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Essential Oils for Pest Control

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Essential Oils and Synthetic Pesticides

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24

Essential Oils and Synthetic Pesticides

Vasakorn Bullangpoti

CONTENTS

24.1 Introduction

The environmental problems caused by the overuse of synthetic pesticides have been of concern in recent years. Thus, many scientists now need to research new, highly selective and biodegradable pesticides to solve problems and develop techniques that can be used to reduce pesticide use while maintaining crop yields (Koul et al., 2008). Essential oil compounds are an alternative to synthetic pesticides as a means to reduce the negative impacts to human health and the environment. They are safe and ecofriendly. Moreover, they are more compatible with environmental components than synthetic pesticides (Isman and Machial, 2006).

Essential oil compounds are defined as any volatile oil compounds that have strong aromatic components and that give a distinctive odor, flavor, or scent to a plant (Pavela, 2015). These are the by-products of plant metabolism and are commonly referred to as volatile plant secondary metabolites. Essential oil compounds are produced by more than 17,500 aromatic plant species commonly belonging to many angiospermic families, for example, Lamiaceae, Rutaceae, Myrtaceae, Zingiberaceae, and Asteraceae (Regnault-Roger et al., 2012). Most essential oils comprise monoterpenes—compounds that contain 10 carbon atoms often arranged in a ring or in acyclic form—as well as sesquiterpenes, which are hydrocarbons comprising 15 carbon atoms. The compounds of essential oil compounds are synthesized and stored in complex secretary structures, that is, glandular trichomes, secretory cavities, and resin ducts, and are present as droplets of fluid in the leaves, stem, flowers, fruits, bark, or roots of plants (Fahn, 2000).

The aromatic characteristics of essential oils provide various functions for the plants, including (1) attracting or repelling insects, (2) protection from heat or cold, and (3) utilizing chemical constituents in the oil as defense materials (Koul et al., 2008; Pavela, 2015).

In the next section are some developments where essential oils have been projected as pesticides in some recent research publications, along with their potential and constraints emphasized.

24.2 Essential Oil Compounds and Their Efficacy as a Pesticide

Essential oil compounds are complex natural mixtures. They are characterized by two or three major components at fairly high concentrations (20%–70%) compared with other components present in trace amounts, and generally, these major components determine the biological properties of the essential oils (Pavela, 2015). The components include two groups of distinct biosynthetical origin. The main group is composed of terpenes, terpenoids, while the other is composed of aromatic and/or aliphatic constituents, all characterized by low molecular weights. Essential oil compounds are synthesized in the cytoplasm and plastids of plant cells via malonic acid, mevalonic acid, and methyl-d-erythritol-4-phosphate (MEP) pathways.

Terpenes are hydrocarbons made up of several units of isoprene (C5), while terpenoids are terpenes that have been biochemically modified via enzymes that add oxygen molecules and move or remove a methyl group (Burt, 2004). Monoterpenes are formed from the coupling of two isoprene units (C10). They are the most represented molecules, constituting about 90% of the essential oil compounds, and allow for a great variety of structures (acyclic, monocyclic, and bicyclic) and several functions (carbures, e.g., myrcene, p-cimene, and camphene; alcohols, e.g., linalool, menthol, and borneol; aldehydes, e.g., geranial and citronellal; ketones, e.g., carvone, pulegone, and camphor; esters, e.g., linalyl acetate, menthyl, and citronellyl acetate; ethers, e.g., 1,8-cineole and menthofurane; peroxides, e.g., ascaridole; phenols, e.g., thymol and carcacrol; etc.). Examples of plants containing these compounds include bay leaves, cannabis, thyme, parsley, hops, laurel, tea tree, mugwort, sweet basil, wormwood, and rosemary.

Sesquiterpenes are formed from the assembly of three isoprene units (C15). The extension of the chain increases the number of cyclizations and thus leads to a great variety of structures. The functions of sesquiterpenoids are similar to those of monoterpenoids (cabures, e.g., azulene, β-caryophyllene, and elemenes; alcohols, e.g., bisabol, cedrol, and patchoulol; ketones, e.g., nootkatone, germacrone, and turmerones; etc.). The principal plant sources for these compounds include angelica, bergamot, celery, mint, orange, rosemary, and sage (Banthorpe, 1991).

Derived from phenylpropane, aromatic compounds occur less frequently than terpenes. The biosynthetic pathways concentrating the terpenes and phenylpropanic derivatives are generally separated in plants but may coexist in some, with one major pathway taking over. The functions of aromatic compounds are similar to those of monoterpenoids and/or sesquiterpenoids and comprise, for example, aldehydes (cynnamal-dehyde), alcohols (cinnamic alcohol), phenols (chavicol and eugenol), methoxy derivatives (anethole, estragole, and methyleugenol), and methylene dioxy compounds (apiole, myristine, and safrole). The principal plant sources for these compounds include anise, cinnamon, clove, and fennel (Grayson, 2000).

Essential oils are usually obtained via steam distillation of aromatic plants. There are many plant species from various families, which show pesticidal efficacy. There are many mixtures that have been considered for use as insecticides (Dev and Koul, 1997). However, the greatest pesticidal efficiency is limited to six families: Lamiaceae (14.72%), Rutaceae (12.88%), Cupressaceae (10.43%), Apiaceae (9.20%), Myrtaceae (8.59%), and Asteraceae (6.13%) (Table 24.1).

TABLE 24.1

Most Common Substances Contained in Essential Oil Compounds of Plants

Family	Compound
Apiaceae	Limonene, α- and β-pinene, sabinene, *trans*-anethole, carvone
Asteraceae	1,8-Cineole, linalool, limonene
Cupressaceae	α-Pinene, 3-carene, sabinene, limonene
Lamiaceae	1,8-Cineole, thymol, p-cymene, cavacol, euglenol, linalool
Myrtaceae	1,8-Cineole, p-cymene
Rutaceae	Limonene, α- and β-pinene

Those substances represented in the essential oil compounds by more than 10% are considered majority substances. Although each of the essential oil compounds contain at least 10 substances and every essential oil compound is unique due to its complex composition, only 1–5 substances can be considered as majority (Pavela, 2015).

In addition, it can be seen that some substances commonly occur in multiple plant species of the same family, and can thus be considered typical for individual families, although sometimes the same compounds can be found in other families. In this chapter, not only the six families mentioned above are considered; various families looking at the most common substances contained in essential oil compounds of plants and their efficacy as pesticides are reviewed (Table 24.2).

Considering Table 24.2, toxicity is indicated as having the greatest efficacy as a fumigant and as contact insecticidal activity for a wide range of pests. Some of these efficient essential oil compounds were obtained from aromatic plants that are grown commercially on relatively large areas, with good cultivation technology (e.g., *Pimpinella anisum*, *Coriandrum sativum*, *Foeniculum vulgare*, *Mentha longifolia*, *Ocimum basilicum*, *Thymus* spp., *Eucalyptus* spp., and *Piper* spp.). Such plants could become a suitable source of active substances for potential botanical pesticides. These essential oil compounds contain less common substances, predominantly from the group of sesquiterpenes (guaiol, β-bisabolol, δ-cadinol, germacrene D, and β-caryophyllene), aromatic acids, and ketones (Table 24.2).

In fact, the concentration needed to achieve mortality depends on many factors, such as the life stage of the pest, ambient temperature, the capacity of the substances to penetrate the cuticle, and the mechanism of action (Pavela et al., 2009; Rattan, 2010). Although many papers have focused on the pestcidal efficacy of essential oil compounds, little information is available on their mechanism of action against insects. The relation between pesticidal effect and chemical composition of the essential oil is difficult to determine because the interactions among compounds can influence the activity of the mixture. In principle, every aromatic compound contained in an essential oil compound is unique in terms of its structure and biological activity. Various mechanisms of action of individual substances, many of which still remain unknown, may in their combinations not only provide a significant increase in effectiveness, but also prevent the development of pest resistance (Rattan, 2010).

The mode of action of essential oil compounds against some pests has been recorded in some publications, including as a neurotoxic by interfering with the neuromodulator octopamine (OA) (Kostyukovsky et al., 2002) and by GABA-gated chloride channels (Priestley et al., 2003). The neurotoxicity of several monoterpenoids (d-limonene, myrcene, terpineol, linalool, and pulegone) was evaluated against the house fly as well as on the German cockroach (Coats et al., 1991). Toxicity from essential oils or their constituents in insects and other arthropods points to a neurotoxic mode of action; the most prominent symptoms are

TABLE 24.2

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
Amaranthaceae	*Chenopodium ambrosioides*	α-Terpinene, p-cymene	66.81 ppm	*P. xylostella* (third instar)	Antifeed	Wei et al. (2015)
			6.142 mg/L air	*P. xylostella* (third instar)	Fumigant	Wei et al. (2015)
			2.916 µl/larva	*P. xylostella* (third instar)	Contact	Wei et al. (2015)
			35 ppm	*Ae. aegypti*	Contact	Leyva et al. (2009)
Amaryllidaceae	*Allium cepa*	Disulfide dipropyl, p-cymene	1.11 µg/g	*Schistocerca gregaria* (third instar)	Topical	Mansour et al. (2015)
			20.153 µg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)
	Allium macrostemon	Methyl propyl disulfide, dimethyl trisulfide	73 ppm	*Aedes albopictus*	Contact	Liu et al. (2014)
	Allium monanthum	Dimethyl trisulfide, dimethyl tetrasulfide	23 ppm	*Ae. aegypti*	Contact	Moon et al. (2011)
	Allium victorialis L. var. *platyphyllum*	Allyl methyl disulfide, dimethyl trisulfide	24 ppm	*Ae. aegypti*	Contact	Chung et al. (2011a)
Anacardiaceae	*Pistacia terebinthus* L. subsp. *palaestina* (Boiss.) Engler	α-Pinene, cyclopentane	59 ppm	*Culex pipiens*	Contact	Cetin et al. (2011)
	Spondias purpurea	Caryophylleneoxide, α-cadinol	39 ppm	*Ae. aegypti*	Contact	Lima et al. (2011)
Annonaceae	*Cananga odorata* (Lam.) Hook. F & Thomson	Benzyl acetate, linalool, methyl benzoate	52 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
Annonaceae	*Cananga odorata* (Lam.) Hook. F. & Thomson	Benzyl acetate, linalool, methyl benzoate	52 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
	Guatteria blepharophylla Mart.	Caryophylleneoxide	58 ppm	*Ae. aegypti*	Contact	Aciole et al. (2011)
	Guatteria friesiana Erkens & Maas	Eudesmols	52 ppm	*Ae. aegypti*	Contact	Aciole et al. (2011)
Apiaceae	*Angelica purpuraefolia*	β-Phellandrene, nerolidol	31 ppm	*Ae. aegypti*	Contact	Park et al. (2010)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Apium graveolens	d-Limonene, 4-chloro-4,4-dimethyl-3-(1- imidazolyl)-valerophenone, 1-dodecanol	42–59 ppm	*Ae. aegypti*	Contact	Pitasawat et al. (2007), Nagella et al. (2012a)
			59 ppm	*Anopheles dirus*	Contact	Pitasawat et al. (2007)
	Bupleurum fruticosum	Pinene, carvone, limonene	64 ppm 54 ppm 72 ppm	*C. pipiens* *Ae. aegypti* *An. dirus*	Contact	Evergetis et al. (2009) Pitasawat et al. (2007)
	Carum carvi	Carvone, limonene	54 ppm	*Ae. aegypti*	Contact	Pitasawat et al. (2007)
			72 ppm	*An. dirus*	Contact	Pitasawat et al. (2007)
	Conopodium capillifolium	Pinene, sabinene	68 ppm	*C. pipiens*	Contact	Evergetis et al. (2009)
	Coriandrum sativum	Linalool	20 ppm	*Ae. aegypti*	Contact	Nagella et al. (2012b)
	Cuminum cyminum	Cuminic aldehyde	1.54 µg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			18.284 µg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)
	Elaeoselinum asclepium	α-Pinene, sabinene	96 ppm	*C. pipiens*	Contact	Evergetis et al. (2009)
	Ferulago carduchorum	(Z)-Ocimene, α-pinene	12 ppm	*Anopheles stephensi*	Contact	Golfakhrabadi et al. (2015)
	Foeniculum vulgare	*trans*-Anethole	49 ppm	*A. aegypti*	Contact	Pitasawat et al. (2007)
			35 ppm	*An. dirus*	Contact	Pitasawat et al. (2007)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Heracleum sphondylium ssp. *pyrenaicum* (Lam.) Bonnier & Layens	Octyl acetate, limonene	77 ppm	*C. pipiens*	Contact	Evergetis et al. (2009)
	Oenanthe pimpinelloide	γ-Terpinene, o-cymene	40 ppm	*C. pipiens*	Contact	Evergetis et al. (2009)
	Pimpinella anisum	*trans*-Anethole	9.3 µl/L 1.9 µl/L 29 µl/L	*Culex quinquefasciatus* *C. quinquefasciatus* *Daphnia magna*	Spray Fumigant Contact	Pavela et al. (2014)
	Petroselinum sativum	Apiol	1.34 µg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			63.406 µg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)
	Seseli montanum ssp. *tomasinii* (Reichenb. fil.) Archangeli	α-Pinene, sabinene, β-phellandrene	86 ppm	*C. pipiens*	Contact	Evergetis et al. (2009)
Apocynaceae	*Cionura erecta* (L.) Griseb.	Cedren-9-one, α-cadinol, eugenol, α-muurolene	77 ppm	*An. stephensi*	Contact	Mozaffari et al. (2014)
Araliaceae	*Dendropanax morbifera* Leveille	γ-Elemene, tetramethyltricyclohydrocarbon, β-selinene, α-zingibirene	62 ppm	*Ae. aegypti*	Contact	Chung et al. (2009)
Asteraceae	*Artemisia gilvescens* Miquel.	1,8-Cineole, camphor, germacrene D	49 ppm	*Anopheles anthropophagus*	Contact	Zhu and Tian (2013)
	Blumea densiflora D.C.	Borneol, germacrene D, β-caryo phyllene	10 ppm	*An. anthropophagus*	Contact	Zhu and Tian (2013)
	Blumea mollis (D. Don) Merr.	Linalool, γ-elemene, copaene, estragole, alloocimene	71 ppm	*C. quinquefasciatus*	Contact	Senthilkumar et al. (2008)
	Tagetes erecta	Piperitone	79 ppm	*Ae. aegypti*	Contact	Marques et al. (2011)
	Tagetes filifolia	*trans*-Anethole	47 ppm	*Ae. aegypti*	Contact	Ruiz et al. (2011)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Tagetes lucida	Methyl chavicol	66 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
	Tagetes minuta	*trans*-Ocimenone	52 ppm	*Ae. aegypti*	Contact	Ruiz et al. (2011)
	Tagetes patula	Limonene, terpinolene	13 ppm	*Ae. aegypti*	Contact	Dharmagadda et al. (2005)
			22 ppm	*C. quinquefasciatus*	Contact	Dharmagadda et al. (2005)
			12 ppm	*An. stephensi*	Contact	Dharmagadda et al. (2005)
	Matricaria chamomilla	Franesene	1.59 µg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			62.389 µg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)
	Tagetes erecta	Piperitone	79 ppm	*Ae. aegypti*	Contact	Marques et al. (2011)
Boraginaceae	*Auxemma glazioviana*	-Bisabolol, α-cadinol	3 ppm	*Ae. aegypti*	Contact	José et al. (2004)
	Cordia curassavica	α-Pinene	97 ppm	*Ae. aegypti*	Contact	Santos et al. (2006)
	Cordia leucomalloides	γ-Cadinene, (E)-caryo phyllene	63 ppm	*Ae. aegypti*	Contact	Santos et al. (2006)
Cupressaceae	*Callitris glaucophylla*	Guaiol, citronellic acid	0.7 ppm	*Ae. aegypti*	Contact	Shaalan et al. (2006)
			0.2 ppm	*Culex annulirostris*	Contact	Shaalan et al. (2006)
	Cryptomeria japonica	16-Kaurene, elemol, eudesmol, sabinene	28–56 ppm	*Ae. aegypti*	Contact	Cheng et al. (2009)
			51–56 ppm	*Ae. albopictus*	Contact	Cheng et al. (2009)
	Cunninghamia konishii	Cedrol	85 ppm	*Ae. aegypti*	Contact	Cheng et al. (2013)
			189 ppm	*Ae. albopictus*	Contact	Cheng et al. (2013)
	Cupressus arizonica	*trans*-Muurola-3,5-diene, *cis*-14-nor-muurol-5-en-4-one	64 ppm	*Ae. albopictus*	Contact	Cheng et al. (2013)
	Cupressus benthamii	Limonene, umbellulone	37 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Cupressus macrocarpa	Sabinene, α-pinene, terpinen-4-ol	54 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)
	Cupressus sempervirens	α-Pinene, δ-3-carene	54 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)
	Cupressus torulosa	α-Pinene, δ-3-carene	57 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)
	Chamaecyparis formosensis	Myrtenol, myrtenal	38 ppm 35 ppm	*Ae. aegypti* *Ae. albopictus*	Contact Contact	Kuo et al. (2007) Kuo et al. (2007)
	Chamaecyparis lawsoniana	Limonene, oplopanonyl acetate, beyerene	47 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)
	Juniperus communis	α-Pinene, sabinene, γ-3-Carene	65 ppm	*C. pipiens*	Contact	Vourlioti-Arapi et al. (2012)
	Juniperus drupacea	α-Pinene, limonene	26 ppm	*C. pipiens*	Contact	Vourlioti-Arapi et al. (2012)
	Juniperus foetidissima	Sabinene, 4-methyl-1-(1-methyl ethyl)-3-cyclohexen-1-ol	53 ppm	*C. pipiens*	Contact	Vourlioti-Arapi et al. (2012)
	Juniperus oxycedrus L. ssp. *oxycedrus*	Myrcene, germacrene-D, α-pinene	55 ppm	*C. pipiens*	Contact	Vourlioti-Arapi et al. (2012)
	Juniperus oxycedrus L. subsp. *macrocarpa* (Sm.) Ball.	α-Pinene	65 ppm	*C. pipiens*	Contact	Vourlioti-Arapi et al. (2012)
	Juniperus phoenicea	α-Pinene, β-3-carene, γ-phellandrene, α-terpinyl acetate	55 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)
	Tetraclinis articulata	α-Pinene, bornyl acetate	70 ppm	*Ae. albopictus*	Contact	Giatropoulos et al. (2013)
Euphorbiaceae	*Croton argyrophylloides*	β-*Trans*-guaiene	94 ppm	*Ae. aegypti*	Contact	Lima et al. (2013)
	Croton nepetaefolius	Methyleugenol	66 ppm	*Ae. aegypti*	Contact	Lima et al. (2013)
	Croton sonderianus	Spathulenol	55 ppm	*Ae. aegypti*	Contact	Lima et al. (2013)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Croton zehntneri	(E)-Anethole	25–56 ppm	*Ae. aegypti*	Contact	Lima et al. (2013), Santos et al. (2007), Morais et al. (2006)
Fabaceae	*Copaifera multijuga*	β-Caryo phyllene, α-humulene	18 ppm 128 ppm	*Ae. aegypti* *An. darlingi*	Contact Contact	Trindade et al. (2013)
	Hymenaea courbaril	α-Copaene, spathulenol, β-silinene	15 ppm	*Ae. aegypti*	Contact	Aguiar et al. (2010)
	Psoralea corylifolia	Caryophyllene oxide, phenol, 4-(3,7-dimethyl-3-ethenylocta-1,6-dienyl), caryophyllene	63 ppm	*C. quinquefasciatus*	Contact	Dua et al. (2013)
Geraniaceae	*Pelargonium radula*	Cetronellol geranial	1.54 μg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			22.719 μg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)
Hypericaceae	Hypericum scabrum	α-Pinene	82 ppm	*C. pipiens*	Contact	Cetin et al. (2011)
Lamiaceae	*Coleus aromaticus*	Thymol	72 ppm	*Culex tritaeniorhynchus*	Contact	Govindarajan et al. (2013a)
			76 ppm	*Ae. albopictus*	Contact	Govindarajan et al. (2013a)
			60 ppm	*Anopheles subpictus*	Contact	Govindarajan et al. (2013a)
	Dracocephalum kotschyi	Limonene	4.4 μl/L	*Myzus persicae*	Contact	Jalaei et al. (2015)
	Hyptis martiusii	γ-3-Carene, 1,8-cineole	18 ppm 27 ppm	*Ae. aegypti* *C. quinquefasciatus*	Contact Contact	Costa et al. (2004) Costa et al. (2005)
	Lavandula gibsoni	α-Terpinolen, thymol	48 ppm 62 ppm 54 ppm	*Ae. aegypti* *An. stephensi* *C. quinquefasciatus*	Contact Contact Contact	Kulkarni et al. (2013) Kulkarni et al. (2013) Kulkarni et al. (2013)
	Lippia sidoides	Thymol, α-felandreno	20–25 ppm 17 ppm	*Ae. aegypti* *C. quinquefasciatus*	Contact Contact	Lima et al. (2013) Costa et al. (2005)

(Continued)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Mentha longifolia	Piperitenone oxid	17 ppm	*C. quinquefasciatus*	Contact	Pavela et al. (2014)
	Mentha spicata	Carvone, *cis*-carveol, limonene	62 ppm	*C. quinquefasciatus*	Contact	Govindarajan et al. (2011)
			52 ppm	*Ae. aegypti*	Contact	Govindarajan et al. (2011)
			49 ppm	*An. stephensi*	Contact	Govindarajan et al. (2011)
	Ocimum americanum	(E)-Methyl-cinnamate	67 ppm	*Ae. aegypti*	Contact	Cavalcanti et al. (2004)
	Ocimum basilicum	Linalool, eugenol, methyl eugenol	1.54 μg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			19.541 μg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)
			14 ppm	*C. tritaeniorhynchus*	Contact	Govindarajan et al. (2013b)
			11 ppm	*Ae. albopictus*	Contact	Govindarajan et al. (2013b)
			9 ppm	*An. subpictus*	Contact	Govindarajan et al. (2013b)
	Ocimum gratissimum	Eugenol, 1,8-cineole	60 ppm	*Ae. aegypti*	Contact	Cavalcanti et al. (2004)
	Ocimum sanctum	Methyleugenol	85 ppm	*Ae. aegypti*	Contact	Gbolade and Lockwood (2008)
	Origanum vulgare	Terpinene 1-ol-4	1.56 μg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			53.333 μg/g	*S. gregaria* (third instar)	Contact	Mansour and Abdel-Hamid (2015)

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TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Plectranthus amboinicus	Carvacrol	52 ppm	*Ae. aegypti*	Contact	Lima et al. (2011)
			55 ppm	*Anopheles gambiae*	Contact	Kweka et al. (2012)
	Plectranthus molli	Piperitone oxide, fenchone	25 ppm	*Ae. aegypti*	Contact	Kulkarni et al. (2013)
			33 ppm	*An. stephensi*	Contact	Kulkarni et al. (2013)
			29 ppm	*C. quinquefasciatus*	Contact	Kulkarni et al. (2013)
	Pulegium vulgare	Pulegone, carvone	64 ppm	*C. quinquefasciatus*	Contact	Pavela et al. (2014)
	Rosmarinus officinalis	2-Methoxy-3-(2-propenyl)-phenol, 1,8-cineole, camphor	0.057 µl/L air: 72 h	*S. oryzae*	Fumigation	Kiran and Prakash (2015)
			0.039 µl/L air: 36 h	*Oryzaephilus surinamensis*	Fumigation	Kiran and Prakash (2015)
			38 ppm	*C. quinquefasciatus*	Contact	Yu et al. (2013)
	Satureja hortensis	γ-Terpinene, carvacrol	36 ppm	*C. quinquefasciatus*	Contact	Pavela (2009)
	Thymus bovei	Thymol, p-cymene	1300 µg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
	Thymus capitatus	Thymol carvacrol	1038 µg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
	Thymus leucospermus	p-Cymene	34 ppm	*C. pipiens*	Contact	Pitarokili et al. (2011)
	Thymus satureoides	Thymol, borneol	43 ppm	*C. quinquefasciatus*	Contact	Pavela (2009)
	Thymus teucrioides subsp. *Candilicus*	p-Cymene, γ-terpinene, thymol	23 ppm	*C. pipiens*	Contact	Pitarokili et al. (2011)
	Thymus vulgaris	Thymol, p-cymene	1128 µg/g	*S. gregaria* (third instar)	Topical	Mansour et al. (2015)
			33 ppm	*C. quinquefasciatus*	Contact	Pavela (2009)
	Vitex agnus castus	*trans*-β-Caryophyllene, 1,8-cineole	83 ppm	*C. pipiens*	Contact	Cetin et al. (2011)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
Lauraceae	*Cinnamomum impressicostatum*	Benzyl benzoate, α-phellandrene	11 ppm	*Ae. aegypti*	Contact	Lima et al. (2011)
	Cinnamomum microphyllum	Benzyl benzoate	7 ppm	*Ae. aegypti*	Contact	Jantan et al. (2005)
	Cinnamomum mollissimum	Benzyl benzoate	10 ppm	*Ae. aegypti*	Contact	
	Cinnamomum osmophloeum	Cinnamaldehyde, cinnamyl acetate	36 ppm	*Ae. aegypti*	Contact	Cheng et al. (2004)
	Cinnamomum pubescens	Benzyl benzoate	13 ppm	*Ae. aegypti*	Contact	Jantan et al. (2005)
	Cinnamomum rhyncophyllum	Benzyl benzoate	6 ppm	*Ae. aegypti*	Contact	Jantan et al. (2005)
	Cinnamomum scortechinii	β-Phellandrene, linalool	22 ppm	*Ae. aegypti*	Contact	Jantan et al. (2005)
	Lindera obtusiloba	α-Copaene, β-caryophyllene	24 ppm	*Ae. aegypti*	Contact	Chung and Moon (2011)
Meliaceae	*Guarea humaitensis*	Caryophyllene epoxide, humulene epoxide II	48 ppm	*Ae. aegypti*	Contact	Magalhães et al. (2010)
	Guarea scabra	*cis*-Caryophyllene, α-*trans*-bergamotene	98 ppm	*Ae. aegypti*	Contact	Magalhães et al. (2010)
Myrtaceae	*Eucalyptus astringens*	Pinene, camphene	13.91–17.58 μl/L air	*Rhyzopertha dominica*	Fumigation	Hamdi et al. (2015)
			121.46–180.432 μl/L air	*Callosobruchus maculatus*	Fumigation	Hamdi et al. (2015)
			274.16–293.15 μl/L air	*Tribolium castaneum*	Fumigation	Hamdi et al. (2015)
	Eucalyptus camaldulensis	1,8-Cineole, α-terpinyl acetate	31 ppm	*Ae. aegypti*	Contact	Cheng et al. (2009)
			55 ppm	*Ae. albopictus*	Contact	Cheng et al. (2009)
	Eucalyptus citriodora	Citronellal, citronellol, α-humulene isopulegol	71 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
	Eucalyptus dunnii	1,8-Cineole, γ-terpinene	25 ppm	*Ae. aegypti*	Contact	Lucia et al. (2008)
	Eucalyptus grandis	α-Pinene, β-pinene, 1,8-cineole	32 ppm	*Ae. aegypti*	Contact	Lucia et al. (2007)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Eucalyptus gunnii	1,8-Cineole, p-cymene, β-phellandrene	21 ppm	*Ae. aegypti*	Contact	Lucia et al. (2008)
	Eucalyptus lehmani	Pinene, camphene	11.51–16.06 µl/L air	*R. dominica*	Fumigation	Hamdi et al. (2015)
			80.43–144.82 µl/L air	*C. maculatus*	Fumigation	Hamdi et al. (2015)
			225.35–282.06 µl/L air	*T. castaneum*	Fumigation	Hamdi et al. (2015)
	Eucalyptus saligna	1,8-Cineole, p-cymene	22 ppm	*Ae. aegypti*	Contact	Lucia et al. (2008)
	Eucalyptus tereticornis	β-Phellandrene, 1,8-cineole	22 ppm	*Ae. aegypti*	Contact	Lucia et al. (2008)
	Eugenia melanadenia	1,8-Cineole	85 ppm	*Ae. aegypti*	Contact	Aguilera et al. (2003)
	Pimenta racemosa	Terpinem-4-ol, 1,8-cineole	27 ppm	*Ae. aegypti*	Contact	Leyva et al. (2009)
	Psidium guajava	1,8-Cineole, β-caryophyllene	25 ppm	*Ae. aegypti*	Contact	Lima et al. (2011)
	Psidium rotundatum	1,8-Cineole, α-pinene	63 ppm	*Ae. aegypti*	Contact	Aguilera et al. (2003)
	Syzigium aromaticum	Eugenol	21 ppm	*Ae. aegypti*	Contact	Costa et al. (2005)
			25 ppm	*C. quinquefasciatus*	Contact	Cardoso and Lemos (2005)
Pinaceae	*Pinus brutia*	α-Pinene, β-pinene	67 ppm	*Ae. albopictus*	Contact	Koutsaviti et al. (2014)
	Pinus halepensis	β-Caryophyllene	70 ppm	*Ae. albopictus*	Contact	Koutsaviti et al. (2014)
	Pinus stankewiczii	Germacrene D, α-pinene, β-pinene	82 ppm	*Ae. albopictus*	Contact	Koutsaviti et al. (2014)
Piperaceae	*Piper aduncum*	β-Pinene	57 ppm	*Ae. aegypti*	Contact	Leyva et al. (2009)
	Piper auritum	Safrole	17 ppm	*Ae. aegypti*	Contact	Leyva et al. (2009)
	Piper capense	δ-Cadinene	34 ppm	*An. gambiae*	Contact	Matasyoh et al. (2011)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Piper hostmanianum	Asaricin, myristicin	54 ppm	*Ae. aegypti*	Contact	Morais et al. (2007)
	Piper klotzschianum	1-Butyl-3,4-methylenedioxybenzene, limonene, α-phellandrene	13 ppm	*Ae. aegypti*	Contact	Nascimento et al. (2013)
	Piper marginatum	(Z)-Asarone, patchouli alcohol	23 ppm	*Ae. aegypti*	Contact	Autran et al. (2009)
	Piper permucronatum	Dillapiole, myristicin	36 ppm	*Ae. aegypti*	Contact	Morais et al. (2007)
Pittosporaceae	*Pittosporum tobira*	Undecane, L-limonene, 4-methyl-1,3-pentadiene	58 ppm	*Ae. aegypti*	Contact	Chung et al. (2010)
Poaceae	*Cymbopogon citartus*	n.d.	33.1 µl/L air	*O. surinamensis*	Fumigation	Lambrano et al. (2015)
			>604 µl/L air	*Sitophilus zeamais*	Fumigation	Lambrano et al. (2015)
	Cymbopogon flexuosus	Geranial, neral	17 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
	Cymbopogon nardus	n.d.	46.9 µl/L air	*O. surinamensis*	Fumigation	Lambrano et al. (2015)
			>604 µl/L air	*S. zeamais*	Fumigation	Lambrano et al. (2015)
	Cymbopogon martinii	n.d.	37.2 µl/L air	*O. surinamensis*	Fumigation	Lambrano et al. (2015)
			159 µl/L air	*S. zeamais*	Fumigation	Lambrano et al. (2015)
Rutaceae	*Citrus aurantium*	Limonene	2.94 µl/L air	*Bemisia tabaci*	Fumigation	Zarrad et al. (2015)
			39 ppm	*C. pipiens*	Contact	Michaelakis et al. (2009)
	Citrus hystrix	β-Pinene, d-limonene, terpinene-4-ol	30 ppm	*Ae. aegypti*	Contact	Sutthanont et al. (2010)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Citrus limon	Limonene	30 ppm	*C. pipiens*	Contact	Michaelakis et al. (2009)
	Citrus reticulata	d-Limonene, ɣ-terpinene	15 ppm	*Ae. aegypti*	Contact	Sutthanont et al. (2010)
	Citrus sinensis	Limonene	20 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
			51 ppm	*C. pipiens*	Contact	Michaelakis et al. (2009)
	Clausena excavata	Safrole, terpinolene	37 ppm	*Ae. aegypti*	Contact	Cheng et al. (2009)
			41 ppm	*Ae. albopictus*	Contact	Cheng et al. (2009)
	Chloroxylon swietenia	Geijerene, limonene, germacrene D	16 ppm	*Ae. aegypti*	Contact	Kiran et al. (2006)
			14 ppm	*An. stephensi*	Contact	Kiran et al. (2006)
	Feronia limonia	Estragole, β-pinene	15 ppm	*An. stephensi*	Contact	Senthilkumar et al. (2013)
			11 ppm	*Ae. aegypti*	Contact	Senthilkumar et al. (2013)
			22 ppm	*C. quinquefasciatus*	Contact	Senthilkumar et al. (2013)
	Murraya tetramera	α-Cedrene caryophyllene, ɣ-elemene, α-selinene, α-eudesmol	0.13–0.63 nL/cm²	*T. castaneum*	Fumigation	You et al. (2015)
	Murraya euchrestifolia	α-Cedrene caryophyllene, clemene, α-selinene, α-eudesmol	0.63 nl/cm²	*T. castaneum*	Fumigation	You et al. (2015)
	Murraya koenigii	α-Cedrene caryophyllene, elemene, α-selinene, α-eudesmol	0.63 nl/cm²	*T. castaneum*	Fumigation	You et al. (2015)
	Murraya kwangsiensis	α-Cedrene caryophyllene, elemene, α-selinene, α-eudesmol	3.15–15.73 nl/cm²	*T. castaneum*	Fumigation	You et al. (2015)
	Murraya exotica	α-Cedrene caryophyllene, elemene, α-selinene, α-eudesmol	3.15–15.73 nl/cm²	*T. castaneum*	Fumigation	You et al. (2015)
	Murraya alata	α-Cedrene caryophyllene, elemene, α-selinene, α-eudesmol	<0.13 nl/cm²	*T. castaneum*	Fumigation	You et al. (2015)

(*Continued*)

TABLE 24.2 (CONTINUED)
Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Ruta chalepensis	2-Undeca none, 2-nonanone	22 ppm	*Ae. aegypti*	Contact	Ali et al. (2013)
			15 ppm	*Anopheles quadrimaculatus*	Contact	Conti et al. (2013)
			35 ppm	*Ae. albopictus*	Contact	Conti et al. (2013)
	Swinglea glutinosa	β-Pinene, piperitenone, α-pinene	65 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
	Toddalia asiatica	Geraniol, d-limonene, isopimpinellin, 4-vinylguaiacol	69 ppm	*Ae. albopictus*	Contact	Liu et al. (2012)
	Zanthoxylum armatum	Linalool, limonene	54 ppm	*Ae. aegypti*	Contact	Tiwary et al. (2007)
			58 ppm	*An. stephensi*	Contact	Tiwary et al. (2007)
			49 ppm	*C. quinquefasciatus*	Contact	Tiwary et al. (2007)
	Zanthoxylum limonella	d-Limonene, terpinen-4-ol	24 ppm	*Ae. aegypti*	Contact	Pitasawat et al. (2007)
			57 ppm	*An. dirus*	Contact	Pitasawat et al. (2007)
	Zanthoxylum oxyphyllum	Methyl heptyl ketone, methyl nonyl ketone	7 ppm	*Ae. aegypti*	Contact	Borah et al. (2012)
	Zanthoxylum rhoifolium	β-Blemene	~1%	*B. tabaci*	Contact	Christofoli et al. (2015)
Scrophulariaceae	*Capraria biflora*	α-Humulene, *trans*-cariophillene	73 ppm	*Ae. aegypti*	Contact	Souza et al. (2012)
	Stemodia maritima	β-Caryophyllene, caryophyllene oxide	23 ppm	*Ae. aegypti*	Contact	Arriaga et al. (2007)
Valerianaceae	*Valeriana fauriei*	Bornyl acetate	34 ppm	*Ae. aegypti*	Contact	Chung et al. (2011b)
Verbenaceae	*Lantana camara*	(Z)-Caryo phyllene, bicyclogermacrene, (E)-caryophyllene	42 ppm	*Ae. aegypti*	Contact	Costa et al. (2010)

(*Continued*)

TABLE 24.2 (CONTINUED)

Most Common Substances Contained in Essential Oil Compounds of Plants as Pesticides

Family	Plant Genus and Species	Major Constituents	LC_{50} or LD_{50}	Target Organism	Method	Reference
	Lippia alba	Carvone, limonene	15.2–16.7 µl/ml	*S. zeamais*	Repellency	Peixoto et al. (2015)
			19.7–28.7 µl/ml	*T. castaneum*	Repellency	Peixoto et al. (2015)
			44 ppm	*Ae. aegypti*	Contact	Vera et al. (2014)
	Lippia origanoides	Carvacrol, p-cymene	53 ppm	*Ae. aegypti*	Contact	Pavela (2015)
	Lippia sidoides	Thymol	63 ppm	*Ae. aegypti*	Contact	Cavalcanti et al. (2004)
Zingiberaceae	*Alpinia purpurata*	n.d.	41.4 µl/L	*S. zeamais*	Fumigant	Soledade de Lira et al. (2015)
	Curcuma aromatica	1H-3a,7-methanoazulene, curcumene	36 ppm	*Ae. aegypti*	Contact	Choochote et al. (2005)
	Curcuma zedoaria	1,8-Cineole, p-cymene, α-phellandrene	31 ppm	*Ae. aegypti*	Contact	Pitasawat et al. (2007)
			29 ppm	*An. dirus*	Contact	Pitasawat et al. (2007)
	Kaempferia galanga	2-Propeonic acid, pentadecane, ethyl-p-methoxycinnamate	53 ppm	*Ae. aegypti*	Contact	Sutthanont et al. (2010)
	Zingiber officinale	Zingiberene, citronellol β-sesguiphel landrene	46 ppm	*Ae. aegypti*	Contact	Moon et al. (2011)
	Zingiber zerumbet	α-Humulene, zerumbone	48 ppm	*Ae. aegypti*	Contact	Sutthanont et al. (2010)

Note: n.d., no data.

hyperactivity, followed by hyperexcitation, leading to rapid knockdown and immobilization (Enan, 2001). The inhibition of acetylcholinesterase (AChE) also plays a key role in modulating pesticidal activity. Several essential oil compounds have been shown to be inhibitors of AChE against different insect species. For example, essential oil compounds of *Zingiber officinale* were found to alter behavior and memory in the cholinergic system (Felipe et al., 2008), while linalool was identified as an inhibitor of acetylcholinesterase (Ryan and Byrne, 1988).

Another possible target suggested for essential oil compounds is interference with GABA-gated chloride channels in insects (Rattan, 2010). Thujone has been classified as a neurotoxic insecticide that acts on GABA_A receptors. Thujone is a competitive inhibitor of [3H]EBOB binding (i.e., of the noncompetitive blocker site of the GABA-gated chloride channel) and is a reversible modulator of the GABA_A receptor (Hold et al., 2000). It has been suggested that thymol potentiates GABA_A receptors through an unidentified binding site (Priestley et al., 2003). The silphinenes antagonize the action of GABA on insect neurons (Bloomquist et al., 2008; Rattan, 2010).

Octopamine is also a target for essential oil compound activity in insects. OA is a naturally occurring, multifunctional, biogenic amine, which plays key roles as a neurotransmitter, neuromodulator, and neurohormone in the invertebrate system, with a physiological function comparable to that of norepinephrine in vertebrates (Enan, 2001). The acute and sublethal behavioral effects of essential oil compounds on insects are consistent with an octopamenergic target site in insects, which acts by blocking octopamine receptors (Rattan, 2010).

In addition, essential oils and their constituents could affect biochemical processes, which specifically disrupt the endocrinological balance of insects. They may act as insect growth regulators, disrupting the normal process of morphogenesis (Reynolds, 1987; Rattan, 2010). However, it is thus apparent that the substances contained in essential oil compounds exhibit not only various mechanisms of action, but also various levels of capacity to penetrate an insect’s cuticle and enter its body, which is directly related to the capacity to provide an insecticidal effect.

Although sesquiterpenes seem to provide better efficacy than some monoterpenes, recent research indicates that the ability of mutual synergistic or antagonistic action may also play a very important role in terms of efficacy, which is probably related to the ability of mutual complementarism of the mechanism of action. Complex mixtures containing substances with different mechanisms of action can significantly hinder the ability of insects to intoxicate substances in the body.

For example, the author team has reported some substances that do not cause mortality alone or show low mortality, but when mixed with other compounds, such substances exert a significant effect on the resulting efficacy as a synergist. This is the case for a pulegone together with thymol and 1,8-cineole (Kumrungsee et al., 2014), or as shown in *Spodoptera littoralis* larvae, borneol by itself causes only very low acute toxicity; however, when mixed with other monoterpenes, it significantly increases their efficacy (Pavela, 2014).

24.3 Essential Oil Compounds as a Synthetic Pesticide

The environmental problems caused by the overuse of pesticides have been of concern to both scientists and the public in recent years. It has been estimated that about 2.5 million tons of pesticides are used on crops each year, and the worldwide damage caused by pesticides reaches $100 billion annually. The reasons for this are twofold: (1) the high toxicity and nonbiodegradable properties of pesticides and (2) the residues in soil, water resources, and crops that affect public health. Thus, on the one hand, one needs to search for new, highly selective, and biodegradable pesticides to solve the problem of long-term toxicity to mammals, while on the other hand, one must study the environmentally friendly pesticides and develop techniques that can be used to reduce pesticide use while maintaining crop yields. Natural products are an excellent alternative to synthetic pesticides as a means of reducing the negative impacts on human health and the environment. The move toward green chemistry processes and the continuing need for developing new crop protection tools with novel modes of action make discovery and commercialization of natural products as green pesticides an attractive and profitable pursuit that is commanding attention. The concept of "green pesticides" refers to all types of nature-oriented and beneficial pest control materials that can contribute to reducing the pest population and increasing food production. They are safe and eco-friendly. They are more compatible with the environmental components than synthetic pesticides (Isman and Machial, 2006).

As noted in the discussion on efficacy above, until now, plant essential oil compounds have been produced commercially from several botanical sources by many companies. The oils are generally sometimes composed of complex mixtures of monoterpenes, biogenetical related phenols, and sesquiterpenes, and examples include 1,8-cineole, the major constituent of oils from rosemary and eucalyptus; eugenol from clove oil; thymol from garden thyme; menthol from various species of mint; asarones from calamus; and carvacrol and linalool from many plant species.

As lipophilicity plays a key role in modulating pesticidal activity, the association between lipophilic compounds and protein deactivation or enzyme inhibition may be a reasonable explanation for this fact (Ryan and Byrne, 1988). This was confirmed in a chemometric study applied to active compounds such as terpenes and phenylpropanoids, and the activity was strongly correlated with independent variables having a hydrophobic profile (Scotti et al., 2013).

Double bonds are important in the pesticidal activity of natural molecules because hydrogenation of these bonds decreases the lipophilic character of these compounds, restricting their passage through the larvae cuticle (Lomonaco et al., 2009). For example, Lucia et al. (2007) and Perumalsamy et al. (2009) found that α-pinene, which possesses an exocyclic double bond, is more toxic to *Aedes aegypti* larvae than β-pinene, which has an endocyclic double bond.

As there is little information available about the mechanism of essential oil action against insects, the relation between pesticidal effect and the chemical composition of the essential oil has been the focus of some scientific work. Thus, some chemists try syntheses by changing the structural composition of essential oil compounds to study the possible mechanism. Other objectives are to increase the activity, as well as economic gain, as then there is no need to use and/or be reliant on the natural source to extract the essential oil compounds. All these objectives have become active fields for research in drug design. For example, Li et al. (2015) described finding potential pesticides against *Plutella xylostella* based on essential oils by synthesizing the oriented chiral esters in their structure. The preliminary results revealed that synthesized compounds showed significantly improved insecticidal activities compared with the essential oil molecules used at the start.

24.4 Advantages of Essential Oil Compounds as a Pesticide

The advantage of using essential oil compounds as pesticides is that they are moderately toxic to mammals (Table 24.3), but with few exceptions, the oils themselves or products based on oils are mostly less toxic to mammals, birds, and fish (Stroh et al., 1998). The toxicity of essential oil compounds based on ecological information is shown in Table 24.4, therefore justifying their placement under acceptable green pesticides. Owing to their volatility, essential oils have limited persistence under field conditions; therefore, although natural enemies are susceptible via direct contact, predators and parasitoids reinvading a treated crop 1 or more days after treatment are unlikely to be poisoned by residue contact, as often occurs with conventional insecticides (Koul et al., 2008). In addition, there are some specific modes of action of neurotoxin between invertebrate and vertebrate that cause differing toxicities between mammals and invertebrate pests.

In fact, pesticides derived from plant essential oils do have several important benefits. Pesticides based on plant essential oils or their constituents have demonstrated efficacy against a range of stored product pests, domestic pests, blood-feeding pests, and certain soft-bodied, agricultural pests, as well as against some plant pathogenic fungi responsible for pre- and postharvest diseases. They may be applied as fumigants, granular formulations, or direct sprays, with a range of effects, from lethal toxicity to repellence and/or oviposition deterrence in insects. These features indicate that pesticides based on plant essential oils could be used in a variety of ways to control a large number of pests.

Oil-in-water microemulsions are being developed as a nanopesticide delivery system to replace the traditional emulsifiable concentrates (oils), to reduce the use of organic solvent, and to increase the disparity and penetration properties of the droplets. The advantages of using pesticide oil-in-water microemulsions for improving the biological efficacy and reducing the dosage of pesticides would be a useful strategy in green pesticide technology.

Due to their volatile nature, there is a much lower level of risk to the environment with essential oil compounds than with current synthetic pesticides. Predator, parasitoid, and pollinator insect populations will be less impacted because of the minimal residual activity, making essential oil–based pesticides compatible with integrated pest management programs such as in the research of Yotavong et al. (2015), where the toxicity on the parasitioid was less than that on the host. It is also clear that resistance will develop more slowly to essential oil–based pesticides owing to the complex mixtures of constituents that characterize many of these oils (Koul et al., 2008). Ultimately, it is in developing countries where the source plants are endemic that these pesticides may have their greatest impact in an integrated pest management strategy. It is expected that these pesticides will find their greatest commercial application in urban pest control, public health, veterinary health, vector control vis-à-vis human health, and protection of stored commodities. In agriculture, these pesticides will be most useful for protected crops (e.g., greenhouse crops), for high-value row crops, and within organic food production systems where few alternative pesticides are available (Koul et al., 2008). Koul et al. (2008) noted the advantages of using essential oil compounds: (1) there are changing consumer preferences toward the use of natural as opposed to synthetic products; (2) there are expanding niche markets, where quality is more important than price; (3) there is strong growth in demand for essential oils and plant extracts; (4) there is potential to extend the range of available products, including new product development through biotechnology; and (5) there is production of essential oils and plant extracts from low-cost, developing countries.

TABLE 24.3

Mammal Toxicity of Some Essential Oil Compounds

Compound	Animal Tested	Route	LD_{50} (mg/kg)	Reference
2-Acetonaphthone	Mice	Oral	599	Sigma-Aldrich (2012a)
	Dog	Intravenous	500	Koul (2005)
Apiol anisaldehyde	Rat	Oral	1,510	Koul (2005)
	Rabit	Dermal	5,000	Thermo Scientific (2015)
trans-Anethole	Rat	Oral	2,090	FAO (1999)
Carene	Rat	Oral	4,800	FAO (1999)
(+)Carvone	Rat	Oral	1,640	FAO (1999)
1,8-Cineole	Rat	Oral	2,480	FAO (1999); Sigma-Aldrich (2013d)
Cinnamaldehyde	Guinea pig	Oral	1,160	FAO (1999)
	Rat	Oral	2,220	Koul (2005)
Citral	Rat	Oral	4,960	FAO (1999)
	Rabbit	Dermal	2,250	Sigma-Aldrich (2013a)
Citronellol	Mice	IMS	4,000	FAO (1999)
	Rat	Oral	3,450	Sigma-Aldrich (2015a)
	Rabbit	Dermal	2,650	Sigma-Aldrich (2015a)
Clove oil	Rat	Oral	3,720	FAO (1999)
Cumin oil	Rat	Oral	2,500	FAO (1999)
Dillapiol	Rat	Oral	1,000–1,500	Koul (2005)
iso-Eugenol	Rat	Oral	1,560	FAO (1999)
Geraniol	Rat	Oral	3,600	FAO (1999)
	Rabbit	Dermal	>5,000	Sigma-Aldrich (2014a)
3-Isothujone	Mice	Subcutaneous	442.2	Koul (2005)
Limonene	Rat	Oral	4,600	FAO (1999)
	Rabbit	Dermal	>5,000	Sigma-Aldrich (2015b)
Linalool	Rat	Oral	2,790	FAO (1999)
	Rabit	Dermal	5,610	Koul (2005)
Maltol	Rat	Oral	2,330	Koul (2005)
	Mice	Oral	550	Sigma-Aldrich (2015c)
	Rabbit	Oral	1,620	Sigma-Aldrich (2015c)
	Mice	Subcutaneous	820	Sigma-Aldrich (2015c)
Menthol	Rat	Oral	3,180	FAO (1999)
4-Methoxyphenol	Rat	Dermal	>2,000	Sigma-Aldrich (2015d)
Methyl chavicol	Rat	Oral	1,820	FAO (1999)
Methyl eugenol	Rat	Oral	810	Sigma-Aldrich (2012b)
Myrcene	Rat	Oral	>11,390	Sigma-Aldrich (2014b)
	Rabbit	Dermal	>5,000	Sigma-Aldrich (2014b)
Origanum oil	Rat	Oral	1,850	FAO (1999)
	Rabbit	Dermal	320	Sigma-Aldrich (2013b)
α-Pinene	Rat	Oral	3,700	Sigma-Aldrich (2014c)
	Rabbit	Dermal	>5,000	Sigma-Aldrich (2014c)
(+)-Pulegone	Mice	Intraperitoneal	150	FAO (1999)
γ-Terpinene	Rat	Oral	3,650	Sigma-Aldrich (2012c)
Terpinen-4-ol	Rat	Oral	4,300	FAO (1999)
Thujone	Mice	Subcutaneous	87.5	Koul (2005)
	Rat	Intraperitoneal	120	FAO (1999)
Thymol	Mice	Oral	1,050–1,200	EFSA (2012)
	Rat	Oral	980	FAO (1999)
	Rat	Dermal	>2,000	EFSA (2012)
	Guinea pig	Oral	880	EFSA (2012)

Note: IMS, intramuscular stimulation.

TABLE 24.4

Ecological Information on Some Essential Oil Compounds

Compound	Animal Tested	Method	Result	Reference
1,8-Cineole	*Pimephales promelas*	Static test	96 h LC50 = 102 mg/L	Sigma-Aldrich (2015f)
Citronellol	*Leuciscus idus*	Static test	96 h LC50 = 10–22 mg/L	Sigma-Aldrich (2015a)
	Daphnia magna	OECD test Guideline 202	48 h LC50 = 17 mg/L	Sigma-Aldrich (2015a)
	Algae	Static test	72 h LC50 = 2.4 mg/L	Sigma-Aldrich (2015a)
Euglenol	*Danio rerio*	Static test	96 h LC50 = 13 mg/L	Sigma-Aldrich (2013c)
	Daphnia magna	OECD test Guideline 202	48 h LC50 = 1.13 mg/L	Sigma-Aldrich (2013c)
Geraniol	*Danio rerio*	Static test	96 h LC50 = 22 mg/L	Sigma-Aldrich (2014a)
	Daphnia magna	OECD test Guideline 202	48 h LC50 = 10.8 mg/L	Sigma-Aldrich (2014a)
	Desmodesmus subspicatus	Growth inhibitor	72 h LC50 = 13.1 mg/L	Sigma-Aldrich (2014a)
Linalool	*Oncorphynchus mykiss*	Static test	96 h LC50 = 27.8 mg/L	Sigma-Aldrich (2015e)
	Daphnia magna	Immobilization	48 h EC50 = 59 mg/L	Sigma-Aldrich (2015e)
	Desmodesmus subspicatus	Static test	96 h LC50 = 156.7 mg/L	Sigma-Aldrich (2015e)
Limonene	*Pimephales promelas*	OECD test Guideline 203	96 h LC50 = 0.72 mg/L	Sigma-Aldrich (2015b)
	Daphnia magna	OECD test Guideline 202	48 h LC50 = 0.36 mg/L	Sigma-Aldrich (2015b)
4-Methoxyphenol	*Oncorhynchus mykiss*	OECD test Guideline 202	96 h LC50 = 28.5 mg/L	Sigma-Aldrich (2015d)
	Daphnia magna	OECD test Guideline 202	48 h LC50 = 3 mg/L	Sigma-Aldrich (2015d)
	Pseudokirchneriella subcapitata	OECD test Guideline 201	72 h EC50 = 54.7 mg/L	Sigma-Aldrich (2015d)
Methyl eugenol	*Oncorhynchus mykiss*	N/A	96 h LC50 = 6 mg/L	Sigma-Aldrich (2012b)
α-Pinene	*Daphnia magna*	OECD test Guideline 202	48 h EC50 = 48 mg/L	Sigma-Aldrich (2014c)
Pulegone	*Daphnia pulex*	N/A	48 h EC50 = 24.4 mg/L	Sigma-Aldrich (2015f)

Note: N/A, no testing method described.

24.5 Limitations of Essential Oil Compounds as a Pesticide

In spite of the considerable research effort in many laboratories throughout the world and an ever-increasing volume of scientific literature on the pesticidal properties of essential oils and their constituents, surprisingly few pest control products based on plant essential oils have appeared in the marketplace. This may be a consequence of regulatory barriers to commercialization (i.e., cost of toxicological and environmental evaluations), or the fact that the efficacy of essential oils toward pests and diseases is not as apparent or obvious as that seen with currently available products.

Many countries still face some problems in the liberal use of essential oil compounds as biopesticides. There are several reasons why farmers are reluctant to adopt biopesticides to replace synthetic chemicals. Essential oil compounds generally act more slowly than synthetic pesticides, killing arthropod pests over a longer time, rather than having an immediately apparent knockdown effect, so the pests can still damage the crops after application. Moreover, essential oils also require somewhat greater application rates (as high as 1% active ingredient) and may require frequent reapplication when used outdoors. Because of this, farmers still prefer to use and rely on the quick-acting synthetic pesticides, causing high pest mortality shortly after application.

In addition, as the chemical profile of plant species can vary naturally, depending on geographic, genetic, climatic, annual, or seasonal factors, pesticide manufacturers must take additional steps to ensure that their products will perform consistently. All this requires substantial cost, and smaller companies may not be willing to invest the required funds unless there is a high probability of recovering the costs through some form of market exclusivity (e.g., patent protection).

Lastly, the poor quality of some of the noncommercial biopesticide products is also a cause for concern (Warburton et al., 2002). A relevant issue is the illegal importation of unregistered products that may contain extremely low levels of active agents and sometimes a cocktail of several agents, so that their use requires high volumes. In addition, some commercial products, which do not pass the registration process, are still being sold in the market, which creates doubts about ineffective products for control, and thus people are reluctant to use them.

Therefore, cost-competitiveness and product quality and performance of essential oils are the two major barriers standing in the way of their adoption. Overcoming these barriers will require more effort in technology transfer, so that research results are more readily translated into field use. Even more importantly, it will require additional funding for the optimization of local production strategies, farmer education, continuing research, and even subsidization of biopesticide retail costs, so that their availability to farmers is ensured.

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