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Evaluation of chemical compounds as deterrents of the brown marmorated stink bug [*Halyomorpha halys* (Stål)]

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Abstract: The brown marmorated stink bug [*Halyomorpha halys* (Stål)] is an invasive pest species. This polyphagous insect, native to Eastern Asia, threatens various cultivated plant species. Control methods often rely on chemical insecticides, but the decreasing use of such agents has prompted a shift towards preventive measures. As a defence mechanism, natural compounds released by plants have gained attention for their potential deterrent or attractant properties. In this study, we evaluated the response of the brown marmorated stink bug to selected chemical substances, including citronellal, hexanal, nonanol, β-caryophyllene, linalool, ocimene, nerolidol, terpinolen, α-humulene, dimethyl sulfide, aggregation pheromone, and ethanol. The experiment was conducted using an olfactometer. Two experiments were performed, comparing the substances against dimethyl sulfoxide and then refining the selection based on initial results; in the first series, nerolidol, ocimene, and terpinolene exhibited promising results as complete deterrents. The second series confirmed nerolidol as the most effective deterrent among all tested substances. These findings contribute to developing preventive strategies for managing the brown marmorated stink bug and reducing reliance on chemical insecticides.

Keywords: BMSB; volatile compounds; nerolidol; ocimene; terpinolene; detterent

The highly polyphagous pest species, the brown marmorated stink bug (BMSB) [*Halyomorpha halys* (Stål)], is native to Asia (Hoebeke & Carter 2003). Since the mid-1990s, this invasive pest species has spread worldwide. It has been reported in several European countries, North America, South America, Africa, and Oceania (Kriticos et al. 2017). Due to its broad host range, including agricultural and ornamental plants and wild hosts, managing the BMSB using conventional methods is challenging (Haye et al. 2015).

Plants have developed direct and indirect defence mechanisms against harmful organisms. When attacked, many release volatile organic compounds (VOCs) that attract natural enemies of herbivores. Studies by Crespo et al. (2012) and Dudareva et al. (2013) highlight the importance of VOCs in agricultural ecosystems, influencing both herbivores and their predators. Research by Rassman et al. (2005) and Laznik and Trdan (2013) shows VOC production in both damaged and undamaged plants, with different compounds released in re-

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sponse to mechanical injuries or herbivore feeding (Ali et al. 2010; Crespo et al. 2012). VOCs also act as repellents, aiding host-finding for pests like *H. halys* (Weber et al. 2014).

Discovering semiochemicals associated with BMSB offers promising pest management opportunities, including monitoring tools and strategies like attract-and-kill techniques, trap plants, and trap crops (Weber et al. 2014). Although the chemical ecology of BMSB has been well-studied (Khrimian et al. 2014; Weber et al. 2014), the role of plant volatiles in BMSB's foraging and interactions remains underexplored. Given BMSB's polyphagous nature, this gap is significant. The BMSB may have a flexible odour profile influenced by internal and external factors or be attracted to common VOCs like green leaf volatiles (Bergmann et al. 2016).

This study evaluated the response of BMSB to various chemical substances, including citronellal, hexanal, nonanol, β-caryophyllene, linalool, ocimene, nerolidol, terpinolen, α-humulene, dimethyl sulfide, aggregation pheromone, and ethanol. These VOCs were chosen based on their known effects in related studies. For instance, Staudt et al. (2010) identified (E)-β-ocimene and E-nerolidol in peach cultivars attacked by aphids. Laznik and Trdan (2018) showed the attraction of lady beetle and green lacewing larvae to synthetic (E)-β-ocimene, while (E)-nerolidol was a deterrent. Rasmann et al. (2005) found E-β-caryophyllene, α-humulene, and linalool released from maize by corn rootworm larvae, attracting EPN species (Laznik & Trdan 2013). Weissteiner et al. (2012) reported that potatoes release nonanol, hexanal, and citronellal when attacked by wireworms, and carrots release terpinolene when attacked by grubs, acting as repellents (Weissteiner et al. 2012). Jagodič et al. (2017) confirmed that sulfur-based VOCs from *Brassica nigra* deter entomopathogenic nematodes (EPNs). We aimed to determine if these VOCs influence BMSB behaviour.

MATERIAL AND METHODS

Laboratory Rearing of *H. halys*. In the first half of May 2022, adult stink bugs were collected from wild-growing and cultivated host plants in gardens and orchards near Nova Gorica (Western Slovenia) and Ljubljana (central Slovenia). We followed the laboratory-rearing methodology for BMSB described by Rot et al. (2021). The stink bugs were placed in ventilated plastic containers measuring 54 × 40 × 30 cm, featuring a solid base and mesh windows on all sides. Their diet consisted of green beans, sunflower seeds, peanuts, and carrot pieces, which were replenished twice a week. To ensure proper humidity levels and water supply, cotton balls soaked in water were included within the containers.

Olfactometer bioassay. To assess the impact of volatile compounds on brown marmorated stink bugs (BMSB) preference, we used a custom-built two-arm T-shaped olfactometer (Figure 1). This device featured a central chamber (15 × 15 × 5 cm) with two extended arms (25 cm long, 2 cm diameter) leading to side chambers (5 cm diameter, 5 cm height). To expedite the process, five T-shaped olfactometers were made. The experiment was carried out in a darkroom illuminated with a 20 W

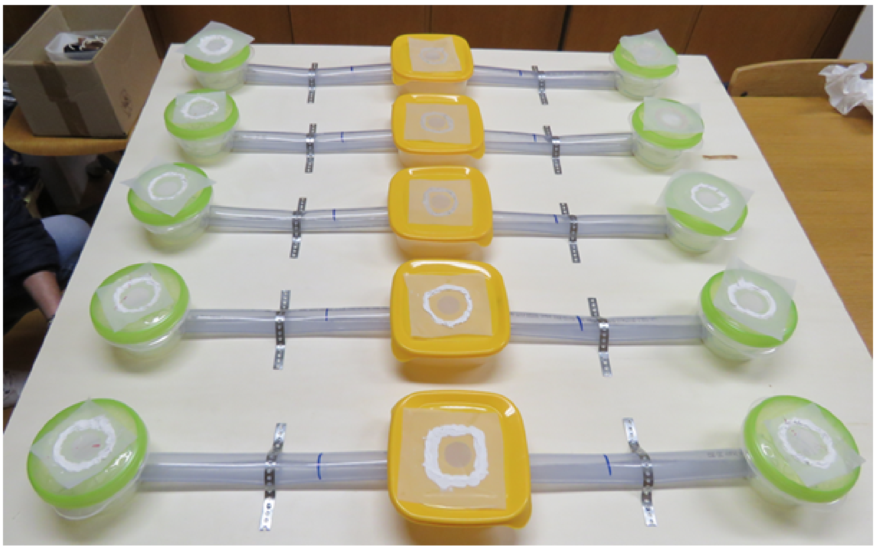

Figure 1. A custom-built two-arm T-shaped olfactometer
This device featured a central chamber (15 × 15 × 5 cm) with two extended arms (25 cm long, 2 cm diameter) leading to side chambers (5 cm diameter, 5 cm height)

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red LED light and maintained at approximately 22 ± 1 °C and 65 % relative humidity. Still, air was used during the experiments to allow passive diffusion of volatiles. The olfactometer relies on passive diffusion, with no pumps or other devices actively moving the air through the system.

The experiment involved pipetting 10 μL of dimethyl sulfoxide, representing the control, onto a piece of cotton gauze in one side chamber. On the other side of the chamber, 10 μL of the selected chemical substance (citronellal, hexanal, nonanol, β-caryophyllene, linalool, ocimene, nerolidol, terpinolen, α-humulene, dimethyl sulfide), ethanol, or a piece of tape with applied aggregation pheromone was pipetted. We utilized synthetically produced compounds from Sigma Aldrich, tested at a concentration of 0.3 ppm, achieved by dissolving pure VOCs in dimethyl sulfoxide (Jagodič et al. 2017). The resulting suspension was immediately used in the laboratory bioassay after vortexing.

Each trial involved placing one newly emerged adult BMSB of unspecified sex in the central chamber. The movement of each BMSB was observed at 5, 15, 30, 45, and 60-minute intervals. To aid orientation, a line was drawn at the midpoint of the tube to define the centre boundary and track each bug's location.

The experiment was conducted in two phases. The first phase (A) included thirteen treatments (citronellal, hexanal, nonanol, β-caryophyllene, linalool, ocimene, nerolidol, terpinolen, α-humulene, dimethyl sulfide, aggregation pheromone, ethanol, and control – dimethyl sulfoxide). Twenty insects were tested for each compound, representing a replicate. After each repetition, the BMSB were removed, and the olfactometer and other apparatus were cleaned with 5% bleach and 95% ethanol between replicates. New BMSB were used for each repetition, and 10 μL of the selected tested substance and dimethyl sulfoxide were freshly pipetted.

In the second experiment series (B), we focused on the chemical substances that exhibited the most attractive or deterrent effects on the BMSB. We compared these compounds to determine their efficacy in influencing the stink bug's behaviour. The experiment consisted of six treatments (terpinolen – ethanol, ocimene – ethanol, terpinolen – ocimene, nerolidol – ethanol, nerolidol – terpinolen, and nerolidol – ocimene), each with 20 repetitions. The same olfactometer from the first series was used in this experiment phase.

Data analysis. We calculated the chemotactic index (CI) based on the test developed by Bargmann and Horvitz (1991) and modified by Laznik and Trdan (2013). The index was calculated using the formula:

$$CI = \frac{\text{\% of bugs in the treated area} - \text{\% of bugs in the control area}}{100}$$

Where: CI – chemotactic index (%).

This experiment used chemotactic index (CI) values to evaluate how the tested substances influenced the brown marmorated stink bug (BMSB) movement. CI values ranged from +1 (complete attractant) to –1 (complete deterrent). The defined CI intervals were as follows: ≥ 0.2 indicated an attractant, 0.2–0.1 indicated a weak attractant, between 0.1 and –0.1 indicated no effect, between –0.1 and –0.2 indicated a weak deterrent, and ≤ –0.2 indicated a complete deterrent (Jagodič et al. 2017). Observations were made at 5, 15, 30, 45, and 60-min intervals to record the bug's location. Bugs were marked as 0 if in the central chamber or up to the midpoint line, –1 if in the tube or side chamber with dimethyl sulfoxide, and one if in the side chamber with the chemical substance. All statistical analyses were conducted using Statgraphics Plus Windows (version 4.0), a comprehensive statistical software package known for its robust data analysis capabilities. A one-way analysis of variance (ANOVA) was employed to assess the overall differences among the BMSB exposed to different substances. Following the one-way ANOVA, Tukey's Honest Significant Difference (HSD) test was conducted as a post-hoc analysis to identify specific pairwise differences between treatment groups. The significance level was set at $P = 0.05$, meaning that differences were considered statistically significant if the p-value was less than 0.05. Substances were classified based on their effects on BMSB movement: *(i)* attractants: substances that significantly increased BMSB movement towards them compared to the control group; *(ii)* deterrents: substances that significantly decreased BMSB movement towards them compared to the control group; *(iii)* no effect: substances that did not cause a statistically significant change in BMSB movement compared to the control group.

Statistical analysis via one-way ANOVA and Tukey's HSD test ($P = 0.05$) was conducted using Statgraphics Plus Windows (version 4.0) to determine whether substances acted as attractants, deterrents, or had no effect on BMSB movement.

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RESULTS

Movement orientation of BMSB in Experiment A. Data analysis revealed that the movement of the BMSB (movement from the inner chamber of the olfactometer to the outer chamber) is dependent on various factors, namely substance type ($F_{12, 1559}$ = 16.01; P < 0.0001), repetitions ($F_{19, 1559}$ = 5.89; P < 0.0001), exposure time ($F_{5, 1559}$ = 11.66; P < 0.0001), and the interaction between substance type and exposure time ($F_{60, 1559}$ = 1.50; P < 0.0001). We analyzed and presented the data in tabular form based on bug exposure time to specific substances to facilitate understanding and subsequent presentation of the results.

Table 1 presents BMSB movement responses to studied substances, independent of experiment duration. Aggregation pheromone acted as an attractant (CI = 0.25 ± 0.04), while substances like ß-caryophyllene, linalool, dimethyl sulfoxide, and nonanal had negligible effects (CI values close to zero). In our study, α-humulene, citronellal, dimethyl sulfide, ethanol, and hexanal acted as weak deterrents on the BMSB's movement orientation (CI values ranged from –0.19 to –0.06). Substances such as nerolidol, ocimene, and terpinolene demonstrated stronger deterrent effects (CI values ranged from –0.36 to –0.28).

Table 2 illustrates how chemical substances influenced BMSB movement over time. ß-caryophyllene weakly dettered 30–45 min. Initially ineffective, α-humulene later deterred. Citronellal transitioned to a strong deterrent. Dimethyl sulfide was weakly deterred after five minutes. Ethanol became a deterrent after 30 min. Aggregation pheromone attracted after five minutes. Hexanal and linalool varied in deterrence. Nerolidol and terpinolene were strong deterrent after five minutes. Nonanal and dimethyl sulfoxide had no effect. Ocimene became a strong deterrent after 15 min. These findings inform targeted deterrent strategies for BMSB management.

Movement orientation of BMSB in experiment B. In experiment B, we included nerolidol, ocimene, terpinolene, and ethanol, which were identified as the most effective repellents on the movement of the BMSB in Experiment A. In experiment B, we compared these studied substances against each other.

Data analysis revealed that the movement of the BMSB is dependent on various factors, namely substance type ($F_{11, 1559}$ = 16.14; P < 0.0001), repetitions ($F_{19, 1559}$ = 6.76; P < 0.0001), exposure time ($F_{5, 1559}$ = 7.71; P < 0.0001), while the interaction between substance type and exposure time ($F_{55, 1559}$ = 1.04; P = 0.4100) had no influence on the movement of the BMSB in the experiment.

Table 3 displays BMSB movement towards tested substances, regardless of experiment duration.

Table 1. Average chemotaxis index (± SE) in Experiment A independent of experiment duration

Substance	Average CI value ± SE	Influence of the studied substance on the movement of adult brown marmorated sting bug
ß-caryophyllene	–0.06 ± 0.05[c]	No effect
α-humulene	–0.18 ± 0.04[b]	Weak repellent
Citronellal	–0.13 ± 0.04[c]	Weak repellent
Dimethyl sufide	–0.11 ± 0.03[c]	Weak repellent
Ethanol	–0.19 ± 0.04[b]	Weak repellent
Aggregation pheromone	0.25 ± 0.04[e]	Attractant
Hexanal	–0.16 ± 0.05[b]	Weak repellent
Linalool	–0.08 ± 0.05[c]	No effect
Nerolidol	–0.36 ± 0.04[a]	Repellent
Nonanol	0.03 ± 0.04[d]	No effect
Ocimene	–0.32 ± 0.04[a]	Repellent
Terpinolene	–0.28 ± 0.04[a]	Repellent
Dimethyl sulfoxide	–0.08 ± 0.02[c]	No effect

CI – chemotactic index

Each data point represents the mean chemotaxis index value ± SE. Statistically significant (P < 0.05) differences between substances tested on the movement of adult brown marmorated sting bug are marked with different letters

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Table 2. Average chemotaxis index (± SE) in Experiment A over time intervals

Substance	5 min	15 min	30 min	45 min	60 min
ß-caryophyllene	0.05 ± 0.09[CDa]	–0.05 ± 0.14[Ba]	–0.15 ± 0.1[7BCa]	–0.15 ± 0.17[CDa]	–0.05 ± 0.17[Ca]
α-humulene	0.00 ± 0.00[Cb]	–0.20 ± 0.09[ABa]	–0.25 ± 0.10[BCa]	–0.25 ± 0.10[Ca]	–0.35 ± 0.11[Ba]
Citronellal	0.00 ± 0.00[Cb]	–0.15 ± 0.11[Ba]	–0.15 ± 0.13[BCa]	–0.20 ± 0.14[Ca]	–0.30 ± 0.15[Ba]
Dimethyl sufide	–0.10 ± 0.07[Aa]	–0.10 ± 0.07[Ba]	–0.15 ± 0.08[BCa]	–0.15 ± 0.08[CDa]	–0.15 ± 0.08[Ca]
Ethanol	–0.05 ± 0.05[BCc]	–0.15 ± 0.08[Bbc]	–0.25 ± 0.10[Bab]	–0.30 ± 0.11[BCab]	–0.40 ± 0.11[Ba]
Aggregation pheromone	0.20 ± 0.09[Da]	0.25 ± 0.10[Ca]	0.25 ± 0.12[Da]	0.40 ± 0.11[Fa]	0.40 ± 0.11[Da]
Hexanal	–0.15 ± 0.08[ABa]	–0.20 ± 0.12[ABa]	–0.20 ± 0.14[BCa]	–0.15 ± 0.15[CDa]	–0.25 ± 0.16[BCa]
Linalool	–0.05 ± 0.11[BCa]	–0.05 ± 0.11[Ba]	–0.10 ± 0.12[Ca]	–0.15 ± 0.13[CDa]	–0.15 ± 0.13[Ca]
Nerolidol	–0.20 ± 0.09[Aa]	–0.40 ± 0.11[Aab]	–0.50 ± 0.11[Aa]	–0.50 ± 0.11[ABa]	–0.55 ± 0.11[ABa]
Nonanol	0.00 ± 0.07[Ca]	–0.05 ± 0.09[Ba]	0.00 ± 0.13[Ca]	0.15 ± 0.13[Ea]	0.05 ± 0.15[Ca]
Ocimene	–0.05 ± 0.05[BCd]	–0.20 ± 0.09[ABc]	–0.40 ± 0.11[Abc]	–0.60 ± 0.11[Aab]	–0.65 ± 0.11[Aa]
Terpinolene	–0.10 ± 0.07[ABc]	–0.25 ± 0.10[ABbc]	–0.35 ± 0.11[ABab]	–0.50 ± 0.11[ABa]	–0.50 ± 0.11[ABa]
Dimethyl sulfoxide	–0.05 ± 0.05[BCa]	–0.15 ± 0.08[Ba]	–0.05 ± 0.05[Ca]	–0.10 ± 0.07[Da]	–0.10 ± 0.07[Ca]

Each data point represents the mean chemotaxis index value ± SE. Statistically significant ($P < 0.05$) differences between substances tested on the movement of adult brown marmorated sting bug are marked with different letters. Capital letters represent statistically significant differences among different substances within the same time interval. Small letter represent statistically significant differences among different time interval within the same tested substance

Nerolidol was a stronger repellent than ethanol (CI = –0.28 ± 0.05) when paired with terpinolene (CI = –0.23 ± 0.04). Nerolidol and ocimene had similar effects on the BMSB movement. Terpinolene attracted more than nerolidol (CI = 0.23 ± 0.04) but repelled when with ethanol (CI = –0.26 ± 0.04) and had no impact with ocimene (CI = 0.00 ± 0.04). Ethanol was the weakest repellent in Experiment B, with other substances directing BMSB towards it.

In summary, the experiments reveal valuable insights into the repellent and attractant properties of the tested substances on the BMSB's movement behaviour. Nerolidol demonstrated strong repellent effects, while terpinolene showed attractive properties when compared to other substances. These findings contribute to our understanding of potential preventive strategies against the brown marmorated stink bug in agricultural settings.

Table 4 displays BMSB movement orientation towards substances over varying experiment durations. After 15 min, specific substance combinations were observed. Nerolidol showed stronger repellent effects than ethanol and terpinolene. However, no significant changes were noted with nerolidol and ocimene. Terpinolene exhibited stronger repellent effects than ethanol when combined. Ocimene demonstrated stronger repellent effects than ethanol, but no notable responses were observed with other substance combinations.

In summary, the experiment demonstrates the varying repellent effects of the studied substances on the BMSB, depending on the combination and the duration of exposure. Nerolidol consistently showed strong repellent properties, while terpinolene and ocimene had limited repel-

Table 3. Average chemotaxis index (± SE) in Experiment B independent of experiment duration

Treatment	Average CI value ± SE
Nerolidol – ethanol	–0.28 ± 0.05[a]
Nerolidol – ocimene	0.00 ± 0.04[b]
Nerolidol – terpinolene	–0.23 ± 0.04[a]
Terpinolene – nerolidol	0.23 ± 0.04[c]
Terpinolene – ocimene	0.00 ± 0.04[b]
Terpinolene – ethanol	–0.26 ± 0.04[a]
Ocimene – ethanol	–0.28 ± 0.04[a]
Ocimene – nerolidol	0.00 ± 0.04[b]
Ocimene – terpinolene	0.00 ± 0.04[b]
Ethanol – nerolidol	0.28 ± 0.05[c]
Ethanol – ocimene	0.28 ± 0.04[c]
Ethanol – terpinolene	0.26 ± 0.04[c]

CI – chemotactic index

Each data point represents the mean chemotaxis index value ± SE. Statistically significant ($P < 0.05$) differences between substances tested on the movement of adult brown marmorated sting bug are marked with different letters

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Table 4. Average chemotaxis index (± SE) in Experiment B over time intervals

Substance	5 min	15 min	30 min	45 min	60 min
Nerolidol – ethanol	-0.05 ± 0.09^{Ab}	-0.35 ± 0.1^{3Aa}	-0.40 ± 0.13^{Aa}	-0.45 ± 0.14^{Aa}	-0.45 ± 0.14^{Aa}
Nerolidol – ocimene	0.10 ± 0.0^{7Ab}	0.05 ± 0.11^{BCb}	-0.05 ± 0.14^{Bb}	-0.50 ± 0.1^{4Aa}	-0.50 ± 0.14^{Aa}
Nerolidol – terpinolene	0.00 ± 0.00^{Ab}	-0.20 ± 0.09^{Aa}	-0.35 ± 0.1^{1Aa}	-0.40 ± 0.11^{Aa}	-0.40 ± 0.11^{Aa}
Terpinolene – nerolidol	0.00 ± 0.00^{Aa}	0.20 ± 0.10^{CDb}	0.35 ± 0.11^{Bb}	0.40 ± 0.11^{Cb}	0.40 ± 0.11^{Cb}
Terpinolene – ocimene	0.00 ± 0.00^{Aa}	-0.05 ± 0.11^{Ba}	0.00 ± 0.10^{Ba}	0.05 ± 0.14^{Ba}	0.00 ± 0.15^{Ba}
Terpinolene – ethanol	0.00 ± 0.00^{Ab}	-0.25 ± 0.10^{Aa}	-0.40 ± 0.11^{Aa}	-0.45 ± 0.11^{Aa}	-0.45 ± 0.11^{Aa}
Ocimene – ethanol	0.00 ± 0.00^{Ab}	-0.35 ± 0.11^{Aa}	-0.40 ± 0.11^{Aa}	-0.45 ± 0.11^{Aa}	-0.50 ± 0.11^{Aa}
Ocimene – nerolidol	-0.01 ± 0.07^{Aa}	-0.05 ± 0.11^{Ba}	0.05 ± 0.13^{Ba}	0.05 ± 0.14^{Ba}	0.05 ± 0.14^{Ba}
Ocimene – terpinolene	0.00 ± 0.00^{Aa}	0.05 ± 0.11^{BCa}	0.00 ± 0.10^{Ba}	-0.05 ± 0.13^{Ba}	0.00 ± 0.15^{Ba}
Ethanol – nerolidol	0.05 ± 0.09^{Aa}	0.35 ± 0.13^{Db}	0.40 ± 0.13^{Cb}	0.45 ± 0.14^{Cb}	0.45 ± 0.14^{Cb}
Ethanol – ocimene	0.00 ± 0.00^{Aa}	0.35 ± 0.11^{Db}	0.40 ± 0.11^{Cb}	0.45 ± 0.11^{Cb}	0.50 ± 0.11^{Cb}
Ethanol – terpinolene	0.00 ± 0.00^{Aa}	0.25 ± 0.10^{Db}	0.4 ± 0.11^{Cb}	0.45 ± 0.11^{Cb}	0.45 ± 0.11^{Cb}

Each data point represents the mean chemotaxis index value ± SE. Statistically significant ($P < 0.05$) differences between substances tested on the movement of adult brown marmorated sting bugs are marked with different letters. Capital letters represent statistically significant differences among different substances within the same time interval. Small letters represent statistically significant differences among different time intervals within the same tested substances

lent effects on the BMSB's movement. Additionally, ethanol emerged as the weakest repellent in these experiments, as the BMSB consistently moved towards ethanol when exposed to other substances. These findings contribute to our understanding of the potential application of these chemical compounds in managing the movement of the brown marmorated stink bug.

DISCUSSION

The brown marmorated stink bug (BMSB), native to Eastern Asia, was introduced to the United States in the mid-1990s and Europe in 2004. As an invasive species, BMSB threatens cultivated and wild plants, causing significant damage: 34 mil USD in apple orchards in the Mid-Atlantic US and 30–50% losses in Italian pear orchards (Bariselli et al. 2016).

To counteract BMSB, experts use monitoring methods like light traps, pheromone traps, mechanical traps, and sticky traps (Haye et al. 2015). Biological control using natural enemies can suppress BMSB populations on a large scale (Stahl et al. 2019; Scaccini et al. 2020; Mele et al. 2022). Sulphur-based treatments are effective deterrents and repellents against BMSB, making them a viable alternative to synthetic pesticides. Laboratory and semi-field experiments show that BMSB adults prefer untreated food sources over sulphur-treated ones, increasing deterrence at higher concentrations. Though sulphur does not affect mortality, its repellence supports its use in Integrated Pest Management (IPM) strategies (Candian et al. 2021; Scaccini et al. 2024). Recently, IPM programs in fruit orchards have faced challenges due to chemicals required for new invasive pests. Exclusion nets offer a sustainable alternative control strategy (Candian et al. 2020; Fornasiero et al. 2023).

In this study, we examined the effects of selected volatile compounds (citronellal, hexanal, nonanol, β-caryophyllene, linalool, ocimene, nerolidol, terpinolene, α-humulene, dimethyl sulfide, aggregation pheromone, ethanol, and dimethyl sulfoxide as a control) on the BMSB. These compounds have been previously studied for their attractant/repellent properties on various organisms (Laznik & Trdan 2013, 2018; Jagodič et al. 2017), and our objective was to investigate their impact on the BMSB.

In the first experiment, we compared various substances to dimethyl sulfoxide. Ethanol, nerolidol, ocimene, and terpinolene strongly repelled BMSB, while aggregation pheromone acted as an attractant. Contrary to previous studies, other chemicals had weaker effects, and β-caryophyllene showed no impact. Zhang et al. (2013) reported that β-caryophyllene significantly reduced trap catches (72–99%) due to its repellent properties. Mahajan et al. (2022) found it decreased *S. litura* populations by extending their exposure

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to natural enemies. Shulaev et al. (1997) observed that (E)-β-caryophyllene deterred the European corn borer in corn. However, in our research, β-caryophyllene did not affect BMSB movement.

In our experiment, α-humulene showed weak repellent effects on BMSB, unlike Martinez et al. (2017), who found it repellent and insecticidal on a wetland insect. In our study, Citronellal, known for its antiparasitic and repellent properties (Mahmud et al. 2022), showed weak repellent effects on BMSB, making its agricultural potential unclear. Dimethyl sulfide, reported as toxic and a good repellent for *Triatoma infestans* (Ramirez et al. 2020), had a mild impact on BMSB. Hexanal, generally attractive to *H. halys* (Noge 2019), acted as a weak repellent in our experiment. In our study, Linalool, suggested as an attractant for *H. halys* by Zhong et al. (2022), had no effect on BMSB movement. Nonanol, which is used to attract male red palm weevils (Abd El-Ghany 2019), also showed no effect on BMSB. These results highlight the complexity of chemical interactions with different insects and the need for further research. However, nerolidol proved a potent repellent, consistent with Zhong et al. (2022). Studies also indicate that *H. halys* presence on *Ailanthus altissima* accelerates nerolidol release, attracting natural enemies (Peterson et al. 2022). Ocimene and terpinolene also showed strong repellent effects on BMSB.

In the second part of our study, we focused on the most effective substances from the initial tests. Nerolidol emerged as the most effective repellent, consistent with previous findings. Our data showed that the specific chemical and exposure duration influenced the BMSB's movement. Nerolidol, ocimene, and terpinolene were repellents, while aggregation pheromone was an attractant. Overall, nerolidol holds promise for future use in repelling BMSB. Regarding the number of insects that made a no-choice decision, we observed that a significant proportion of insects did not make a clear choice in the olfactometer. Specifically, 30% did not choose either arm of the olfactometer out of the total number of insects tested. This outcome aligns with expectations for olfactometer studies with these insects, particularly without an attractive source in the olfactometer arms.

CONCLUSION

In conclusion, the BMSB significantly threatens agriculture due to its invasive nature and wide-ranging diet, causing major economic losses in the United States and Europe. Experts use various monitoring methods, including traps and native parasitoids, to mitigate its impact. This study explored the effects of volatile compounds on BMSB, identifying ethanol, nerolidol, ocimene, and terpinolene as strong repellents, while others had weaker or no significant effects. Contrary to previous studies, β-caryophyllene and other compounds did not repel BMSB. These results highlight the complexity of chemical interactions with insects and the need for further research. Notably, nerolidol consistently showed strong repellent properties, making it a promising candidate for future pest control. This study offers valuable insights into BMSB behaviour and suggests natural compounds for sustainable pest management. Further research and field trials are needed to confirm the practical effectiveness of nerolidol and other repellents in controlling BMSB infestations.

Conflict of interest

The authors declare that they do not have any known competing financial interests or personal ties that could appear to have influenced the work disclosed in this study.

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