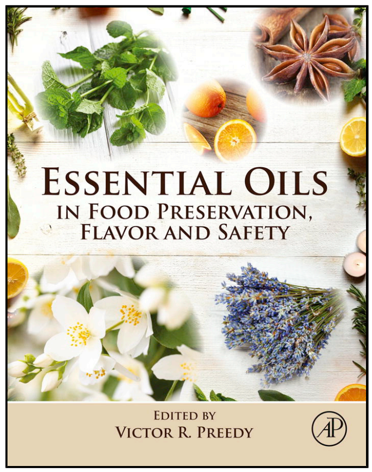




From Park, Y.-L., Tak, J.-H., 2016. Essential Oils for Arthropod Pest Management in Agricultural Production Systems. In: Preedy, V.R. (Ed.), Essential Oils in Food Preservation, Flavor and Safety. Academic Press, 61–70.
ISBN: 9780124166417

Chapter 6

# Essential Oils for Arthropod Pest Management in Agricultural Production Systems

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## List of Abbreviations

**EIL** Economic injury level
**GABA** Gamma aminobutyric acid
**IPM** Integrated pest management

## INTRODUCTION

Essential oils are secondary metabolites of plants. In general, they are volatile compounds that have a tendency to be readily broken down by abiotic environmental factors (Isman, 2000). Essential oils can be extracted mostly from leaves, but also can be draw from other nonwoody parts of plants (Batish et al., 2008). Approximately 17,500 species of plants are known to possess essential oils and most plants belong to the families of Myrtaceae, Lauraceae, Lamiaceae, and Asteraceae (Regnault-Roger et al., 2012). Extracted essential oils retain scent, of which the major components are monoterpenes, sesquiterpenes, phenols, oxides, ethers, alcohols, esters, aldehydes, and ketones (Batish et al., 2008). These compounds can affect arthropod pests and benefitial insects in production agriculture.

This chapter is mainly focused on arthropod pest management in crop production and production agriculture using essential oils. Target organisms of this chapter include insects and mites, but exclude stored product insects and medically important arthropod pests. In addition, nontarget effects of essential oils as insecticides or acaricides on crop pollinators and natural enemies of arthropod pests in crop production are discussed in this chapter. More detailed information about stored product pests can be found in Chapter 5. Technology for delivery of essential oils as pesticides can be found in Chapter 12.

## ESSENTIAL OILS AS PESTICIDES

Essential oils are by-products of plant metabolism and plants use them for protection from various plant-feeding arthropods (e.g., insects and mites) and plant pathogens. For example, volatile monoterpenes in plants can deter or repel herbivorous insect pests and pathogenic fungi (Langenheim, 1994). Some plants use their essential oils as a chemical for communication with different species of plants or animals (i.e., allelochemical). Volatiles of essential oils acting as semiochemicals can benefit plants (i.e., allomone—sender benefits), insects, or mites (i.e., kairomone—receiver benefits) or both the plants and insects (i.e., synomone—both sender and receiver benefit). Example usages of essential oils as semiochemicals are presented in Figure 1. These essential oils are thought to be important chemicals triggering coevolution between plants and insects.

Essential oils can be extracted from plants by using various methods such as hydrodistillation, steam distillation, dry distillation, or cold pressing (Regnault-Roger et al., 2012); hydrodistillation is the oldest way to extract essential oils, dating back to 5000 years ago (Brud, 2010). Quantity and quality of chemical components in an essential oil can be dramatically changed depending on extraction methods (Chiasson et al., 2001) (Figure 2). Extracted essential oils can be widely used for various purposes including medicinal and pharmaceutical treatment, food flavor, and perfumery. Essential oils have

**Essential Oils in Food Preservation, Flavor and Safety.** http://dx.doi.org/10.1016/B978-0-12-416641-7.00006-7



Essential Oils in Food Preservation, Flavor and Safety, First Edition, 2016, 61-70

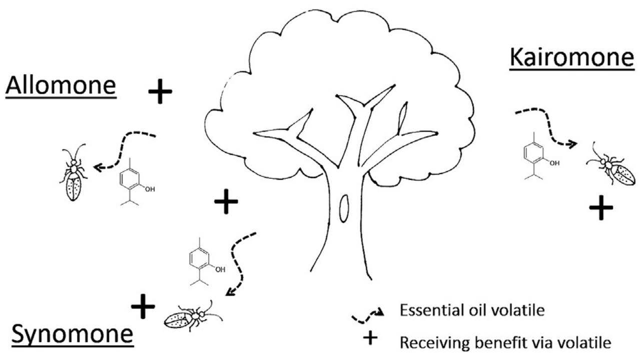


**FIGURE 1** An example of use of essential oils as allelochemicals. Volatiles of essential oils produced by plants (senders) may affect arthropod pests (receivers) as an allomone (benefits the sender), kairomone (benefits the receiver), or synomone (benefits both the sender and the receiver).

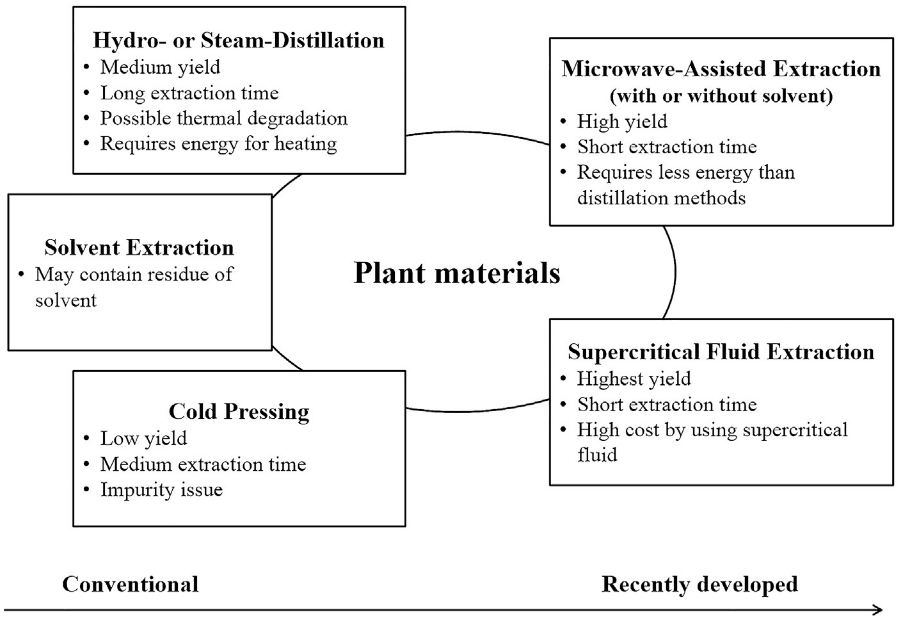


**FIGURE 2** Overview of essential oils extraction methods.

received much attention from researchers and pest management practitioners because of their capability to kill pests including insects, plant pathogens, and weeds. Indeed, essential oils have been categorized as botanical pesticides since the 1980s (Regnault-Roger, 1997). Because essential oils are low-risk and naturally driven pesticides, they are can be good control measures, specifically for organic farming.

Plant species that contain essential oils with pesticide properties are found in the families of Amaryllidaceae, Apiaceae, Asteraceae, Atherospermataceae, Burseraceae, Cupressaceae, Fabaceae, Lamiaceae, Lauraceae, Myrtaceae, Phytolaccaceae, Piperaceae, Poaceae, Rutaceae, and Zingiberaceae. Essential oils from these plants can be used as contact poison, stomach poison, repellent, and growth regulator (Regnault-Roger et al., 2012). In the past, many studies have tested the effectiveness of essential oils as pesticides against insect pests in cropping fields, medically important arthropod pests (e.g., mosquitoes, flies, ticks, and mites), and stored product insect pests (e.g., been weevils, flour beetles, and Indian meal moths).

## MODES OF ACTION OF ESSENTIAL OILS

Understanding pesticide mode of action is fundamental to the selection and application of pesticides. Pesticide mode of action explains how a pesticide kills target pests. The mode of action involves anatomical, physiological, and biochemical interactions and responses of organisms to pesticides. In other words, mode of action is the way in which a pesticide causes physiological disruption of pests at its target site inside organisms. Essential oils have various modes of action as pesticides. First, monoterpenes in essential oils are neurotoxic to insect pests by blocking neurotransmitters such as acetylcholinesterase (Regnault-Roger, 1997). In addition to monoterpenes, thymol is associated with gamma aminobutyric acid

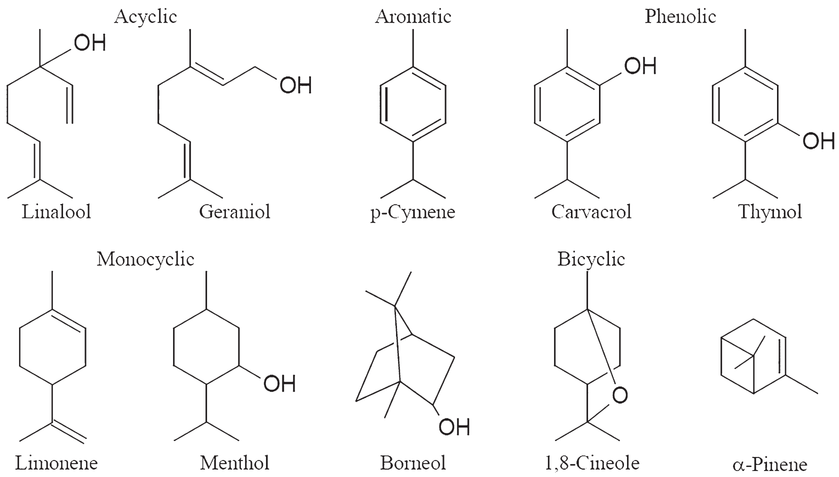


**FIGURE 3** Chemical structure of major terpenes that have pesticidal effects on arthropod pests.

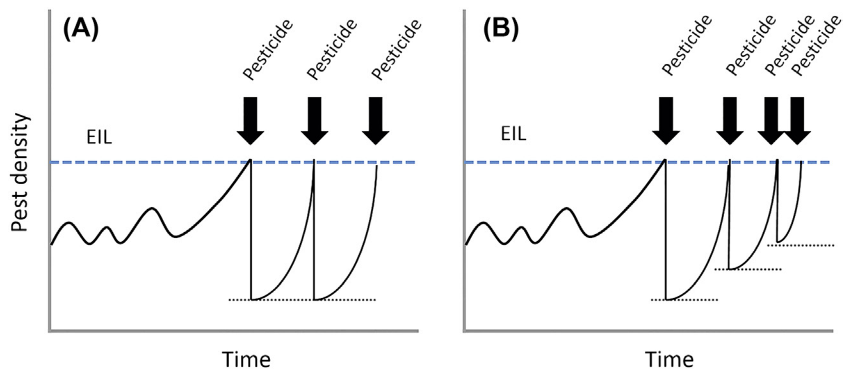


**FIGURE 4** Pest management concept of integrated pest management (IPM). (A) Pesticides are used to keep pest density under economic injury level (EIL) and essential oils can be used as a control measure. (B) Many conventional pesticides cause pesticide resistance when the same or similar pesticides are used over and over again. So far, there have been no reports on pest resistance to essential oils.

receptors and chloride channels, and eugenol activates octopanime receptors (Enan, 2001). The rapid toxic effects of essential oils on insect pests are a good indication of a neurotoxic effect (Isman and Machial, 2006). Major terpenes that have pesticidal properties are shown in Figure 3. Second, essential oils can be used as insect growth regulators. Some essential oils are known to block growth hormones (Tarelli et al., 2009), hence insect growth at various life stages can be disrupted (Regnault-Roger et al., 2012). Third, soft-bodied insects are killed by lipophilic plant oils because the oils penetrate waxy layers of the cuticle, causing death by excessive water loss in the insect body (Gillilan, 2012). Fourth, P450 cytochromes responsible for exterminating foreign organisms inside an insect body can be inhibited by essential oils from dill and *Piper* spp. (Regnault-Roger et al., 2012). Lastly, essential oils can block digestive enzymes (Tarelli et al., 2009).

To deliver essential oils to the target site of the insect body, two applications are generally used: fumigation and topical application. Fumigation is possible because essential oils are highly volatile. Such delivery of essential oils can affect pests as antifeedant, repellent, ovicide, or insect growth regulator (Isman, 2000; Regnault-Roger, 1997). Active ingredients of essential oil pesticides include, but are not limited to, monoterpenes, sesquiterpenes carvacrol, cymene, and thymol.

## ESSENTIAL OILS FOR ARTHROPOD PEST MANAGEMENT

Modern pest management is based on the concept of bioeconomics and integrated pest management (IPM), that is, using multiple pest control methods together to reduce pest density under economic injury level (EIL). EIL is the lowest number of insects that will cause economic damage (Pedigo, 2002) (Figure 4). This concept was coined originally to reduce the use and amount of synthetic pesticides in cropping fields by utilizing nonchemical methods, such as employing natural enemies (i.e., biological control), modifying environment to render it unfavorable to insects (i.e., ecological control), and utilizing mechanical means (i.e., mechanical control). In addition, the use of natural chemicals extracted from plants (i.e., botanicals) can substitute or supplement the use of synthetic pesticides.

Currently, essential oils are used in IPM strategies as broad-spectrum pesticides, organic pesticides, and low-risk pesticides where high-risk pesticides cannot be generally applied such as greenhouses, schools, and homes. Because essential oils have various modes of action to kill arthropod pests, they can play an important role in IPM, specifically when low residual activity of pesticides is necessary. For example, low-residue essential oils allow short reentry intervals after application or treatment close to harvest. In addition to being used in IPM, essential oils can be an important control measure against arthropod pests in organic farming systems because they are natural products. Essential oils are generally low-risk pesticides and relatively less harmful to humans, so they can be used for greenhouse pest management (Regnault-Roger et al., 2012). Also, the mixture of active ingredients in essential oils can reduce development of insecticide resistance. However, some essential oils still can affect nontarget organisms, so it is important to select essential oils that can kill target pest arthropods while being harmless to beneficial organisms and safe for humans and the environment.

Essential oils are known as broad-spectrum pesticides, meaning that they can harm multiple species of arthropod pests. This is possible because one essential oil can possess multiple active ingredients with pesticide properties. Multiple active ingredients of essential oils can also be antifeedants, molting inhibitors, respiratory inhibitors, oviposition inhibitors, ovicides, deterrents, attractants, or repellents. Table 1 shows a list of arthropod pests and source plant species with essential oils containing pesticidal

**TABLE 1 List of Arthropod Pests in Agricultural Production Systems and List of Plant Species Containing Essential Oils Showing Pesticidal Properties**

| Arthropod Species (Common Name) | Application Method | Plant Species (Common Name) | Key References |
|---|---|---|---|
| *Meligethes aeneus* (pollen beetle) | Contact | *Carum carvi* (caraway seed) | Pavela (2011) |
| | | *Thymus vulgaris* (thyme) | |
| *Anomala orientalis* (oriental beetle) | Topical | *Thymus vulgaris* (thyme) | Ranger et al. (2013) |
| *Cyclocephala borealis* (northern masked chafer) | | | |
| *Popillia japonica* (Japanese beetle) | | | |
| *Rhizotrogus majalis* (European chafer) | | | |
| *Camptomyia corticalis* (mushroom fly) | Fumigant | *Carum carvi* (caraway seed) | Kim et al. (2012) |
| | | *Artemisia vulgaris* (Armoise) | |
| | | *Salvia sclarea* (sage, clary) | |
| | | *Origanum vulgare* (oregano) | |
| *Ceratitis capitata* (Mediterranean fruit fly) | Topical/fumigant | *Lavandula angustifolia* (lavender) | Benelli et al. (2012) |
| | | *Rosmarinus officinalis* (rosemary) | |
| *Bemisia tabaci* (silverleaf whitefly) | Fumigant | *Lippia sidoides* (pepper-rosmarin) | Cavalcanti et al. (2010) |
| | Contact | *Thymus vulgaris* (thyme) | Yang et al. (2010) |
| | Contact/fumigant | *Allium sativum* (garlic) | Kim et al. (2011) |
| *Trialeurodes vaporariorum* (greenhouse whitefly) | Fumigant | *Citrus limon* (lemon) | Delkhoon et al. (2013) |
| *Lipaphis erysimi* (turnip aphid) | Topical | *Piper nigrum* (black pepper) | Monika et al. (2013) |
| | | *Psoralea corylifolia* (babchi) | |
| *Aphis fabae* (black bean aphid) | Fumigant | *Mentha pulegium* (pennyroyal) | Kimbaris et al. (2010) |
| *Aphis gossypii* (cotton aphid) | Contact | *Artemisia dracunculus* (tarragon) | Mousavi and Valizadegan (in press) |
| *Macrosiphoniella sanborni* (chrysanthemum aphid) | Fumigant | *Mentha pulegium* (pennyroyal) | Kimbaris et al. (2010) |
| *Myzus persicae* (green peach aphid) | | | |

**TABLE 1** List of Arthropod Pests in Agricultural Production Systems and List of Plant Species Containing Essential Oils Showing Pesticidal Properties—cont'd

| Arthropod Species (Common Name) | Application Method | Plant Species (Common Name) | Key References |
|---|---|---|---|
| *Acyrthosiphon pisum* (pea aphid) | Fumigant | *Mentha pulegium* (pennyroyal) | Kimbaris et al. (2010) |
| | | *Laurelia sempervirens* (Peruvian nutmeg) | Zapata et al. (2010) |
| *Nezara viridula* (southern green stink bug) | Contact/fumigant | *Origanum vulgare* (oregano) | González et al. (2011) |
| | | *Thymus vulgaris* (thyme) | |
| *Diaphorina citri* (Asian citrus psyllid) | Topical | *Allium tuberosum* (garlic chive) | Mann et al. (2012) |
| | | *Lavandula angustifolia* (lavender) | |
| *Cacopsylla chinensis* (pear psyllid) | | *Allium sativum* (garlic) | Zhao et al. (2013) |
| *Glyphodes pyloalis* (lesser mulberry pyralid) | Contact | *Lavandula angustifolia* (lavender) | Yazdani et al. (2013) |
| *Agrotis ipsilon* (black cutworm) | | *Gaultheria procumbens* (American wintergreen) | Jeyasankar (2012) |
| *Pseudaletia unipuncta* (armyworm) | Contact/fumigant | *Anethum graveolens* (dill) | Sousa et al. (2013) |
| | | *Cuminum cyminum* (cumin) | |
| | Fumigant | *Foeniculum vulgare* (fennel) | |
| | Contact | *Petroselinum crispum* (parsley) | |
| | | *Laurus azorica* (Azores laurel) | Rosa et al. (2010) |
| *Spodoptera littoralis* (African cotton leaf worm) | Antifeedant | *Artemisia absinthium* (wormwood) | Bailena et al. (2013) |
| | Fumigant | *Salvia officinalis* (sage) | Souguir et al. (2013) |
| | Topical | *Pimenta racemosa* (ciliment) | Pavela (2012) |
| | | *Thymus vulgaris* (thyme) | |
| | | *Origanum vulgare* (oregano) | |
| *Trichoplusia ni* (cabbage looper) | Topical/contact | *Syzygium aromaticum* (cloves) | Jiang et al. (2012) |
| | | *Thymus vulgaris* (thyme) | |
| | Topical | *Allium sativum* (garlic) | Machial et al. (2010) |
| | | *Cymbopogon citratus* (lemongrass) | |
| | | *Thymus vulgaris* (thyme) | |
| *Plutella xylostella* (diamondback moth) | Fumigant | Mentha pulegium (pennyroyal) | Yi et al. (2007) |
| | | Rosmarinus officinalis (rosemary) | |
| | | *Salvia officinalis* (sage) | |
| *Choristoneura rosaceana* (oblique-banded leafroller) | Topical | *Allium sativum* (garlic) | Machial et al. (2010) |
| | | *Cymbopogon citratus* (lemongrass) | |
| | | *Thymus vulgaris* (thyme) | |
| *Chaetodactylus krombeini* (Krombine's hairy-footed mite) | Fumigant | *Gaultheria* spp. (wintergreen) | White et al. (2009) |
| | | *Mentha spicata* (spearmint) | |
| | | *Cymbopogon citratus* (lemongrass) | |
| *Varroa destructor* (varroa mite) | Contact | *Laurus nobilis* (laurel) | Damiani et al. (2009) |
| | | *Thymus vulgaris* (thyme) | |
| | | *Lavandula officinalis* (lavender) | |
| | Fumigant | *Thymus vulgaris* (thyme) | El-Wahab et al. (2012) |
| | | *Pimpinella anisum* (anise) | |
| | | *Cinnamomum zeylanicum* (cinnamon) | |
| | | *Cymbopogon flexuosus* (lemongrass) | |

*Continued*

**TABLE 1** List of Arthropod Pests in Agricultural Production Systems and List of Plant Species Containing Essential Oils Showing Pesticidal Properties—cont'd

| Arthropod Species (Common Name) | Application Method | Plant Species (Common Name) | Key References |
|---|---|---|---|
| *Tetranychus cinnabarinus* (carmine spider mite) | Fumigant | *Origanum onites* (oregano) | Sertkaya et al. (2010) |
| | | *Thymus vulgaris* (thyme) | |
| *Tetranychus urticae* (two-spotted spider mite) | Contact | *Deverra scoparia* | Attia et al. (2012) |
| | | *Haplophyllum tuberculatum* | |
| | | *Mentha pulegium* (pennyroyal) | |
| | | *Chrysanthemum coronarium* (garland chrysanthemum) | |
| | | *Hertia cheirifolia* | |
| | Fumigation | *Protium bahianum* | Pontes et al. (2007) |
| | Contact | *Rosmarinus officinalis* (rosemary) | Miresmailli and Isman (2006) |
| | Fumigation | *Petiveria alliacea* (Guinea henweed) | Neves et al. (2011) |
| | | *Mentha spicata* (spearmint) | Omar et al. (2009) |

properties. Essential oils tend to be more effective on soft-bodied insects such as aphids, whiteflies, and thrips than hard-bodied insects (Isman, 2000). In addition, essential oils can be mixed with conventional pesticides as synergists (Isman et al., 2011).

## ADVANTAGES AND DISADVANTAGES OF ESSENTIAL OILS AS PESTICIDES

### Ecotoxicology of Essential Oils

In general, essential oils are considered as safe pesticides. There has been no report of biomagnification of essential oils through the food chain (Regnault-Roger et al., 2012). Although allergic reaction of essential oils in humans is reported with clinical and pharmaceutical studies, they show relatively low mammalian toxicity; thus essential oils have been widely used for medicinal and clinical purposes. In addition, essential oils show low toxicity to other vertebrates including fishes and birds because they are readily broken down by light or other abiotic environmental factors and do not persist in soil and water (Isman, 2000). Therefore, essential oils can play an important role in pest management specifically where environmentally friendly control measures are needed such as organic farming, public places, and homes. Essential oils are also known to be used as environmentally friendly herbicides (Batish et al., 2007) and fungicides (Isman, 2000).

### Nontarget Effects of Essential Oils in Pest Management

Although essential oils are considered as safe pesticides, there have been several reports about their nontarget effects (see Table 2 for a list of essential oils that affect beneficial insects and mites). Bostanian et al. (2005) showed that four days after topical spray, a *Chenopodium*-based insecticide can affect natural enemies including minute pirate bugs and a parasitoid wasp (*Aphidius colemani*) that are commonly used for controlling aphids and thrips. In contrast, a study by Chiasson et al. (2004) revealed that essential oils were able to control aphids, thrips, and whiteflies successfully, but showed no effect on natural enemies of whitefly. Such nontarget effects of essential oils were further studied with pollinator insects. Amrine (2006) showed that essential oils killed varroa mites affecting honey bees in bee hives. He applied wintergreen oil as an ingredient to grease patties, on which the honey bees feed, while volatiles were slowly emitted to kill mites. Honey bees feed on grease patties and as they do, the wintergreen oil acts as an irritant to the varroa mite causing the mite to fall off the bee through the frames of the hive to the sticky bottom board (Amrine, 2006). White et al. (2009) showed that Krombein's hairy-footed mites parasitizing Japanese horn-faced bees (i.e., a solitary pollinator bee) can be controlled effectively with

**TABLE 2** List of Beneficial Arthropods (Nontarget Organisms) in Agricultural Production Systems and List of Plant Species Containing Essential Oils that Can Harm the Beneficial Arthropods

| Arthropod Species (Common Name) | Application Method | Plant Species (Common Name) | Key References |
|---|---|---|---|
| *Adalia bipunctata* (two-spotted ladybird) | Fumigant | *Mentha pulegium* (pennyroyal) | Kimbaris et al. (2010) |
| *Coccinella septempunctata* (seven-spotted lady beetle) | | | |
| *Orius* sp. (minute pirate bug) | Contact | *Allium sativum* (garlic) | Mousa et al. (2013) |
| *Orius insidiosus* (insidious flower bug) | | *Chenopodium ambrosioides* (epazote) | Bostanian et al. (2005) |
| *Apis mellifera* (honeybee) | | *Thymus vulgaris* (thyme) | Damiani et al. (2009) |
| *Cotesia glomerata* (white butterfly parasite) | Fumigant | *Artemisia vulgaris* (armoise) | Yi et al. (2007) |
| | | *Thuja occidentalis* (white cedar) | |
| | | *Eucalyptus globulus* (eucalyptus) | |
| | | *Myrtus communis* (myrtle) | |
| | | *Melaleuca viridiflora* (broad-leaved paperbark) | |
| *Aphidius colemani* | Contact | *Chenopodium ambrosioides* (epazote) | Bostanian et al. (2005) |
| *Osmia cornifrons* (Japanese horn-faced bee) | Topical | *Gaultheria* spp. (wintergreen) | White et al. (2009) |
| | | *Cymbopogon citratus* (lemongrass) | |
| | | *Mentha spicata* (spearmint) | |
| *Dinarmus basalis* | Contact | *Jatropha curcas* (physic nut) | Boateng and Kusi (2008) |
| *Trissolcus basalis* | Contact/fumigant | *Schinus molle* var. *areira* (American pepper) | González et al. (2013) |
| | Contact | *Ocimum basilicum* (sweet basil) | Momen and Amer (2003) |
| *Neoseiulus cucumeris* | | *Ocimum basilicum* (sweet basil) | Momen et al. (2006) |
| *Phytoseiulus persimilis* (Chilean predatory mite) | Topical | *Mentha piperita* (peppermint) | Choi et al. (2004) |
| | Contact | *Allium sativum* (garlic) | El-Deen and Abdallah (2013) |

wintergreen oils applied as a fumigant. When the bee nests were fumigated with wintergreen oils the parasitic mites were killed in less than 1.8 h, but the Japanese horn-faced bee was not affected. However, direct contact of wintergreen oil on the Japanese horn-faced bee caused a high mortality. Contrarily, some essential oils can attract pollinator bees, for example, euglossine bees are attracted by plant emitting volatiles of cineole, a major component of eucalyptus oil (Dressler, 1982).

## Major Disadvantages of Using Essential Oils in Pest Management

Although essential oils have many advantages as environmentally friendly pesticides in many agricultural production systems, there are three major disadvantages. First, although effects of individual active ingredients have been studied intensively, very little is known about effects of a mixture of active ingredients of essential oils due to difficulties in their evaluation for effectiveness (Regnault-Roger et al., 2012). Second, while the use of essential oils for pest control has been in practice for many years, there are few commercialized agricultural essential oil-based products available on the market. Third, although some essential oils are highly effective as pesticides, it would be less popular in conventional farming because they are more expensive and less available. However, as stated previously, essential oils can play an important role in organic farming or places where worker and environmental safety is of primary concern (Isman, 2000).

## SUMMARY POINTS

- Essential oils with pesticidal properties are found in plants belonging to the Amaryllidaceae, Apiaceae, Asteraceae, Atherospermataceae, Burseraceae, Cupressaceae, Fabaceae, Lamiaceae, Lauraceae, Myrtaceae, Phytolaccaceae, Piperaceae, Poaceae, Rutaceae, and Zingiberaceae families.
- Because essential oils have various modes of action for killing arthropod pests, they can play an important role in IPM and organic farming.
- Currently, essential oils are used as a part of IPM strategies: as broad-spectrum pesticides, organic pesticides, and low-risk pesticides.
- Known modes of action of essential oils include neurotoxicity, insect growth regulation, degradation of waxy layers of insect cuticle, blockage of digestive enzymes, and inhibition of P450 cytochromes.
- Essential oils are readily broken down in the environment and do not persist in soil and water, and there has been no report of biomagnification of essential oils through the food chain.
- Essential oils have fewer nontarget effects on natural enemies, but direct contact of essential oils on beneficial insects (e.g., pollinator bees) can cause mortality.
- There are a few commercialized agricultural and garden essential oil-based products available on the market although some essential oils have shown their effectiveness as pesticides.

## REFERENCES


Amrine, J., 2006. Formic acid fumigator for controlling varroa mites in honey bee hives. Int. J. Acarol. 32, 115–124.

Attia, S., Grisssa, L.K., Ghrabi, G.Z., Mailleux, A.-C., Lognay, G., Hance, T., 2012. Acaricidal activity of 31 essential oils extracted from plants collected in Tunisia. J. Essent. Oil Res. 24, 279–288.

Bailena, M., Julio, L.F., Diaz, C.E., Sanz, J., Martínez-Díaz, R.A., Cabrera, R., Burillo, J., Gonzalez-Coloma, A., 2013. Chemical composition and biological effects of essential oils from *Artemisia absinthiu*m L. cultivated under different environmental conditions. Crop Prot. 49, 102–107.

Batish, D.R., Singh, H.P., Kohli, R.K., Kaur, S., 2008. Eucalyptus essential oil as a natural pesticide. For. Ecol. Manag. 256, 2166–2174.

Batish, D.R., Singh, H.P., Setia, N., Kohli, R.K., Kaur, S., Yadav, S.S., 2007. Alternative control of littleseed canary grass using eucalypt oil. Agron. Sust. Dev. 27, 171–177.

Benelli, G., Flamini, G., Canalea, A., Cioni, P.L., Conti, B., 2012. Toxicity of some essential oil formulations against the Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae). Crop Prot. 42, 223–229.

Boateng, B.A., Kusi, F., 2008. Toxicity of Jatropha seed oil to *Callosobruchus maculatus* (Coleoptera: Bruchidae) and its parasitoid, *Dinarmus basalis* (Hymenoptera: Pteromalidae). J. Appl. Sci. Res. 4, 945–951.

Bostanian, N.J., Akalach, M., Chiasson, H., 2005. Effects of a *Chenopodium*-based botanical insecticide/acaricide on *Orius insidiosus* (Hemiptera: Anthocoridae) and *Aphidius colemani* (Hymenoptera: Braconidae). Pest Manag. Sci. 61, 979–984.

Brud, W.S., 2010. Industrial uses of essential oils. In: Baser, K.H.C. (Ed.), Handbook of Essential Oils: Science, Technology and Applications. CRC Press, Boca Raton, FL.

Cavalcanti, S.C.H., Niculau, E.S., Blank, A.F., Câmara, C.A.G., Araújo, I.N., Alves, P.B., 2010. Composition and acaricidal activity of *Lippia sidoides* essential oil against two-spotted spider mite (*Tetranychus urticae* Koch). Bioresour. Technol. 101, 829–832.

Chiasson, H., Bélanger, A., Bostanian, N.J., Vincent, C., Poliquin, A., 2001. Acaricidal properties of *Artemisia absinthium* and *Tanacetum vulgare* (Asteraceae) essential oils obtained by three methods of extraction. J. Econ. Entomol. 94, 167–171.

Chiasson, H., Bostanian, N.J., Vincent, C., 2004. Acaricidal properties of a *Chenopodium*-based botanical. J. Econ. Entomol. 97, 1373–1377.

Choi, W.I., Lee, S.G., Park, H.M., Ahn, Y.J., 2004. Toxicity of plant essential oils to *Tetranychus urticae* (Acari: Tetranychidae) and *Phytoseiulus persimilis* (Acari: Phytoseiidae). J. Econ. Entomol. 97, 553–558.

Damiani, N., Gende, L.B., Bailac, P., Marcangeli, J.A., Eguaras, M.J., 2009. Acaricidal and insecticidal activity of essential oils on *Varroa destructor* (Acari: Varroidae) and *Apis mellifera* (Hymenoptera: Apidae). Parasitol. Res. 106, 145–152.

Delkhoon, S., Fahim, M., Hosseinzadeh, J., Panahi, O., 2013. Effect of lemon essential oil on the developmental stages of *Trialeurodes vaporariorum* West (Homoptera: Aleyrodidae). Arch. Phytopath. Plant Prot. 5, 569–574.

Dressler, R.L., 1982. Biology of the orchid bees (Euglossini). Annu. Rev. Ecol. Syst. 13, 373–394.

El-Deen, M.E.M., Abdallah, A.A.M., 2013. Effect of different compounds against *Tetranychus urticae* Koch and its predatory mite *Phytoseiulus persimilis* A.H. under laboratory conditions. J. Appl. Sci. Res. 9, 3965–3973.

El-Wahab, T.E., Ebadah, I.M.A., Zidan, E.W., 2012. Control of varroa mite by essential oils and formic acid with their effects on grooming behaviour of honey bee colonies. J. Basic Appl. Sci. Res. 2, 7674–7680.

Enan, E.E., 2001. Insecticidal activity of essential oils: octopaminergic sites of action. Comp. Biochem. Physiol. C 130, 325–337.

Gillilan, J., 2012. Improvement of U.S. EPA Minimum Risk Essential Oils' Pesticide Activity through Surfactant Enhancement and Synergy (Ph.D. dissertation). The Ohio State University, Columbus, OH.

González, J.O.W., Gutiérrez, M.M., Murray, A.P., Ferrero, A.A., 2011. Composition and biological activity of essential oils from Labiatae against *Nezara viridula* (Hemiptera: Pentatomidae) soybean pest. Pest Manag. Sci. 67, 948–955.

González, J.O.W., Laumann, R.A., Silveirac, S., Moraes, M.C.B., Borges, M., Ferrero, A.A., 2013. Lethal and sublethal effects of four essential oils on the egg parasitoids *Trissolcus basalis*. Chemosphere 92, 608–615.

Isman, M.B., 2000. Plant essential oils for pest and disease management. Crop Prot. 19, 603–608.

Isman, M.B., Machial, C.M., 2006. Pesticides based on plant essential oils: from traditional practice to commercialization. In: Rai, M., Carpinella, M.C. (Eds.), Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam, pp. 29–44.

Isman, M.B., Miresmailli, S., Machial, C., 2011. Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products. Phytochem. Rev. 10, 197–204.

Jeyasankar, A., 2012. Antifeedant, insecticidal and growth inhibitory activities of selected plant oils on black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae). Asian Pac. J. Trop. Dis. 2, 347–351.

Jiang, Z.L., Akhtar, Y., Zhang, X., Bradbury, R., Isman, M.B., 2012. Insecticidal and feeding deterrent activities of essential oils in the cabbage looper, *Trichoplusia ni* (Lepidoptera: Noctuidae). J. Appl. Entomol. 136, 191–202.

Kim, J.R., Haribalan, P., Son, B.K., Ahn, Y.J., 2012. Fumigant toxicity of plant essential oils against *Camptomyia corticalis* (Diptera: Cecidomyiidae). J. Econ. Entomol. 105, 1329–1334.

Kim, S.I., Chae, S.H., Youn, H.S., Yeon, S.H., Ahn, Y.J., 2011. Contact and fumigant toxicity of plant essential oils and efficacy of spray formulations containing the oils against B- and Q-biotypes of *Bemisia tabaci*. Pest Manag. Sci. 67, 1093–1099.

Kimbaris, A.C., Papachristos, D.P., Michaelakis, A., Martinou, A.F., Polissiou, M.G., 2010. Toxicity of plant essential oil vapours to aphid pests and their coccinellid predators. Biocontr. Sci. Technol. 20, 411–422.

Langenheim, J.H., 1994. Higher plant terpenoids: a phytocentric overview of their ecological roles. J. Chem. Ecol. 10, 1223–1280.

Machial, C.M., Shikano, I., Smirle, M., Bradbury, R., Isman, M.B., 2010. Evaluation of the toxicity of 17 essential oils against *Choristoneura rosaceana* (Lepidoptera: Tortricidae) and *Trichoplusia ni* (Lepidoptera: Noctuidae). Pest Manag. Sci. 66, 1116–1121.

Mann, R.S., Tiwari, S., Smoot, J.M., Rouseff, R.L., Stelinski, L.L., 2012. Repellency and toxicity of plant-based essential oils and their constituents against *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae). J. Appl. Entomol. 136, 87–96.

Miresmailli, S., Isman, M.B., 2006. Efficacy and persistence of rosemary oil as an acaricide against two-spotted spider mite (Acari: Tetranychidae) on greenhouse tomato. J. Econ. Entomol. 99, 2015–2023.

Momen, F.M., Amer, S.A.A., 2003. Influence of the sweet basil, *Ocimum basilicum* L. on some predacious mites of the Family Phytoseiidae (Acari: Phytoseiidae). Acta Phytopathol. Entomol. Hung. 38, 137–143.

Momen, F.M., Amer, S.A.A., Saber, S.A., 2006. Acaricidal potentials of some essential, mineral and plant oils against the predacious mite *Neoseiulus cucumeris* (Oudemans) (Acari: Phytoseiidae). Acta Phytopathol. Entomol. Hung. 41, 383–393.

Monika, G., Aditi, G., Sudhakar, G., 2013. Insecticidal activity of essential oils obtained from *Piper nigrum* and *Psoralea corylifolia* seeds against agricultural pests. Asian J. Res. Chem. 6, 360–363.

Mousa, K.M., Khodeir, I.A., El-Dakhakhni, T.N., Youssef, A.E., 2013. Effect of garlic and eucalyptus oils in comparison to organophosphate insecticides against some piercing-sucking faba bean insect pests and natural enemies populations. Egypt. Acad. J. Biol. Sci. 5, 21–27.

Mousavi, M., Valizadegan, O. Insecticidal effects of *Artemisia dracunculus* L. (Asteraceae) essential oil on adult of Aphis gossypii Glover (Hemiptera: Aphididae) under laboratory conditions. Arch. Phytopathol. Plant Prot. 47, 1737–1745.

Neves, I.A., Camara, C.A.G., Oliviera, J.C.S., Almeida, A.V., 2011. Acaricidal activity and essential oil composition of *Petiveria alliacea* L. from Pernambuco (Northeast Brazil). J. Essent. Oil Res. 23, 23–26.

Omar, N.A., El-Sayed, Z.I.A., Romeh, A.A., 2009. Chemical constituents and biocidal activity of the essential oil of *Mentha spicata* L. grown in zagazig region. J. Agric. Biol. Sci. 6, 1089–1097.

Pavela, R., 2011. Insecticidal and repellent activity of selected essential oils against of the pollen beetle, *Meligethes aeneus* (Fabricius) adults. Ind. Crops Prod. 34, 888–892.

Pavela, R., 2012. Sublethal effects of some essential oils on the cotton leafworm *Spodoptera littoralis* (Boisduval). J. Essent. Oil Bear. Plants 15, 144–156.

Pedigo, L.P., 2002. Entomology and Pest Management, fourth ed. Prentice Hall, Upper Saddle River, NJ.

Pontes, W.J.T., Oliveira, J.C.S., Camara, C.A.G., Lopes, A.C.H.R., 2007. Composition and acaricidal activity of the resin's essential oil of *Protium bahianum* daly against two spotted spider mite (*Tetranychus urticae*). J. Essent. Oil Res. 19, 379–389.

Ranger, C.M., Reding, M.E., Oliver, J.B., Moyseenko, J.J., Youssef, N., Krause, C.R., 2013. Acute toxicity of plant essential oils to scarab larvae (Coleoptera: Scarabaeidae) and their analysis by gas chromatography-mass spectrometry. J. Econ. Entomol. 106, 159–167.

Regnault-Roger, C., Vincent, C., Thor, J., 2012. Essential oils in insect control: low-risk products in a high-stakes world. Annu. Rev. Entomol. 57, 405–424.

Regnault-Roger, C., 1997. The potential of botanical essential oils for insect pest control. Int. Pest Manag. Rev. 2, 25–34.

Rosa, J.S., Mascarenhas, C., Oliveira, L., Teixeira, T., Barreto, M.C., Medeiros, J., 2010. Biological activity of essential oils from seven Azorean plants against *Pseudaletia unipuncta* (Lepidoptera: Noctuidae). J. Appl. Entomol. 134, 346–354.

Sertkaya, E., Kaya, K., Soylu, S., 2010. Acaricidal activities of the essential oils from several medicinal plants against the carmine spider mite (*Tetranychus cinnabarinu*s Boisd.) (Acarina: Tetranychidae). Ind. Crops Prod. 31, 107–112.

Souguir, S., Chaieb, I., Cheikh, Z.B., Laarif, A., 2013. Insecticidal activities of essential oils from some cultivated aromatic plants against *Spodoptera littoralis* (Boisd). J. Plant Prot. Res. 53, 388–391.

Sousa, R.M.O.F., Rosa, J.S., Oliveira, L., Cunha, A., Fernandes-Ferreira, M., 2013. Activities of Apiaceae essential oils against armyworm, *Pseudaletia unipuncta* (Lepidoptera: Noctuidae). J. Agric. Food Chem. 61, 7661–7672.

Tarelli, G., Zerba, E.N., Alzogaray, R.A., 2009. Toxicity to vapor exposure and topical application of essential oils and monoterpenes on *Musca domestica* (Diptera: Muscidae). J. Econ. Entomol. 102, 1383–1388.

White, J.B., Park, Y.L., West, T.P., Tobin, P.C., 2009. Assessment of potential fumigants to control *Chaetodactylus Krombeini* (Acari: Chaetodactylidae) associated with *Osmia cornifrons* (Hymenoptera: Megachilidae). J. Econ. Entomol. 102, 2090–2095.

Yang, N.W., Li, A.L., Wan, F.H., Liu, W.X., Johnson, D., 2010. Effects of plant essential oils on immature and adult sweet potato whitefly, *Bemisia tabaci* biotype B. Crop Prot. 29, 1200–1207.

Yazdani, E., Sendi, J.J., Aliakbar, A., Senthil-Nathan, S., 2013. Effect of *Lavandula angustifolia* essential oil against lesser mulberry pyralid *Glyphodes pyloalis* Walker (Lepidoptera: Pyralidae) and identification of its major derivatives. Pestic. Biochem. Physiol. 107, 250–257.

Yi, C.G., Kwon, M., Hieu, T.T., Jang, Y.S., Ahn, Y.J., 2007. Fumigant toxicity of plant essential oils to *Plutella xylostella* (Lepidoptera: Yponomeutidae) and *Cotesia glomerata* (Hymenoptera: Braconidae). J. Asia Pac. Entomol. 10, 157–163.

Zapata, N., Lognay, G., Smagghe, G., 2010. Bioactivity of essential oils from leaves and bark of *Laurelia sempervirens* and *Drimys winteri* against *Acyrthosiphon pisum*. Pest Manag. Sci. 66, 1324–1331.

Zhao, N.N., Zhang, H., Zhang, X.C., Luan, X.B., Zhou, C., Liu, Q.Z., Shi, W.P., Liu, Z.L., 2013. Evaluation of acute toxicity of essential oil of garlic (*Allium sativum*) and its selected major constituent compounds against overwintering *Cacopsylla chinensis* (Hemiptera: Psyllidae). J. Econ. Entomol. 106, 1349–1354.