine the insecticidal and repellent properties of citronella oil on A. gossypii, with the goal of determining the mechanisms by which the oil reduces this pest's population. The results of the laboratory test showed that citronella oil can kill *A. gossypii* adults. The oil is lethal from 1 mL/L. During the observation period, there is a noticeable increase in the mortality percentage of this pest in relation to the concentration levels. Foliar spraying is the most effective method for applying botanical insecticide, ensuring uniform coverage and direct pest contact to maximize its repellent and insecticidal effects in field conditions (Isman, 2006). However, the toxicity of citronella oil is still lower than the toxicity of synthetic pesticides (K+) (Table 4).

The insecticidal effects of citronella oil on *Aphis gossypii* were most pronounced at a concentration of 3 mL/L, achieving 50% mortality within 12 hours of application. The 2 mL/L treatment showed a comparable effect within the same period, whereas the 1 mL/L concentration required approximately 24 hours to reach the same mortality rate. In contrast to the synthetic pesticide abamectin, which resulted in 50% mortality within only 3 to 6 hours, citronella oil showed significantly lower toxicity. Similar findings were reported by Saleh *et al.* (2023), highlighting that botanical insecticides generally require longer exposure times to reach peak effectiveness. This delayed mortality implies that to achieve effective pest suppression in the field, it may be necessary to apply citronella oil repeatedly, thereby presenting a feasible natural alternative to synthetic insecticides in integrated pest management strategies.

Tests of citronella oils repellence to A. gossypii

The repellence test results demonstrated that adults of *A. gossypii* are repelled by citronella oil. As the concentration of citronella oil rose, its repellency percentage also increased. The comprehensive results of this experiment are displayed in Table 5.

The results of the repellency assay indicated that citronella oil was effective in deterring Aphis gossypii, and its repellent properties became stronger with increased concentration. At a concentration of 3 mL/L, repellency reached 48% within the first hour, highlighting citronella oil's potential as a natural deterrent against aphid infestations. These findings are consistent with the work of Nerio *et al.* (2010), who also observed strong repellent properties of essential oils against agricultural pests. Citronella oil's effectiveness in repelling pests without exterminating them indicates its significant potential in integrated pest management, especially for thwarting the initial invasion of crops. Analysis of variance revealed that

Table 5: Repellence percentage of *Cymbopogon nardus* oil against *A. gossypii*

Treatment	Repellence (%)*		
	1 HAA	2 HAA	3 HAA
1 mL/L	21.22 a	16.44 a	8.77 a
2 mL/L	39.44 b	24.55 ab	12.77 a
3 mL/L	48.00 c	31.77 b	18.60 b

*Significant differences are indicated by the numbers in the same column that are followed by different letters according to Tukey's test at a 5% error level. HAA is hours after application and Control + is the abamectin treatment. The data were transformed into $\sqrt{x + 0,5}$ for data analysis purposes.

the highest repellency was observed at 3 mL/L, and this was significantly higher compared to the lower concentrations of 1 and 2 mL/L. No significant difference was found between the repellency rates at 1 and 2 mL/L within the first 1-2 hours after application. Furthermore, repellency increased gradually from 1 to 3 hours across all treatments.

Environmental impact and sustainability

Citronella oil offers a sustainable alternative to synthetic insecticides, reducing environmental contamination and pesticide resistance. The use of botanical insecticides, characterized by their complex blend of bioactive compounds, should be complemented with other pest control methods and ongoing resistance monitoring to effectively manage the potential for resistance development over time (Chaturvedi, 2007). Unlike chemical pesticides, citronella oil biodegrades rapidly, minimizing its persistence in soil and water. Additionally, botanical pesticides are recognized for their reduced effects on non-target species, including beneficial insects such as pollinators and natural predators (Jankowska *et al.,* 2017). This makes citronella oil an environmentally friendly option for integrated pest management programsAdditional studies are necessary to assess the long-term impacts of this approach on agroecosystems and to determine how well it integrates with other biological control strategies. The efficacy of citronella oil in controlling *Aphis gossypii* is likely influenced by environmental conditions, with factors such as temperature, humidity, and rainfall affecting its volatility and degradation rate; therefore, seasonal and multi-location trials are recommended to optimize its use (Cloyd *et al.,* 2009). In addition to analyzing the management of *A. gossypii*, it is essential to consider the possible effects of citronella oil on beneficial insects like pollinators and natural predators. It is recommended that subsequent studies consistently monitor these non-target species (Nerio *et al.,* 2010). Citronella oil provides eco-friendly repellent and insecticidal effects, rapid biodegradation, and minimal non-target impact, though its short residual activity requires frequent applications, which is offset by its environmental benefits (Isman, 2006). Citronella oil is deemed safe owing to its natural formulation and swift degradation; however, its extensive use must align with regulatory requirements and be subject to rigorous safety evaluations (Pathak *et al.,* 2022).

Advanced considerations for future research

This study is to determine the potential of citronella oil as a control agent for *A. gossypii.* While this study confirms the efficacy of citronella oil in controlling *A. gossypii*, additional research is necessary to optimize application frequency, dosage, and formulation for enhanced effectiveness. Investigations into the durability of its action, the likelihood of developing resistance, its effectiveness relative to other botanical pesticides, and its effects on other organisms, especially those that are beneficial, may reveal synergistic relationships between citronella oil and other botanical extracts, paving the way for more powerful formulations. Furthermore, economic feasibility, multi-location trials across different climatic conditions would provide insights into citronella oil's adaptability and broader agricultural applicability. Several obstacles hinder the large-scale adoption of citronella oil, including the stability of its formulations, the need for regular applications, and higher initial expenses. These factors highlight the need for further economic and logistical analysis to determine its practical feasibility (Lengai *et al.,* 2020). Moreover, the field observations suggest that citronella oil applications do not adversely affect chili plant growth or fruit quality, and may enhance yield by reducing pest-induced damage, although further comparative productivity analysis is warranted (Istianto and Emilda, 2021).

CONCLUSION

The findings of this study highlight the significant potential of citronella oil as an effective, environmentally sustainable solution for managing *Aphis gossypii* infestations in agricultural settings, particularly in chili cultivation. The oil exhibited both insecticidal and repellent characteristics, successfully decreasing aphid populations by repelling and poisoning pests, ultimately resulting in their mortality. This study adds to the growing body of evidence supporting the efficacy of citronella oil in pest management, reinforcing its potential as an alternative to synthetic insecticides. Citronella oil's ability to repel and kill insects is linked to its bioactive substances, such as citronellal, citronellol, geranyl acetate, and limonene, which have been proven to disrupt the respiratory processes of insects. These natural compounds offer a promising alternative to chemical insecticides by providing an eco-friendly solution with minimal adverse effects on the environment. Research has previously pointed out that botanical pesticides, including citronella oil, offer the advantage of being less harmful to non-target species, such as pollinators and predatory insects, which are crucial for preserving ecological equilibrium. This characteristic distinguishes citronella oil from synthetic pesticides, which are known to have a negative impact on beneficial species, thus making citronella oil a more sustainable option for integrated pest management (IPM). The study also found that, while citronella oil was successful in lowering aphid numbers, its effects were slower in comparison to those of synthetic insecticides. This finding underscores the need for repeated applications of botanical treatments to achieve the same level of control as chemical options. However, the long-term benefits of using citronella oil, including its environmental safety and the reduced risk of resistance development, make it an attractive alternative. Utilizing citronella oil as part of pest management strategies, particularly in conjunction with synthetic insecticides in a rotational manner, can effectively delay resistance and enhance the sustainability of pest control practices. The use of citronella oil in pest management aligns with global initiatives to promote sustainable agricultural practices. Citronella oil contributes to reducing environmental pollution and promoting biodiversity by decreasing the dependence on synthetic pesticides. Additionally, its biodegradability ensures a lower ecological impact compared to persistent chemical pesticides. These elements establish citronella oil as an essential resource in sustainable agriculture, providing efficient pest management while also promoting ecological conservation. This study provides compelling evidence for the use of citronella oil as a botanical pesticide that not only reduces dependence on chemical insecticides but also offers a more sustainable and environmentally friendly approach to pest management. Its efficacy in controlling *Aphis gossypii* infestations, combined with its minimal impact on non-target organisms, makes citronella oil a valuable addition to integrated pest management strategies. As studies delve deeper into its capabilities, citronella oil has the potential to become a key component in advancing sustainable pest management practices within the agricultural sector.

AUTHOR CONTRIBUTIONS

M. Istianto performed the literature review, conceptualized the central research idea, and designed the study, conducted the experiment, interpretation of results, and manuscript preparation. K.D. Sutanto Performed the literature review, interpreted the data, manuscript preparation and helped in improvement of the manuscript. S. Ikawati performed the literature review, conceptualized the central research idea, designed the study, and analyzed and interpreted the data. R.C. Wicaksono performed the literature review, conceptualized the central research idea, designed the study, data collection and analyzed and interpreted the data, draft manuscript preparation. U. Triasih Performed data collection and analysis and helped in improvement of the manuscript. O. Endarto Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. Affandi Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. Handoko Performed data collection and analysis and helped in improvement of the manuscript. S. Widyaningsih Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. S. Agustini Performed data collection and analysis and helped in improvement of the manuscript. M.E. Dwiastuti Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. L. Mufidah Performed data collection and analysis and helped in improvement of the manuscript. S. Wuryantini Performed data collection and analysis,

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
µm	Micrometer
µL	Microliter
a	Number of dead *Aphis gossypii*
A. gossypii	*Aphis gossypii*
ANOVA	Analysis of Variance
b	Number of *A. gossypii* in the treatment
B. tabaci	*Bemisia tabaci*
BPS	Badan Pusat Statistik
C	Quantity of insects in the control
Cm	Centimeter
CMV	Cucumber Mosaic Virus
Conc.	Concentration
E	East
Eq.	Equation
GC–MS	Gas Chromatography–Mass Spectrometry
g/L	Grams per liter
HAA	Hours After Application
ha	Hectare
h	Hours
IPM	Integrated Pest Management
K+	Synthetic insecticide treatment (abamectin)
K-	Untreated control
L	Liter
masl	Meters above sea level
m/z	Mass-to-charge ratio
ml	Milliliter
mL/L	Milliliter per liter
m	Meters
mm³	Cubic meter
P2	Rotation treatment between citronella oil and synthetic insecticides
P4	Sole application of citronella oil
PVY	Potato Virus Y
Po	Mortality percentage
RBD	Randomized Block Design
R.I.	Repellence index
SE	Standard error
S	South
T	Quantity of insects in the treatment

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