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Chemical composition, insecticidal and insect repellent activity of *Schinus molle* leaf essential oil against *Tribolium confusum*, *Rhyzopertha dominica* and *Sitophilus granarius*

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The present study determines the chemical profile of *Schinus molle* L. essential oil and its toxicity and repellent effect on *Tribolium confusum*, *Rhyzopertha dominica* and *Sitophilus granarius* adults. Ninety-seven compounds were identified and the most abundant were ß-eudesmol (5.872%), elemol (9.028%), α-phellandrene (12.104%) and ß-phellandrene (16.613%). The phytochemical analysis of *Schinus molle* showed the presence of quinones, flavonoids, leucoanthocyanin, steroids and saponins. The oil demonstrated an insecticidal activity against *Tribolium confusum* (LC_{50} = 170.30 µL/L), *Rhyzopertha dominica* (LC_{50} = 174.30 µL/L) and *Sitophilus granarius* (LC_{50} = 241.20 µL/L) at 12h after treatment. *T. confusum* is the most sensitive to the treatment followed by *R. dominica* and *S. granarius*. Contact is the most effective mode of application compared to fumigation. Moreover, this essential oil exhibited a repellent activity as a function of the exposure time and concentrations. A selection index (Si) of 0.26, 0.35 and 0.15 with 20 µL/mL concentration was registered, showing the highest repellent activity against *T. confusum*, *R. dominica* and *S. granarius*, respectively.

Keywords: *Schinus molle;* chemical composition; stored product pests; insecticidal activity; repellent property.

Introduction

For many years, essential oils (EOs) have been seen as possible alternatives to synthetic pesticides including dichlorvos, methyl bromide, and phosphine (Smriti et al., 2019). They contain secondary metabolites in their composition (Lamboro et al., 2020), that can act as toxicants, repellents, antifeedants and oviposition inhibitors, showing potential as broad-spectrum insecticides (Martynov et al., 2019a, 2019b; Prieto-Rodríguez et al., 2025; Rybalka & Brygadyrenko, 2025). Furthermore, these botanical pesticides demonstrate potential in terms of human safety, insecticidal effectiveness, and minimal environmental impact (Boyko et al., 2020; Karabörklü & Ayvaz, 2023).

The insects of the genera *Tribolium*, *Sitophilus* and *Rhyzopertha* are pests with considerable worldwide economic importance because of the losses they cause in stored grains (Wang et al., 2019; Guettal et al., 2020; Titov & Brygadyrenko, 2021; Abes et al., 2024). The infestation by these insects leads to weight loss, diminished germination, decreased levels of nutrient, aroma, and flavor in grains, as well as elevated temperature and humidity conditions that facilitate the growth of microorganisms (Deb & Kumar, 2020; Prieto-Rodríguez et al., 2025).

Schinus molle L. (Anacardiaceae) or Peruvian pepper tree belongs to the family of Anacardiaceae. It is rich in various bioactive compounds and is used for pest control as a fumigant and repellent (Landero-Valenzuela et al., 2022; Laoudi et al., 2023). Therefore, this study characterized the chemical composition of *Schinus molle* EO and evaluated the EOs' fumigant and contact toxicity and repellent activity against three agricultural interest insects such as *Tribolium confusum*, *Rhyzopertha dominica* and *Sitophilus granarius*.

Materials and methods

Sitophilus granarius, *Rhyzopertha dominica* and *Tribolium confusum* were originally collected from the Algerian interprofessional cereals office in Tebessa (Northeast Algeria). The rearing of these species was carried out at the Water and Environment Laboratory (Echahid Cheikh Larbi Tebessi University, Tebessa) in cubic containers, each containing 1 kg of wheat, and maintained at a relative humidity (RH) of 65 ± 5% and a temperature of 27 ± 1 °C. Both female and male adults less than 15 days old were used in all experiments.

Schinus molle leaves were collected at El Hamamet (36°23′59″ N, 10°37′00″ E, altitude – 878 m) located in Tebessa a semi-arid region (Northeast Algeria) in December of 2018. Specimens were identified in the laboratory by botanists using books and plant catalogues and vouchered under the number (FTSM/12/18).

Dried leaves of the plants (50 g) were hydrodistilled with 500 mL distilled water in a Clevenger type apparatus for 2 to 3 h according (British Pharmacopoeia, 1998). The essential oil was conserved in an amber glass bottle at 4 ºC prior to GC-MS analysis. Its yield was determined according to plant dried weight (Costa et al., 2014).

Using GC-MS, the *S. molle* EO was investigated. A HP-5MS column (30 m × 0.25 mm × 0.25 m film thickness) was used in an HP Agilent 6890 Plus gas chromatograph. The injector temperature was raised to 250 °C at a rate of 2 °C per minute after being set at 60 °C for 8 minutes. Helium was the carrier gas, 0.5 ml/min was the flow rate through the column, and 0.2 µL of oil sample was injected to set the split ratio at 50:1. Operating at 70 eV, a quadrupole mass spectrometer was used for the GC/MS analysis. The retention index associated with the n-alkane series was used to identify the constituents, and the elution order was determined by comparing the index with the reference mass spectra.

The fumigant toxicity of leaves of *S. molle* EO on *T. confusum*, *R. dominica* and *S. granarius* was tested in plastic jars (60 mL) using the Huang et al. (2000) approach as previously described (Tine et al., 2023). In each jar, 10 adults were released. Whatman filter paper No. 2 disks were cut to 2 cm dia and attached with thread to the under surface of plastic bottles' screw caps. After a screening test, several concentrations ranged from 42 to 672 µL/L air were applied to the disks of filter paper. Control insects were kept in bottles without essential oil. Experiments with experimental and control groups were replicated six times. Numbers of dead and surviving individuals were also counted at 24h, 48h and 72 h after treatment. No mortality was recorded in the control series. Those insects unable to move their body, antennae and head were considered dead. Lethal concentrations (LC_{25} and LC_{50}) were determined by non-linear regression.

Various concentrations (4–64 µL/mL) of *S. molle* EO dissolved in acetone were applied on 3 g of wheat in plastic vials (60 mL) as described by González et al. (2014). After total evaporation of the solvent for 15 minutes, 10 adults (both sexes) of *T. confusum*, *S. granarius* and *R. dominica* were introduced into the vials. In a parallel series, wheat grains were given only acetone as a control. Treatment and control were replicated five times. Numbers of live and dead adults were also counted at 12, 24 and 48 hours after treatment and corrected by formula.

The preferential zone method was used to determine the repellent activity of SMEO against *R. dominica*, *S. granarius* and *T. confusum*, following the procedure described previously (Tine et al., 2023). The filter papers were halved and various concentrations of the solution were applied evenly to half of a filter paper disk. As a control, acetone alone was used to treat the other half of the filter paper. After air drying, the two halves were joined and positioned in the Petri dishes. Ten adults were released at the center of each filter paper, with five replications used for each concentration. Observations were conducted at different periods ranging from 30 minutes up to 12 hours, recording the number of insects present on the treated and untreated halves. The percentage of repellency (RP) is calculated using the formula of Nerio et al. (2009) as follows: RP (%) = [(NC-NT) / NC+NT)] ×100, where "NC" represents the percentage of beetles located in the control half and "NT": represents the percentage of beetles located in the treated half. The Selection Index (Si) was calculated as proposed by Mazzonetto & Vendramin (2003). Si = (2 X NT) / (NC + NT).

The Selection Index of EO was grouped into categories proposed by Arivoli et al. (2013):

0: neutral activity (Si = 1);
–: no-repellent activity (Si > 1.00);
+: low repellent activity (Si = 0.75–0.99);
++: middle repellent activity (Si = 0.50–0.74);
+++: high repellent activity (Si = 0.25–0.49);
++++: very high repellent activity (Si = 0.00–0.24).

Results and discussion

Essential oil yield and chemical composition. The yield of SMEO extraction was 2.64% (dry seeds of the plant). GC/MS analysis showed the existence of 97 components which represents 97.51% of the total of essential oil (Fig. 1). The percentage of all constituents, their retention time and retention index are listed in Table 1. The most abundant compounds included α-phellandrene (16.61%), ß-phellandrene (12.10%), elemol (9.02%), ß-eudesmol (5.87%) and D-limonene (4.90%).

Nevertheless, this yield seems to be more important than those obtained in leaves of *S. molle* EO collected from Tunis (0.95%) (Belloumi et al., 2024), from Brazil (1.2%) (Volpini-Klein et al., 2021), from Jordan (1%) and Turkey (1.2%) (Aboalhaija et al., 2019), and from Algeria (1.62%) (Miloudi & Dib, 2024). Consequently, yield variations may be elucidated, as per several research, by abiotic variables, origin, collection season, plant organ, duration, and the extraction and drying techniques applied (Yaman et al., 2020).

In comparison to previous investigations carried out in other countries, the chemical composition of *S. molle* EO collected in Algeria (Tebessa) presents similarities and differences. The chemical composition of *S. molle* EO grown in South West Algeria (Bechar) revealed the presence of α-phellandrene (20.45%), β-phellandrene (13.68%), dehydroxy-isocalamendiol (11.66%), (-)-germacrene D (8.93%) and δ-cadinene (5.46%) (Miloudi & Dib, 2024). The major compounds in the leaf essential oil collected in Rabat, Morocco include limonene (18.49%), α-terpinene (8.15%), γ-terpinene (8.15%), longifolene (8.48%). Kouachi et al. (2024) investigated the chemical composition of *S. molle* leaves EO obtained from Mascara (SMM), Algiers (SMA), and Djelfa (SMD), three regions in Algeria. The main components of SMA oil were camphene (31.82%), limonene (14.71%), and p-cymene (9.25%). In SMM and SMD oils, α-phellandrene (12.70% and 14.25%), limonene (11.90% and 13.02%), and germacrene D (10.15% and 10.62%) were the major components, respectively.

The major components of *S. molle* collected from Turkey were identified as α-phellandrene, limonene and ß-phellandrene respectively (Alnawari et al., 2018). According to published research, the most oxygenated sesquiterpenes in the *S. molle* EO grown in Egypt include β-eudesmol (10.34%), elemol (10.27%) and β-bisabolenol (5.06%) while the most prevalent monoterpene hydrocarbon in leaf oil is ρ-cymene (9.42%) (Hamdan et al., 2016). EO of *S. molle* collected from Tunisia contained eudesmol (14.82%), elemol (13.71%) and α-eudesmol (12.76%) (Kasmi et al., 2016). In Saudi Arabia, a study reported that δ-cadinene, guaiol and α-phellandrene were their major constituents (Abdel-Hameed & Bazaid, 2017). The results of Laoudi et al. (2023) showed a total of 23 components of *S. molle* EO, in which β-eudesmol (15.19%), elemol (13.97%), and D-limonene (9.89%) are the major constituents. Caryophyllene oxide (9.8% and 10.0%), β-caryophyllene (13.3% and 15.6%) and spathulenol (16% and 20.8%) were the main components of fresh and dry leaves of *S. molle*, respectively (Da Silva et al., 2023).

The variations can result from various reasons, including the extraction material (fresh or dried leaves), the plant's phenological age, climate conditions, and the season of leaf harvesting (Jayasundara & Arampath, 2021; Yang et al., 2018). The variations in chemical compositions indicate distinct chemotypes, which directly influence the efficacy of essential oils in integrated pest management (Landero-Valenzuela et al., 2022).

Table 1
Compounds obtained from essential oil of *Schinus molle* leaves analyzed by GC–MS

Peak	Compounds	RT	KI	Peak area, %
1	*α*-thujene	7.17	930	tr
2	*α*-pinene	7.54	934	3.34
3	camphene	8.26	943	tr
4	sabinene	10.18	967	0.63
5	*β*-pinene	11.90	988	4.83
6	*α*-phellandrene	13.08	1004	16.61
7	3-carene	13.65	1009	tr
8	*α*-terpinene	14.26	1014	tr
9	*p*-cymene	15.19	1023	1.65
10	*β*-phellandrene	16.02	1030	12.10
11	*D*-limonene	16.21	1032	4.90
12	*β*-ocimene (E)	18.26	1050	tr
13	*γ*-terpinene	18.92	1056	tr
14	linalool oxide F	20.50	1070	tr
15	terpinolene	21.77	1082	0.15
16	*trans*-linalool oxide F	22.01	1084	tr
17	linalool	23.52	1097	0.79
18	*n*-nonanal	23.82	1100	tr
19	*p*-menth-2-en-1-ol (Cis)	24.87	1121	0.11
20	camphor	26.38	1133	tr
21	*β*-terpineol (Cis)	26.55	1141	tr
22	borneol	28.55	1165	tr
23	angustifolenone	28.74	1167	tr
24	terpinen-4-ol	29.58	1177	0.13
25	cryptone	30.16	1184	0.13
26	cymene-8-ol	30.51	1188	tr
27	*α*-terpineol	30.83	1192	0.15
28	piperitol (*Cis*)	32.16	1196	tr
29	*trans*-piperitol	32.29	1210	tr
30	*trans*-carveol	33.14	1221	tr
31	carveol (*Cis*)	34.11	1233	tr
32	nerol	34.21	1234	tr
33	cumin aldehyde	34.36	1236	tr
34	carvone	34.84	1242	0.85
35	piperitone	35.54	1251	tr
36	piperitone epoxide (*Cis*)	35.75	1253	0.30
37	linalyl acetate	36.37	1261	0.19
38	decenal (*2E*)	36.57	1264	tr
39	geraniol	36.78	1266	tr
40	*p*-menth-1-en-7-al	36.88	1267	tr
41	pregeijerene *B*	37.60	1276	0.11
42	bornyl acetate	38.03	1282	tr
43	tetradecatriene (*3Z, 6Z, 9Z*)	38.58	1289	tr
44	lavandulyl acetate	39.00	1294	tr

Peak	Compounds	RT	KI	Peak area, %
45	prenyl hexanoate	39.24	1297	tr
46	carvacrol	39.87	1306	0.20
47	*exo*-2-Hydroxycineole acetate	42.06	1342	tr
48	*α*-cubebene	42.37	1347	tr
49	dihydro carveol acetate	42.55	1350	tr
50	nepetalactone (*4aα, 7α, 7aα*)	43.21	1361	tr
51	*α*-ylangene	43.95	1373	0.19
52	*β*-bourbonene	44.45	1381	tr
53	*β*-cubebene	45.01	1390	tr
54	*β*-elemene	45.22	1393	0.73
55	*α*-gurjunene	46.10	1407	0.39
56	caryophyllene (E)	46.63	1416	0.51
57	*β*-copaene	47.30	1426	tr
58	*γ*-elemene	47.83	1434	0.35
59	*α*-humulene	48.76	1449	0.45
60	*allo*-aromadendrene	49.19	1455	0.16
61	dehydro-aromadendrene	49.39	1458	tr
62	caryophyllene (*9-epi-E*)	50.00	1468	tr
63	*γ*-gurjunene	50.27	1472	0.16
64	germacrene *D*	50.65	1478	2.31
65	*β*-selinene	50.83	1481	0.19
66	*δ*-selinene	50.95	1483	tr
67	*β*-guaiene (*Cis*)	51.13	1486	0.17
68	bicyclogermacrene	51.67	1494	3.74
69	*α*-muurolene	52.00	1499	0.91
70	*α*-bulnesene	52.64	1510	0.34
71	*δ*-amorphene	52.77	1512	0.38
72	bisabolene (*Z- γ*)	52.97	1516	tr
73	δ -cadinene	53.39	1523	2.09
74	bisabolene (*E-iso-γ*)	53.61	1527	tr
75	zonarene	53.76	1530	0.11
76	*α*-cadinene	54.06	1535	tr
77	elemol	55.00	1551	9.03
78	palustrol	55.70	1564	0.17
79	nerolidol (*E*)	56.14	1571	0.15
80	spathulenol	56.48	1577	2.55
81	globulol	56.73	1582	0.13
82	viridiflorol	57.14	1589	0.52
83	cubeban-11-ol	57.45	1594	tr
84	humulene epoxide II	57.99	1604	2.90
85	eudesmol (10-epi- *γ*)	58.57	1615	0.34
86	cubenol (1-épi)	59.20	1628	0.64
87	*γ*-eudesmol	59.57	1635	2.65
88	cubenol	60.00	1644	0.66
89	*α*-epi-cadinol	60.10	1646	0.36
90	*β*-eudesmol	60.66	1657	5.87
91	*α*-eudesmol	60.84	1661	2.55
92	*α*-cadinol	60.96	1663	1.11
93	bulnesol	61.57	1675	3.52
94	guaia-3,10(14)-dien-11-ol	61.80	1680	tr
95	shyobunol	62.50	1693	1.93
96	amorpha-4,9-dien-14-al	63.21	1706	tr
97	14-hydroxy-humulene	63.55	1712	tr
	Total			97.51%

Note: Kovats retention index calculated.

Fumigant toxicity. Corrected mortalities recorded in *S. granarius* during fumigation toxicity test increased significantly depending on the doses applied and the time after treatment in *S. granarius* treated by fumigation at 24 h ($F_{4,15}$ = 162.6; P < 0.001), at 48 h ($F_{4,15}$ = 111.8; P < 0.001), and at 72 h ($F_{4,15}$ = 118.10; P < 0.001) after treatment.

Furthermore, application of this oil increased the mortality rate of *R. dominica* in relation to the applied concentrations and the exposure duration at 24 h ($F_{4,20}$ = 142.8; P < 0.001), 48 h ($F_{4,15}$ = 73.17; P < 0.001), and 72 h ($F_{4,15}$ = 95.92; P < 0.001).

Finally, the mortalities of *T. confusum* increased significantly according to the applied concentrations and the time after treatment at 24 h ($F_{4,10}$ = 89.07; P < 0.0001), 48 h ($F_{4,10}$ = 59.35; P < 0.0001) and 72 h ($F_{4,10}$ = 115.60; P < 0.0001).

The lethal concentrations values of the essential oil and their fiducial limits were mentioned in Table 2. Based on calculated lethal concentrations, *T. confusum* is the most sensitive to the treatment followed by *R. dominica* and *S. granarius*.

EO has varying effects on different insects according to the plant species and physiological properties of the insect (Hikal et al., 2017). It acts at various sites including the insect nervous system and has several modes of action such as induction of detoxification system (Giunti et al., 2023; Karabörklü & Ayvaz, 2023). Essential oils may disrupt insect physiological activities upon absorption through the integument or ingestion, resulting in malformations, decreased fertility, neurotoxic effects, and alterations in respiratory systems at different developmental stages (Khursheed et al., 2022). A significant part of the research on *S. molle* essential oil was conducted to find its efficacy against pest insects primarily from the orders Coleoptera, Lepidoptera, and Hemiptera (Scalvenzi et al., 2024). Our experiments reveal that *T. confusum* is more sensitive to EO extracted from *S. molle* than *R. dominica* and *S. granarius*. The data corroborate the previous results, confirming the high efficacy of *S. molle* EO against the studied pests (Sekrane et al., 2022).

The most prevalent compounds are α-phellandrene and ß-phellandrene, followed by elemol, ß-eudesmol and limonene. The insecticidal effect of α-phellandrene has been previously reported by various researchers (Chaaban et al., 2019; Radice et al., 2022), and although the activities of EOs can generally be attributed to a synergistic effect of the components, several studies support the hypothesis of a potential role of α-phellandrene in the biopesticide activity of *S. molle* EO (Scalvenzi et al., 2024). The study of Belloumi et al. (2024) demonstrated that the SMEO revealed a high toxicity against *T. castaneum* (LC_{50} = 0.019 μL/cm^2) and even greater potency against *R. dominica* (LC_{50} = 0.010 μL/cm^2). This efficacy may be attributed to the presence of DL-limonene and α-phellandrene, which have a potential role in the biopesticide activity of *S. molle* EO (Belloumi et al., 2024; Scalvenzi et al., 2024).

The efficiency of this EO by fumigation has been shown against *R. dominica* (LC_{50} = 0.6 mg/cm^2) (Benzi et al., 2009), *T. confusum* (LC_{50} = 46.9 μL/L) (Gad et al., 2022), *Ephestia kuehniella* (LC_{50} = 170.7 μL/L) (Chaaban et al., 2022) and *S. oryzae* (75% mortality at 5 μL/L) (Belhoussaine et al., 2022).

Several studies have demonstrated the effectiveness of *S. molle* by contact against *Drosophila suzukii* (LC_{50} = 19.3 μL/mL) (de Souza et al., 2022), *S. zeamais* (LC_{50} = 38.2 mL/kg and LC_{50} = 781.5 ppm) (Arias et al., 2017; Landero-Valenzuela et al., 2022) and *Anticarsia gemmatalis* (30.0% mortality at 2.0% v/v) (Vicenço et al., 2020). Benzi et al. (2009) evaluated the insecticidal efficacy of essential oils derived from the leaves and fruits of *S. molle* against *S. oryzae*, concluding that these oils did not exhibit a fumigant effect on adult *S. oryzae* over the four-day assessment period. The mortality may have resulted from the chemicals entering through the cuticle at higher doses or from prolonged exposure time.

Table 2

Efficacy of *S. molle* essential oil applied to *T. confusum*, *S. granarius* and *R. dominica* adults: lethal concentrations (μL/L of air) and their fudicial limits (95%)

Species	Time, hours	Correlation coefficient	Hill Slope	LC_{25} (μL/L of air) (CL 95%)	LC_{50} (μL/L of air) (CL 95%)
T. confusum	24	0.98	1.85	94.23 [61.81–134.10]	170.30 [130.80–219.80]
	48	0.98	1.89	70.52 [46.90–98.00]	126.10 [98.64–159.30]
	72	0.99	1.84	44.14 [34.52–53.87]	79.96 [69.08–92.06]
S. granarius	24	0.99	3.33	173.50 [165.90–180.60]	241.20 [233.70–249.50]
	48	0.99	3.07	141.90 [130.30–152.20]	202.80 [194.40–211.50]
	72	0.99	3.47	123.80 [108.70–136.00]	169.80 [159.70–179.00]
R. dominica	24	0.99	3.26	124.50 [119.70–129.10]	174.30 [170.40–178.20]
	48	0.96	2.64	99.25 [71.40–121.00]	150.40 [129.90–169.80]
	72	0.98	2.91	83.43 [66.00–97.31]	121.70 [108.10–133.50]

Variations in the climatic, geographic and edaphic, storage methods, type of plant material and post-harvest drying and extraction method used can affect the yield and chemical profile of EO (Saulle et al., 2018) and as a result, their biological activities (Machado et al., 2019).

Contact toxicity. The mortalities of *S. granarius* increase significantly according to the applied concentrations and the time after treatment at 12 h ($F_{4,15}$ = 152.9; $P < 0.0001$), 24 h ($F_{4,15}$ = 147.8; $P < 0.0001$) and 48 h ($F_{4,15}$ = 98.15; $P < 0.0001$). The application of *S. molle* by contact revealed an increase in mortality as function of the time after treatment and the applied doses at 12 h ($F_{3,12}$ = 90.36; $P < 0.0001$), 24 h ($F_{3,12}$ = 59.97; $P < 0.0001$) and 48 h ($F_{3,12}$ = 51.89; $P < 0.001$, Fig. 2). In *T. confusum* adults treated by SMEO, the mortality increased significantly according to the time after treatment and the applied concentrations at 12 h ($F_{3,8}$ = 142.30; $P < 0.001$), at 24 h ($F_{3,8}$ = 166.20; $P < 0.0001$) and at 48 h ($F_{3,8}$ = 78.13; $P < 0.0001$, Fig. 1).

Moreover, based on lethal concentrations, *T. confusum* adults were more sensitive to *S. molle* EO as compared to *S. granarius* and *R. dominica* adults.

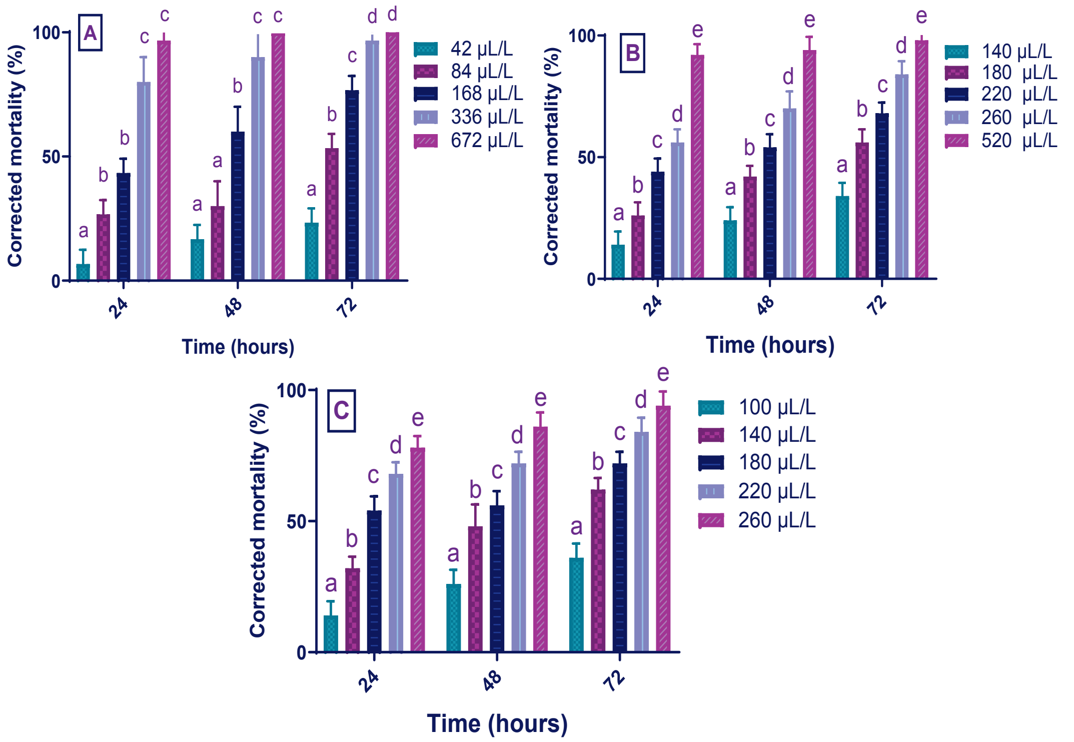

Fig. 1. Fumigant (μL/L of air) toxicity of *S. molle* EO against *T. confusum* (*A*), *S. granarius* (*B*) and *R. dominica* (*C*) adults: corrected mortality (mean ± SE, n = 5 and 4 replicates each containing 10 adults respectively); in the same period, different small letters denote a significant difference (HSD Tukey test at P < 0.05)

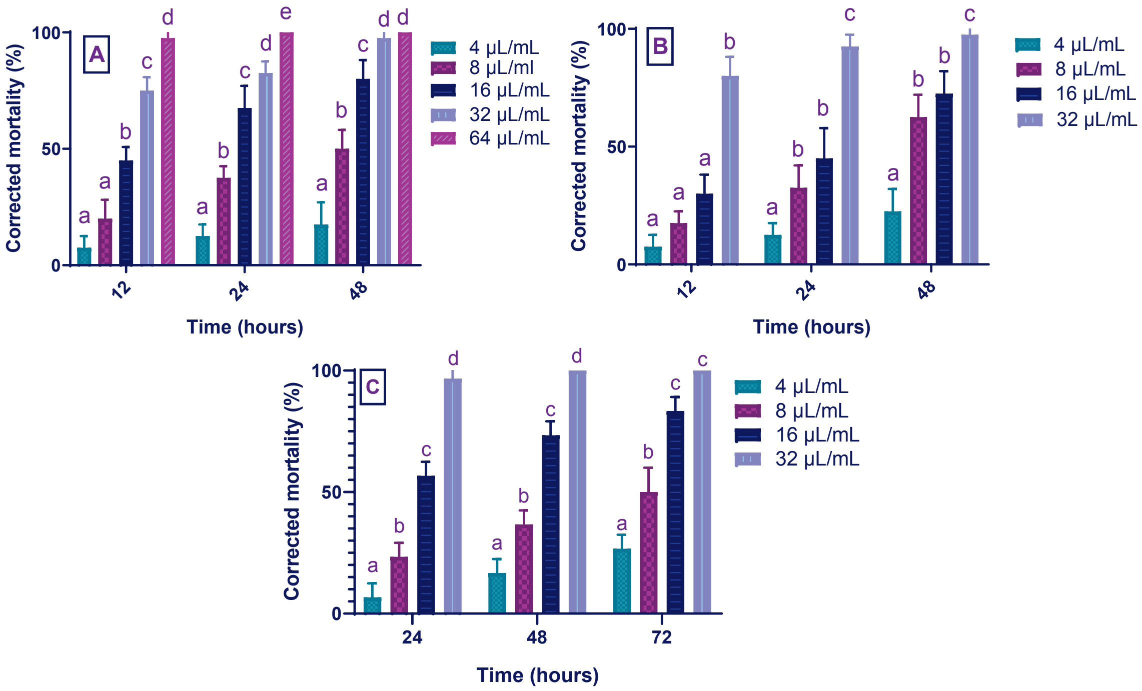

Fig. 2. Contact (μL/mL) toxicity of *S. molle* EO against *S. granarius* (*A*), *R. dominica* (*B*) and *T. confusum* (*C*) adults: corrected mortality (mean ± SE, n = 5 and 4 replicates, each containing 10 adults respectively); in the same period, different small letters denote a significant difference (HSD Tukey test at P < 0.05)

Table 3
Efficacy of *S. molle* essential oil applied to *T. confusum*, *S. granarius* and *R. dominica* adults: lethal concentrations (μL/mL) and their confidence limits (95%)

Species	Time, hours	Correlation coefficient	Hill slope ± SD	LC_{25} (μL/mL) (CL 95%)	LC_{50} (μL/mL) (CL 95%)
T. confusum	12	0.98	2.55 ± 0.45	8.72 [4.82–9.10]	13.42 [9.45–18.65]
	24	0.98	2.23 ± 0.38	5.96 [2.84–9.60]	9.76 [6.57–13.99]
	48	0.98	1.98 ± 0.31	4.22 [1.85–6.69]	7.35 [4.86–10.34]
S. granarius	12	0.99	1.91 ± 0.03	9.72 [7.60–12.10]	17.24 [14.67–20.21]
	24	0.99	1.77 ± 0.03	5.90 [4.35–7.58]	10.97 [9.06–13.25]
	48	0.99	2.19 ± 0.01	4.89 [4.34–5.45]	8.09 [7.48–8.73]
R. dominica	12	0.95	2.36 ± 0.64	12.55 [3.18–15.17]	19.99 [11.29–54.56]
	24	0.91	1.80 ± 0.59	7.51 [0.01–21.15]	13.81 [3.93–115.20]
	48	0.94	1.76 ± 0.45	3.82 [0.19–7.72]	7.11 [2.12–13.31]

Note: CL – confidence limits.

Repellent activity. The repellency percent varied according to the tested pest species, EO concentration, and exposure duration. The highest repulsion rates (73.3%, 65.0% and 85.0%) are found at 3 h with the highest concentrations (20 μL/mL) for *T. confusum*, *R. dominica* and *S. granarius* respectively.

In addition, we noticed that the high values are observed in *S. granarius* and EO is classified in category +++ (very high repellent activity), followed by *R. dominica* and *T. confusum*.

The number of insects on the treated area decreased while essential oil concentration increased. A Si of 0.26, 0.35 and 0.15 with 20 μL/mL concentration was recorded denoting a high (+++) and very high repellent activity (++++); while with the lowest ones (5 μL/mL) a Si of 0.86, 0.75 and 0.70 were registered in *T. confusum*, *R. dominica* and *S. granarius*.

Essential oils are categorized as secondary metabolites and are vital for plants due to their repelling properties against herbivorous pests, their ability to attract pollinators, and their allelopathic effects (Scalvenzi et al., 2024). The current investigation demonstrated a strong repellent activity of *S. molle* EO against *R. dominica*, *T. confusum* and *S. granarius*. This activity was likely related to the content of D-limonene in the EO, which is considered a potent insecticidal agent (Sarma et al., 2019).

The repellent activity of this oil has been shown against *T. granarium* and *T. castaneum* (Abdel-Sattar et al., 2010), *R. dominica* (Benzi et al., 2009), *S. oryzae* (Belhoussaine et al., 2022), *S. zeamais* (Arias et al., 2017; Senthil-Nathan, 2020), against oriental cockroach (Deveci et al., 2010) and against mosquitoes (Tseghai et al., 2019). The efficacy of essential oils (EOs) against pests is influenced by various factors, including the type of repellent (active ingredient and formulation), environmental conditions (wind, humidity, and temperature), application method, and the insects' vulnerability to repellents (Hikal et al., 2017).

Table 4
Repellency effect of SMEO against *R. dominica*, *S. granarius* and *T. confusum* adults

Species	Time	Concentrations, μL/mL	RI ± SD	1 – SD	1 + SD	Effect	RP (%) ± SD
T. confusum	1/2 h	5	0.86 ± 0.11	0.88	1.11	+	13.33 ± 8.88[a]
		10	0.73 ± 0.11	0.88	1.11	++	26.66 ± 8.88[a]
		20	0.60 ± 0.00	1.00	1.00	++	40.00 ± 0.00[b]
	1 h	5	0.73 ± 0.11	0.88	1.11	++	26.66 ± 8.88[a]
		10	0.46 ± 0.11	0.88	1.11	+++	53.33 ± 8.88[a]
		20	0.33 ± 0.11	0.88	1.11	+++	66.66 ± 8.88[b]
	3 h	5	0.66 ± 0.11	0.88	1.11	++	33.33 ± 8.88[a]
		10	0.33 ± 0.11	0.88	1.11	+++	66.66 ± 8.88[b]
		20	0.26 ± 0.11	0.88	1.11	+++	73.33 ± 8.88[b]
R. dominica	1/2 h	5	0.75 ± 0.10	0.90	1.10	+	25.00 ± 7.50[a]
		10	0.65 ± 0.10	0.90	1.10	++	35.00 ± 7.50[a]
		20	0.45 ± 0.10	0.90	1.10	+++	55.00 ± 7.50[b]
	1 h	5	0.70 ± 0.11	0.88	1.11	++	30.00 ± 10.00[a]
		10	0.55 ± 0.10	0.90	1.10	++	45.00 ± 7.50[a]
		20	0.40 ± 0.16	0.83	1.16	+++	60.00 ± 10.00[b]
	3 h	5	0.65 ± 0.10	0.90	1.10	++	35.00 ± 7.50[a]
		10	0.55 ± 0.10	0.90	1.10	++	45.00 ± 7.50[a]
		20	0.35 ± 0.10	0.90	1.10	+++	65.00 ± 7.50[b]
S. granarius	1/2 h	5	0.70 ± 0.11	0.88	1.11	++	30.00 ± 10.00[a]
		10	0.45 ± 0.19	0.80	1.19	+++	55.00 ± 15.00[a]
		20	0.30 ± 0.11	0.88	1.11	+++	70.00 ± 10.00[ba]
	1 h	5	0.55 ± 0.25	0.74	1.25	++	45.00 ± 17.50[a]
		10	0.35 ± 0.10	0.90	1.10	+++	65.00 ± 7.50[a]
		20	0.25 ± 0.10	0.90	1.10	+++	75.00 ± 7.50[a]
	3 h	5	0.40 ± 0.16	0.83	1.16	+++	60.00 ± 10.00[a]
		10	0.30 ± 0.11	0.88	1.11	+++	70.00 ± 10.00[a]
		20	0.15 ± 0.10	0.90	1.10	++++	85.00 ± 7.50[a]

Conclusion

GC/MS analysis of *S. molle* essential oil resulted in an identification of 97 components. The main constituents are α-phellandrene (16.61%), ß-phellandrene (12.10%) and elemol (9.02%). The *S. molle* leaf essential oil exhibited a high level of toxicity against *T. confusum*, *S. granarius* and *R. dominica*. The chemical investigation can demonstrate a relationship between the biological activity and compounds identified by GC-MS analysis. Further, additional research is required to completely assess the insecticidal, and repellent activities of individual compounds found in EO as well as any potential synergistic effects. Overall, the results obtained can be considered to point towards further studies of this plant with the aim of developing new insecticides or repellent agents.

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