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# The application of essential oils as a next-generation of pesticides: recent developments and future perspectives

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**Abstract:** The overuse of synthetic pesticide, a consequence of the rush to increase crop production, led to tremendous adverse effects, as they constitute a major pollutant for both soils and water, with a high toxicity towards humans and animals and, at the same time, led to development of pest resistance. In the last period, the researches were directed towards finding new solutions with a lower toxicity, less damaging behaviour towards the environment, and a better specificity of action. In this context, the use of essential oils, a complex and unique mixture of compounds, can be considered for the next-generation pesticides. This review aims to present the main applications of the essential oils as insecticides, herbicides, acaricides, and nematicides, as they emerged from the scientific literature published in the last 5 years (2015 to present). From the identified articles within the time period, only those dealing with essential oils obtained by the authors (not commercially available) were selected to be inserted in the review, characterized using established analytical techniques and employed for the envisaged applications. The review is concluded with a chapter containing the main conclusions of the literature study and the future perspectives, regarding the application of essential oils as next-generation pesticides.

**Keywords:** acaricides; essential oils; herbicides; insecticides; nematicides.

## 1 Introduction

When referring to the possible threats for the agricultural sector, the pests are accountable for a reduction of the production up to 50% [1]. Over the last decades, this has led to an extensive usage of pesticides, mostly of synthetic origin [Figure 1 presents the global use of pesticide (Figure 1A), as well as details on the global pesticide trade (Figure 1B)].

Under the general term *pesticides*, a wide range of compounds with very different actions can be found (such as herbicides, insecticides, nematicides, rodenticides, avicides, algicides, fungicides, bactericides, and others) [4]. Although the introduction of synthetic pesticides in the agricultural practice contributed to an increase in the agricultural output [4], the continuing need of a more performant crop production led to the overuse of these types of compounds in such extent that they become a major pollutant for both soils and water, with a high toxicity towards humans and animals [5, 6]. The worldwide usage of synthetic pesticides has presented the research community with the rise of several issues, such as the continuous development of pesticide resistance. This can be attributed to a misuse of the pesticides, meaning that the shortcoming of specific substances for certain pests will increase their adaptability and make the resistance traits to be passed on to the next pest generations [7]. One of the biggest concerns regarding the effects of synthetic pesticides is the influence upon human and animal health.

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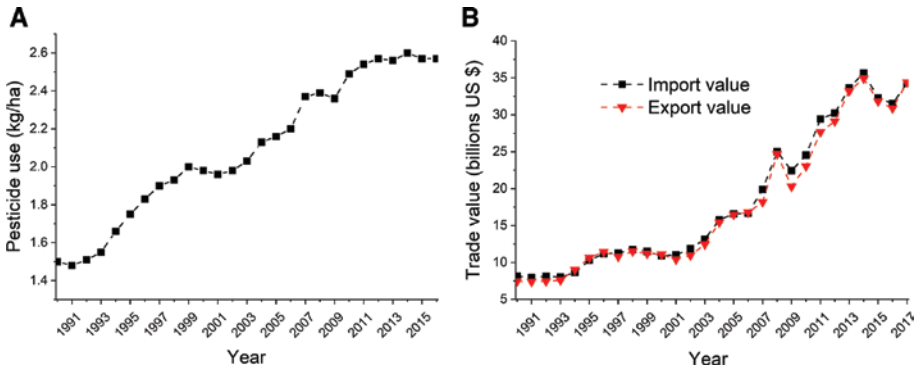


**Figure 1:** (A) Pesticide use per cropland (world level); (B) pesticide trade (world level) – data collected from the Food and Agriculture Organization of the United Nations [2, 3].

Several studies have linked a higher occurrence of cancer within the farmers' communities that have been exposed to pesticides. Ochoa-Acuña and Carbajo have pointed out the connection between birth defects, such as prematurity and congenital abnormalities, and the extensive use of pesticides [8]. Associated with the increased use of synthetic pesticides, the economic losses induced by their use also increased. For example, in the United States alone, the costs related to the pesticide use were estimated at greater than US $10 billion per year (2005), including the costs related to public health, development of pesticide resistance in pests, crop and bird losses, or groundwater contamination [9].

In the last years, in order to inhibit some of the negative effects of the existent pesticides, a new approach had risen to the attention of the research community, that of the essential oil–based pesticides [10, 11]. In previous studies, it has been proven that essential oils used as pesticides can be more advantageous, as their toxicity is much lower; they present a less damaging behaviour towards the environment and have a better specificity of action [12–14].

Essential oils (EOs), due to their nature (as plant secondary metabolites), represents a safer alternative in many applications, such as food preservation, biomedicine, cosmetics, or agriculture [15]. From the chemical point of view, EOs represent a complex and unique mixture of compounds, specific for each plant and extraction procedure, including, but not limited to alkaloids, flavonoids, isoflavones, monoterpenes, phenolic acids, carotenoids, and aldehydes [16], strongly lipophilic and volatile and nearly insoluble in water.

Although the costs for obtaining EOs for such applications are increased (when compared with synthetic pesticides), they represent a viable alternative (especially for application in organic agriculture, where the focus is shifted from costs and absolute efficacy towards human and animal safety) [17]. Their application can solve the problem of pesticide-resistant pests, as well as avoid the health issues related to pesticide accumulation [18]. Moreover, the world market for EOs is expected to reach 403.06 kilotons by 2025 [19]; the large-scale and worldwide production is expected to have a positive effect on the price of EOs, whereas their volatility makes EOs environmentally nonpersistent [17], thus eliminating several of the side effects of synthetic pesticides. The increasing interest in the application of EO formulations as pesticides can be observed by evaluating the number of scientific articles published on this topic over the years, in Web of Science indexed journals (Figure 2). Web of Science database was

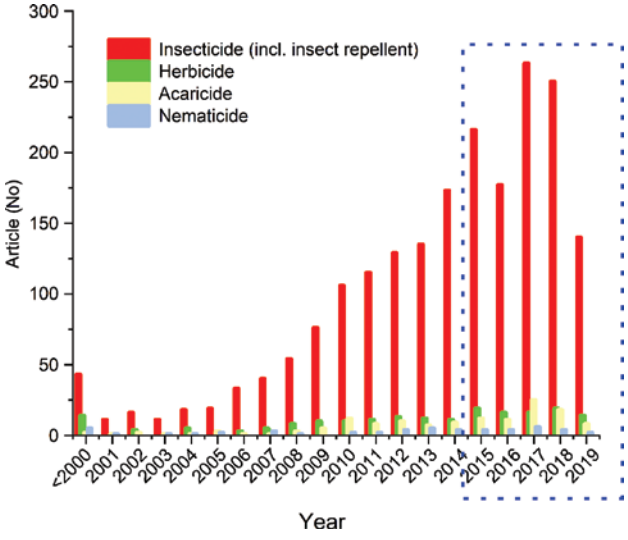


**Figure 2:** Evolution of the scientific articles published on the topic EO application as pesticides (bactericidal, fungicidal, and virucidal applications excluded). Highlighted area represents the time frame considered for the present review.

selected in order to consider the review-only research articles published in ISI-indexed journal. From the larger class of pesticides, the application of EOs as bactericidal, fungicidal, and virucidal agents was not considered. The primary selection in this review was made by using the following keywords: "essential oil" and selection "article" (52,804 results). Within those results, particular searches were made using "insecticide/insecticidal/insect repellent" (2025 results), "herbicide/herbicidal" (190 results), "acaricide/acaricidal" (140 results), and "nematicide/nematicidal" (51 results). From this preliminary selection, articles published in the last 5 years (2015–2019) were considered for the present review (1224 articles). The final selection of the articles was made after careful evaluation: "false-positive" articles were removed (articles containing the keywords but not truly presenting the application); only those articles dealing with EOs obtained by the authors in the laboratory (not commercialized EOs) and characterized using established analytical techniques (such as gas chromatography-mass spectrometry) were included in the present review (82 articles).

The review covers the extraction procedures followed by the author, main components identified, and the targeted organisms. In addition, exhaustive tables, containing the main data regarding the application of EOs, are provided, for quick reference. The review ends with a chapter containing the main conclusions of the literature study and the future perspectives, regarding the application of EOs as "green" pesticides.

## 2 Application of EOs as insecticides and insect repellent

One of the most important categories of pesticides is represented by insecticides, as they can minimize the damages produced by pests and can lead to an improvement of the productivity of the horticultural sector. At the same time, insects can lead to a series of serious health issues, such as the yellow fever or those developed by dengue and chikungunya viruses [20]. The difference between *insecticide* and *insect repellent* is represented by the desired application (usually insect repellents are designed for human protection, whereas the insecticides are designed for agricultural applications) and by the interaction pathway between the pesticide and the targeted pest: insecticides act by direct contact, whereas for a compound to be classified as an insect repellent, it should create within 4 cm of the skin an atmosphere that would prevent the contact insect/skin [20]. The wide application of insecticides and insect repellents led to the proposal of "green" alternatives, based on natural products. As the two applications are often evaluated together, we have chosen to present the recent developments in those areas chronologically, in a single chapter.

Akkari et al. [21] used *Ruta chalepensis* (Rutaceae) EO obtained by vapour dragging and water distillation and evaluated it in terms of larvicidal effect against larvae of *Orgyia trigotephras* (a phytophagous insect). The authors obtained a mean time of mortality of 1.40 min (flower oil) and 1.27 min (leaf oil) for the third instar larvae, respectively, 42.53 and 20.68 min against the fourth instar larvae (at 0.5% EO in ethanol vol/vol), superior to a commercial insecticide (deltamethrin) used as positive control (time of mortality of 31.1 min against the third instar larvae, respectively, 596.35 min, against the fourth instar larvae, at 0.015% concentration).

Jalaei et al. [22] used the EO of *Dracocephalum kotschyi* Boiss. obtained by water distillation (with high monoterpene content) as an efficient insecticide against *Myzus persicae* Sulz. (an aphid causing major losses to the peach cultures), with $LC_{50}$ (50% mortality) after 72 h of 0.27 μL/L and $LC_{90}$ of 2.35 μL/L after 72 h (fumigant), comparable to the commercial insecticide Actara used as positive control. Li et al. [23] applied EO obtained by water distillation from the aerial parts of *Clinopodium chinense* (Benth.) Kuntze against the booklice (*Liposcelis bostrychophila*), with a 50% lethal concentration ($LC_{50}$) of 215.25 μg/cm$^2$ (contact), respectively, 423.39 μg/L air (fumigant), whereas Sumitha and Thoppi [24] used *Ocimum gratissimum* L. leaf EO as insecticidal agent against *Aedes albopictus* Skuse, with $LC_{50}$ value of 26.10 mg/L and $LC_{90}$ of 82.83 mg/L, at 24 h.

Wang et al. [25] used *Dahlia pinnata* Cav. EO against *Sitophilus zeamais* and *Sitophilus oryzae* (pests of stored cereals), with $LC_{50}$ value of 308.11 and 163.55 mg/cm$^2$ for the insecticidal effect (contact), respectively, and strong insect repellent properties at 13 nL/cm$^2$. A similar approach regarding the evaluation of EOs as insecticide and insect repellent can be encountered in the studies published in the same year (2015), by Martínez-Evaristo et al. [26], Aguiar et al. [27], de Lira et al. [28], Guo et al. [29], Haider et al. [30], Wu et al. [31], Yang et al. [32], You et al. [33], and Zhang et al. [34] (details provided in Table 1). Among these articles, the work of Haider et al. [30] presents the variation in composition and effect of the EO of *Tanacetum nubigenum* Wallich. ex DC harvested from three different sites, at different elevations. Considering their results, it can be stated that the potential application of EOs is strongly correlated with their composition, which in turn varies with several factors, including the value of the cultivar, the harvesting time, and the environmental factors.

**Table 1:** Origin and major composition of the essential oils presented in the review with insecticidal and insect repellent effects.

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| I | *Ruta chalepensis* leaves | 2-Undecanone (85.94), 2-decanone (5.63), 2-dodecanone (1.21), by GC-MS | *Orgyia trigotephras* larvae | MTM = 1.27 min for third instar larvae, 20.68 min for fourth instar larvae | [21] |
| I | *Ruta chalepensis* flowers | 2-Undecanone (89.89), 2-decanone (4.23), 2-dodecanone (1.22), by GC-MS | *Orgyia trigotephras* larvae | MTM = 1.40 min for third instar larvae, 42.53 min for fourth instar larvae | [21] |
| I | Aerial flowering parts of *Dracocephalum kotschyi* | Limonene-10-al (73.75), limonene (19.96), menth-1-en-9-ol (1.14), by GC-MS | *Myzus persicae* | $LC_{50}$ = 0.27 μL/L air, $LC_{90}$ = 2.35 μL/L air after 72 h (fumigant) | [22] |
| I | Aerial parts of *Clinopodium chinense* | Spathulenol (18.54), piperitone (18.9), caryophyllene (12.04), by GC-MS | *Liposcelis bostrychophila* | $LC_{50}$ = 215.25 μg/cm² (contact), $LC_{50}$ = 423.39 μg/L air (fumigant) | [23] |
| I | *Ocimum gratissimum* L. leaves | 3-Allyl-6-methoxyphenol (19.30), 4-(5-ethenyl-1-azabicyclo (2, 2, 2) octan-2) (16.82), 1-(2, 5-dimethoxyphenyl)-propanol (12.23), by GC-MS | *Aedes albopictus* | $LC_{50}$ = 26.10 mg/L air, $LC_{90}$ = 82.83 mg/L air, at 24 h | [24] |
| I, IR | *Dahlia pinnata* | 4-Terpineol (25.71), methallyl cyanide (13.96), D-limonene (10.53), by GC-MS | *Sitophilus zeamais*, *Sitophilus oryzae* | $LC_{50}$ = 308.11/163.55 mg/cm² (contact); strong insect repellent properties at 13 nL/cm² | [25] |
| I, IR | *Lippia palmeri* S. Watson | Thymol (58.9), *p*-cymene (21.8), carvacrol (5.2) by GC-MS | *Sitophilus zeamais*, *Prostephanus truncatus* | $LC_{50}$ = 441.45 μL/L air/320.52 μL/L air (fumigant) $LC_{90}$ = 1177.2 μL/L air/1558.9 μL/L air (fumigant) RI = 0.45/0.5 at 1000 μL/L air after 72 h | [26] |
| I, IR | *Siparuna guianensis* Aubl. leaves | β-Myrcene (79.71), 2-undecanone (14.58), bicyclo-germacrene (1.21%), by GC-MS | *Aedes aegypti*, *Culex quinquefasciatus* | $LC_{50}$ = 1.76 (*A. aegypti)*, 1.36 mg/L air (*C. q.*), fourth instar larvae; $RD_{50}$ = 0.438/0.662 μg/cm² | [27] |
| I, IR | *Siparuna guianensis* Aubl. stem | β-Myrcene (26.91), δ-elemene (20.92), germacrene D (9.4%), by GC-MS | *Aedes aegypti*, *Culex quinquefasciatus* | $LC_{50}$ = 0.98 (*A. aegypti)*, 0.89 mg/L air (*C. q.*), fourth instar larvae; $RD_{50}$ = 0.438/0.662 μg/cm² | [27] |
| I, IR | *Siparuna guianensis* Aubl. fruits | 2-Tridecanone (38.75), 2-undecanone (26.5) and β-myrcene (16.42), by GC-MS | *Aedes aegypti*, *Culex quinquefasciatus* | $LC_{50}$ = 2.46 (*A. aegypti)*, 2.45 mg/L air (*C. q.*), fourth instar larvae; $RD_{50}$ = 0.438/0.662 μg/cm² | [27] |
| I, IR | *Alpinia purpurata* inflorescences | β-Pinene (35.76), α-pinene (20.57), *trans*-caryophyllene (13.23), by GC-MS | *Sitophilus zeamais* Motsch | $LC_{50}$ = 41.4 μL/L air (fumigant) No repellent effect | [28] |
| I, IR | *Etlingera yunnanensis* rhizomes | Estragole (65.2), β-caryophyllene (6.4), 1,8-cineole (6.4), by GC-MS | *Tribolium castaneum* (Herbst) and *Liposcelis bostrychophila* (Badonnel) | $LC_{50}$ = 23.33 μg/adult/47.38 μg/cm² (contact) PR = 84%, 2 h, 15.73 nL/cm²/82%, 2 h, 12.63 nL/cm² | [29] |
| I, IR | *Tanacetum nubigenum* Wallich. ex DC from 4000 m | Selin-11-en-4-α-ol (10.3), methyl acetopyronone (9.5), 2,6,8-trimethyl-4-nonanone (8.8), by GC-MS | *Tribolium castaneum* (Herbst) | $LC_{50}$ = 33.25 μL/L air, at 48 h; RE = 1.3 adults, 1 h treatment, 20 μL/plate EO | [30] |
| I, IR | *Tanacetum nubigenum* Wallich. ex DC from 3200 m | Borneol (19.8), *p*-menthene-1-ol (11.7), 1,8-cineole (10.9), by GC-MS | *Tribolium castaneum* (Herbst) | $LC_{50}$ = 36.88 μL/L air, at 48 h; RE = 2.7 adults, 1 h treatment, 20 μL/plate EO | [30] |
| I, IR | *Tanacetum nubigenum* Wallich. ex DC from 3500 m | Bornyl acetate (38.1), borneol (9.5), 1,8-cineole (7.3), by GC-MS | *Tribolium castaneum* (Herbst) | $LC_{50}$ = 35.28 μL/L air, at 48 h; RE = 2.2 adults, 1 h treatment, 20 μL/plate EO | [30] |

**Table 1** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| I, IR | *Liriope muscari* aerial parts | Methyl eugenol (42.15), safrole (17.15), myristicin (14.18), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne*, *Liposcelis bostrychophila* | $LC_{50}$ = 13.36/11.28 μg/adult, respectively, 21.37 μg/cm² PR = 92%, 2 h, 15.73 nL/cm² (*T.c.*), 86%, 2 h, 78.63 nL/cm² (*L.s.*), 100% 2 h, 6.32 nL/cm² (*L.b.*) | [31] |
| I, IR | *Dictamnus dasycarpus* roots | Syn-7-hydroxy-7-anisylnorbornene (49.9), 1,3,4,5,6,7-hexahydro-2H-inden-2-one (11.6), 5,6-diethenyl-1-methylcyclohexene (7.38), by GC-MS and | *Lasioderma serricorne*, *Liposcelis bostrychophila* | $LC_{50}$ = 12.4 mg/adult/27.2 mg/cm² PR = 90%, 4 h, 39.32 nL/cm²/98%, 4 h, 6.32 nL/cm² | [32] |
| I, IR | *Artemisia mongolica* aerial parts | Eucalyptol (39.88), (S)-*cis*-verbenol (14.93), 4-terpineol (7.20), by GC-MS | *Lasioderma serricorne* | $LC_{50}$ = 22.32 μg/adult; $LC_{50}$ = 6.08 mg/L air RE = ~76%, 39.32 ng/cm², 2, 4 h | [33] |
| I, IR | *Mentha haplocalyx* aerial parts | Menthol (59.71), menthyl acetate (7.83), limonene (6.98), by GC-MS and | *Lasioderma serricorne* | $LC_{50}$ = 16.5 μg/adult RE = >95%, 2 h, 39.32 ng/cm² | [34] |
| I | *Pinus kesiya* Royle ex. Gordon needles | β-Pinene (38.9), α-pinene (21.8), myrcene (11.6), by GC-MS | *Anopheles stephensi*, *Aedes aegypti*, *Culex quinquefasciatus* | $LC_{50}$ = 52/57/62 mg/L air; $LC_{90}$ = 101/110/115 mg/L air (fumigant) | [35] |
| I | *Teucrium quadrifarium* aerial parts | Germacrene D (8.8), linalool (8.2), camphene (7.8), by GC-MS | *Liposcelis bostrychophila* | $LC_{50}$ = 95.1 μg/cm² (contact), 222.0 μg/L (fumigant) | [36] |
| I | *Cyperus rotundus* rhizomes | α-Cyperone (29.38), cyperene (13.97), caryophyllene oxide (6.71), by GC-MS | *Liposcelis bostrychophila* | $LC_{50}$ = 102.11 μg/cm² (contact) | [37] |
| I | *Elsholtzia ciliate* aerial parts | Dehydroelsholtzia ketone (26.5), (R)-carvone (16.6), elsholtzia ketone (14.6), by GC-MS | *Liposcelis bostrychophila* | $LC_{50}$ = 145.5 μg/cm² (contact), 475.2 μg/L (fumigant) | [38] |
| I | *Mentha pulegium* L. leaves | Pulegone (70.66), neo-menthol (11.21), menthone (2.63), by GC-MS | *Sitophilus granarius* (L.) | $LC_{50}$ = 9.11 mL/L (contact), 100% mortality at inhalation and ingestion after 24 h, using 5/10 mL EO/L acetone | [39] |
| I | *Pistacia atlantica* subsp. *kurdica* gum | α-Pinene (81.6), terpinolene (4.09), β-pinene (3.6), by GC-MS | *Tribolium castaneum* (Herbst) | $LC_{50}$ = 29 μL/L air; $LC_{90}$ = 57 μL/L air (fumigant) | [40] |
| I | *Pistacia atlantica* subsp. *kurdica* fruit | α-Pinene (47.7), β-myrcene (16.1), D-limonene (8.75), by GC-MS | *Tribolium castaneum* (Herbst) | $LC_{50}$ = 39 μL/L air; $LC_{90}$ = 66 μL/L air (fumigant) | [40] |
| I | *Pistacia atlantica* subsp. *kurdica* leaves | Spathulenol (24.1), α-pinene (19.2) and δ-elemene (7.05), by GC-MS | *Tribolium castaneum* (Herbst) | $LC_{50}$ = 64 μL/L air; $LC_{90}$ = 87 μL/L air (fumigant) | [40] |
| I, IR | *Cinnamomum camphora* L. Presl leaves | Camphor (18.48), eucalyptol (16.46), linalool (11.58), by GC × GC-TOFMS | *Aphis gossypii* Glover | $LC_{50}$ = 245.79 mg/L at 48 h (contact); PR = 83.83 at 24 h, 20 mL/L EO | [41] |
| I, IR | *Cinnamomum camphora* L. Presl twigs | Eucalyptol (17.21), camphor (13.17), 3,7-dimethyl-1,3,7-octatriene (11.47), by GC × GC-TOFMS | *Aphis gossypii* Glover | $LC_{50}$ = 274.99 mg/L at 48 h (contact); PR = 72.13 at 24 h, 20 mL/L EO | [41] |
| I, IR | *Cinnamomum camphora* L. Presl seeds | Eucalyptol (20.90), methyleugenol (19.98), linalool (14.66), by GC × GC-TOFMS | *Aphis gossypii* Glover | $LC_{50}$ = 146.78 mg/L at 48 h (contact); PR = 89.86 at 24 h, 20 mL/L EO | [41] |
| I, IR | *Pluchea carolinensis* (Jacq.) G. Don flowers | 5-Angeloyloxycarvotagetone (18.1), selin-11-en-4α-ol (17.7), 2,5-dimethoxycymene (8.9), linalool (14.66), by GC-MS, NMR, HRMS | *Aedes aegypti* | PTA = 1.6% at 1% EO; PIA = 66.2% at 0.1% EO; PR = 36.6% at 1% EO | [42] |

**Table 1** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| I, IR | *Cryptocarya alba* [Molina] Looser foliage | (E)-β-bergamotene (15.6), viridiflorol (8.5), germacrene-D (7.65), by GC-MS | *Sitophilus zeamais* Motschulsky | $LC_{50}$ = 14.6 mL/kg grain; RI = 0.28 at 2.5 mL EO/kg grain | [43] |
| I, IR | *Juniperus formosana* leaves | α-Pinene (21.66), 4-terpineol (11.25), limonene (11.00), by GC-MS | *Tribolium castaneum*, *Liposcelis bostrychophila* | $LC_{50}$ = 29.14 μg/adult/81.50 μg/cm² (contact); PR = > 90% at 2 h, 78.63 nL/cm² (*T.c.*), 76% at 4 h, 63.17 nL/cm² (*L.b.*) | [44] |
| I, IR | *Rhododendron thymifolium* leaves | Germacrone (20.83), γ-elemene (11.10), selina-3,7(11)-diene (6.18), by GC-MS | *Liposcelis bostrychophila*, *Tribolium castaneum* | $LC_{50}$ = 19.63 μg/cm²/29.82 μg/cm² (contact); PR >90% at 4 h, at 15.73 nL/cm² (*T.c.*), 12.64 nL/cm² (*L.b.*) | [45] |
| I, IR | *Laureliopsis philippiana* (Looser) Schodde leaves | Methyleugenol (61.38), safrole (17.04), β-terpinene (4.49), by GC-MS | *Sitophilus oryzae*, *Sitophilus zeamais*, *Sitophilus granarius* | MR = 94.8/60.2/67.1 at 4% EO (contact); MR = 100% at 200 μL EO/L air (fumigant); RI = 0.4/0.2/0.5 at 4% EO | [46] |
| I, IR | *Eucalyptus floribundi* leaves | 1,8-Cineole (58), α-pinene (26.2), *trans*-pinocarveol (4.05), by GC-MS | *Rhyzopertha dominica*, *Oryzaephilus surinamensis* | $LC_{50}$ = 34.39/43.54 μg/L air (fumigation); RI = 0.21/0.11 at 280/140 μL/L air | [47] |
| I | *Bidens frondosa* L. aerial parts | Caryophyllene oxide (20.50), borneol (17.66), 4-terpineol (17.26), by GC-MS | *Liposcelis bostrychophila* | $LC_{50}$ = 507.35 μg/L (fumigation); $LC_{50}$ = 210.73 μg/cm² (contact) | [48] |
| I | Leaves of *Psidium guajava* L. cultivars | (E)-Caryophyllene (26.6-7.6), caryophyllene oxide (3.2-16.6), β-bisabolol (2.4-19.5), others, by GC-MS | *Aedes aegypti* L. | $LC_{50}$ = 39.48-64.25 mg/L | [49] |
| I | *Citrus sinensis* peels | Limonene (92.14), β-myrcene (2.7), 1,8-cineole (0.33), by GC-MS | *Tribolium confusum*, *Callosobruchus maculatus*, *Sitophilus oryzae* | $LC_{50}$ = 14.45/10/29.51 μL/L, at 72 h (fumigant) | [50] |
| I, IR | *Zingiber zerumbet* (L.) Smith rhizomes | Zerumbone (40.2), α-caryophyllene (8.6), humulene epoxide II (7.3), by GC-MS | *Lasioderma serricorne* | $LC_{50}$ = 48.3 μg/adult (contact); PR = 72%, at 2 h, 78.63 nL/cm² | [51] |
| I, IR | *Cymbopogon nardus* L. leaves | Geraniol (19.34), methyl eugenol (8.8), (E)-methyl isoeugenol (8.19), by GC-MS | *Bemisia tabaci* | $LC_{50}$ = 1.028 μL/L, at 24 h (fumigant); RI = 0.29% at 6 h, 0.5% EO | [52] |
| I, IR | *Eupatorium buniifolium* Hook et Arn. aerial parts | (–)-α-Pinene (38.02-75.77), others, depending on year and location, by GC-MS | *Triatoma infestans* | Mortality 92-100% for 50-150 μL/L (fumigant); Repellent at 25 and 50% EO | [53] |
| I | *Lantana camara* | Sabinene (32.1), 1.8 cineole (20.9), (E)-caryophyllene (13), by GC-MS | *Anopheles gambiae* (Meigen) | $LC_{50}$ = 0.24/1.04/0.85/1.22%; $LC_{90}$ = 0.89/1.54/1.38/2.00% (contact) | [54] |
| I | *Hyptis spicigera* | α-Pinene (24.5), (E)-caryophyllene (23.6), β-pinene (10.3), by GC-MS | *Anopheles gambiae* (Meigen) | $LC_{50}$ = 1.04%; $LC_{90}$ = 1.54% (contact) | [54] |
| I | *Hyptis suaveolens* | Sabinene (26.9), 1.8 cineole (26.4), (E)-caryophyllene (11.1), by GC-MS | *Anopheles gambiae* (Meigen) | $LC_{50}$ = 0.85%; $LC_{90}$ = 1.38% (contact) | [54] |
| I | *Ocimum canum* | 1.8 Cineole (44.6), camphor (15.9), α-pinene (7.1), by GC-MS | *Anopheles gambiae* (Meigen) | $LC_{50}$ = 1.22%; $LC_{90}$ = 2.00% (contact) | [54] |
| I | *Geranium macrorrhizum* L. – wild aerial parts | β-Elemenone (30.53), thymol (18.52), germacrone (15.54), by GC-MS | *Spodoptera littoralis*, *Myzus persicae*, *Rhopalosiphum padi* | FI = 55.5 (*S.l.*); SI = 31.1 (*M.p.*), 69.9 (*R.p.*), at 10 mg/mL | [55] |

**Table 1** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| I | *Geranium macrorrhizum* L.–commercial aerial parts | Linalool (26.45), linalyl acetate (25.11), geranyl acetate (7.56), by GC-MS | *Spodoptera littoralis*, *Myzus persicae*, *Rhopalosiphum padi* | FI = 87.8 (*S.l.*); SI = 55.1 (*M.p.*), 77.8 (*R.p.*), at 10 mg/mL | [55] |
| I, IR | *Evodia lenticellata* Huang | Caryophyllene oxide (28.5), β-caryophyllene (23.1), β-elemene (14.5, by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne*, *Liposcelis bostrychophila* | $LD_{50}$ = 41.5 μg/adult (*L.s.*), 98 μg/cm² (against *L.b.*) (contact); PR = >80% against *T.c.*, *L.s.*, at 78.63nL/cm² and 2 h | [56] |
| I, IR | *Evodia rutaecarpa* (Juss.) Benth. leaves | α-Pinene (39.4), β-elemene (13.5), α-ocimene (7.6), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne*, *Liposcelis bostrychophila* | $LD_{50}$ = 46.2 μg/adult (*L.s.*) (contact); PR = >80% *E.l.* against *T.c.*, *L.s.*; >80% against all insects, at 78.63nL/cm² and 2 h | [56] |
| I, IR | *Amomum villosum* Lour. fruits | Bornyl acetate (51.6), camphor (19.8), camphene (8.9), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne* | $LD_{50}$ = 32.4/20.4 μg/adult (contact); $LC_{50}$ = 6.2 mg/L air (fumigant); PR = >70%, 2 h, 78.63 nL/cm² | [57] |
| I | *Rosmarinus officinalis*–Middle Atlas site | 1, 8-Cineole (46.23), camphor (17.29), β-pinene (5.62), by GC-MS | *Bruchus rufimanus* | $LC_{50}$ = 1.19 μL/L air (males, after 7 days)/2.08 μL/L air (females, after 7 days) | [58] |
| I | *Rosmarinus officinalis*–Loukkos site | Camphor (21.33), 1, 8-cineole (17), β-pinene (8.58), by GC-MS | *Bruchus rufimanus* | $LC_{50}$ = 11.57 μL/L air (males, after 6 days)/5.38 μL/L air (females, after 11 days) | [58] |
| I | *Boenninghausenia albiflora* | 1,8-Cineol (18.5), germacrene-D (17.75), bicyclo germacrene (14.60)/, by GC-MS | *Spilarctia obliqua* | MR = 66.67 at 2.5 μL (larval stage); 26.33 at 2.5 μL (pupal stage) | [59] |
| I | *Teucrium quadrifarium* | E-caryophyllene (25.0), α-cubebene (20.1) and copane 4-α-ol (10.0), by GC-MS | *Spilarctia obliqua* | MR = 70.83 at 2.5 μL (larval stage); 20 at 2.5 μL (pupal stage) | [59] |
| I | *Pimpinella anisum* | (E)-anethole (96.7), methyl chavicol (1.6), γ-himachalene (0.5), by GC-EIMS | *Culex quinquefasciatus* | $LC_{50}$ = 2.39 mL microemulsion (1.5% EO)/L on 3rd instar larvae LM = 80.7 after 144 h; AE = 9.3% at 1.7 mL/L emulsion | [60] |
| I | *Trachyspermum ammi* schizocarps | Thymol (62.6), *p*-cymene (18.7), γ-terpinene (15.8), by GC-EIMS | *Culex quinquefasciatus* | $LC_{50}$ = 1.57 mL microemulsion (1.5% EO)/L on 3rd instar larvae LM = 51.7 after 144 h; AE = 45.2% at 1.3 mL/L emulsion | [60] |
| I | *Crithmum maritimum* flowering aerial parts | γ-Terpinene (33.0), thymol methyl ether (22.0), dillapiole (17.5), by GC-EIMS | *Culex quinquefasciatus* | $LC_{50}$ = 2.23 mL microemulsion (1.5% EO)/L on 3rd instar larvae LM = 56.7 after 144 h; AE = 27.7% at 1.8 mL/L emulsion | [60] |
| I, IR | *Severinia monophylla* leaves–site 1 | β-Caryophyllene (14.8), bicyclogermacrene (8.9), germacrene D (7), by GC-MS | *Aedes aegypti*, *Aedes albopictus*/*Triatoma rubrofasciata* | $LC_{50}$ = 7.1 μg/mL at 48 h; PR = 80% after 48 h | [61] |
| I, IR | *Severinia monophylla* leaves–site 2 | β-Caryophyllene (10.9), bicyclogermacrene (9.2), germacrene D (7.6), by GC-MS | *Aedes aegypti*, *Aedes albopictus*/*Triatoma rubrofasciata* | $LC_{50}$ = 36 μg/mL at 48 h; PR = 80% after 48 h | [61] |
| I | *Plectranthus amboinicus* | Carvacrol (61.53), β-caryophyllene (12.79), *p*-cymene (9.42), by GC-MS | *Aedes aegypti*, *Aedes albopictus*, *Culex quinquefasciatus* | $LC_{50}$ = 42.9/51.62/22.88 mg/L air | [62] |
| I | *Mentha requienii* | Pulegone (60.33), isopulegone (17.32), isomenthone (2.55), by GC-MS | *Aedes aegypti*, *Aedes albopictus*, *Culex quinquefasciatus* | $LC_{50}$ = 53.92/56.13/49.65 mg/L air | [62] |
| I | *Vitex rotundifolia* | α-Pinene (23.64), 1.8-cineole (23.86), sabinene (8.94), by GC-MS | *Aedes aegypti*, *Aedes albopictus*, *Culex quinquefasciatus* | $LC_{50}$ = 53.53/68.06/47.46 mg/L air | [62] |

**Table 1** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| I | *Crossostephium chinense* | Santolina triene (50.90), 1.8-cineole (17.89), thuj-3-en-10-al (5.68), by GC-MS | *Aedes aegypti*, *Aedes albopictus*, *Culex quinquefasciatus* | $LC_{50}$ = 72.20/72.77/65.74 mg/L air | [62] |
| I | *Ocimum campechianum* | Eugenol (18.6), β-caryophyllene (17), 1,8-cineole (11.4), by GC-MS | *Aedes aegypti* | $LC_{50}$ = 69.3 mg/L air | [63] |
| I | *Ocotea quixos* | 1,8-Cineole (39.2), sabinene (6.5), α-pinene (6.3), by GC-MS | *Aedes aegypti* | $LC_{50}$ = 75.5 mg/L air | [63] |
| I | *Piper aduncum* | Dillapiole (48.2), trans-ocimene (7.5), β-caryophyllene (17.0), by GC-MS | *Aedes aegypti* | $LC_{50}$ = 25.7 mg/L air | [63] |
| I | *Myrciaria floribunda* leaves | 1,8-Cineole (10.4), β-selinene (8.4), α-selinene (7.4), by GC-MS | *Rhodnius prolixus* | $LD_{50}$ = 742.49-10.51 (1st–30th days after treatment) μg/insect | [64] |
| I | *Kadsura coccinea* (Lem.) A. C. Sm | β-Caryophyllene (24.73), caryophyllene oxide (5.91), α-humulene (3.48), by GC-MS | *Cimex lectularius* L. | MR = 61.9%, Bayonne strain, 1st day of treatment, 90.5% Ft. Dix strain, 5th day of treatment, at 100 μg/bug | [65] |
| I | *Atriplex cana* Ledeb. aerial parts | Dibutyl phthalate (21.79), eucalyptol (20.14), myrtenyl acetate (15.56), by GC-MS | *Aphis pomi* DeGeer | MR = 84.5% at 12 h, 100% at 48 h, with 5 μL/Petri dish | [66] |
| I, IR | *Origanum vulgare* | Carvacrol (78.2), *p*-cymene (4.4), γ-terpinene (3.2), by GC-MS | *Ips typographus* | $LC_{50}$ = 0.006 μL/cm² at 96 h RI = 70.1% at 0.286 μL/cm², 2 h | [67] |
| I, IR | *Thymus vulgaris* | Thymol (50.4), limonene (33.6), fenchyl acetate (4.6), by GC-MS | *Ips typographus* | $LC_{50}$ = 0.11 μL/cm² at 96 h RI = 83.7% at 0.286 μL/cm², 4 h | [67] |
| I, IR | *Hyssopus officinalis* | *cis*-Pinocamphone (44.4), isopinocamphone (25.2), β-pinene (12.3), by GC-MS | *Ips typographus* | RI = 91.3%, at 0.286 μL/cm², 2 h | [67] |
| I, IR | *Mentha* × *piperita* | Menthol (49.3), menthone (22.4), limonene (9.4), by GC-MS | *Ips typographus* | No repellent activity | [67] |
| I, IR | *Pimpinella anisum* | Anethole (88.6), estragole (4.4), linalool (1.4), by GC-MS | *Ips typographus* | $LC_{50}$ = 0.053 μL/cm² at 96 h, RI = 79.5%, at 0.077 μL/cm², 2 h | [67] |
| I, IR | *Foeniculum vulgare* | Anethole (65.5), fenchone (20.2) and estragole (5.0), by GC-MS | *Ips typographus* | RI = 93.6% at 0.077 μL/cm², 2 h | [67] |
| I, IR | *Agave Americana* leaves | Hexacosane (23.38), heptacosane (21.48), pentacosane (16.66), by GC-MS | *Sitophilus oryzae* (L.) | $LC_{50}$ = 10.55 μg/insect (topical), $LC_{50}$ = 8.99 μg/cm² (treated filter paper); $RC_{50}$ = 0.055 μg/cm² | [68] |
| I, IR | *Valeriana officinalis* roots | Bornyl acetate (48.2), camphene (13.8), β-pinene (2.8), by GC-MS | *Liposcelis bostrychophila*, *Tribolium castaneum* | $LC_{50}$ = 2.8 mg/L air (fumigant) (*L.b.*); $LD_{50}$ = 50.9/10 μg/cm² PR = >95% at 2 h at 12.63/15.73 nL/cm² | [69] |
| I, IR | *Haplophyllum dauricum* (L.) G. Don October fruits | β-Pinene (42.37), limonene (15.77), β-thujene (13.15), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne* | $LC_{50}$ = 14.55/25.89 mg/L air (fumigant); $LC_{50}$ = >50/31.24 μg/adult (contact) RE = 92% at 2 h, 78.63 nL/cm²/72% at 2 h, 3.15 nL/cm² | [70] |
| I, IR | *Haplophyllum dauricum* (L.) G. Don October stems and leaves | β-Pinene (29.19), β-thujene (17.77), α-pinene (17.61), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne* | $LC_{50}$ = 14.91/17.17 mg/L air (fumigant); $LC_{50}$ = 20.21/25.46 μg/adult (contact) RE = 92% at 2 h, 78.63 nL/cm²/34% at 2 h, 3.15 nL/cm² | [70] |
| I, IR | *Haplophyllum dauricum* (L.) G. Don November fruits | β-Pinene (40.86), α-pinene (16.47), β-phellandrene (14.49), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne* | $LC_{50}$ = 54.41/19.54 mg/L air (fumigant); $LC_{50}$ = 39.58/26.18 μg/adult (contact) RE = 100% at 2 h, 15.83 nL/cm²/86% at 4 h, 3.15 nL/cm² | [70] |

**Table 1** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| I, IR | *Haplophyllum dauricum* (L.) G. November leaves | β-Pinene (30.57), 3-carene (26.84), β-phellandrene (21.34), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne* | $LC_{50}$ = 12.09/74.08 mg/L air (fumigant); $LC_{50}$ = >50/28.04 μg/adult (contact) RE = 100% at 4 h, 78.63 nL/cm²/76% at 2 h, 78.63 nL/cm² | [70] |
| I, IR | *Haplophyllum dauricum* (L.) G. Don November stems | α-Bisabolol oxide B (12.04), bornyl acetate (7.12), limonene (6.24), by GC-MS | *Tribolium castaneum*, *Lasioderma serricorne* | $LC_{50}$ = 22.75/19.08 mg/L air (fumigant); $LC_{50}$ = 20.21/25.46 μg/adult (contact) RE = 100% at 2 h, 15.83 nL/cm²/100% at 4 h, 78.63 nL/cm² | [70] |

All EOs were obtained by water distillation/steam distillation. Entries are ordered chronologically. FI, Feeding inhibition; GC-MS, gas chromatography-mass spectrometry; I, insecticidal; IR, insect repellent; $LC_{50}$, lethal concentration that kills 50% of the exposed organisms; $LC_{90}$, lethal concentration that kills 90% of the exposed organisms; LM, larval mortality; MR, mortality rate; PIA, percentage of irritating activity; PR, percentage repellency; PTA, percentage of toxic activity; $RC_{50}$, concentration that repels 50% of organisms; $RD_{50}$, (repellency dose) dose that repels 50% of insects; RE, repellent efficiency; RI, repellency index; SI, setting inhibition.

A very interesting study was published in 2016 by Govindarajan et al. [35] regarding the application of EO extracted from an Asian pine species (*Pinus kesiya* Royle ex. Gordon) as a potent insecticide against three species of mosquitos (malaria vector *Anopheles stephensi*, dengue vector *Aedes aegypti*, lymphatic filariasis vector *Culex quinquefasciatus*). Their results (mortality between 96% and 100% for all species at a 125 mg/L concentration EO) suggested the potential of EOs for controlling the larvae of dangerous mosquito species. The insecticidal effect of different EOs was tested in the same year by several groups against the booklice (*L. bostrychophila*) [36–38] and against stored products pests (*Sitophilus granarius*, *Tribolium castaneum*) [39, 40], with good results (more details provided in Table 1).

Jiang et al. [41] evaluated the insecticidal and insect repellent potential of EOs obtained from leaves, twigs, and seeds of *Cinnamomum camphora* L. Presl against the cotton aphid (*Aphis gossypii* Glover), the best results being obtained for the seeds EO ($LC_{50}$ = 146.78 mg/L after 48 h, respectively, 89.86% repellency at 20 mL/L EO after 24 h), whereas Kerdudo et al. [42] evaluated the insecticidal and insect repellent potential of *Pluchea carolinensis* (Jacq.) G. Don flowers EO against the yellow fever mosquito (*A. aegypti*), obtaining superior results for the repellent and irritating activities (36.6%, respectively, 66.2%, at 1% EO in ethanol vol/vol), compared to the commercial standard DEET (N,N-diethyl-3-methylbenzamide) (20.7%, respectively, 21%). Similar studies, incorporating the evaluation of the insecticidal and insect repellent activity, were performed in the same year by Pinto et al. [43], Guo et al. [44], Liang et al. [45], Norambuena et al. [46], and Aref et al. [47] against some common pests (*S. zeamais* Motschulsky, *T. castaneum*, *L. bostrychophila*, *S. oryzae*, *S. granarius*, *Rhyzopertha dominica*, *Oryzaephilus surinamensis*).

In their works published in 2017, Li et al. [48], Mendes et al. [49], and Oboh et al. [50] studied the insecticidal effect of EOs obtained from *Bidens frondosa* L. aerial parts, different *Psidium guajava* L. cultivars, respectively, orange peels, against different pests (*L. bostrychophila*, *A. aegypti*, respectively, *Tribolium confusum*, *Callosobruchus maculatus*, and *S. oryzae*). Other authors used both assays discussed in this chapter for the evaluation of EOs. Wu et al. [51] presented the potent contact and repellent activity effect of EOs obtained from *Zingiber zerumbet* (L.) Smith rhizomes on the cigarette beetles (*Lasioderma serricorne*), whereas Saad et al. [52] used citronella EO against the sweet potato whitefly, contributing to the list of pests that could be controlled by the use of EOs.

Application of EO as insecticides against some severe illnesses vectors was described in 2018 by Guerreiro et al. [53], who used *Eupatorium buniifolium* against the Chagas disease vector *Triatoma infestans* (Klug), and Wangrawa et al. [54], who applied several EOs against the malaria vector *Anopheles gambiae* (results detailed in Table 1), assigning the biological potential of EOs to the presence of oxygenated monoterpenes, sesquiterpenes hydrocarbons, and hydrocarbon monoterpenes. Several other studies describe the application of various EOs for the control of insects causing severe economic losses [55–59]. Among those studies, it is worth to mention the studies of Navarro-Rocha et al. [55], who evaluated two populations of *Geranium macrorrhizum* L. The wild variety (cultivated in Hungary) showed superior properties (in terms of feeding inhibition and setting inhibition) against *Spodoptera littoralis*, *M. persicae*, and *Rhopalosiphum padi*,

respectively, of Hannour et al. [58], who evaluated the properties of rosemary EO collected from two different sites and obtained superior results for EO richer in oxygenated monoterpenes.

In their 2019 study, Pavela et al. [60] encapsulated EOs of *Pimpinella anisum*, *Trachyspermum ammi*, and *Crithmum maritimum* into microemulsions, as effective mosquito larvicides. Their study (on *C. quinquefasciatus*, a known vector of *Wuchereria bancrofti*, avian malaria, and several arboviruses, including Zika or West Nile viruses) showed toxicity against the larvae (registering high larval mortality and low percentage hatched adults). Satyal et al. [61] evaluated the *Severinia monophylla* EO as a larvicidal agent (against *Aedes* mosquito) and insect repellent (against *Triatoma rubrofasciata*). Their results showed good larvicidal activity of EOs, as well as repellent activity at a concentration of 0.5%. The larvicidal activity of several EOs was also evaluated by Huang et al. [62] and Scalvenzi et al. [63] against the mosquito species *C. quinquefasciatus*, *A. albopictus*, and *A. aegypti*, whereas other studies identified the insecticidal potential of EOs against *Rhodnius prolixus* nymphs (vector of Chagas disease) and *Cimex lectularius* (bed bug) [64, 65]. Regarding the agricultural pests, several studies evaluated the insecticidal role of EOs against *Aphis pomi* DeGeer [66], *Ips typographus* [67], *S. oryzae* [68], *L. bostrychophila*, and *T. castaneum* [69], respectively, and *T. castaneum* and *L. serricorne* [70]. Noteworthy is the study performed by Cao et al. [70], who evaluated the differences in terms of insecticidal and insect repellent activity of EO obtained from different parts of *Haplophyllum dauricum* (L.) G. Don (fruits, stems, leaves) harvested in different months (October and November). The authors assign the repellent activity to the content in oxygenated monoterpenes and the insecticidal effect to their monoterpene content.

The presented examples do not intend to exhaustively review all the articles published in the selected time period on the topic of EO applications as insecticides and insect repellents, but to paint a picture of recent developments on this topic, briefly presenting the targeted pests and the results obtained, results that allow the perspective of developing of "green" insecticides (valuable for the agricultural domain in special) and pest repellents (valuable tools in the context of serious illnesses of which various insects are vectors). The insecticidal potential of the described EOs was often found to be superior to the commercial synthetic insecticides, at very low concentrations (generally <1% EO concentration; Table 1). The mechanisms of action of EOs as insecticidal agents represent a topic of interest and current debate. Starting from the fact that most monoterpenes are toxic to plants and animal tissues, many authors assign the main role in EOs' insecticidal action to these compounds. The mechanism through which EOs act as insecticidal or insect repellent agent is also different, considering the method of application: for direct contact, the most probable mechanism is through a neurotoxic action [71]; for fumigant application, the most probable mechanism is through the action of monoterpenoids on the respiratory system [18], whereas for the repellent activity, the exact mechanisms through which EOs act still remain unclear, considering the differences between the olfactory receptors of insects, despite the relatively high number of studies on this topic [18].

## 3 Herbicidal properties of EOs

One important category of pesticides, both synthetic and natural, is the herbicides. As in the case of insecticides, the extensive use of synthetic herbicide can lead to a wide range of toxic effects both on the environment and fauna [72, 73]. These potential harmful effects led in turn to the development of alternative, "greener" herbicides, either of microbial or plant origin [74, 75]. Although EO-based herbicides could help overcome many disadvantages of the synthetic products, some of the chemical and physical properties of EOs can prove to be impediments, such as high volatility and low water solubility [76].

Blázquez and Carbó [77] used boldo EO (compared with a commercially available lemon EO) as an efficient herbicide against *Portulaca oleracea* (a highly adaptable weed encountered on the summer crops). The herbicidal effect was tested by the authors against weed seeds, evaluating the germination of the seeds when exposed to EOs. If the commercial lemon EO does not affect the germination, the boldo EO induced complete inhibition of the germination at 0.5 and 1 mL/L concentration in some growth conditions (details presented in Table 2). Fouad et al. [78] evaluated the herbicidal effect of EOs obtained from four plants cultivated in Morocco against wild mustard (a weed especially affecting the cereals and row crops). The best results were obtained for *Cymbopogon citratus*, which provided 100% inhibition at a 0.4 mL/L dose (EO in 1:1 twin:water solution), much superior to the commercial herbicides 2.4 D (for which the same inhibition was achieved for a 2 mL/L concentration) and glyphosate (36.5% inhibition at a 1 mL/L concentration). Mahdavikia and Saharkhiz [79] evaluated the herbicidal potential of peppermint EO against three common weeds: field bindweed, purslane, and jungle rice. Their study showed complete inhibition of purslane and jungle rice (at concentrations of 1.8 mL/L,

**Table 2:** Origin and major composition of the essential oils presented in the review with herbicidal effect.

| Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|
| *Peumus boldus* Mol. leaves | Ascaridole (31.56), *p*-cymene (21.58), 1,8-cineole (12.57), by GC-MS | *Portulaca oleracea* L. | PSG = 0 (paper/sand/clay soilless culture and silty clay soil), 9 (loam soil), 47.5 (sandy clay) | [77] |
| *Cymbopogon citratus* (DC) Stapf | Neral (29.2), geranial (18.2), α-pinene (4.8), by GC-MS | *Sinapis arvensis* L. | PSG = 0 at 0.4 mL/L EO | [78] |
| *Eucalyptus cladocalyx* | Spathulenol (21.6), 1,8-cineole (20.5), *p*-cymene (15.1), by GC-MS | *Sinapis arvensis* L. | PSG = 0 at 1 mL/L EO | [78] |
| *Origanum vulgare* L. | Carvacrol (34.0), γ-terpinene (21.6), *p*-cymene (9.4), by GC-MS | *Sinapis arvensis* L. | PSG = 0 at 2 mL/L EO | [78] |
| *Artemisia absinthium* L. | β-Thujone (35.6), chamazulene (3.1), linalool (1.9), by GC-MS | *Sinapis arvensis* L. | PSG = 0 at 2 mL/L EO | [78] |
| *Mentha × piperita* L. CV. Mitcham | Menthol (35), mentone (17.48), menthofuran (11.7), by GC-MS | *Convolvulus arvensis* L., *Portulaca oleracea* L., *Echinochloa colonum* L. | PSG = 0 at 1.2 mL/L (*P.o.*) at 1.8 mL/L (*E.c.*), 23.5 at 1.8 mL/L (*C.a.*) | [79] |
| *Thymus algeriensis* Boiss. et Reut. leaves | α-Pinene (13.6–23.2),1,8-cineole (7.4–17.8), caryophyllene oxide (4.3–17.8), by GC-MS | *Medicago sativa* L., *Triticum aestivum* L. | PSG = 0, at 1 mg/mL concentration | [80] |
| *Cullen plicata* (Delile) C.H. Stirt. aerial parts | (–)-Caryophyllene oxide (33.42), Z-nerolidol (17.92), epi-cadinol (9.06), by GC-MS | *Bidens Pilosa*, *Urospermum picroides* | PSG = 0, at 200 μg/L concentration | [81] |
| *Origanum onites* L. | Carvacrol (57.1), linalool (8.39), *p*-cymene (7.86), by GC-MS | *Avena sterilis*, *Sinapis arvensis* | PSG = 0 at 4 μL EO/Petri dish | [82] |
| *Rosmarinus officinalis* L. | 1,8-Cineole (21.45), camphor (19.7), borneol (8.58), by GC-MS | *Avena sterilis*, *Sinapis arvensis* | PSG = 0 at 4 μL EO/Petri dish (*S.a.*) and <15% at 16 μL EO/Petri dish *A.a* | [82] |
| *Tetraclinis articulata* (Vahl.) Masters | α-Pinene (56.21), β-myrcene (3.08), 1,8-cineole (9.91), GC-MS | *Sinapis arvensis* L., *Phalaris canariensis* L. | PSG = 0 (*S.a.*) at 4 mL/L, 6.66 (*P.c.*) at 3 mL/L | [83] |
| Different genotypes of *Myrtus communis* L. fruits | 1,8-Cineole (29.20–31.40), linalool (15.67–19.13), α-terpineol (8.40– 18.43), α-pinene (6.04–20.71), by GC-MS | *Amaranthus retroflexus* L., *Chenopodium album* L., *Cirsium arvense* (L.) Scop., *Lactuca serriola* L., *Rumex crispus* L. | Best results: PSG = 0 for 1 mg/mL (*A.r.*, *C.a.*, *L.s.*), <5 (*Ch.a.*), <35 (*R.c.*), superior to 2,4 D | [84] |
| *Cupressus macrocarpa* Hartweg | Thujene (15.35), citronellal (11.09), farnesol (9.9), by GC-MS | *Dactyloctenium australe* L., *Amaranthus hybridus* L. | PSG = 0 at 5 mL/L EO in laboratory, 13/10.8 in pot culture | [85] |
| *Murraya koenigii* (L.) Spreng | Caryophyllene (30.21), selinene (12.09), α-humulene (11.23), by GC-MS | *Dactyloctenium australe* L., *Amaranthus hybridus* L. | PSG > 40% in laboratory, >50% in pot culture, at 5 mL/L EO | [85] |
| *Plectranthus amboinicus* (L.) Spreng | Carvacrol (27.11), caryophyllene (16.6), α-humulene (10.23), by GC-MS | *Dactyloctenium australe* L., *Amaranthus hybridus* L. | PSG > 50% in laboratory, >55% in pot culture, at 5 mL/L EO | [85] |
| *Persicaria odorata* (L.) Sojak | Dodecanal (31.66), decanal (21.47), 1-decanol (8.12), by GC-MS | *Dactyloctenium australe* L., *Amaranthus hybridus* L. | PSG < 10% in laboratory, >30% in pot culture, at 5 mL/L EO | [85] |
| *Pelargonium radula* (Cav.) | *cis*-Geraniol (31.16), γ-eudesmol (10.84), geranyl tiglate (8.49), by GC-MS | *Dactyloctenium australe* L., *Amaranthus hybridus* L. | PSG = 0 at 5 mL/L EO in laboratory, 9/6.7 in pot culture | [85] |
| Twenty Asteraceae species | Oxygenated monoterpenes, monoterpenes hydrocarbons, sesquiterpenes hydrocarbons, heterogeneous among species, individual components identified by GC-EIMS | *Amaranthus retroflexus*, *Setaria viridis* | Best results PSG = 0 (*Artemisia annua*, *Artemisia verlotiorum*, *Xanthium strumarium*, against *A.r.*, at 10 μg/L, *Artemisia annua*, *Xanthium strumarium*, against *S.v.*, at 100 μg/L) | [86] |
| *Nepeta nuda* subsp. *albiflora* aerial parts | 4aα,7α,7α,β-Nepetalactone (74.27), 2(1H)-naphthalenone, octahydro-8a-Methyl-*trans*- (10.09), *trans*-caryophyllene (1.98), by GC-MS | *Portulaca oleracea* | PSG = 14% at mL/L | [87] |

**Table 2** (continued)

| Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|
| *Citrus aurantiifolia* leaves | Limonene (40.92), citral (27.46), geranyl acetate (4.67), by GC-MS | *Avena fatua*, *Echinochloa crus-galli*, *Phalaris minor* | PSG = 0 at 1 mg/mL (*A.f.*), 1.5 mg/mL (*E.c-g.*), 0.75 mg/mL (*P.m.*) | [88] |
| *Satureja hortensis* L. aerial parts | Carvacrol (55.6), γ-terpinene (31.9), α-terpinene (3.75), by GC-MS | *Amaranthus retroflexus*, *Chenopodium album* | PSG = 0 (laboratory conditions), 16.6 (greenhouse), at 1 mL/L | [89] |
| *Tagetes erecta* L. leaves | Piperitone (17.12), neophytadiene (16.18), caryophyllene (11.10), by GC-MS | *Echinochloa crus-galli* (L.) Beauv. | PSG = 0 at 2 mL/L formulation (pre-emergence); CaC = 17.72, CbC = 20.99, CC = 10.08, at 6 h after treatment, at 80 mL/L formulation foliar application | [90] |
| *Cuminum cyminum* L. seeds | α-Pinene (29.20), limonene (21.70), 1,8-cineole (18.10), by GC-MS | *Rumex crispus* L., *Convolvulus arvensis* L. | PSG = 0. at 5 μg/cm$^2$ | [91] |
| *Mentha longifolia* L. leaves | *trans*-Piperidone epoxide (48.70), piperidone oxide (21.20), germacrene D (9.80), by GC-MS | *Rumex crispus* L., *Convolvulus arvensis* L. | PSG = 0 at 5 μg/cm$^2$ | [91] |
| *Allium sativum* L. bulbs | Diallyl trisulfide (33.40), diallyl disulfide (20.80), allyl methyl trisulfide (19.20), by GC-MS | *Rumex crispus* L., *Convolvulus arvensis* L. | PSG = 0 (*C.a.*) at 5 μg/cm$^2$; 0 (*R.c.*) at 10 μg/cm$^2$ | [91] |
| *Rosmarinus officinalis* L. leaves and flowers | 1,8-Cineole (54.6), camphor (12.27), α-pinene (7.09), by GC-MS | *Trifolium incarnatum*, *Silybum marianum*, *Phalaris minor* | PSG = 0 at 5 mM (pre-emergence); HA = 71.3/18/46.33 at 3.4% formulated EO (foliar application) | [92] |
| *Hyptis suaveolens* leaves | α-Phellandrene (22.8), α-pinene (10.1), limonene (8.5), by GC-MS | *Echinochloa crus-galli* | PSG = 0 at 2 mg/mL (pre-emergence); VI = 100% after 21 days of spray, 5% formulated EO (foliar application) | [93] |
| *Eucalyptus citriodora* Hook | Citronellal (73.6), isopulegol (4.5), citronellol (2.6), by GC-MS | *Angallis arvensis*, *Cyperus rotundus*, *Cynodon dactylon* | *A.a.*–VI = 100% after 7 days, at 50 mM, after 1 day at 100 mM; *C.r.*–VI = 70% 1st day, second spray at 100 mM; *C.d.*–VI = >80% 1st day, second spray, at 150 mM | [76] |
| *Ocimum basilicum* L. | Methyl chavicol (71.2), linalool (24), geranial (18.9), by GC-MS | *Angallis arvensis*, *Cyperus rotundus*, *Cynodon dactylon* | *A.a.*–VI = 100% after 7 days, at 50 mM, after 1 day at 100 mM; *C.r.*–VI = 80% 7 days, second spray at 100 mM; *C.d.*–VI = 100% 7 days, third spray, at 150 mM | [76] |
| *Mentha arvensis* L. leaves | Menthol (60.13), menthone (11.83), iso-methanone (5.46), by GC-MS | *Angallis arvensis*, *Cyperus rotundus*, *Cynodon dactylon* | *A.a.*–VI = 100% after 7 days, at 50 mM, after 1 day at 100 mM; *C.r.*–VI = 100% 1st day, second spray at 100 mM; *C.d.*–VI = 100% 7 days, first spray at 150 mM | [76] |

All EOs were obtained by water distillation/steam distillation. Entries are ordered chronologically. CaC, Chlorophyll a content; CbC, chlorophyll b content; CC, carotenoid content; H, herbicidal; HA, herbicidal activity; GC-MS, gas chromatography-mass spectrometry; PSG, percentage seed germination; VI, visible injury.

respectively, 1.2 mL/L), but also revealed the lack of selectivity, as also inhibiting the germination of tomato and radish seeds. Ali et al. [80] proposed the potential use of *Thymus algeriensis* Boiss. et Reut. EO obtained from different parts of plants, using *Medicago sativa* L. and *Triticum aestivum* L. as plant models.

In his 2016 study, El-Gawad [81] evaluated the herbicidal potential of EO obtained from the aerial parts of *Cullen plicata* (Delile) C.H. Stirt. against *Bidens pilosa* and *Urospermum picroides*, whereas Atak et al. [82] used oregano and rosemary EO as herbicides against *Avena sterilis* and *Sinapis arvensis*. Ghnaya et al. [83] evaluated *Tetraclinis articulata* (Vahl.) Masters. EO against *S. arvensis* L. and *Phalaris canariensis* L., whereas Kordali et al. [84] used EOs obtained from four myrtle genotypes on *Amaranthus retroflexus* L., *Chenopodium album* L., *Cirsium arvense* (L.) Scop., *Lactuca serriola* L., and *Rumex crispus* L. In the same year, Almarie et al. [85] evaluated a series of EOs extracted from Malaysian plants against *Amaranthus hybridus* and *Dactyloctenium australe*, the best results being obtained for *Cupressus macrocarpa* and *Pelargonium radula* EOs.

In a 2017 study, Benvenuti et al. [86] evaluated 20 EOs extracted from Asteraceae species collected in Tuscany as natural herbicides against *A. retroflexus* and *Setaria viridis*, the best results being obtained for EOs of *Artemisia annua*, *Artemisia verlotiorum*, and *Xanthium strumarium* against *A. retroflexus* (0% germination at 10 µg/L EO), respectively, for *A. annua* and *X. strumarium* against *S. viridis* (0% germination at 100 µg/L EO). Bozok et al. [87] evaluated EOs obtained from the aerial parts of *Nepeta nuda* subsp. *albiflora* against *P. oleracea*, whereas Fagodia et al. [88] used *Citrus aurantiifolia* EO as herbicide against *Avena fatua*, *Echinochloa crus-galli*, and *Phalaris minor*. In the same year, Hazrati et al. [89] formulated nanoemulsion containing *Satureja hortensis* L. EO (2%) and evaluated its herbicidal activity against *A. retroflexus* and *C. album*, with good efficiency, both in laboratory and greenhouse conditions.

In a 2018 study, Laosinwattana et al. [90] used *Tagetes erecta* L. EO formulated as emulsifiable concentrate (50%) as herbicidal agent against *E. crus-galli* (L.) Beauv., applied both pre- and post-emergence. The pre-emergence application led to a complete inhibition, that the authors assign to the inhibition of α-amylase activity, whereas the post-emergence application led to the degradation of the weed (wilted and desiccated appearance, decreased chlorophyll a, chlorophyll b, and carotenoid content), assigned to the interference of the herbicide with the photosynthetic metabolism. In the same year, Üstüner et al. [91] applied EOs obtained from *Cuminum cyminum* L., *Mentha longifolia* L., and *Allium sativum* L. as herbicidal agents against *R. crispus* L. and *Convolvulus arvensis* L., two widely encountered crop weeds. Their results showed remarkable inhibition of the seed germination at almost all tested concentrations.

Kaab et al. [92] used EO obtained from the leaves and flowers of *Rosmarinus officinalis* L. as herbicidal agent in a formulation containing 3.4% EO against the weeds *Trifolium incarnatum*, *Silybum marianum*, and *P. minor* obtaining a complete seed germination inhibition at 5 mM EO concentration. Sharma et al. [93] used *Hyptis suaveolens* EO as herbicidal agent (pre- and post-emergence) against *E. crus-galli* (the major weed of rice). More than the very good herbicidal results, it is to be noticed that the formulation containing EO shows good selectivity to the weed (60% germination of the rice, compared with 0% for the weed at 2 mg/mL EO concentration), thus allowing the practical use of the herbicide for the protection of rice culture. In the same year, Khare et al. [76] evaluated the herbicidal impact of three EOs (*Eucalyptus citriodora* Hook, *Ocimum basilicum* L., and *Mentha arvensis* L.) formulated as emulsions against *Angallis arvensis*, *Cyperus rotundus*, and *Cynodon dactylon*, in greenhouse conditions. The most promising material (from the obtained results) was the formulation containing *M. arvensis* EO, which at 100- to 150-mM concentration and different foliar application conditions led to 100% visible injuries (weed death).

When considering the use of EOs as a potential herbicide, one of the most important aspects is the selectivity, as the formulation should affect mainly the weeds and not the crops, as demonstrated by Sharma et al. [93]. The general mechanism through which EOs act as herbicides is considered to be inhibition of mitochondrial respiration, accompanied by damages induced to the membrane integrity (increasing membrane permeability), and oxidative stress, affecting pH homoeostasis and equilibrium of inorganic ions [86].

## 4 Application of EOs as acaricidal and nematicidal agents

In close connection to their insecticidal potential, the natural extracts and EOs can be applied as acaricidal agents. The *Acari*, in its largest sense, refers to mites and ticks, both types of arachnids having economical and medical importance, affecting multiple crops types, as well as representing vectors for a large number of diseases [94–96]. In the last years, several review articles described the use of natural alternatives to the synthetic acaricides [97–99], works that we recommend for further reading. As the *Acari*, the nematodes represent important pests, affecting both the agricultural and horticultural crops, but also affecting the livestock and human health [100, 101].

Zandi-Sohani and Ramezani [102] evaluated in 2015 five EOs (*S. hortensis* L., *Mentha pulegium* L., *Mentha viridis*

L., *R. officinalis* L., *Zataria multiflora* Bioss.) as acaricidal solutions against *Tetranychus turkestani* Ugarov and Nikolskii (strawberry spider mite). The best results were obtained for *Z. multiflora*, with an $LC_{50}$ value of 5.5 µL/L air (fumigant assay) and 100% mortality at 24-h exposure time to 12 µL/L EO. The acaricidal effect against *Rhipicephalus (Boophilus) microplus* (a thick that parasites multiple livestock species) of EOs obtained from different *Ocimum* species was studied by Hüe et al. [103], the best results being obtained for *Ocimum urticaefolium* and *O. gratissimum* originating from Cameroon. The same tick was used by Costa-Júnior et al. [104], Monteiro et al. [105], and Vinturelle et al. [106] to test the acaricidal effect of EOs isolated from *Lippia gracilis*, *Cinnamomum verum* Presl, respectively, *Piper nigrum*, and *Citrus limonum* (further details presented in Table 3). While Costa-Júnior et al. [104] assigned the acaricidal effect of EOs to the monoterpenes present, especially carvacrol and thymol, Vinturelle et al. [106] compared the efficiency of two different composition EOs (*C. limonum* dominated by monoterpenes, respectively, *P. nigrum* dominated by sesquiterpenes), obtaining superior results for the *C. limonum* EO, thus suggesting a more potent acaricidal effect related to the presence of monoterpenes.

Jeon et al. [107] used EO obtained from *Cinnamomum zeylanicum* bark cultivated in France and India as acaricidal agents against *Dermatophagoides* spp. and *Tyrophagus putrescentiae* mites, offering the possibility to develop natural acaricides against the dust and stored food mites. Fatemikia et al. [108] applied the EO obtained from *Ferula gummosa* Boiss. as acaricidal agent against the plant-feeding mite *Tetranychus urticae* Koch., showing toxicity against the eggs and adults, as well as oviposition deterrent and repellent activity. Good results ($LC_{50}$ = 0.06 mL/L air) were also obtained by Born et al. [109] against the same mite species, using *L. gracilis* EO; the results also proved a high selectivity towards the tested mite, compared with its natural enemy, *Neoseiulus californicus*. Similar results were also obtained by Mahmoud et al. [110] and Ribeiro et al. [111]. Rey-Valeirón et al. [112] used *Schinus molle* EO against *Rhipicephalus sanguineus* (brown tick of the dog) larvae and engorged adult females, obtaining superior results compared with the control acaricide used (cypermethrin).

Similar with the insecticidal potential, the acaricidal potential of EOs is usually assigned by the authors to their monoterpenes content [104], and more than that, those monoterpenes components (such as carvacrol or thymol) were proposed as efficient agents against the metabolic resistance mechanisms or insensitive acetylcholinesterases (AChE) in the case of organophosphate resistant *Acari* [104].

Avato et al. [113] used EOs obtained from Moroccan ecotypes of *Artemisia herba-alba*, *Citrus sinensis*, *R. officinalis*, and *Thymus satureioides* for the control of the phytonematodes *M. incognita*, *Pratylenchus vulnus*, and *Xiphinema index*, whereas Álvarez et al. [114] used EO extracted from the leaves and inflorescences of *Tagetes zypaquirensis* against *Meloidogyne* spp. (further details presented in Table 3). Barros et al. [115] used EO of *Dysphania ambrosioides* aerial parts (formulated in aqueous Tween 80 solutions) against *Meloidogyne incognita* applying in vitro and in vivo assays, observing a significant nematicidal activity, compared with commercial EOs.

The mechanism responsible for the nematicidal action of EOs still represents a subject of debate. Avato et al. [113] propose as most probable action of EOs the permeability change of nematode cell membranes or the inhibition of AChE activity (as already observed for insects), whereas Barros et al. [115] observed the neurotoxicity effects of EOs on nematodes.

## 5 Current limitations and future perspectives

The application of EOs current represents an attractive area of research, focusing especially on their potential insecticidal and herbicidal potential (covered by the present article; Figure 3), as well as on their antibacterial, antifungal, and antiviral potential (not covered by the review), based on the properties of constituent compounds. Several databases regarding the composition of EOs and the toxicity of the individual compounds are available to the public [117, 118], constituting an important instrument for specialists working in this area. A closer look at progress in the last years can offer the first key perspective: the study on the pesticidal applications of EOs should also focus on other areas (insufficiently explored up to date), such as their applications as rodenticidal/rodent repellent or algicidal agents.

Indifferent on their final applications, the selectivity of EOs should be explored. Several works reviewed described the selectivity of the materials used. The proposed pesticides should have a high selectivity (either we are talking about herbicides, insecticides, or other activities) towards the targeted organisms, influencing as little as possible the nontarget organisms.

Another key factor that should be explored in future research is represented by their application methods. Being limited by the physicochemical characteristics of EOs (especially by their volatility and a generally low

**Table 3:** Origin and major composition of the essential oils presented in the review with acaricidal and nematicidal effect.

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| A | *Satureja hortensis* L. | Carvacrol (38.33), γ-terpinene (22.72), *p*-cymene (9.55), by GC-MS | *Tetranychus turkestani* Ugarov and Nikolskii | $LC_{50}$ = 9.4 μL/L air; $LC_{90}$ = 31.3 μL/L air(fumigant); MR = 100% at 24 h, 12 μL/L | [102] |
| A | *Mentha pulegium* L. | Piperitone (32.16), piperitenone (29.62), α-terpineol (6.4), by GC-MS | *Tetranychus turkestani* Ugarov and Nikolskii | $LC_{50}$ = 14.5 μL/L air; $LC_{90}$ = 19.9 μL/L air (fumigant); MR = 100% at 24 h, 20 μL/L | [102] |
| A | *Mentha viridis* L. | Carvone (51.03), limonene (21.12), *cis*-dihydrocarvone (3.23), by GC-MS | *Tetranychus turkestani* Ugarov and Nikolskii | $LC_{50}$ = 15.3 μL/L air; $LC_{90}$ = 23.4 μL/L air (fumigant); MR = 100% at 24 h, 20 μL/L | [102] |
| A | *Rosmarinus officinalis* L. | Borneol (21.17), α-pinene (15.17), α-terpineol (7.54), by GC-MS | *Tetranychus turkestani* Ugarov and Nikolskii | $LC_{50}$ = 29.8 μL/L air; $LC_{90}$ = 35.6 μL/L air (fumigant); MR = 91.1% at 24 h, 17 μL/L | [102] |
| A | *Zataria multiflora* Bioss | Thymol (30.61), carvacrol (22.18), *p*-cymene (7.34), by GC-MS | *Tetranychus turkestani* Ugarov and Nikolskii | $LC_{50}$ = 5.5 μL/L air; $LC_{90}$ = 11.8 μL/L air (fumigant); MR = 100% at 24 h, 12 μL/L | [102] |
| A | *Ocimum gratissimum L.*–Cameroon | γ-Terpinene (33), thymol (30.5), *p*-cymene (7), by GC-MS | *Rhipicephalus (Boophilus) microplus* | MR at 2.5% EO = 100 $LC_{50}$ = 0.98% | [103] |
| A | *Ocimum gratissimum L.*–New Caledonia | (Z)-β-ocimene (49.8), eugenol (22,3), β-caryophyllene (4.7), by GC-MS | *Rhipicephalus (Boophilus) microplus* | MR at 5% EO = 65.17 | [103] |
| A | *Ocimum urticaefolium* Roth | Eugenol (33), β-bisabolene (21.6), elemicin (18.1), by GC-MS | *Rhipicephalus (Boophilus) microplus* | MR at 2.5% EO = 100 $LC_{50}$ = 0.90% | [103] |
| A | *Ocimum canum* Sims leaves | 1,8-Cineole (70.2), β-pinene (5.7), α-terpineol (4), by GC-MS | *Rhipicephalus (Boophilus) microplus* | MR at 5% EO = 0 | [103] |
| A | *Lippia gracilis* Schauer leaves genotype 106 | Thymol (59.26), β-caryophyllene (8.57), methylthymol (8.32), by GC-MS | *Rhipicephalus (Boophilus) microplus* susceptible and organophosphate-resistant larvae | $LC_{50}$ = 1.02 (susceptible strain), 0.84 mg/mL (resistant strain) | [104] |
| A | *Lippia gracilis* Schauer leaves genotype 201 | Carvacrol (35.28), γ-terpinene (21.11), *p*-cymene (13.74), by GC-MS | *Rhipicephalus (Boophilus) microplus* susceptible and organophosphate-resistant larvae | $LC_{50}$ = 1.03 (susceptible strain), 0.65 mg/mL (resistant strain) | [104] |
| A | *Cinnamomum verum* Presl leaves | Benzyl benzoate (65.4), linalool (5.4), E-cinnamaldehyde (4.0), by GC-MS | *Rhipicephalus (Boophilus) microplus* | $LC_{50}$ = 1 mg/mL (larvae) and 60.78 mg/mL (engorged female) | [105] |
| A | *Piper nigrum* | β-Caryophyllene (26.2), σ-ocymene (5.8), α-pinene (5.5), by GC-MS | *Rhipicephalus (Boophilus) microplus* | $LC_{50}$ = 3.70%; $LC_{90}$ = 14.80% MR = 81.7% at 10% EO | [106] |
| A | *Citrus limonum* | Limonene (50.3), β-pinene (14.4), γ-terpinene (11.7), by GC-MS | *Rhipicephalus (Boophilus) microplus* | $LC_{50}$ = 2.2%; $LC_{90}$ = 4.9% MR = 100 at 10% EO | [106] |
| A | *Cinnamomum zeylanicum* bark - France | Cinnamaldehyde (63.97), eugenol (6.84), cinnamyl acetate (3.90), by GC-MS | *Dermatophagoides farinae*, *Dermatophagoides pteronyssinus*, *Tyrophagus putrescentiae* | $LD_{50}$ = 0.92/0.81/1.82 μg/cm³ (fabric disk); 2.07/1.94/6.20 μg/cm² (F) (paper assay) | [107] |
| A | *Cinnamomum zeylanicum* bark - India | Cinnamaldehyde (67.21), eugenol (19.79), cinnamyl acetate (4.34), by GC-MS | *Dermatophagoides farinae*, *Dermatophagoides pteronyssinus*, *Tyrophagus putrescentiae* | $LD_{50}$ = 0.64/0.51/1.72 μg/cm³ (India) (fabric disk); 1.82/1.55/3.08 μg/cm² (paper assay) | [107] |
| A | *Ferula gumosa* Boiss. Resins | β-Pinene (50.1), α- pinene (14.9), δ-3-carene (6.7), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 6.98/6.52 μL/L (eggs/adults) (fumigant) | [108] |
| A | *Lippia gracilis* leaves | Carvacrol (61), *p*-cymene (11), thymol (11), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 0.06 μL/L air (fumigant), $LC_{50}$ = 29.7 μL/L air (residual effect) | [109] |

**Table 3** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| A | *Cupressus macrocarpa* Hartw. ex Gordon | Terpinen-4-ol (20.29), sabinene (18.67), β-citronellol (13.01), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 40.66 mg/L air (fumigant, 24 h), 17.39 mg/L air (slide dip, 48 h) | [110] |
| A | *Callistemon viminals* (Sol. ex Gaertn.) G. Don | 1,8-Cineole (71.77), α-pinene (11.47), terpinen-4-ol (3.18), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 5.69 mg/L air (fumigant, 24 h), 22.76 mg/L air (slide dip, 48 h) | [110] |
| A | *Origanum vulgare* L. | Pulegone (77.45), menthone (4.86), *cis*-isopulegone (2.22), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 8.52 mg/L air (fumigant, 24 h), 10.26 mg/L air (slide dip, 48 h) | [110] |
| A | *Pelargonium graveolens* L'Her | β-Citronellol (35.92), geraniol (11.66), citronellylformate (11.40), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 12.27 mg/L air (fumigant, 24 h), 23.83 mg/L air (slide dip, 48 h) | [110] |
| A | *Thuja orientalis* L. leaves | α-Pinene (35.49), δ-3-carene (25.42), α-cedrol (9.05), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 7.51 mg/L air (fumigant, 24 h), 114.46 mg/L air (slide dip, 48 h) | [110] |
| A | *Citrus paradisi* Macfad peel | Limonene (74.29), linalool (4.61), linalool oxide (4.18), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 6.96 mg/L air (fumigant, 24 h), 160.75 mg/L air (slide dip, 48 h) | [110] |
| A | *Citrus aurantiifolia* peels | Limonene (37.73), β-pinene (9.89), α-terpineol (5.04), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 11.24 μL/L air (fumigation); 106.14 mL/L (residual) | [111] |
| A | *Citrus limon* peels | Limonene (40.70), β-pinene (18.14), α-fenchene (3.84), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 9.34 μL/L air (fumigation); 25.18 mL/L (residual) | [111] |
| A | *Citrus reticulata* peels | Limonene (77.79), myrcene (6.50), linalool (3.56), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 6.09 μL/L air (fumigation); 167.8 mL/L (residual) | [111] |
| A | *Citrus reticulata* × *Citrus sinensis* peels | Limonene (60.96), p-mentha-2,4(8) -diene (9.8), myrcene (4.61), by GC-MS | *Tetranychus urticae* Koch | $LC_{50}$ = 10.39 μL/L air (fumigation); 159.75 mL/L (residual) | [111] |
| A | *Schinus molle* L. fruits | *p*-Cymene (40.0), limonene (19.5), myrcene (7.7), by GC-MS | *Rhipicephalus sanguineus* | MR = 99.31 at 2% EO (larvae), IOv = 29.62%, EH = 59.43%, 22.61% at 2% EO (adults) | [112] |
| N | *Artemisia herba-alba* | Camphor (25.88), *cis*-thujone (24.95), *trans*-thujone (16.26), by GC-MS | *Meloidogyne incognita*, *Pratylenchus vulnus*, *Xiphinema index* | MR = 97.5 (*M.i.* at 48 h, 15 mg/L), 100 (*X.i.* at 24 h, 2 mg/L), 67 (*P.v.* at 96 h, 15 mg/L); 68.2% reduction of nematodes/g roots at 200 μg/kg soil (fumigation); 65.5% reduction at 100 μg/kg soil (drench) | [113] |
| N | *Citrus sinensis* | Limonene (95.6), β-myrcene (1.96), α-pinene (0.54), by GC-MS | *Meloidogyne incognita*, *Pratylenchus vulnus*, *Xiphinema index* | MR = 39.2/18.2/73.2 at 96 h, 15 mg/L; 46.7% reduction of nematodes/g roots at 200 μg/kg soil (fumigation); 61.18% reduction at 100 μg/kg soil (drench) | [113] |
| N | *Rosmarinus officinalis* | 1,8-Cineole (47), α-pinene (14.55), camphor (12.07), by GC-MS | *Meloidogyne incognita*, *Pratylenchus vulnus*, *Xiphinema index* | MR = 100 (*X.i.* at 24 h, 2 mg/L), 98.3/75.2 at 96 h, 15 mg/L (*M.i.*, *P.v.*) 67.5% reduction of nematodes/g roots at 200 μg/kg soil (fumigation); 56.74% reduction at 100 μg/kg soil (drench) | [113] |
| N | *Thymus satureioides* | Borneol (29.31), thymol (11.76), *o*-cymene (6.78), by GC-MS | *Meloidogyne incognita*, *Pratylenchus vulnus*, *Xiphinema index* | MR = 100 (*X.i.* at 24 h, 2 mg/L), 85.7/39.9 (*M.i.*, *P.v.*) at 96 h, 15 mg/L (in vitro); 53.89% reduction of nematodes/g roots at 200 μg/kg soil (fumigation); 60.17% reduction at 100 μg/kg soil (drench) | [113] |

**Table 3** (continued)

| Effect | Plant material | Major composition (%) | Targeted pest | Effect quantification | Ref. |
|---|---|---|---|---|---|
| N | *Tagetes zypaquirensis* | Dihydrotagetone (42.2), tagetone (22.9), *trans*-ocimene (20.8), by GC-FID, GC-MS | *Meloidogyne* spp. | 52% reduction of eggs/100 g roots; 42% reduction of stage 2 juvenils/100 g of soil | [114] |
| N | *Dysphania ambrosioides* aerial parts | (Z)-ascaridole (87.3), (E)-ascaridole (8.4), *p*-cymene (3.3), by GC-MS | *Meloidogyne incognita* | $LC_{50}$ = 307 mg/L; $LC_{90}$ = 580 mg/L (in vitro); Significant reduction of galls and eggs at 800 mg/L, respectively, 1100 mg/L | [115] |

All EOs were obtained by water distillation/steam distillation. Entries are ordered chronologically. A, Acaricidal; EH, egg hatching; GC-MS, gas chromatography-mass spectrometry; IOv, inhibition of oviposition; $LC_{50}$, lethal concentration that kills 50% of the exposed organisms; $LC_{90}$, lethal concentration that kills 90% of the exposed organisms; MR, mortality rate; N, nematicidal.

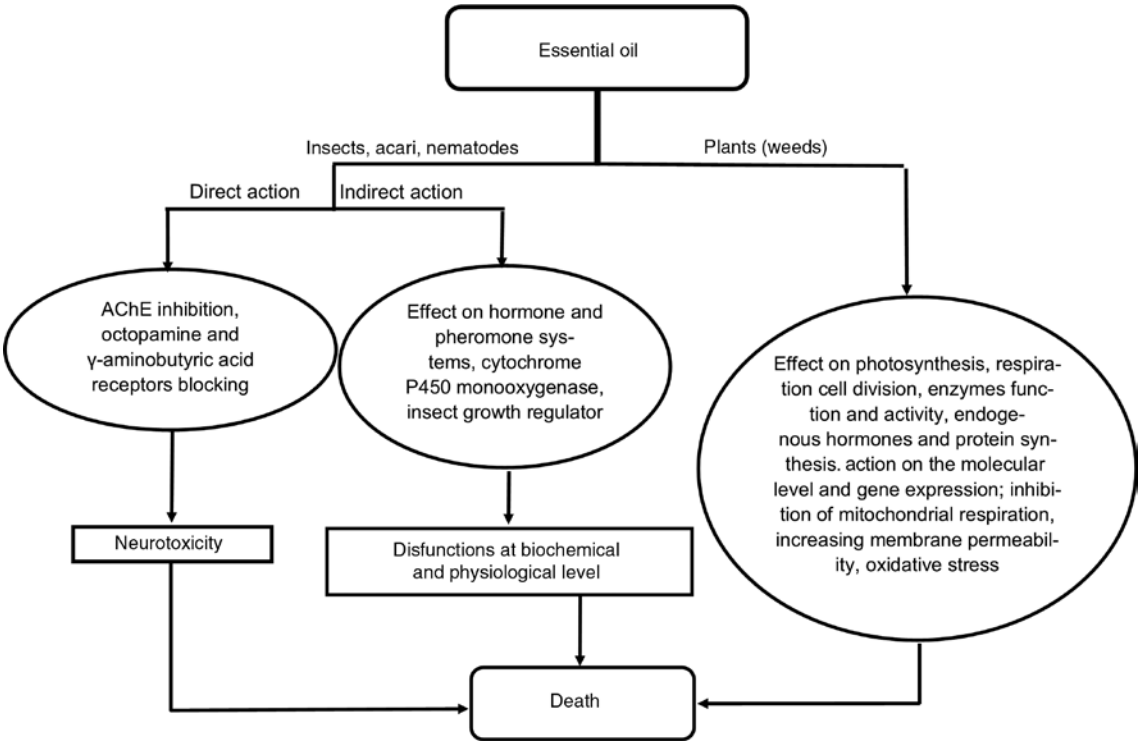


**Figure 3:** General pathways of EOs' pesticide action (adapted from Mossa [18], Benvenuti et al. [86], and El-Hadary and Chung [116]).

bioavailability of the active polyphenolic compounds), EOs should usually be formulated as microemulsion or nanoemulsion. The current research is focused on the application of aqueous microemulsions using commercially available surfactants. In this area, the use of natural surfactants could bring a supplementary "green" component. More than that, the application of nanotechnology tools for developing new formulations, using polymer-based nanocapsules, could enhance or encapsulation with metallic nanoparticles could increase the availability of EOs and, at the same time, potentiate their activities.

An important aspect to be considered by future studies is the advantages that can be provided by biotechnology, from the cocultures that can be used for pesticidal screening [119] to engineering plants with higher EO content or richer in biological active terpenoids [120, 121].

Finally, the extraction method of EOs could benefit from the latest technological developments. The reviewed articles used hydrodistillation (either water or steam distillation for isolation of EOs, the method of choice being based on the sensitivity of known compounds in EOs and availability). Other techniques developed in the last years, such as microwave-assisted extraction (with or without solvent) [122] or membrane extraction [123], proved to be efficient for the extraction of EOs and can be used for industrial-scale development of pesticides based on EOs.

## 6 Conclusions

The captivating field of EOs finds practical applications in numerous areas. Among those areas, the application of EOs for replacing the synthetic pesticides currently used can lead to a tremendous increase in the life quality (by considering the potential toxic effect of the pesticides on the environment and on fauna and human health) and, at the same time, provide an efficient tool for preventing resistance development in the targeted pests. Although several authors proposed some type of compounds (especially monoterpenes and oxygenated monoterpenes) as responsible for the pesticidal effect of EOs, in our opinion, the most probable mechanism is represented by a synergistic action of several compounds found in EOs.

As a concluding remark, EOs, although currently under study for their pesticidal activity, should be further explored, as they can provide important tools in fighting the pests that not only have important economic implications, but can also prove to be vectors of serious illnesses.

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