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Comparative study of essential oil composition and biological activities of pink pepper (*Schinus molle* L.) plant organs from Tunisia

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The antioxidant, antibacterial, and repellent activities of essential oils from different plant parts of Tunisian *Schinus molle* were determined. Gas chromatography-mass spectrometry (GC-MS) analyses revealed that the stems' essential oils are dominated by Geraniol (20.94%), α-eudesmol (28.42%), and Germacrene B (13.6%). Leaves and seeds were characterised by α-limonene (30.43 and 37.66%, respectively) and α-eudesmol (12.48 and 8.55%, respectively) as the most abundant compounds. The antioxidant activity of essential oils was assessed using two techniques: inhibition of the free radical DPPH and the iron reduction effect (FRAP). Considerable levels of antioxidant activities of the investigated essential oils were highlighted. Stems essential oils revealed the best activity with 0.42 mg/mL for the antiradical capacity and 35.52 μmoL TROLOX/g HE for the FRAP assay. Based on the determination of the diameter of inhibition, the minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC), a high antibacterial activity was observed against Gram-positive strains *Staphylococcus aureus* and *Enterococcus feacium* (57 and 53 mm, respectively) in the presence of stems' essential oils. For repellent activity, the essential oils of stems showed the best potential, followed by the oils of seeds. The differences in the biological activities of the tested essential oils were attributed to their essential oil compositions. Consequently, *S. molle* stems essential oil can serve as a natural source of bioactive compounds for use in the food and pharmaceutical industries.

Keywords: Antimicrobial, Antioxidant, Essential oil, Repellent activity, *Schinus molle* L.

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Introduction

Aromatic plants have long been recognised as a valuable source of pharmaceutical compounds and food additives, contributing significantly to both traditional and modern therapeutic applications[1,2]. Among the diverse bioactive compounds present in aromatic plants, essential oils and their individual constituents are particularly notable for their potent therapeutic properties. These bioactive molecules are increasingly recognised for their efficacy in traditional medicine, as well as in the food and fragrance industries, where they are valued for their antimicrobial, antioxidant, and flavour-enhancing effects[3-5]. Another key factor driving research on essential oils is the quest for natural bioactive compounds with insecticidal properties, as well as minimal environmental impact and low toxicity to human health. These compounds are increasingly seen as promising alternatives to conventional agricultural pesticides[6].

The *Anacardiaceae* family consists of 73 genera and approximately 850 species, including both trees and shrubs. Plants in this family are noted for their fruitfulness and high-quality wood. Many species are prevalent in tropical and subtropical regions[7]. The genus *Schinus* includes about 30 species, with the majority occurring naturally in South America[8]. Two species, *S. molle* L. and *S. terebinthifolius* Raddi, have been introduced to North Africa, particularly Tunisia[4].

The pepper tree (*Schinus molle* L.), a member of the *Anacardiaceae* family, is commonly cultivated as an ornamental tree in the Mediterranean region. It is native to South America, with a habitat extending

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from southern Brazil to Chile and Mexico[9]. The tree features persistent foliage with fine, drooping branches. Its small, white flowers measure 3 to 4 mm and its pink, globular berries[10]. The leaves are composed of 3 to 10 pairs of serrated leaflets. The flowers are unisexual, hermaphroditic, and arranged in elongated panicles. The fruits are round, red drupes, 4 to 6 mm in diameter, and are clustered in hanging formations[8].

S. molle is widely recognised in traditional medicine for its antiseptic, anti-inflammatory, antirheumatic, and antidiarrheal properties. Additionally, it is known for its tonic, astringent, vasoconstrictor, and diuretic effects[11,12,13]. This plant has been traditionally used to treat a wide range of conditions, including fever, cough, colds, bronchitis, conjunctivitis, ophthalmia, gastrointestinal disorders, and hemorrhoids[14,15]. Recent studies have further highlighted its potential in managing metabolic disorders, including hyperglycemia, due to its anti-inflammatory and antioxidant properties. Moreover, *S. molle* L. has also been used to treat conditions such as rheumatism, respiratory and urinary tract infections, toothaches, and rheumatoid arthritis[16]. These findings underline the continued relevance of this plant in both traditional and modern medicine.

The essential oils of *S. molle* from various locations have been studied, revealing some variation in their chemical composition[11]. Essential oils from the leaves of *S. molle* in Tunisia and Turkey were notably rich in α-phellandrene and β-phellandrene. Nevertheless, the essential oils extracted from the berries of *S. molle* in Tunisia were dominated by α-phellandrene, β-phellandrene, and β-pinene[9]. In contrast, the essential oils from the aerial parts of *S. molle* L. grown in Southern Brazil contained significant amounts of Limonene, (E)-caryophyllene, and bicyclogermacrene.

To the best of our knowledge, there are few reports on the chemical composition of essential oils from the leaves, stems, and seeds of *S. molle* L. collected in Tunisia. Therefore, the objective of this study is to analyse the chemical composition of essential oils derived from the stems, leaves, and seeds of *Schinus molle* from Tunisia, and to evaluate their biological activities, including antioxidant, antibacterial, and repellent properties. The findings aim to provide valuable insights into the identification and selection of essential oils rich in bioactive compounds, with potential applications in the food and pharmaceutical industries. This research could also contribute to a better understanding of the potential of *S. molle* essential oils as natural and sustainable alternatives for addressing health issues and insect-related concerns.

Materials and Methods

Plant material

Plant organs (stems, leaves, and seeds) of *S. molle* were collected in March 2022 from Mograne (Governorate of Zaghouan, North of Tunisia). Samples were identified by Pr. Slim Rouz at the Higher School of Agriculture of Mograne (ESAMO), and voucher specimens were deposited at the Herbarium in the cited institute (S.m.03.2022). Plant materials were air-dried at room temperature for two weeks.

Extraction of essential oils

Dried samples (stems, leaves, and seeds) were subjected to hydro-distillation using a Clevenger apparatus for 3 hours. The oils were collected directly from the distillate and stored in dark vials at 4°C. Three replications of distillation were performed.

Gas chromatography/mass spectrometry (GC–MS) analysis

GC-MS analyses were conducted using an Agilent 7890A gas chromatograph equipped with a HP-5MS capillary column (30 m length, 0.25 mm inner diameter, 0.25 µm film thickness) coupled to a mass selective detector (Agilent 5975C inter MSD). Helium was used as the carrier gas at a flow rate of 0.8 mL/min. The oven temperature was programmed to increase from 60 to 240°C at a rate of 4°C/min. The injector temperature was kept at 250°C, while the quadrupole and source temperatures were set at 150 and 230 °C, respectively. Mass scanning was conducted over a range of 50 to 550 m/z at 70 eV[17].

The identification of essential oil components was carried out using several methods: comparing their retention times with those of authentic standards analysed under the same chromatographic conditions, comparing their retention indices with literature values, and co-injecting the essential oils with available authentic standards. Furthermore, identification was confirmed by comparing the mass spectra of terpenic compounds with those stored in the W8N08 and NIST08 libraries.

Antioxidant activity

Free radical scavenging activity

The DPPH free radical test was conducted as described by Jaouadi *et al.*[17]. One millilitre of diluted oil was added to 3 mL of a methanolic DPPH solution. After 60 minutes, it was measured against a blank at 517 nm. Analyses were conducted in triplicate, and the results (IC_{50}) were expressed as mg/mL.

FRAP assay

The iron-reducing activity was assessed using the method outlined by Jaouadi *et al.*[17], with some modifications. The FRAP reagent was prepared using a sodium acetate buffer solution (300 mM, pH 3.6), tripyridyltriazine (TPTZ) (10 mM in 40 mM HCl), and FeCl3·6H2O (20 mM) in a volumetric ratio of 10:1:1. An aliquot of each essential oil (25 µL), previously diluted, was mixed with 200 µL of the FRAP solution. After incubation for 30 minutes, the absorbance was measured at 593 nm. A Trolox standard curve was used, and results were expressed in µmol Trolox equivalents/g EO.

Antibacterial activity assays

The antibacterial activity was assessed using both the agar disc diffusion method and the microdilution broth susceptibility assay. The minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) were determined.

Microbial strains

The antibacterial activity was tested against two gram-negative bacteria, *Escherichia coli* ATCC 8739, *Salmonella typhimurium* ATCC 14028, and two positive ones, *Enterococcus faecium* ATCC 19434, *and Staphylococcus aureus* ATCC 6538.

Disc diffusion method

The tested microorganisms were initially suspended and spread onto appropriate solid media plates, which were incubated overnight at 37°C. After 24 hours, 4–5 loops of pure colonies from each bacterial strain were transferred to a saline solution in test tubes[18]. These suspensions were adjusted to match the 0.5 McFarland turbidity standard (~108 cells/mL). Sterile cotton swabs were then dipped into each bacterial suspension. The agar plates were streaked three times using each swab, rotating the plate 60° between each streak. Finally, the swab was carefully rubbed along the edge of the plate to ensure an even distribution. Sterile paper discs were then placed onto the inoculated plates and impregnated with oil solutions diluted in dimethyl sulfoxide (DMSO). After incubation, the diameters (mm) of the inhibition zones were measured. Gentamycin (10 µg/disc) and dimethyl sulfoxide (DMSO) were used as positive and negative controls, respectively.

Determination of minimum inhibitory (MIC) and bactericidal (MBC) concentrations

MIC and MBC concentrations were revealed using the method described by Bejaoui *et al.*[18].

Repellent activity against *Tribolium castaneum*

The repellency bioassay was conducted at ambient laboratory temperature and relative humidity using the area presence method, as described by Mediouni-Ben Jemâa *et al.*[19]. The number of insects present on different sides of the paper were recorded after 1,3, 5, and 24 h.

Statistical analysis

The variations in essential oil compositions and their biological activities were evaluated using a one-way Analysis of Variance (ANOVA), followed by Duncan's multiple range test. Correlations between the chemical components of the essential oils and their antioxidant and antibacterial activities were also analysed. All statistical analyses were performed using SPSS software, version 26.0 for Windows.

Results

Variation of essential oil yield and composition among *S. molle* organs

The determination of the yield according to the used parts of the plant revealed a difference between the leaves, stems, and seeds (Table 1). Essential oil yields ranged between 0.17 and 3.25% for stems and seeds, respectively. The profiles of essential oils were significantly different (Table 1, Fig. 1). Monoterpenes hydrocarbons highly dominated the essential oils of both leaves and seeds (42.29 and 68.87%, respectively). Oxygenated monoterpenes and sesquiterpenes hydrocarbons were the major constituents of the stems' essential oils (20.94 and 28.41%, respectively).

Stems of essential oils were distinguished by the presence of high amounts of α-eudesmol (28.42%), Geraniol (20.94%), and Germacrene B (13.6%). However, α-limonene was the dominant component of the essential oils of the leaves and seeds (30.43 and 37.66%, respectively). A high level of α-phellandrene (18.9%) was also revealed as one of the most abundant components of seeds' essential oils.

Table 1 — Mean percentage of the essential oil compounds.

Compounds	RI	Stems	Leaves	Seeds	Species level
Yield (%)		0.17	1	3.25	1.47
α-pinene	938	tr^{b}	tr^{b}	2.92±0.0^{a}	0.97±0.0
β-myrcene	992	tr^{c}	1.95±0.0^{b}	9.39±0.1^{a}	3.78±0.0
α-phellandrene	1005	tr^{c}	9.91±0.0^{b}	**18.9±0.5^{a}**	**9.60±0.17**
α-limonene	1041	7.4±0.3^{c}	**30.43±2.1^{b}**	**37.66±0.8^{a}**	**25.16±1.07**
Geraniol	1231	**20.94±0.8^{a}**	0.59±0.0^{b}	tr^{c}	**7.18±0.27**
Linalyl acetate	1259	tr^{c}	2.29±0.1^{a}	2.27±0.1^{b}	1.52±0.06
Bornyl acetate	1286	tr^{b}	0.35±0.0^{a}	tr^{b}	0.12±0.0
β-elemene	1388	0.58±0.0^{a}	tr^{b}	tr^{b}	0.86±0
β-elemene	1391	1.67±0.6^{a}	tr^{b}	tr^{b}	0.56±0.2
β-panasinsene	1397	3.1±0.0^{a}	tr^{b}	tr^{b}	1.00±0.0
Aristolene	1403	4.38±0.0^{a}	3.11±0.0^{b}	tr^{c}	2.50±0.0
β-caryophyllene	1412	tr^{c}	7.69±1.1^{a}	4.33±1.0^{b}	4.01±0.7
Germacrene D	1477	tr^{b}	1.5±0.4^{a}	1.4±0.1^{a}	0.97±0.17
Lepidozene	1485	5.47±0.8^{a}	4.55±0.1^{b}	tr^{c}	3.34±0.3
Δ-cadinene	1526	**7.09±0.0^{a}**	4.62±0.2^{c}	5.74±0.6^{b}	**5.82±0.27**
Elemol	1549	tr^{b}	7.84±0.4^{a}	tr^{b}	2.61±0.13
Germacrene B	1552	**13.6±0.3^{a}**	tr^{b}	tr^{b}	4.53±0.1
Caryophyllene oxyde	1561	**5.45±0.0^{a}**	tr^{b}	tr^{b}	1.82±0.0
Spathulenol	1573	tr^{c}	6.99±0.9^{a}	5.68±0.4^{b}	4.22±0.43
α-eudesmol	1629	**28.42±1.3^{a}**	**12.48±0.5^{b}**	8.55±0^{c}	**16.48±0.6**
Total identified (%)		98±1.37	94.3±1.93	93.92±1.2	96.07±1.5
Monoterpenes hydrocarbons (%)		7.4	42.29	68.87	39.51
Oxygenated monoterpenes (%)		20.94	3.23	2.27	8.82
Sesquiterpenes hydrocarbons (%)		28.41	18.36	11.47	20.09
Oxygenated sesquiterpenes (%)		41.3	22.58	14.23	26.02

Means followed by different letters within the same row are significantly different ($p < 0.05$). RI: Retention indices relative to n-alkans on HP-5MS column.

Antioxidant activity

The antioxidant capacity was evaluated using two complementary methods: free radical scavenging activity (DPPH) and ferric reducing power (FRAP). A notable variation was observed among plant organs in their ability to scavenge DPPH (Table 2). In fact, essential oils extracted from stems exhibited the highest radical scavenging activity (0.42 mg/mL). An intermediate activity was revealed for the leaves' essential oils (12.6 mg/mL). Following the antiradical capacity, the stems essential oil exhibited the best ferric reducing power with 35.52 µmoL Trolox equivalents/g EO. A moderate reducing power activity was observed in the seeds' essential oil, with a value of 17.8 µmoL Trolox equivalents/g EO. A significant correlation (p <0.01) was noted between Δ-cadidene, the antiradical capacity, and ferric reducing power.

Antibacterial activity

The antibacterial activity estimated by the diameter of inhibition varied according to species and bacterial strains (Table 3). The strongest activity was observed against *Staphylococcus aureus*, exhibiting the largest inhibition zones with 49, 55, and 57 mm recorded for leaves, seeds, and stems oils, respectively.

The MIC and MBC values are presented in Table 4. The broth dilution assay demonstrated that the essential oils from all plant organs exhibited a bactericidal effect on the tested strains, with varying degrees of potency. Stems essential oils revealed the best bactericidal activity (MBC = 0.25 µL/mL) against the Gram-positive bacteria *S. aureus*.

Correlations between antioxidant, antibacterial activities, and terpenic compounds

According to axes 1 and 2, the plot of the principal component analysis (PCA) based on the antioxidant, antibacterial activities and major essential oil components, showed two major groups (Fig. 2). The first group, at the positive side of axis 1, enclosed stems essential oils characterised by high amounts of α-eudesmol, Geraniol, Germacrene B and Δ-Cadinene

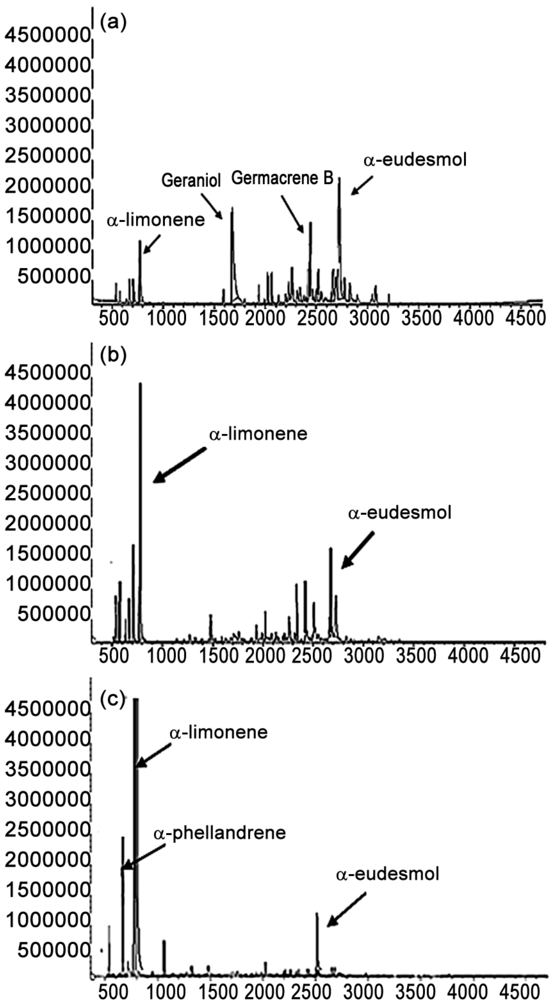

Fig. 1 — GC-MS profiles, a) stems, b) leaves, and c) seeds *of S. molle* essential oils.

Table 2 — Antioxidant activity of tested essential oils.

Assays	Stems	Leaves	Seeds
DPPH	0.42±0.2^b	12.6±0.3^a	-^{c}
FRAP	35.52±0.0^a	3.85±0.0^c	17.8±0.4^b

Means followed by different letters within the same row are significantly different (p <0.05).

revealed the best activities. The second group, situated at the negative side of axis 1, was formed by leaves and seeds, essential oils that were less bioactive.

Repellent activity against *Tribolium castaneum*

The repellent activity of the tested essential oils against *T. castaneum* adults was assessed using the area preference method. The efficacy of the essential oils was found to be strongly influenced by both the concentration and exposure time, as indicated in Table 5. Our results revealed that the essential oil extracted from the stems achieved 100% repellency, at a concentration of 0.08 µL/cm² after both 1 and 3 hours.

Discussion

The essential oil yield of *S. molle* exhibits significant variation across different plant organs. Berries produced a much higher yield (3.25%) compared to the leaves (1%) and stems (0.17%). This variation is largely attributed to the differential biosynthesis and accumulation of volatile terpenoids in specialised secretory structures[20]. In line with that, different yields of *S. molle* essential oils were found in the literature, such as 2.7% for berries[4], and 1.24% for leaves[8]. At the species level, *S. molle* essential oil was distinguished by high levels of α-Limonene, α-Eudesmol, α-Phellandrene and Geraniol. The studied essential oil composition varied considerably across different plant organs, with significant differences in the dominant compounds. By referring to the literature, the investigated *S. molle* L. essential oil displayed a significant variation in composition, compared to essential oil from the same species collected from Northern[21] and Southern East of Tunisia[4]. In fact, these essential oils revealed high amounts of α-Phellandrene and β-Phellandrene. However, essential oils from *S. molle* grown in Morocco contained mainly β-pinene (10.36–5.44%), ɣ-terpinene (12.01–8.15%), Limonene (22.94–18.49%), 10-epi-elemol (7.64–8.03%), ɣ-eudesmol (5.17–4.09%), and longifolene (7.67–8.48%)[8]. Laila *et al.*[22] reported Shyobunone (10.14%), 1-phellandrene (9.63%), α-cadinol (7.46%), δ-cadinene (7.45%), and germacrene D (7.09%) as the major components in the essential oils of *S. molle* aerial parts collected from Algeria. Furthermore, a recent study also found that the essential oil of *S. molle* leaves and fruits collected from different regions of Jordan showed a high percentage of α-phellandrene and β-phellandrene[23]. However, α-phellandrene was the predominant component of *S. molle* essential oil from Turkey and Mexico[24,25]. The chemical variation could be attributed to several factors, including the extraction method, storage conditions, edaphic factors, plant part extracted, ecosystem, plant genetic traits, and environmental factors[26-29]. Therefore, the variations in chemical compositions indicate the presence of different chemotypes, which directly influence the effectiveness of the essential oil.

Table 3 — Antibacterial activity estimated by the diameter (mm) of inhibition of *S. molle* essential oils

Bacteria	Stems	Leaves	Seeds	Gentamycin
Gram-negative				
Escherichia coli	22±1,4^{a}	10,5±0,7^{b}	10±1,4^{b}	28±0.0
Salmonella typhimurium	24±1,4^{a}	10±0,7^{b}	11±0,7^{b}	28,5±0.7
Gram-positive				
Staphylococus aureus	57±0,7^{a}	55±0,7^{a}	49±0,7^{b}	44,5±0.7
Enterococcus feacium	53±0,7^{a}	48±1,4^{b}	40±0,7^{c}	35±0.0

Means followed by different letters within the same row are significantly different (p <0.05).

Table 4 — Antimicrobial activity (µL/mL) expressed as minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC)

Bacteria	Stems		Leaves		Seeds	
	MIC	MBC	MIC	MBC	MIC	MBC
Gram-negative						
Escherichia coli	1	1	2	4	2	3
Salmonella typhimurium	1	2	2	2	2	2
Gram-positive						
Staphylococcus aureus	0,25	0,25	0,5	1	2	2
Enterococcus feacium	0,0625	0,5	0,0625	1	0,5	3

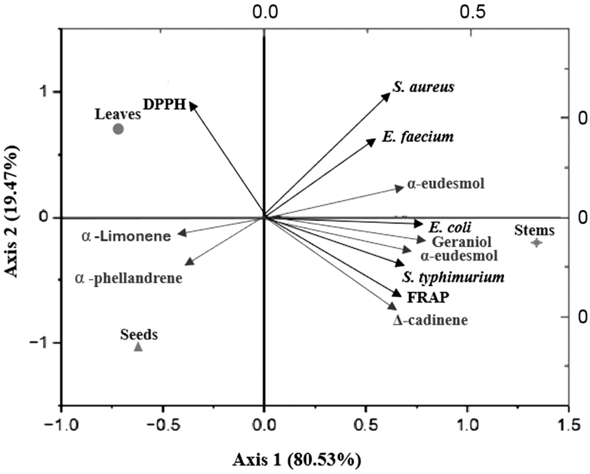

Fig. 2 — Plot of the principal component analysis performed on values of antioxidant, antibacterial activities and terpenic components.

The essential oils were further evaluated for their antioxidant, antibacterial, and repellent activities to identify new bioactive natural compounds. Our findings showed that the stem essential oils were characterised by the best free radical scavenging activity. The higher activity of the stems' essential oils in contrast with the leaves and seeds may be linked to the variation in the content of oxygenated sesquiterpenes in the leaves and the presence of hydroxyl groups in these compounds[8,30]. For the remaining samples, their low antioxidant activity may be linked to the limited ability of monoterpene hydrocarbons to scavenge DPPH radicals[23]. In fact, the biological activity of essential oils is influenced by their chemical composition and functional groups (such as alcohols, phenols, terpenes, and ketones). Therefore, the nature of the terpenic compounds and their relative proportions play a crucial role in the antioxidant activity of the oils[31,32]. Additionally, essential oils derived from plant species typically have complex compositions, making it difficult to attribute their antioxidant effects to just one or a few active compounds. Both minor and major components contribute significantly to the oil's overall activity[17].

Our results revealed significant differences between the antibacterial activity of the tested essential oils. The different responses can be explained by the diversity of the composition and concentration of each component in the tested essential oils. Our results revealed that the stems' essential oils exhibited the best antibacterial activity. This activity may be attributed to its predominant constituents, Geraniol, which is reported to have antibacterial properties against many species[33]. Previous studies revealed that wood branch essential oils revealed good antibacterial activity against *Bacillus subtilis*, *Bacillus cereus*, *Staphylococcus aureus*, *Escherichia coli*, *Sarcina lutea*, *Pseudomonas aeruginosa*, and *Micrococcus luteus*[9]. There is indeed a strong positive correlation between the antibacterial activity of essential oils and their chemical composition[34]. However, it is challenging to attribute

Table 5 — Repellency effect of *S. molle* L. essential oils (EO) to *T. castaneum*

Period of exposure (h)	Concentrations (µL/cm^2)				Response class			
	0.01	0.02	0.04	0.08				
Stems EO								
1	70	85.71	90	100	IV	V	V	V
3	62.3	70	85.71	100	IV	IV	V	V
5	60	62.3	70	85.71	IV	IV	IV	V
24	50	57.14	60	80	III	III	III	IV
Leaves EO								
1	62.3	70	80	90	IV	IV	IV	V
3	62.3	60	70	85.71	IV	III	IV	V
5	60	60	62.3	80	III	III	IV	V
24	50	57.14	62.3	70	III	III	IV	IV
Seeds EO								
1	70	80	90	100	IV	IV	V	V
3	60	70	85.71	90	III	IV	IV	V
5	57.14	62.3	80	85.71	III	IV	IV	V
24	50	60	70	80	III	III	IV	IV

Repellency classes: O = < 0.1: is not repulsive; class I = 0.1–20: Very weak repulsive; class II = 20.1–40: weakly repulsive; class III = 40.1–60: moderately repulsive; class IV = 60.1–80: repulsive; class V = 80.1–100: very repulsive.

the effects of such a complex mixture to a specific component. Both major and minor compounds may contribute to the observed antibacterial activity[5].

The extracted essential oils were also tested as a repellent agent against adults of red flour beetle, *T. castaneum*. In terms of insecticidal activity, various synthetic chemicals have been used for repellents, vector control, and insecticides. However, over the past year, some of these chemicals have been withdrawn due to concerns about their carcinogenic, genotoxic, or environmentally harmful effects, particularly related to bioaccumulation. In contrast, using natural products as insecticides could offer a more effective, cost-efficient, biodegradable, and safer alternative to synthetic options[23]. The differences in repellency potential between the tested essential oils against *T. castaneum* might be due to the active structural groups and ratios of the chemical constituents of each oil. Terpenoids are the predominant components in essential oils, and their primary mechanism of action against insects is neurotoxicity. Rizvi *et al.*[35] reported that essential oils effectively inhibit acetylcholinesterase activity in insects. In our study, stem essential oils revealed the best activity. In fact, Geraniol, one of the two major components identified from the stems' essential oil, has been reported as showing repellent activity[36,37]. Seeds' essential oils rich in Limonene revealed an intermediate repellent activity. Indeed, this monoterpene was reported as an insect repellent, feeding deterrent, growth disruptor, and reproduction inhibitor against a wide range of pest complexes. Nevertheless, the repellent activity of the essential oils is not solely determined by the presence of individual chemical compounds and their concentrations; it is also influenced by the synergistic effects of their various major and minor components.

Conclusion

This work was carried out in order to describe the essential oil variability of *S. molle* organs from Tunisia and to evaluate their antioxidant, antibacterial, and repellent activities. Among the investigated organs, stems essential oil exhibited the strongest activity, showing promising antioxidant capacity (IC_{50} = 0.42 mg/mL for DPPH and 35.52 µmol TROLOX/g HE for FRAP). It also displayed pronounced antibacterial activity against Gram-positive bacteria, particularly *Staphylococcus aureus* and *Enterococcus faecium*, with inhibition zones of 57 and 53 mm, respectively. Furthermore, stems essential oil showed the highest repellent efficacy. These findings indicate that *S. molle* essential oil should be considered a natural alternative for a wide range of applications, including agro-food, pharmaceuticals, and biological defence, as a substitute for toxic synthetic compounds.

Conflicts of interest

The authors declare no conflict of interest.

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