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Review

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Review

Essential Oils in Urban Insect Management—A Review

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Abstract

The allures of city life have culminated in the rise of urban populations resulting in conditions that promote the establishment of certain insect pests. Globally, the public health significance of these urban insect pests is enormous, ranging from billions of dollars to loss of lives. Most chemical insecticides no longer provide the anticipated level of control, and significant insecticide resistance has been reported. Therefore, there has been a spike in interest for alternatives to conventional insecticides. Among them, natural products from plants such as essential oils (EOs) and essential oil components (EOCs) have enjoyed the most attention owing to widespread reports of efficacy and toxicity even against insecticide-resistant urban insects. Yet, there is no comprehensive synthesis on the extent and impact of the management of urban insects using EOs or EOCs. Such a review is highly relevant since it provides a means to assess the extent of progress made, shortfalls, limitations, and prospects. More so, we hope it can be used to make informed decisions and develop relevant policies reliably. We present the ranges of insecticidal effects of EOs, EOCs, and commercially available EO-based products from laboratory and field studies. Finally, we discuss the gaps in our knowledge and prospects for the sustainable use of EOs.

Key words: ant, bed bug, cockroach, stored product moths, termite

The allures of city life have culminated in the rise of urban populations resulting in conditions such as overcrowding, poor housing, inadequate sanitation, and solid waste disposal. These conditions promote the establishment of certain urban insects. Globally, urban insect pests' economic and public health significance is enormous.

Urban insect pests are usually managed with synthetic insecticides (Wang et al. 2016, 2020; Rabito et al. 2017). While the argument about the current efficacy of synthetic insecticides is equivocal, what is clear is the genuine concerns associated with their usage. Examples of such problems include increasing insecticide resistance, increasing legislation against use, effects on nontarget pests, and environmental contamination (Zhu et al. 2016, Wu and Appel 2017, Fardisi et al. 2019). There has been a paradigm shift in the attitude of homeowners about insecticides and increasing interest in the use of alternatives such as natural products (Koul et al. 2008).

The use of natural products to manage insect pests is not new. The Chinese used natural products such as chalk, wood ash, and botanicals in 1200 BC for fumigation and seed coating (Flint and Van Den Bosch 1981). Pulverized *Chrysanthemum* flowers were used to manage head lice in the Achaemenid empire, present-day Iran (486–465 BC) (Addor 1995). Since then, there have been over 30,000 articles on natural product research globally (PubMed quick search). In the US, research scientists and companies leverage the registration exemption of section 25b of the US Environmental Protection Agency (EPA 2000) to continue laboratory bioassays to provide empirical information on the insecticidal profiles of natural products against urban insects. The registration exemption could, perhaps, be seen as good or bad. On one hand, registration exemption could lead to lack of standardization and neglect for the need of toxicological evaluations. The lack of standardization could culminate in the introduction of poor products into the market. On the other hand, the registration exemption could save cost and time by circumventing expensive toxicology studies and accelerating potential discovery and marketing for natural products.

Consequently, essential oils (EOs) have witnessed deserving attention due to the widespread efficacy reports even to insecticide-resistant urban insect pests (Albuquerque et al. 2013; Oladipupo et al. 2019, 2020a,b; Gaire et al. 2020; Lee and Rust 2021). Yet, there is no synthesis on the extent and the impact of the management of urban insects using essential oils or essential oil components (EOCs) or commercially available EO formulations. Such a review is of high importance since it provides a measure for the objective evaluation of the range of their effectiveness. Such information can be used to reliably make informed decisions and policies regarding widely reported efficacies and assess shortfalls, limitations, and prospects.

Therefore, this review attempts to systematically present knowledge on EOs, EOCs, and commercially available EO formulations employed in the management of urban insects. Based on the intersection of the most common and often encountered insect pests, control efforts, and homeowners' frustrations, the emphasis was placed on ants, bed bugs, cockroaches, fleas, head lice, silverfish, stored product moths, and termites. Furthermore, highlighting each urban insect pest, we presented the range of insecticidal effects of these natural products and outlined laboratory and field evidence. Finally, we discussed the gaps in knowledge and possible prospects for EOs in urban insect management.

Natural Products, Plants Extracts, and Essential Oils

Natural Products

As defined by Asolkar et al. (2013), a natural product refers to any naturally occurring organic compounds that do not appear to participate directly in the growth and development of the source organism. Natural products from plants are a source of secondary metabolites that are categorized as terpenoids, phenolic compounds, and alkaloids (Agostini-Costa et al. 2012). Plants utilize these metabolites for communication and defense to limit insect-feeding damage (Aljbory and Chen 2018).

Plant Extracts, Essential Oils, and Essential Oil Components

The extraction method (from plants) determines if the product is a plant extract or essential oil. If obtained via solvent extraction, it is termed plant extract, whereas it is termed an essential oil if distilled or expressed. The term 'essential oil' was coined by a Swiss physician, Theophrastus von Hohenheim, popularly known as Paracelsus, in an attempt to isolate the 'Quinta essentia' of certain herbal drugs in ca. 1523 (Guenther 1950). Essential oils are a mixture of many components whose composition is determined by the plant family, plant part, expressed method, edaphic factors, and other environmental conditions (Isman and Paluch 2011). In other words, essential oils are concentrated hydrophobic/hydrophilic liquids containing aromatic/aliphatic volatile compounds from plants. Usually, the components (or constituents) of an EO (hereafter referred to as EOC) are identified by gas chromatography coupled with mass spectrometry (GC-MS). Steam distillation is the most preferred method of EO extraction, thereby implying that the components are heat stable.

These essential oil components (EOCs) can be classified based on (1) the number of isoprene units (i.e., five carbon atoms with double bonds), (2) functional groups, and (3) the molecular structure of terpenes (Fig. 1) (Buckle 2015, Perveen 2018). Based on isoprene units, there are hemiterpenes (1 isoprene unit), monoterpenes (2 isoprene units), sesquiterpenes (3 isoprene units), and up to tetraterpene (8 isoprene units) (Fig. 1a). The functional groups include aldehydes, ketones, alcohol esters, phenols, and ethers (Fig. 1b). The molecular structure of the terpenes can be cyclic (one ring; e.g., D-Limonene), bicyclic (two rings; e.g., zingiberene), tricyclic (three rings), or acyclic (linear and has no ring; e.g., isoprene) (Fig. 1) (Buckle 2015, Perveen 2018).

Application methods routinely employed to deliver EOs and EOCs in the laboratory to their target urban insect pest is diverse (Philips and Appel 2010, Gaire et al. 2017, Wu and Appel 2017, Oladipupo et al. 2020a). Common examples include topical, continuous exposure to dry residue, fumigant, contact, and repellency bioassays. Briefly, topical applications involve delivering a known concentration of a toxicant to a defined area of the insect body. While concentrations routinely employed for topical applications are expected to achieve intended effects within a short time (mostly 24–48 hr), the continuous application involves providing a concentration that the insect is continuously exposed to for an extended period. Fumigation involves the delivery of the toxicant through vapor while preventing physical contact with the toxicant. Contact is the opposite as it involves direct contact with the toxicant. Repellency combines contact and fumigation effects with avoidance behavior. The toxicant is placed within the experimental arena, and the insects' behavior is measured.

Nevertheless, the application method employed depends on practicality (i.e., convenience) and the probit metric of evaluation sought. As a gold standard, the probit metric 50 (i.e., P_{50}) evaluates the dose in milligram (LD_{50}) (i.e., for a topical bioassay), concentration in milligram/liter of air (LC_{50}) (i.e., for a fumigant bioassay, or time in minutes (LT_{50}) (i.e., for a continuous exposure or a fumigant bioassay) of a toxicant per body weight (mg g^{-1}) that would kill 50% of the population of interest. When the intent is to knock down or to inhibit egg-laying/hatch, KT_{50} and hatch inhibition are used, respectively.

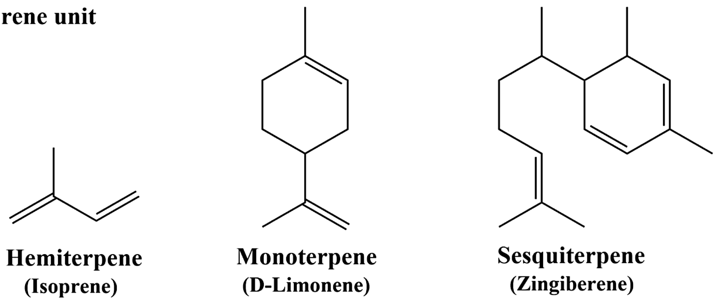
Management of Urban Insect Pests Using Natural Products

Ants

Ants can be found indoors or peridomestic areas. Some species can sting while others can negatively impact wildlife or by displacing other species (Collins and Scheffrahn 2001, Allen et al. 2004). Some species display aggressive nature (e.g., fire ants), cryptic behavior (e.g., black garden ants), high reproductive rate, mound relocation (especially with fire ants), and polygyny (i.e., multiple queen colonies) that readily frustrates control efforts (Appel et al. 2004, Fu et al. 2015, de Oliveira et al. 2020). Indoors, stingless ants such as the black garden ant, *Lasius niger* (L.) (Hymenoptera: Formicidae), and the Argentine ant, *Linepithema humile* (Mayr) (Hymenoptera: Formicidae), are frequently encountered. The tawny crazy ant, *Nylanderia fulva* (Mayr) (Hymenoptera: Formicidae), a stingless species, can be found indoors and outdoors. These ant species colonize gardens, lawns, compost piles, pavement cracks, and schoolyards in southeastern US and Brazil (Collins and Scheffrahn 2001, Cheng et al. 2008, Albuquerque et al. 2013, Fu et al. 2015, de Oliveira et al. 2020). These ant species constitute a nuisance by building colonies in electrical circuits within utility boxes.

About six plant families have been explored for their insecticidal effects against urban ant species (Table 1). Most of these experiments were conducted on ants via a fumigant toxicity test. Many ants exist in colonies underground, and a fumigant bioassay is a close simulation that reflects control methods in such environments. The insecticidal activity of each EO, the plant details, bioassay type, and range of toxicity reported are compiled in Table 1. However, no direct comparison can be made due to the wide range of bioassay methods, ant species, and insecticidal endpoints reported. Mint oil (Lamiaceae) resulted in a 49–100% repellency at 147.8 mg cm^{-2} against *S. invicta* workers (Appel et al. 2004). The fumigation activity of *Varronia currasavica* Jacq. EO (Cordiaceae) was greater (LC_{50} range: 0.7–1.3 µl $liter^{-1}$) against *D. thoracius* than other EOs against *S. invicta* (de Oliveira et al. 2020). In general, *S. invicta* minor workers (LC_{50}: 1.7

(a) Isoprene unit



(b) Functional group

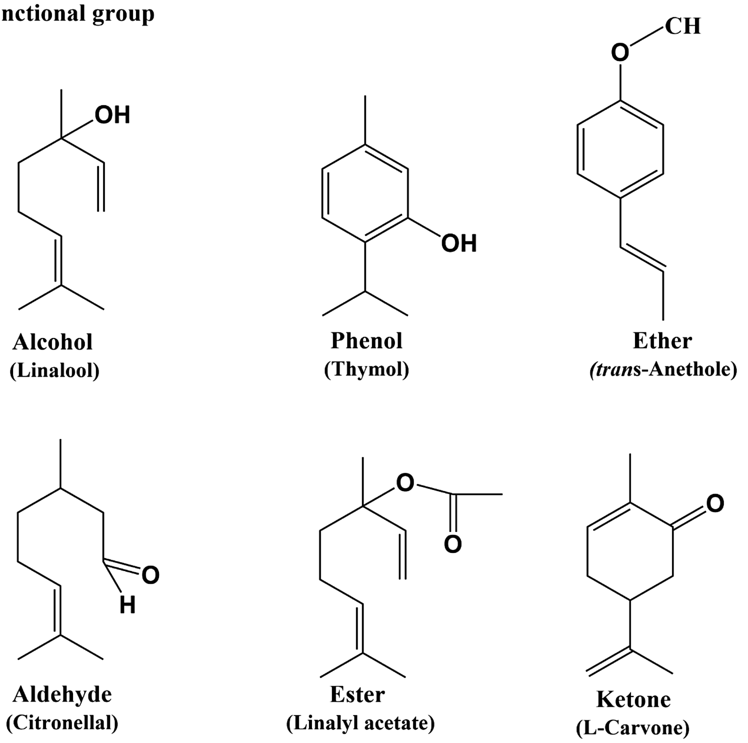


Fig. 1. Classification of terpenes based on (a) isoprene unit and (b) functional group.

μg mol^{-1}) were more affected than major workers LC$_{50}$: 4.3 μg mol^{-1}) in a series of fumigation toxicity tests exploring *Cinnamomum camphora* EOs (Zhang et al. 2014, Fu et al. 2015). The knockdown time (LT$_{50}$) was least (21.2 min) for *C. osmophloeum* EO against *S. invicta* in a closed fumigation experiment (Cheng et al. 2008). For both *Cinnamonum spp.* (Lauraceae), the most abundant EOC isolated, had a comparable level of control against *S. invicta* as *Cinnamonum* EO (Table 1). In another study, Addesso et al. (2017) observed that *Cuppressus nootkanensis* D. Don EO (Cuppressaceae) suppressed *S. invicta* x *ritcheri* digging behavior by 50%. In contact tests, EOs distilled from aerial parts of *Piper aduncum* L. had remarkable activity (LD$_{50}$: 114.4 mg liter^{-1}) compared to other *Piper spp.* (LD$_{50}$ range: 207.8–571.1 mg liter^{-1}) (Souto et al. 2012). In an electroantennographic investigation, *Eucalyptus maculata* Hook EO stimulated the antennae response of *Atta sexdens rubropilosa* Forel (Batista-Pereira et al. 2006). A stimulatory response such as this suggests that *E. maculata* EOs contain bioactive components which could be explored for their behavioral roles

The above reports show that one way to affect urban ant pests is through fumigation using EOCs. This suggests that EOs vapors gain access into ants' bodies via the spiracles to exert their effect in ants. But such an application might have limited effect on ants that colonize above-ground galleries and open air which would require direct/contact application. Besides, in practice, the treatment methods for ants are via insecticidal baits or contact application sprayed over the ground. This is because contact is the primary delivery approach for ants. Nevertheless, based on the information provided in Table 1, lower concentrations are required for fumigant toxicity. EOs from Cordiaceae appear to possess the most potent insecticidal activity against ants. Perhaps the injection of EOs/EOCs into ant mounds or even wall voids would be similar enough to act as a fumigant.

Bed Bugs

Two species of bed bugs are important ectoparasites of people and occasionally other animals; the common bed bug, *Cimex lectularius* L., and the tropical bed bug, *C. hemipterus* F. (Hemiptera: Cimicidae) (Liu et al. 2014). Both species rely on blood meals for growth, development, and reproduction, and thus have become synanthropic (Lai et al. 2016). In the last two decades, there have been reports of a resurgence of both species, presumably owing to reduced use of spray insecticides indoors, increased global travel, and increased incidences of insecticide resistance (Doggett et al. 2004, Politi et al. 2017). The

Table 1. Insecticidal effects of plant essential oils and their components against ants

						Insecticidal effect				
Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Caste	Repellency (%)	Mortality (LC$_{50}$)[b]	Knockdown (LT$_{50}$)[a]	References
Lauraceae	*Cinnamomum*							LC after 24 hr;	10.82 hr	Fu et al. (2015)
	Camphora (L.) J.Presl.	Leaf	Camphor (36.6)	*Solenopsis invicta* Buren	Fumigant (24 hr exposure)	Minor worker; Major worker		1.67 µg mol^{-1} 4.28 µg mol^{-1}	14.73 hr	
	C. osmophloeum Kaneh	Leaf	*trans*-Cinnamaldehyde (79.9)	*S. invicta*	Exposure at 2%: Open Close	Worker Worker			105.0 min 18.5 min	Cheng et al. (2008)
Piperaceae	*Piper aduncum* L.	Aerial part	Dillapiole (64.4)	*S. saevissima* (Smith)	Contact; filter-paper technique (24 hr)	Worker		LC; 114.4 mg liter^{-1}		Souto et al. (2012)
	P. marginatum Jacq. A		(*E*)-β-Ocimene (9.8)			Worker		207.8 mg liter^{-1}		
	P. marginatum B		(*E*)-Isoosmorhizole (32.2)			Worker		419. mg liter^{-1}		
	P. divaricatum G. Mey		Methyleugenol (69.2)			Worker		552.2 mg liter^{-1}		
	P. callosum Ruiz & Pav		Safrole (69.2)			Worker		571.1 mg liter^{-1}		
Lamiaceae	Mint oil granules			*S. invicta*	Repellency	Worker	49–100 for 147.8 mg cmmg cm^{-2}		1.2–15.3 hr with ~ 1.65 mg cmmg cm^{-2} of 2% mint oil granules	Appel et al. (2004)
	Pogostemon cablin Benth	Leaf	Patchoulol (36.6)	*Camponotus novogranadensis*	Topical application	Worker	24 hr	LD; 2.31 µg mg^{-1}		Albuquerque et al. (2013)
						Worker	48 hr	2.34 µg mg^{-1}		
				C. melanoticus	Topical application	Worker	4 hr	3.58 µg mg^{-1}		
						Worker	24 hr	3.23 µg mg^{-1}		
						Worker	48 hr	2.95 µg mg^{-1}		
				Dorymyrmex thoracicus	Topical application	Worker	4 hr	5.12 µg mg^{-1}		
						Worker	24 hr	5.02 µg mg^{-1}		
						Worker	48 hr	2.02 µg mg^{-1}		

Table 1. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Insecticidal effect				References
						Caste	Repellency (%)	Mortality (LC_{50})[b]	Knockdown (LT_{50})[a]	
Rutaceae	*Skimmia laureola* (DC.)	Leaf	D-Limonene (32.3)	*Lasius niger* L.	Contact; filter-paper technique	Worker		LC; 10.15 µl		Mehmood et al. (2016)
		Stem	β-Linalool (43.6)							
		Root	1,3-Cycloheptadiene (36.9)							
						Worker		10.15 µl		
						Worker		10.15 µl		
		Leaf	D-Limonene (32.3)		Repellency at 10%	Worker	3.5 hr (100)			
		Stem	β-Linalool (43.6)			Worker	4 hr (100)			
		Root	1,3-Cycloheptadiene (36.9)			Worker	4 hr (100)			
Cuppressaceae	*Cuppressus nootkatensis* D.Don		Nootkatene (57)	*S. invicta* x *richteri*	Contact	Worker		LC; 0.26 %		Addesso et al. (2017)
					Fumigant	Worker		8.85 µl oil-liter		
					Digging	Worker	Digging suppressed by 50 %			
Cordiaceae	*Varronia curassavica* Jacq.	Leaf		*Dorymyrmex thoracius* Gallardo						de Oliveira et al. (2020)
	VAC-316		(E)-Caryophyllene (6.1)		Fumigant	Worker		LC; 1.5 µl liter^{-1}		
	VAC-324		(E)-Caryophyllene (22.3)		Fumigant	Worker		2.5 µl liter^{-1}		
	VAC-326		(E)-Caryophyllene (16.1)		Fumigant	Worker		0.7 µl liter^{-1}		
	VAC-503		(E)-Caryophyllene (10.8)		Fumigant	Worker		1.5 µl liter^{-1}		
	VAC-509`		(E)-Caryophyllene (20.8)		Fumigant	Worker		2.5 µl liter^{-1}		
	VAC-510		(E)-Caryophyllene (12.1)		Fumigant	Worker		1.3 µl liter^{-1}		
Commercial product/EOC										
(E)-Caryophyllene				*D. thoracius*	Fumigant	Worker		1.5 µl liter^{-1}		de Oliveira et al. (2020)
α-Humulene					Fumigant	Worker		3.8 µl liter^{-1}		
trans-Cinnamaldehyde				*S. invicta*	Exposure at 2%:					Cheng et al. (2008)
					Open	Worker		32.2 min		
					Close	Worker		21.2 min		
Camphor				*S. invicta*	Fumigant (24 hr exposure)	Minor worker Major worker		1.91 µg mol^{-1} 5.59 µg mol^{-1}		Fu et al. (2015)
Cineole				*S. invicta*	Fumigant (24 hr exposure)	Minor worker Major worker		2.34 µg mol^{-1} 5.99 µg mol^{-1}		

[a] Unless otherwise stated; knockdown time is expressed as LT_{50}; LT_{50} = lethal time required to kill 50% of the population.
[b] LC_{50} = lethal concentration required to kill 50% of the population.

Table 2. Insecticidal effects of plant essential oils and their components against bed bugs

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage	Insecticidal effect		References
							Repellency (%)	Mortality (% or LD$_{50}$, or LC$_{50}$)[a]	
Lamiaceae	*Oreganum vulgare* L.	Leaf	Terpineol (22.9)	*Cimex lectularius* L.	Treated surface method	Adult	At 10 %	[b] EC$_{50}$;	Sharififard et al. (2018)
						After 3 hr	100	0.3 mg cm mg cm^{-2}	
						5 hr	86	0.9 mg cm mg cm^{-2}	
						9 hr	65	1.6 mg cm mg cm^{-2}	
						24 hr	17	4.5 mg cm mg cm^{-2}	
Asteraceae	*Tagetes patula* L.	Aerial part	α-Terpinolene (15.5)	*C. lectularius*	Impregnated paper disk test	Adult		LC; 0.17 mg ml^{-1}	Politi et al. (2017)
Schisandraceae	*Kadsuna coccinea Kaempf. ex Juss.*	NS[c]	β-Caryophyllene (24.7)	*C. lectularius*	Topical application	Post-treatment days		% Mortality at 100 µg	Rehman et al. (2019)
						1	Resistant	61.9	
						1	Susceptible	66.7	
						3	Resistant	61.9	
						3	Susceptible	66.7	
						5	Resistant	61.9	
						5	Susceptible	90.5	
						7	Resistant	61.9	
						7	Susceptible	90.5	
Commercial product/EOC									
EcoRaider									
				C. lectularius	Spray treatment	Adult	92% reduction after 12 wk		Wang et al. (2014)
								Mortality in Petri dishes	Feldlaufer and Ulrich (2015)
CirkilT RTU				*C. lectularius*	Fumigant	Adult		100	
Acetophenone					Fumigant	Adult		100	
Cedarwood					Fumigant	Adult		0	
Cinnamon					Fumigant	Adult		100	
Citronella					Fumigant	Adult		86.9	
Clove					Fumigant	Adult		98.7	
Geranium					Fumigant	Adult		97.8	
Lemongrass					Fumigant	Adult		100	
Neem seed oil					Fumigant	Adult		2.4	
Peppermint					Fumigant	Adult		100	
Rosemary					Fumigant	Adult		100	
Thyme					Fumigant	Adult		100	
Methyl benzoate						Susceptible adult		LC; 4.1 mg liter^{-1}	Larson et al. (2020)

Table 2. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage	Insecticidal effect		References
							Repellency (%)	Mortality (% or LD_{50}, or LC_{50})[a]	
Acetaphenone				*C. lectularius*	24 hr exposure in flask (fumigant)			2.4 mg liter^{-1}	
						Resistant adult		6.2 mg liter^{-1}	
								4.1 mg liter^{-1}	
Carvacrol					Topical toxicity	Adult male		LD; 27.5 µg mg^{-1}	Gaire et al. (2019)
Thymol					Topical toxicity	Adult male		32.5 µg mg^{-1}	
Citronellic acid					Topical toxicity	Adult male		49 µg mg^{-1}	
Eugenol					Topical toxicity	Adult male		52 µg mg^{-1}	
Geraniol					Topical toxicity	Adult male		64 µg mg^{-1}	
α-Pinene					Topical toxicity	Adult male		70.5 µg mg^{-1}	
R(+)-Limonene					Topical toxicity	Adult male		91.5 µg mg^{-1}	
Linalool					Topical toxicity	Adult male		112 µg mg^{-1}	
Eucalyptol					Topical toxicity	Adult male		132 µg mg^{-1}	
(-)-Terpinen-4-ol					Topical toxicity	Adult male		138.5 µg mg^{-1}	
trans-Cinnamaldehyde					Topical toxicity	Adult male		138.5 µg mg^{-1}	
Menthone					Topical toxicity	Adult male		165 µg mg^{-1}	
(±)-Citronellal					Topical toxicity	Adult male		240 µg mg^{-1}	
(±)-Camphor					Topical toxicity	Adult male		515 µg mg^{-1}	
Methyl eugenol					Topical toxicity	Adult male		560 µg mg^{-1}	
Thymol					Fumigant (24 hr exposure)	Adult male		LC; 20.50 mg liter^{-1}	Gaire et al. (2019)
Carvacrol						Adult male		46.3 mg liter^{-1}	
Linalool						Adult male		51.2 mg liter^{-1}	
(±)-Camohor						Adult male		133.3 mg liter^{-1}	
Menthone						Adult male		150.7 mg liter^{-1}	
Euclayptol						Adult male		191.1 mg liter^{-1}	
(-)-Terpinen-4-ol						Adult male		388.3 mg liter^{-1}	
trans-Cinnamaldehyde						Adult male		389.0 mg liter^{-1}	
R(+)- Limonene						Adult male		454.0 mg liter^{-1}	
α-Pinene						Adult male		488.8 mg liter^{-1}	
(±)-Citronellal						Adult male		1474.6 mg liter^{-1}	
Carvacrol + Thyme + Eugenol								19 µg mg^{-1}	Gaire et al. (2020)

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.
[b] EC_{50} = effective concentration required to cause 50% repellency against bed bug.
[c] NS = not stated by the author.

Table 3. Insecticidal effects of plant essential oils and their components against cockroaches

							Insecticidal effect			
Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Repellency (%)	Mortality (LD$_{50}$ or LC$_{50}$) [a]	Knock-down (LT$_{50}$) [c]	References
Piperaceae	*Piper nigrum* L.	Fruit	Piperine (34.8)	*Blattella germanica* (L.)	Repellency	Nymph Adult	49.1 at 12 hr 55 at 12 hr			Wagan et al. (2017)
Lamiaceae	*Nepeta cataria* L.	Aerial part	Z,E-nepetalactone (85)	*B. germanica*	Repellency	Adult male	55.6 at 800 µg cm^{-2}			Peterson et al. (2002)
	Pogostemon cablin (Blanco) Benth.	Leaf	Patchoulol (41.3)	*B. germanica*	Contact Repellency	Male Nymph	47.6 at 5 ppm after 4 hr	LC; 23.5 µg/adult		Liu et al. (2015)
	Thymus persicus (Ronniger ex Rech. f.)	Aerial part	ND[b]	*B. germanica*	Fumigant	Adult		LC after 24 hr; 28.8 µl liter^{-1}		Rezaei et al. (2019)
Myrtaceae	*Eucalyptus camaldulensis* Dehn.	Aerial part	ND	*B. germanica*	Fumigant	Adult		LC after 24 hr; 21.8 µl liter^{-1}		Rezaei et al. (2019)
Anacardiaceae	*Schinus molle* L.	Leaf	δ-Cadinene (11.3)	*Blatta orientalis* L.	Repellency	Adult	100 at 176 µg cm^{-2}			Batista et al. (2016)
Asteraceae	*Artemisia sieberi* Besser	Aerial part	ND	*B. germanica*	Fumigant	Adult		LC after 24 hr; 17.3 µl liter^{-1}		Rezaei et al. (2019)
Chenopodiaceae	*Chenopodium ambrosioides* L.	Aerial part	*(Z)*-ascaridole (29.7)	*B. germanica*	Fumigant Topical	Male Male		After 24 hr: LC; 4.1 mg liter^{-1} LD; 64.5 µg/adult		Zhu et al. (2012)
Commercial products/EOC										
Oregano oil				*Supella longipalpa* Fabricius	Repellency	Nymph	96.5 at 30%			Sharififard et al. (2016)
Rosemary oil				*S. longipalpa*	Repellency	Nymph	94.5 at 2.5%			
Mint oil				*S. longipalpa*	Repellency	Nymph	63.3 at 30%			
Yarrow oil				*S. longipalpa*	Repellency	Nymph	86.7 at 30%			
Eucalyptus oil				*S. longipalpa*	Repellency	Nymph	27.7 at 30%			
Geranium oil				*B. germanica*	Contact	Adult		After 72 hr exposure LC; 0.2 mg cm mg cm^{-2}		Werdin González et al. (2015)
Bergamot oil				*B. germanica*	Contact	Adult		After 72 hr exposure LC; 0.4 mg cm mg cm^{-2}		
Red thyme oil				*Blatta lateralis* (*Walker*)	Topical Fumigant	Nymph Nymph		1.6 mg/nymph 160.5 mg liter^{-1} air		Gaire et al. (2017)
Clove bud oil				*Blatta lateralis*	Topical Fumigant	Nymph Nymph		1.7 mg/nymph 319.0 mg liter^{-1} air		

Table 3. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD$_{50}$ or LC$_{50}$) ^{a}	Knock-down (LT$_{50}$) ^{c}	
Java citronella oil				*Blatta lateralis*	Topical Fumigant	Nymph Nymph		7.9 mg/nymph 746.7 mg liter^{-1} air		
Mint oil				*B. germanica* *Periplaneta Americana* (L.)	Topical Contact Topical Contact	Adult male Adult male Adult male Adult male		LD; 3.8 µl LT; 1 min at 100% LD; 2.6 µl LT; 11.1 min at 100%		Appel et al. (2001)
Clove bud oil				*B. germanica*	Contact Repellency	Adult Adult	80% repellency at 2 ml cm^{-2} after 0.5 hr	95% mortality at 4 ml cm $^{-2}$		Neupane et al. (2019)
Z,*E*-nepetalactone				*B. germanica*	Repellency	Adult male	68.2 at 800 µg cm $^{-2}$			Peterson et al. (2002)
E,*Z*-nepetalactone				*B. germanica*	Repellency	Adult male	79.4 at 800 µg cm $^{-2}$			
(+)-α-Pinene				*B. germanica*	Repellency	First instar			11.8 min	Alzogaray et al. (2013)
				B. germanica	Fumigant	Male Female		LC; 11.8 mg liter^{-1} 26.1 mg liter^{-1}		Phillips and Appel (2010)
(-)-α-Pinene				*B. germanica*	Repellency	First instar			14.6 min	Alzogaray et al. (2013)
Limonene				*B. germanica*	Repellency	First instar			81.0 min	Alzogaray et al. (2013)
				B. germanica	Fumigant	Male Female		LC; 13 mg liter^{-1} 15.3 mg liter^{-1}		Phillips and Appel (2010)
Menthone				*B. germanica*	Repellency	First instar			141.0 min	Alzogaray et al. (2013)
				B. germanica	Fumigant	Male Female		LC; 7.4 mg liter^{-1} 13.9 mg liter^{-1}		Phillips and Appel (2010)
Linalool				*B. germanica*	Repellency	First instar			238.6 min	Alzogaray et al. (2013)

Table 3. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD$_{50}$ or LC$_{50}$) [a]	Knock-down (LT$_{50}$) [c]	
				B. germanica	Contact + fumigant Contact + fumigant	Susceptible Male Female Resistant Male Female		LD at 24 hr exposure; 0.3 mg cm mg cm^{-2} 0.4 mg cm mg cm^{-2} 0.4 mg cm mg cm^{-2} 0.5 mg cm mg cm^{-2}		Chang et al. (2012)
				B. germanica	Fumigant	Male Female		LC; 15.7 mg liter^{-1} 142 mg liter^{-1}		Phillips and Appel (2010)
Terpinolene				*B. germanica*	Vapor-phase	Female		87% at 0.06 mg cm mg cm^{-3}		Chang et al. (2012)
Nerol				*B. germanica*	Vapor-phase	Female		97% at 0.03 mg cm mg cm^{-3}		
1,8-cineole				*B. germanica*	Vapor-phase	Female		87% at 0.05 mg cm mg cm^{-3}		
				B. germanica	Fumigant	Male Female		LC; 6.8 mg liter^{-1} 8.4 mg liter^{-1}		Phillips and Appel (2010)
				B. germanica	Topical	Adult male Adult female		LD; 0.16 mg/insect 0.27 mg/insect		Philips et al. (2010)
p-cymene				*B. germanica*	Vapor-phase	Female		97% at 0.04 mg cm mg cm^{-3}		Chang et al. (2012
				B. germanica	Fumigant Topical	Male Male		After 24 hr: LC; 9.92 mg liter^{-1} LD; 119.9 µg/adult		Zhu et al. (2012)
				Blatta lateralis	Topical Fumigant	Nymph Nymph		9.9 mg/nymph 441.8 mg liter^{-1} air		Gaire et al. (2017)
Pogostone				*B. germanica*	Contact Repellency	Male Nymph	62.4 at 5 ppm after 4 hr	LC; 8.5 µg/adult		Liu et al. (2015)
Caryophyllene				*B. germanica*	Contact Repellency	Male Nymph	55.2 at 5 ppm after 4 hr	LC; 339.9 µg/adult		
Patchoulol				*B. germanica*	Contact Repellency	Male Nymph	40.5 at 5 ppm after 4 hr	LC; 207.6 µg/adult		

Table 3. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50}) [a]	Knock-down (LT_{50}) [c]	
Isoascaridole				*B. germanica*	Fumigant Topical	Male Male		After 24 hr: LC; 2.1 mg $liter^{-1}$ LD; 96.3 µg/ adult		Zhu et al. (2012)
Ascaridole				*B. germanica*	Fumigant Topical	Male Male		After 24 hr: LC; 0.6 mg $liter^{-1}$ LD; 22 µg/adult		
Carvacrol				*B. germanica*	Fumigant	Male Female		LC; 80.7 mg $liter^{-1}$ >1,000 mg $liter^{-1}$		Phillips and Appel (2010)
				B. germanica	Topical	Adult male Adult female		LD; 0.1 mg/insect 0.18 mg/insect		Philips et al. (2010)
trans-Cinnamaldehyde				*B. germanica*	Fumigant	Male Female		LC; 32 mg $liter^{-1}$ 34.4 mg $liter^{-1}$		Phillips and Appel (2010)
				Blatta lateralis	Topical Fumigant	Nymph Nymph		1.0 mg/nymph 150.8 mg $liter^{-1}$ air		Gaire et al. (2017)
				B. germanica	Topical	Adult male Adult female		LD; 0.08 mg/ insect 0.19 mg/insect		Philips et al. (2010)
Eugenol				*B. germanica*	Fumigant	Male Female		LC; 95.9 mg $liter^{-1}$ >1,000 mg $liter^{-1}$		Phillips and Appel (2010)
				P. americana	Contact Repellency	Female Female	RP; 77.1 $µgxm^{-2}$	LC; 0.1 mg cm^{-2}		Ngoh et al. (1998)
				Blatta lateralis	Topical Fumigant	Nymph Nymph		1.6 mg/nymph 251.2 mg $liter^{-1}$ air		Gaire et al. (2017)
				B. germanica	Contact Repellency	Adult Adult	85% repellency at 1 ml cm $^{-2}$ after 0.5 hr	85% mortality at 4 ml cm $^{-2}$		Neupane et al. (2019)
				B. germanica	Topical	Adult male Adult female		LD; 0.11 mg/ insect 0.29 mg/insect		Philips et al. (2010)

Table 3. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect: Repellency (%)	Insecticidal effect: Mortality (LD_{50} or LC_{50})[a]	Insecticidal effect: Knock-down (LT_{50})[c]	References
Eugenol acetate				*B. germanica*	Contact Repellency	Adult Adult	85% repellency at 2.5 ml cm $^{-2}$ after 0.5 hr	87% mortality at 4 ml cm $^{--3}$		Neupane et al. (2019)
Thymol				*B. germanica*	Fumigant	Male Female		LC;19.3 mg liter^{-1} 142.9 mg liter^{-1}		Phillips and Appel (2010)
				Blatta lateralis	Topical Fumigant	Nymph Nymph		0.3 mg/nymph 27.6 mg liter^{-1} air		Gaire et al. (2017)
Safrole				*P. americana*	Fumigant Contact	Female Female		LC; 0.2 mg cm^{-2} 0.3 mg cm^{-2}		Ngoh et al. (1998)
Isosafrole				*P. americana*	Fumigant Contact	Female Female		LC; 0.3 mg cm^{-2} 0.2 mg cm^{-2}		
Citronellic acid				*B. germanica*	Topical	Adult male Adult female		LD; 0.25 mg/insect 0.49 mg/insect		Philips et al. (2010)
Geraniol				*B. germanica*	Topical	Adult male Adult female		LD; 0.26 mg/insect 0.83 mg/insect		Philips et al. (2010)
Thymol				*B. germanica*	Topical	Adult male Adult female		LD; 0.12 mg/insect 0.07 mg/insect		Phillips et al. (2010)

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.
[b] ND = not done by the authors.
[c] Knockdown time is expressed as LT_{50}; LT_{50} = lethal time required to kill 50% of the population.

Table 4. Insecticidal effects of plant essential oils and their components against flea

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect		
							Repellency (%)	Mortality (LD$_{50}$ or LC$_{50}$)[a]	References
Lauraceae	*Cinnamomum osmophloeum* Kaneh.	Leaf	*trans*-Cinnamaldehyde (87.1)	*Ctenocepalides felis felis* (Bouché)	Repellency	Adult	68.6–97.7		Su et al. (2014)
Lamiaceae	*Plectranthus amboinicus* (Lour) *Ocimum gratissimum* L. *Mentha spicata* L. *Laurus nobilis* L. *Cinnamomum spp.* *Ziziphora tenuiore* L. *Mentha piperita* L.	Leaf Leaf Leaf Leaf Leaf Shoot Shoot	Thymol (58.1) Eugenol (74.5) Carvone (83.3) Eucalyptol (19.2) (E)-Cinnamaldehyde (91.7) Thymol (36.3) Mentha (26.7)	*C. felis felis* *C. felis felis* *C. felis felis* *C. felis felis* *C. felis felis* *Pulex irritans* L. *P. irritans*	Repellency Impregnated filter-paper test Impregnated filter-paper test Impregnated filter-paper test Impregnated filter-paper test Repellency Repellency	Adult Egg Larva Adult (24 hr) Adult (48 hr) Egg Larva Adult (24 hr) Adult (48 hr) Egg Larva Adult (24 hr) Adult (48 hr) Egg Larva Adult (24 hr) Adult (48 hr) Adult Adult	68.6–97.7 At 1,600 µg cm^{-2} = 98 At 1,600 µg cm^{-2}= 69.	LC; 1.8 µg cm^{-2} 1.2 µg cm^{-2} 5.9 µg cm^{-2} 4.5 µg cm^{-2} 30.4 µg cm^{-2} 12.6 µg cm^{-2} 597.6 µg cm^{-2} 380.1 µg cm^{-2} 2.4 µg cm^{-2} 0.5 µg cm^{-2} 412.1 µg cm^{-2} 454.9 µg cm^{-2} 1.8 µg cm^{-2} 0.4 µg cm^{-2} 67.9 µg cm^{-2} 41.9 µg cm^{-2} [b]ED; 229 µg cm^{-2} 776 µg cm^{-2}	Su et al. (2014) Barbosa dos Santos et al. (2020) Ghavami et al. (2017)
Cuppressaceae	*Calocedrus decurrens* (Torr.) *Chamaecyparis lawsoniana* (A. Murr.) *Juniperus occidentalis* (Hook)	Heart wood Heart wood Wood shavings	ND[c] ND ND	*Xenopsylla cheopis* (Rothchild) *X. cheopis* *X. cheopis*	Contact test Contact test Contact test	Adult (24 hr) Adult (24 hr) Adult (24 hr)		LC; 0.24 mg ml^{-1} 1.21 mg ml^{-1} 0.31 mg ml^{-1}	Dolan et al. (2007)
	Taiwania cryptomerioides Hayata	Heartwood	α-Cadinol (27.8)	*C. felis felis*	Repellency	Adult	68.6–97.7		Su et al. (2014)
Myrtaceae	*Syzigium aromaticum* Merr. & Perry *Myrtus communis* L.	Stem Shoot	Eugenol (61.4) α-Pinene (32.5)	*C. felis felis* *P. irritans*	Filter-paper test Repellency	Egg Adult (24 hr) Adult (48 hr) Adult	At 1,600 µg cm^{-2} = 96	LC; 0.3 µg cm^{-2} 5.7 µg cm^{-2} 3.9 µg cm^{-2} ED; 229 µg cm^{-2}	Lambert et al. (2020) Ghavami et al. (2017)
Poaceae	*Cymbopogon nardus* (L.) Rendl	Leaf	Citronellal (45.8)	*C. felis felis*	Impregnated filter-paper test	Egg Larva Adult (24 hr) Adult (48 hr)		LC; 12.0 µg cm^{-2} 7.3 µg cm^{-2} 597.1 µg cm^{-2} 486.1 µg cm^{-2}	Barbosa dos Santos et al. (2020)
Zingiberaceae	*Alpinia zerumbet* (Pers.)	Leaf	4-Terpineol (22.1)	*C. felis felis*	Impregnated filter-paper test	Egg Larva Adult (24 hr) Adult (48 hr)		LC; 13.1 µg cm^{-2} 7.3 µg cm^{-2} 553.3 µg cm^{-2} 456.3 µg cm^{-2}	Barbosa dos Santos et al. (2020)

Table 4. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect		References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	
Anacardiaceae	*Schinus molle* L.	Leaf	Cubenol (13.0)	*C. felis felis*	Impregnated filter-paper test	Adult (24 hr)		LD; 12.0 µg cm $^{-2}$	Batista et al. (2016)
		Fruit	Myrtenal (20.9)	*C. felis felis*	Impregnated filter-paper test	Adult (48 hr)		9.1 µg cm $^{-2}$	
						Adult (24 hr)		354.0 µg cm $^{-2}$	
						Adult (48 hr)		138.2 µg cm $^{-2}$	
Asteraceae	*Achillea wilhelmsii* L.	Shoot	Dimethylhepta (10.2)	*P. irritans*	Repellency	Adult	At 1,600 µg cm $^{-2}$ = 87	ED; 457 µg cm $^{-2}$	Ghavami et al. (2017)
Commercial product/EOC									
Eugenol				*C. felis felis*	Filter-paper test	Egg	97.6	0.1 µg cm $^{-2}$	Lambert et al. (2020)
trans-Cinnamaldehyde (2%)				*X. cheopis*	Repellency	Adult (24 hr)	90.6	1.4 µg cm $^{-2}$	Su et al. (2014)
				X. cheopis	Repellency	Adult (48 hr)		2.4 µg cm $^{-2}$	
Thymol (0.5%)									Panella et al. (2005)
				X. cheopis	Contact test	Adult		LD; 0.01 (wt:vol)	
Carvacrol									
				X. cheopis	Contact test	Adult		0.04 (wt:vol)	
Valencene									
				X. cheopis	Contact test	Adult (24 hr)		0.02 (wt:vol)	
Nootkatene									
				X. cheopis	Contact test	Adult (24 hr)		0.01 (wt:vol)	
Nootkatone (crystal)									
				X. cheopis	Contact test	Adult (24 hr)		0.003 (wt:vol)	
Nootkatone									
					Contact test	Adult (24 hr)		0.01 (wt:vol)	
Valencene-13-ol									
					Contact test	Adult (24 hr)		0.02 (wt:vol)	
Valencene-13-aldehyde									
						Adult (24 hr)			
						Adult (24 hr)			

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.
[b] ED_{50} = effective dose required to kill 50% of the population.
[c] ND = not done by the authors.

Table 5. Insecticidal effects of plant essential oils and their components against head lice

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knockdown (KD_{50})[c]	
Lauraceae	*Cinnamomum porphyrium* Kosterm	Leaf	ND[b]	*P. humanus capitis*	Fumigant	Adult	49.5		>1.1 min	Toloza et al. (2010b)
	C. aromaticum Nees	Bark	Cinnamaldehyde (70.1)	*P. humanus capitis*	Contact	Adult			11.4 min	Yones et al. (2016)
	C. zeylanicum J. Presl	Bark	Cinnamaldehyde (58.1)	*P. humanus capitis*	Contact	Adult			LT; 27.6 at 0.5 mg cm^{-2}	Yang et al. (2005)
	Laurus nobilis L.	Leaf	1,8-Cineole (50.8)	*P. humanus capitis*	Fumigant	Adult			24.4 min	Tolozo et al. (2006)
	Litsea cubeba (Lour.) Pers.	Leaf	Geraniol (36.7)	*P. humanus capitis*	Contact	Adult			LT; 30 min	Candy et al. (2018)
Lamiaceae	*Mentha spicata* L.	Aerial part	*l*-Carvone (32.8)	*P. humanus capitis*	Contact	Adult			8.8 min	Yones et al. (2016)
	Thymus vulgaris L.	Aerial part	Thymol (33.8)	*P. humanus capitis*	Contact	Adult			29.9 min	
	M. pulegum L.	Leaf	Pulegone (51.1)	*P. humanus capitis*	Fumigant	Adult	75.5		57.7 min	Tolozo et al. (2006)
	Origanum vulgare L.	Leaf	Carvacrol (80.5)	*P. humanus capitis*	Fumigant	Adult	34.5		>60 min	
	Monarda fistulosa L.	Seed	Geraniol (91.7)	*P. humanus capitis*	Contact	Adult			LT; 180 min	Candy et al. (2018)
Myrtaceae	*Melaleuca* alternifolia (Maiden & Betche)	Leaf	ND	*P. humanus capitis*	Impregnated filter-paper test Ovicidal	Adult Eggs		100% mortality at 1% EO after 30 min 50% abortive eggs at 25% EO after 4 d		Di Campli et al. (2012)
	Eucalyptus globulus L.	Leaf	1,8-Cineole (21.4)	*P. humanus capitis*	Contact	Adult			43.2 min	Yones et al. (2016)
	E. dunnii Maiden	Leaf	1,8-Cineole (49.6)	*P. humanus capitis*	Fumigant (closed container)	Adult			40 min	Toloza et al. (2010a)
	E. gunni Hook.f.	Leaf	1,8-Cineole (26.7)	*P. humanus capitis*	Fumigant	Adult			73. 4	
	E. cinerea F. Muell. Ex Benth.	Leaf	1,8-Cineole (62.1)	*P. humanus capitis*	Fumigant	Adult	50.2		12 min	Tolozo et al. (2006)
	E. viminalis Labill.	Leaf	1,8-Cineole (46.9)	*P. humanus capitis*	Fumigant	Adult	33.3		14.9 min	
	E. tereticornis Sm.	Leaf	1,8-Cineole (37.5)	*P. humanus capitis*	Fumigant	Adult	34.5		23.5 min	
	E. citriodora Hook	Leaf	Thymol (76)	*P. humanus capitis*	Fumigant	Adult	59.3		>60 min	

Table 5. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knockdown (KD_{50})[c]	
	E. saligna Sm.	Leaf	1,8-Cineole (93.2)	*P. humanus capitis*	Fumigant	Adult	64.8		17.4 min	
	Eugenia aromaticum L.	Bud	Eugenol (72.9)	*P. humanus capitis*	Contact	Adult			19.7 min	Yones et al. (2016)
	E. aromaticum	Bud	Chavibetol (58.8)	*P. humanus capitis*	Fumigant (closed container)	Adult			LT; 5. 4 min	Bagavan et al. (2011)
				P. humanus capitis	Fumigant (open container)	Adult			LT; 47.9 min	
					Contact	Adult		6.54 min at 0.25 mg cm^{-2}		
		Bud	Eugenol (74.6)	*P. humanus capitis*	Contact	Adult			LT; 10 min	Candy et al. (2018)
	Myrcianthes cisplatensis (Cambess.) O.Berg	Leaf	1,8-Cineole (45.7)	*P. humanus capitis*	Fumigant	Adult			1.3 min	Tolozo et al. (2006)
Asteraceae	*Tagetes filifolia* Lag.	Leaf	ND	*P. humanus capitis*	Fumigant	Adult			>60 min	Toloza et al. (2010b)
	T. mendocina Phil.	Leaf	ND	*P. humanus capitis*	Fumigant	Adult			>60 min	
	Baccharis vernicosa Hook. & Arn.	Leaf	ND	*P. humanus capitis*	Fumigant	Adult			>60 min	
	B. salicifolia Pers.	Leaf	ND	*P. humanus capitis*	Fumigant	Adult			>60 min	
	Artemisia annua L.	Leaf	ND	*P. humanus capitis*	Fumigant	Adult			41.4 min	
	Argerantum conyzoides L.	Leaf	ND	*P. humanus capitis*	Fumigant	Adult		LD; 6.3 for 1 hr exposure		Shailajan et al. (2013)
Cucurbitaceae	*Momordica charantia* L.	Leaf	Nonacosone(NS)	*P. humanus capitis*	Contact	Adult		LC; 75.1 mg $liter^{-1}$		Gandhi et al. (2017)
Verbenaceae	*Aloysia citrodora* Paláu	Leaf	ND	*P. humanus capitis*	Fumigant	Adult			3.02 min	Toloza et al. (2010b)
	A. polystachia (Griseb.)	Leaf	1,8-Cineole (84.6)	*P. humanus capitis*	Fumigant	Adult	30.7		23.4 min	Tolozo et al. (2006)
	Lippia multifora Moldenke	Leaf	Linalool (26.7)	*P. humanus capitis*	Contact	Adult			At 10%; 22 min	Oladimeji et al. (2000)
				P. humanus capitis	Contact (close)	Adult			16. 5 min	
Apiaceae	*Pimpinella anisum* L.	Fruit	Anise camphor (85.2)	*P. humanus capitis*	Contact	Adult			45.4 min	Yones et al. (2016)

Table 5. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knockdown (KD_{50})[c]	
Pedaliaceae	*Sesamum indicum* L.	Seed	Undecane (8.2)	*P. humanus capitis*	Contact	Adult			>180 min	Yones et al. (2016)
Commercial product/EOC										
Nerolidol				*P. humanus capitis*	Impregnated filter-paper test Ovicidal	Adult Eggs		<33% mortality at 2% after 30 min 50% abortive eggs at 1% after 4 d		Di Campli et al. (2012)
Tea tree EO (10% v/v in EtOH)				*P. humanus capitis*	Impregnated filter-paper test	Adult		90% mortality after 210 min		Williamson et al. (2007)
Lavender EO 10% v/v in EtOH)				*P. humanus capitis*	Impregnated filter-paper test	Adult		50% mortality after 210 min		
Lemon EO 10% v/v in EtOH)				*P. humanus capitis*	Impregnated filter-paper test	Adult		10% mortality after 210 min		
α-Pinene				*P. humanus capitis*	Fumigant (closed container)	Adult			42.7 min	Tolozo et al. (2010a)
p-Cymene				*P. humanus capitis*		Adult			>80 min	
1,8-Cineole				*P. humanus capitis*		Adult			11.10 min	
Limonene				*P. humanus capitis*	Fumigant	Adult	5.1		27.2 min	Tolozo et al. (2006)
β-Myrcene				*P. humanus capitis*	Fumigant	Adult			48.9 min	
Menthone				*P. humanus capitis*	Fumigant	Adult	36.5		39.7 min	
Pulegone				*P. humanus capitis*	Fumigant	Adult	39.2		46.9 min	
Thymol				*P. humanus capitis*	Fumigant	Adult	52.7		60 min	

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.
[b] ND = not done by the authors.
[c] Unless otherwise stated; knockdown time is expressed as KT_{50}.; KT_{50} = Knockdown time required to kill 50% of the population. LT = Lethal time required to kill 50% of the population.

Table 6. Insecticidal effects of plant essential oils and their components against silverfish and the brown marmorated stink bug

							Insecticidal effect		
Family	**Plant species**	**Plant part**	**Major component (%)**	**Species**	**Bioassay type**	**Life-stage (condition)**	**Repellency (%)**	**Mortality (LD_{50} or LC_{50}) [a]**	**References**
Cuppressaceae	*Chamaecyparis formosensis* Matsum	Wood chip	Myrtenol (48.9)	*Lepisma saccharina* L.	Mortality test	Adult		0.16 mg cm^{-3} initiated 100% mortality after 2 hr	Kuo et al. (2007)
Taxodioideae	*Cryptomeria japonica* (L.f.)	Leaf	Elemol (18.2)	*L. saccharina*	Repellency Impregnated filter-paper test	Adult Adult	80% repellency at 0.01 mg cm^{-3}	LD; 0.087 mg cm^{-3}	Wang et al. (2006)
Lamiaceae	*Satureja spicigera* (C. Koch)	Aerial part	Carvacrol (32.1)	*Halyomorpha halys* Stål	Contact	First instar Second instar Third instar Fourth instar Fifth instar Adult		LD; 0.63 µl ml^{-1} 0.78 µl ml^{-1} 1.02 µl ml^{-1} 1.47 µl ml^{-1} 2.87 µl ml^{-1} 4.66 µl ml^{-1}	Gokturk (2021)
Commercial Product/EOC									
Methyl benzoate				*H. halys*	Contact	Nymph (1st–5th)		LC; 1.01–2.39 µl/vial	Feng and Zhang (2017)
EcoSmart				*H. halys*	Ovicidal				
Neem oil					Topical application	Egg Nymph Adult		0.020 mg cm^{-2} 48 hr post treatment; 100 % mortality 15 % mortality	Bergman and Raupp (2014)

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.

Table 7. Insecticidal effects of plant essential oils and their components against moths

							Insecticidal effect			
Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Repellency (%)	Mortality (LD$_{50}$ or LC$_{50}$)[a]	Knockdown (LT$_{50}$)	References
Lamiaceae	*Satureja hortensis* L.	Leaf	ND	*Ephestia kuehniella*(Zell.) *Plodia interpunctella*(Hubner)	Fumigant Contact Fumigant Contact	Adult Adult Adult Adult		After 9 hr exposure; LC; 80.9 µl liter^{-1} 0.27 µlcm^{-2} 139.8 µl liter^{-1} 0.19 µlcm^{-2}		Maedeh et al. (2011)
	Ocimum basilicum L.	Leaf + fruit	Linalool (63.1)	*E. kuehniella*	Fumigant	Adult		100% mortality at 100 µL^{-1}		Pandır and Baş (2016)
	O. basilicum	NS	Linalool (45.9)	*E. kuehniella* *P. interpunctella*	Fumigant	Egg Larva Pupa Adult Egg Larva Pupa Adult		After 24 hr exposure, LD 776 µl liter^{-1} 2,096 µl liter^{-1} 1,567 µl liter^{-1} 1.4 µl liter^{-1} 779.2 µl liter^{-1} 2036.2 µl liter^{-1} 1799.7 µl liter^{-1} 1.2 µl liter^{-1}		Eliopoulos et al. (2015)
	Mentha piperita L.	Leaf + fruit	Menthol (28.3)	*E. kuehniella*	Fumigant	Adult		100% mortality at 20 µL^{-1}		Pandır and Baş (2016)
	M. piperita	NS	Isomenthone (48)	*P. interpunctella*	Contact Fumigant	Adult Adult		After 2 hr, LD; 53.8 µg cm $^{-2}$	KT; 27.1 min	Jesser et al. (2020)
	M. spicata L.	NS	Carvone (67.1)	*E. kuehniella* *P. interpunctella*	Fumigant	Egg Larva Pupa Adult Egg Larva Pupa Adult		After 24 hr exposure, LD 896.5 µl liter^{-1} 2277.6 µl liter^{-1} 1824.3 µl liter^{-1} 0.5 µl liter^{-1} 1231.4 µl liter^{-1} 2437.5 µl liter^{-1} 1981.9 µl liter^{-1} 0.4 µl liter^{-1}		Eliopoulos et al. (2015)
	Lavandula angustifolia Mill.	NS	Linalool (40.5)	*P. interpunctella*	Contact Fumigant	Adult Adult		After 2 hr, LD; 76.3 µg cm $^{-2}$	KT; 35.2 min	Jesser et al. (2020)
	Rosmarinus officinalis L.	Leaf + fruit	Cineole (25.7)	*E. kuehniella*	Fumigant	Adult		100% mortality at 10 µL^{-1}		Pandır and Baş (2016)
	R. officinalis	Aerial part	ND	*P. interpunctella*	Fumigant	Adult		After 24 hr, LD = 0.93 µl liter^{-1}		Mahmoudvand et al. (2011)

Table 7. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knockdown (LT_{50})	
	Zataria multiflora Boiss	Aerial part	ND	*P. interpunctella*	Fumigant	Adult		After 24 hr, LD = 1.75 µl $liter^{-1}$		
	Origanum onites L.	Leaf	Carvacrol (70.3)	*E. kuehniella*	Fumigant	Adult		LC after 24 hr;		Ayvaz et al. (2009)
				P. interpunctella				7.5 µl $liter^{-1}$		
	Saturaja thymbra L.	Leaf	Carvacrol (53.7)	*E. kuehniella*	Fumigant	Adult		4.1 µl $liter^{-1}$ LC after 24 hr;		
				P. interpunctella				10.3 µl $liter^{-1}$		
	Vitex negundo L.	Leaf	1,8-Cineole (19.5)	*P. interpunctella*	Fumigant	Adult		3.4 µl $liter^{-1}$ LC after 24 hr;	3.1 hr	Borzoui et al. (2016)
Myrtaceae	*Myrtus communis* L.	Leaf	Linalool (31.3)	*E. kuehniella*	Fumigant	Adult		23.1 µl $liter^{-1}$ LC after 24 hr;		Ayvaz et al. (2009)
				P. interpunctella				12.7 µl $liter^{-1}$		
Asteraceae	*Artemisia khorassanica* Podl.	Leaf	Camphor (23.4)	*P. interpunctella*	Fumigant	Adult		22.6 µl $liter^{-1}$ LC after 24 hr;	2.1 hr	Borzoui et al. (2016)
Apiaceae	*Coriandrum sativum* L.	Seed	Linalool (66.8)	*P. interpunctella*	Fumigant	Adult		9.6 µl $liter^{-1}$ After 24 hr; LD; 18.8 µg cm^{-3}		Lee et al. (2018)
	C. sativum	Seed	(+)-(s)-Carvone (40)	*E. kuehniella*	Fumigant	Adult		After 24 hr;		Maroufpoor et al. (2016)
				P. interpunctella	Fumigant	Larva		LD; 62.6 µl $liter^{-1}$		
	Petroselinum crispum L.	Aerial part	D-Limonene (18.8)	*E. kuehniella* *P. interpunctella*	Fumigant Fumigant	Adult Larva		55.2 µl $liter^{-1}$ After 24 hr; LD; 62.4 µl $liter^{-1}$ 55.1 µl $liter^{-1}$		
	Prangos ferulacea (L.)	NS	ND	*E. kuehniella*	Fumigant	Egg Larva Adult		After 24 hr; LC; 320.4 µl $liter^{-1}$ 379.7 µl $liter^{-1}$ 0.6 µl $liter^{-1}$		Ercan et al. (2013)

Table 7. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knockdown (LT_{50})	
Zingiberaceae	*Zingiber officinale* (Roscoe)	Rhizome	ND	*E. kuehniella* *P. interpunctella*	Fumigant Contact Fumigant Contact	Larva Larva Larva Larva		After 9 hr exposure; LC; 259 μl liter^{-1} 0.61 μl cm^{-2} 69.1 μl liter^{-1} 0.81 μl cm^{-2}		Maedeh et al. (2012)
Solanaceae	*Capsicum annuum* L.	Leaf + fruit	Capsaicin (35.4)	*E. kuehniella*	Fumigant	Adult		100% mortality at 5 μL^{-1}		Pandır and Baş (2016)
Geraniaceae	*Geranium maculatum* L	NS	Citronellol (26.1)	*P. interpunctella*	Contact Fumigant	Adult Adult		After 2 hr, LD; 37.2 μg cm $^{-2}$	KT; 32.6 min	Jesser et al. (2020)
Poaceae	*Cymbopogon martini* (Roxb.) Wats.	NS	Geranyl acetate (59.4)	*P. interpunctella*	Contact Fumigant	Adult Adult		After 2 hr, LD; 22.8 μg cm $^{-2}$	KT; 92.8 min	
Rutaceae	*Citrus bergamia* Risso	NS	Limonene (17.5)	*P. interpunctella*	Contact Fumigant	Adult Adult		After 2 hr, LD; 116.2 μg cm $^{-2}$	KT; 68.7 min	
Brassicaceae	*Armoracia rusticana* (L.)	NS	Allyl isothiocyanate (97.8)	*P. interpunctella*	Fumigant	Egg Larva Pupa Adult		After 72 hr exposure LD; 10 μl liter^{-1} 17.2 μl liter^{-1} 22.7 μl liter^{-1} 4.5 μl liter^{-1}		Chen et al. (2011)
Amaryllidaceae	*Allium sativum* L.	Bulb	ND	*P. interpunctella* *E. kuehniella*	Fumigant Fumigant	Egg Egg		After 24 hr exposure; LC; 17.7 μl liter^{-1} 6.6 μl liter^{-1}		Isikber et al. (2009)
Betulaceae	*Betula lenta L.*	Bark	ND	*P. interpunctella* *E. kuehniella*	Fumigant Fumigant	Egg Egg		After 24 hr exposure; LC; 29.1 μl liter^{-1} 20 μl liter^{-1}		
Commercial product/EOC										
3-Carvomenthenone				*P. interpunctella*	Fumigant Fumigant	Larva Adult		After 24 hr exposure; LC; 52.4 μg cm $^{-3}$ 68.7 μg cm $^{--3}$		Park and Lee (2018)
Cyclohexenone				*P. interpunctella*	Fumigant Fumigant	Larva Adult		After 24 hr exposure; LC; 2.5 μg cm $^{-3}$ 3.6 μg cm $^{-3}$		

Table 7. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knockdown (LT_{50})	
Methylcyclohexenone				*P. interpunctella*	Fumigant	Larva		After 24 hr exposure;		
					Fumigant	Adult		LC; 3.0 µg cm^{-3} 4.2 µg cm^{-3}		
Seudenone				*P. interpunctella*	Fumigant	Larva		After 24 hr exposure;		
					Fumigant	Adult		LC; 3.0 µg cm^{-3} 4.4 µg cm^{-3}		

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.

ND = not done by the authors; NS = not stated by authors. Unless otherwise stated; knockdown time is expressed as LT_{50}; LT_{50} = lethal time required to kill 50% of the population. KT_{50} = Knockdown time required to kill 50% of the population.

available literature on EOs, EOCs, and commercially available EOs for insecticidal effects against bed bugs are summarized in Table 2.

Notably, EOs from the families Asteraceae, Lamiaceae, and Schisandraceae were investigated against adult *C. lectularius* using treated surfaces, impregnated paper disk tests, and topical application (Table 2). Sharififard et al. (2018) reported an EC_{50} (i.e., effective concentration required to cause 50% repellency) of 4.5 mg cm^{-2} with EO from *Oreganum vulgare* L. leaf against *C. lectularius* after 24 hr in a treated surface bioassay and 100% repellency after 3 hr when 10% of the EO was used. Politi et al. (2017) reported an LC_{50} of 0.17 mg ml^{-1} with EO of *Tagetes patula* L. in an impregnated filter-paper test. The most dominant compound in the extract of Asteraceae and Lamiaceae plants was terpineol. In topical (LD_{50}; 27.5–560 µg mg^{-1}) and fumigant (LC_{50}; 20.5–1474.6 mg $liter^{-1}$) bioassays, Gaire et al. (2019) demonstrated the efficacy of several essential oil components used to control bed bugs. In synergistic mixtures, EOCs certainly tend to achieve an even better result with lower concentrations. Gaire et al. (2020) reported that a mixture of carvacrol, thymol, and eugenol was much more effective (LD_{50}; 19 µg mg^{-1}) against *C. lectularius* in topical application studies than if administered singly (carvacrol = 27.5 µg mg^{-1}, thymol = 32.5 µg mg^{-1}, and eugenol = 52 µg mg^{-1}). Commercially available EO blends are also more effective than when individual EOCs are applied singly. For example, rosemary, peppermint, thyme, and Cinnamon EO blends, respectively, were more effective than their respective components against *C. lectularius* in a fumigation test (Feldlaufer and Ulrich 2015). Despite the variety of bioassay designs, one constant was that only adult *C. lectularius* were investigated for their susceptibility to EOs and EOCs (Table 2). This is surprising as there are generally more nymphs in a population than adults (Liu et al. 2014). One might argue that the behavior of adult females to lay eggs in secluded places is the rationale for adopting a more practical approach such as fumigation or fogging. Practically, this would involve sealing up such an environment. Also, these EOs and their components could be applied on a sleeping host, protect luggage, personal items, and fumigate a sleeping space to ward-off bed bugs in an area.

Cockroaches

The German cockroach, *Blattella germanica* (L.) (Blattodea: Ectobiidae), and the American cockroach, *Periplaneta americana* (L.) (Blattodea: Periplaneta), are common indoor cockroach species. These species and several others have become an important pest in urban environments. They are important because of environmental contamination, efficient mechanical vector of pathogens, and a source of allergens (Togias et al. 2010, Fakoorziba et al. 2014, Menasria et al. 2014). In response to the call for research on sustainable alternatives, some plant EOs, and their components have been investigated for their insecticidal effects against *B. germanica* and *P. americana* (Table 3). Studies conducted using natural products and essential oils against *B. germanica* are also summarized in Lee and Rust (2021).

Wagan et al. (2017) reported 49 and 55% repellency by *Piper nigrum* L. EO delivered at 31.5 µg cm^{-2} (Piperaceae) against *B. germanica* nymphs and adults, respectively after 12 hr. Similar effects against *B. germanica* nymphs and adults were observed when Lamiaceae EOs were used (Peterson et al. 2002). Interestingly, the most abundant component from the Lamiaceae plant (Z, E-nepetalactone from *Nepeta cataria* L.) achieved a higher level of repellency (68.2%) than the EO (55%) (Peterson et al. 2002). Eugenol appears to be more repellent to *B. germanica* (85%) than to *P. americana* (77.1%) (Ngoh et al. 1998, Neupane et al. 2019). Eucalyptus oil is a poor repellent (27.7%) of the brownbanded cockroach, *Supella longipalpa* Fabricius (Blattodea: Ectobiidae) while rosemary, oregano, and yarrow oils are better repellents (86.7–96.5%) (Sharififard et al. 2016). The use of repellents for cockroach management is likely to be problematic. At worst, a repellent would disperse the cockroaches throughout a house or apartment. A better approach would be to seal off the intended treatment area (i.e., cockroach-proof an area) before applying such repellent.

In fumigant toxicity studies, Zhu et al. (2012) reported an LC_{50} of 4.1 mg $liter^{-1}$ by *Chenopodium ambrosoides* L. (Chenopodiaceae). *Thymus persicus* EO (Lamiaceae) had an LC_{50} of 28.8 µl $liter^{-1}$ against *B. germanica* while *Eucalyptus camaldulensis* Dehn. EO (Myrtaceae) LC_{50} was 21.8 µl $liter^{-1}$ (Rezaei et al. 2019). Some commercially available EOs were also explored for their fumigant toxicity against *B. germanica* nymphs. The results suggest that these oils may not be effective fumigants. For example, Gaire et al. (2017) reported the range of toxicity (LD_{50}) of Red thyme, Clove bud, and Java citronella oils to be 160.5–746.7 mg $liter^{-1}$ against *Blatta lateralis* (Walker) nymphs. However, EOCs were much more effective as fumigants against *B. germanica* than some commercially available EOs. For example, α-pinene had an LC_{50} of 11.8 mg $liter^{-1}$ against adult males and 26.1 mg $liter^{-1}$ against adult females, while limonene achieved 13 mg $liter^{-1}$ and 15.3 mg $liter^{-1}$ against adult males and females, respectively (Phillips and Appel 2010). Similalry, Zhu et al. (2012) reported a better fumigant effect (LC_{50}; 2.1 mg $liter^{-1}$ and 0.6 mg $liter^{-1}$) by another EOC (isoascaridole and ascaridole) against *B. germanica*. In homes, cockroaches live in crevices, holes or occupy areas beyond the reach of humans. In this situation, fumigation or fogging might be appropriate by taping and sealing before application.

American cockroaches are much larger than German cockroaches. Thus, a greater concentration or volume of EO is required to achieve the same effect. For example, in topical toxicity studies, Appel et al. (2001) demonstrated that 32% more mint oil is needed to achieve the same effect (LD_{50}) against *P. americana* than for *B. germanica*. Philips et al. (2010) reported that males are generally more susceptible to insecticidal effects of EOCs than females. Females require larger doses of EOs to achieve similar insecticidal effects as males. This is because females are larger than males and have more fat in which the EO/EOC dissolves.

Fleas

The human flea, *Pulex irritans* L., oriental rat flea, *Xenopsylla cheopsis* Rothchild, and the cat flea, *Ctenocephalides felis* (Bouché) (Siphonaptera: Pulicidae) are commonly found in homes due to the association of people with pets (such as cats and dogs) and rats (de Avelar et al. 2011, Batista et al. 2016). They can cause flea allergic dermatitis and be a source of discomfort to pets and homeowners (de Avelar et al. 2011, Batista et al. 2016). These ectoparasites can transmit or serve as an intermediate host of a broad spectrum of pathogens (Su et al. 2014, Rust 2017).

Given the safety concerns about current insecticides used to manage fleas, a series of plant essential oil and their components were examined for flea management (Table 4). Extract of leaves of *Cinnamomum osmophloeum* Kaneh (Lauraceae) and *Plectranthus amboinicus* (Lour) (Lamiaceae) and *Taiwania cryptomeriodes* Hayata (Cupressaceae) were repellent (68.6–97.7%) against *C. felis* (Su et al. 2014). Similarly, Barbosa dos Santos et al. (2020) reported ovicidal, larvicidal, and adulticidal effects of Lamiaceae, Poaceae, and Zingiberaceae EOs against *C. felis* in impregnated filter-paper tests. The susceptibility of *C. felis* to the EOs was larvae > egg > adult. In contact toxicity tests, Dolan et al. (2007) reported that the median lethal concentration (LC_{50}) of EOs obtained from the heartwood and woodshavings of Cuppressaceae plants ranged from 0.24 – 1.21 mg ml^{-1}. At 1.6 mg cm^{-2}, *Myrtus communis* EO (Myrtaceae) had an effective dose (ED_{50}) of 229 µg cm^{-2} against *P. irritans* (Ghavami et al. 2017).

Similar to EOs, EOCs were quite repellent to fleas. Su et al. (2014) reported that the major components (*trans*-cinnamaldehyde and thymol) identified from *C. osmophloeum* and *P. amboinicus* EOs had comparative effects (repellency of 90–97%) against *C. felis* as with the EOs. In contact tests, the LD_{50} required to kill 50% of *X. cheopsis* ranged from 0.003–0.04 (wt:vol) for carvacrol, valencene, nootkatene, and nootkatone (Panella et al. 2005). Collectively, the insecticidal effects of EOs and EOCs against fleas suggest their potential use.

Head lice

The human head louse, *Pediculus humanus capitis* De Geer (Psocodea: Pediculidae), is an urban insect pest commonly associated with school-aged children (Toloza et al. 2010a). Its life cycle is completed entirely on the host, and its infection can cause scalp irritation, pruritus, social disruption, sleep loss, nausea, loss of school time, and introduce secondary bacterial infection from wounds made from scratching (Yang et al. 2004, Koch et al. 2016). The insecticidal effects of EOs and EOCs against *P. humanus capitis* have been widely investigated and are summarized in Table 5. Notably, plants from Myrtaceae were examined for their ovicidal (Di Campli et al. 2012), contact (Bagavan et al. 2011, Yones et al. 2016, Candy et al. 2018), and fumigant (Toloza et al. 2006, 2010a, b) effects against *P. humanus capitis*. The range of the median knockdown time (KD_{50}) of the Myrtacae EOs against adult *P. humanus capitis* in contact (1–8%) and fumigant (0.25–1.75 mg cm^{-2}) bioassays was 10–43.2 min and 1.2–73.4 min, respectively. The most abundant component of the Myrtaceae plant was 1,8-cineole which alone had a KD_{50} of 11.10 min against *P. humanus capitis* in a fumigant bioassay. EOs from Apiaceae, Asteraceae, Cucurbitaceae, Lamiaceae, Lauraceae, and Verbenaceae also had impressive adulticidal effects against *P. humanus capitis*. EO from *Aloysia citrodora* Paláu (Verbenecae) leaf had a KD_{50} of 3.02 min against *P. humanus capitis* in a fumigation bioassay (Toloza et al. 2010a). Yones et al. (2016) reported a KD_{50} of 11.4 min from EO from the bark of *Cinnamomum aromaticum* (Lauraceae) against *P. humanus capitis*.

Beyond adulticidal effects, EOs also demonstrated ovicidal effects against head lice. Yones et al. (2016) reported a 97% hatching inhibition against *P. humanus capitis* eggs at 0.25 mg cm^{-2} of *Mentha spicata* L. Di Campli et al. (2012) observed that 25% of the EO from the leaf of *Melaleuca alternifolia* (Maiden & Betche) (Myrtaceae) produced 50% abortive eggs four days after treatment. These results from EO-fumigation experiments in open containers imply that *P. humanus capitis* infestations could be managed via fumigation or fogging. This can be done with a shampoo or a combination of shampoo with a plastic headcover.

Silverfish and Brown Marmorated Stink Bug

The common silverfish (*Lepisma saccahrina* L.) (Zygentoma: Lepismatidae) is a domestic indoor pest that inhabits homes due to food or warmer conditions. The brown marmorated stink bug (*Halyomorpha halys* Stål) (Hemiptera: Pentatomidae) only seeks over-wintering shelters indoors; populations rarely establish indoor. Only a few studies have explored using EOs and EOCs to manage these urban insects (Table 6). Kuo et al. (2007) reported 100% mortality of *L. saccharina* after 2 hr of exposure to *Chamaecyparis formosensis* Matsum Cuppressaceae EO obtained from wood chips. The commercially available products, methyl benzoate and EcoSmart neem oil, were investigated for their insecticidal effects against *H. halys* (Bergmann and Raupp 2014, Feng and Zhang 2017). Methyl benzoate had impressive ovicidal (LC_{50}; 0.02 mg cm^{-3}) and nymphcidal (LC_{50}; 1.01–2.39 µl vial^{-1}) effects while neem oil resulted in 15% mortality against *H. halys* in 48 hr post-exposure in topical application experiments (Bergmann and Raupp 2014, Feng and Zhang 2017).

Stored Product Moths

The Mediterranean flour moth, *Ephestia kuehniella* (Zell.), and the Indianmeal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), are important stored-product insect pests that cause significant damage to nuts, grains, and processed foods (Maedeh et al. 2012, Jesser et al. 2020). Usually, the infestation of both species is controlled using fumigants such as methyl bromide or phosphine (Maedeh et al. 2012, Maroufpoor et al. 2016). However, the associated detrimental effects of these gases including residues and effects on the ozone layer have stimulated the research for alternatives (Maedeh et al. 2012, Pandir and Bas, 2016).

As expected, fumigant bioassays were the most preferred for the investigation of insecticidal properties of EOs and EOCs against both species (Table 7). Fumigation, especially within the context of stored-product management, offers a superior economic advantage and is most practical over other exposure methods. Among the plant families explored, EOs from Lamiaceae were dominant (Ayvaz et al. 2009, Maedeh et al. 2011, Mahmoudvand et al. 2011, Eliopoulos et al. 2015, Pandir and Bas 2016, Jesser et al. 2020). In general, the genera *Mentha* and *Ocimum* had menthol and linalool as the most abundant EOC, respectively. Eliopoulos et al. (2015) reported the effects (i.e., LD_{50}) of *Ocimum basilicum* L. EO to include ovicidal (776 µl liter^{-1}), larvicidal (2,096 µl liter^{-1}), pupacidal (1,567 µl liter^{-1}), and adulticidal activities (1.4 µl liter^{-1}) against *E. kuehniella* in a fumigant toxicity bioassay. *O. basilicum* had similar effects against *P. interpunctella* eggs (779.2 µl liter^{-1}), larvae (2,036 µl liter^{-1}), pupae (1,799 µl liter^{-1}), and adults (1.2 µl liter^{-1}) (Eliopoulos et al. 2015). In fumigant toxicity bioassays, *Zingiber officinale* Roscoe EO (Zingiberaceae) was four times more toxic to the larvae of *P. interpunctella* (LC_{50}; 69.1 µl liter^{-1}) than to *E. kuehniella (*259 µl liter^{-1}). However, the larvicidal effects were similar in contact toxicity bioassays (Maedeh et al. 2012). Similar adulticidal effects were observed between both species when *Coriandrum sativum* L. (Apiaceae) EOs were tested (Maroufpoor et al. 2016). These results indicate that larvae of these moths are the hardest to kill, followed by pupae. Unlike conventional interventions such as methyl bromide and phosphine [typically tested at 10–476.5 mg liter^{-1} against same species (Small 2007)], EOs and EOCs would probably leave no residue and after-effects on treated stored products post-period of application.

Few commercial EO products have been investigated for *P. interpunctella* management. In a fumigant toxicity bioassay, Park and Lee (2018) reported a range of toxicity (LC_{50}) of cyclohexenone compounds against *P. interpunctella* larvae (2.5–3.0 µg cm^{-3}) and adults (3.6–4.2 µg cm^{-3}). Seudenone had an LC_{50} of 3.0 µg cm^{-3} and 4.4 µg cm^{-3} against *P. interpunctella* larvae and adults, respectively (Park and Lee 2018). These results demonstrate that these EOCs are more toxic to larvae than to adults of *P. interpunctella*.

Termites

Throughout history, no structural insect pest commands more attention than termites. Termites cause billions of dollars worth of damage to wooden structures and incur huge expenditures for control efforts and repair of damage (Su and Schelfrahn 1990, Potter 2011, Su 2002).

Some plant EOs and EOCs were explored for their antitermitic effects; and this information is summarized in Table 8. In a no-choice test, Elango et al. (2012) reported toxicity (LD_{50}) in the range of 253–409 ppm against *Coptotermes formosanus* Shiraki (Blattodea: Rhinotermitidae) from EOs obtained from Acanthaceae, Aristolochiaceae, Compositae, Fabaceae, Moraceae, Papaveraceae, and Solanopceae plants. The topical toxicity (LD_{50}) and contact toxicity (LC_{50}) of *Nepta cataria* L. EO (Lamiaceae) against *R. flavipes* were 8,200 µg g^{-1} and 44.4 µg cm^{-2}, respectively (Peterson and Ems-Wilson 2003). The use of impregnated filter paper to deliver the EO required only about 3% of *Eucalyptus spp.* EOs (Myrtaceae) kill 50% of *C. gestroi* Wasmann workers (Mikola et al. 2017).

EOCs also possess antifeedant, contact, fumigant, and repellent activities against subterranean and drywood termites (Table 8). Beyond toxic effects, the EO from the leaf of *Lantana camara* L. (Verbenaceae) exhibited a 78% antifeedant effect against *R. flavipes* (Yuan and Hu 2011), while the repellent effects of the growing plant were greater against *C. formasanus* than *R. flavipes* (Ding and Hu 2010). For the drywood termite, *C. brevis*, the antifeedant index of *Citrus latifolia* Tanaka (Rutaceae) was 100% at 100 mg cm^{-3} of the oil (Sbeghen-Loss et al. 2011).

General Synthesis, Knowledge Gaps, and Conclusions

General Synthesis

Based on the presented literature, it has become increasingly clear that plant metabolites, known as EOs, and their components (i.e., EOCs) exhibit toxicity and repellency to insects and are much safer (according to EPA 24b list) than conventional insecticides. In truth, there is little human/rat toxicity data to demonstrate the safety of EOs/EOCs. Effects include ovicidal, larvicidal, nymphcidal, and adulticidal toxicity against urban insect pests in primarily laboratory and a few field studies. These plant-based products may represent an alternative approach for urban insect pests management.

In general, our synthesis suggests that EOs from several specific plant families have promising effects on urban pests. This includes Myrtaceae, Lamiaceae, Lauraceae, Zingiberaceae, and Asteraceae (in descending order of effectiveness). EOCs such as eugenol, carvacrol, *trans*-cinnamaldehyde, and thymol are consistently more toxic to urban insect pests than other tested EOCs. These EOCs have an oral toxicity of about 1,000–5,000 mg kg^{-1} to rat (Kalita et al. 2013). Consistent with the physical properties hypothesis (Philips et al. 2010, Yeom et al. 2015, Oladipupo et al. 2020a), it appears that EOCs with a log *P* value within the range of 1.9–3.3, boiling point of 233–254°C, vapor pressure of 0.010–0.030 mm Hg, solubility of 0.96–2.98 g liter^{-1}, and molecular weight of 132.2–164.2 g mol^{-1} are the most toxic. These aforementioned plant families and EOCs had specific patterns of toxicity based on the insect order and method of exposure. For Hymenoptera (i.e., Formicidae/ants), fumigation was the most used to test ants in laboratory studies. This approach could be extended to field studies by dissolving EOs/EOCs in a micelle or via encapsulation or simply injecting them into the ground. For Hemipterans (specifically, Cimicidae/bed bugs), fumigant assays appear to deliver the most effective result to insects.

Fumigation required about 1,000-fold less than the concentration needed for topical protocols to achieve killing. For Siphonapterans, EOs are effective as contact insecticides against all life stages. Phthirapterans (i.e., Pediculidae) have been well managed by fumigation. A practical way of extending fumigation to field studies on humans would be to cover the scalp with a plastic hairnet or shower cap upon application. EO-fumigation works better on killing lepidopteran adults than larvae. Isoptera (i.e., termites) are probably better managed using antifeedant, contact, and fumigant bioassays. The synthesis of the data on the management of Blattodea (i.e., cockroaches) demonstrates that females are much more difficult to control than males. This is due to their larger body size and fat composition. Females require larger doses of EOs to achieve similar effects as males. Importantly, cockroaches can be killed using either a contact or fumigant approach. Both approaches have their advantages. In homes, cockroaches live in crevices, holes, or occupy spots beyond the reach of humans. In this situation, a fumigant is desired if the application can be made and such holes are sealed off. In other cases, cockroaches crawl up in walls and other places not welcomed in homes. Thus, EOs can be utilized as contact insecticides. Hence, it is imperative to seek EOCs with high vapor pressure and low boiling point or perhaps investigate formulations that could be used to overcome limitations of the physical properties. To move the field of EO research forward, rather than investigating or revealing new EOs/EOCs with insecticidal actions, future studies should focus on consolidating past studies.

Knowledge Gaps and Conundrums

Unknown Mode of Action

Given the widespread indiscriminate use of synthetic insecticides, the time is now right for plant-based products to take center stage. Unfortunately, despite the extensive research done on EOs worldwide, there are still fundamental questions that remain. For example, the mode of action of most, if not all, EOs and their components are poorly understood. Only a few studies have attempted to describe the mode of action (MoA) of some EOs (Yeom et al. 2015, Gaire et al. 2021). To date, the most direct point of reference is the works of Enan (2005a, b) which, interestingly, were done to identify the binding sites, and not MoA of thymol, carvacrol, α-terpineol, and L-carvone. This work is exemplary because it focuses on the molecular basis of essential oil specificity by investigating the binding sites of specific essential oils on *D. melanogaster* and *P. americana*. The authors implicate tyramine and octopamine ligands explaining why EOs and EOCs trigger neurotoxic-like effects. Such an approach expands our understanding of the potential novel sites of EOs/EOCs. Oladipupo et al. (2022) also show that essential oils disrupt respiration pattern in *B. germanica*. This supports the neurotoxic effects of EOCs. But there is still the need to identify these oils' primary site of action. Evidence suggests that EOs inhibit acetylcholine esterase and cytochrome P450 enzymes (Yeom et al. 2015, Gaire et al. 2021). This suggests a broad spectrum of activity. Future studies should invest in determining MoA of EOCs (such as eugenol, carvacrol, limonene, thymol) that are widely reported as toxic against a range of urban insect pests. Such information, when generated, would be central to the optimization and commercialization of EOs.

Response of Urban Insect's Sensory System to EOs and EOCs?

Relatively little is known about these urban insect pests' chemical communication and olfactory mechanisms to EOs. Neither is there an understanding of the interactions between EOCs and the sensory system of urban insect pests. For example, out of six EOCs investigated, only thymol elucidated significant avoidance behavior in Turkestan cockroaches (Gaire et al. 2017). Interestingly this list included eugenol and trans-cinnamaldehyde, two out of the four EOCs associated with toxicity against a broad range of urban insect pests. Two out of 12 EOs evaluated against *B. germanica* showed repellency in the range of 76.6–88.5% (Huang et al. 2020). Thus, electroantennogram studies that document the perception of EOs and EOCs by urban pests are required.

Additionally, identifying odorant receptors can provide valuable information on the chemical ecology of these insects that can be exploited to develop efficient control agents. For example, Pelletier et al. (2015) identified a sensitive receptor, PhumOR2, in *Pediculus spp.* involved in the avoidance of specific chemical cues. PhumOR2 is an odorant receptor that mediates repellency to the hydroxyl functional group EOCs such as thymol, carvacrol, and eugenol. Such a finding demonstrates that understanding the interactions between EOs/EOCs and the insect sensory system could improve our comprehension of the mode of action.

The Cost-Effectiveness and Economic Viability of EOs and Their Components

For successful commercialization and adoption, the documentation of EO efficacy against target pests documented in many publications is not enough. It is not enough for an EO to only be toxic (i.e., possess insecticidal effects); it must also be economically viable. In general, essential oils are more expensive than conventional insecticides. Hence, much is required to optimize the economic viability and cost competitiveness of EOs against currently used synthetic insecticides.

Relationship Between Bioactivity and Physical Properties of EOs and Their Components

The physical properties of EOCs such as molecular weight (g mol^{-1}), log *P*, solubility, and vapor pressure (kPa) must be considered. For example, log *P* is a measure of the lipophilicity of an EOC. EOCs with a $\log P > 0$ are hydrophobic, while $\log P < 0$ are hydrophilic. The vapor pressure (vp) is a property of a liquid-based on the strength of its intermolecular forces. Thus, a high intermolecular force would indicate such EOC has high vapor pressure and a high boiling point (bp). EOCs with such characteristics are likely to be more volatile and persist less. This could be good, bad, or both depending on the context.

High Volatility of EOs and Their Components

One recurring challenge of EOs and EOCs is the issue of high volatility resulting in rapid evaporation, faster than desired. An obvious way to tackle this would be to develop formulations that can deliver and retain EOs and EOCs without interfering with bioactivity. This ensures a slow release to provide an effective dose against targeted pests. Oladipupo et al. (2020b) provided an example of this by employing super absorbent polymer gels to prolong the bioavailability of EOCs to *B. germanica*. They reported significant impairment of reproductive parameters of *B. germanica*.

Similarly, Lucia et al. (2017) employed novel poloxamer shells to improve the dispersion of EOCs in water and found them to be physicochemically stable while delivering impressive pediculicidal activity against *P. humanus capitis*. Jesser et al. (2020) observed that EOs loaded in polymeric nanoparticles could withstand temperature variation while increasing contact toxicity to *P. interpunctella*. Song et al. (2018) microencapsulated EOs in a film and reported a prolonged release rate. The encapsulation of EOs in insect-proof halloysite nanotubes provided two folds effects: (1) an efficient

Table 8. Insecticidal effects of plant essential oils and their components against termite

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD$_{50}$ or LC$_{50}$)[a]	Knock-down (LT$_{50}$)[e]	
Lauraceae	*Cinnamomum parthenoxylon* Meisn.	Leaf	1,2-Benzenedicarboxylic acid, bis (2-ethylhexyl) ester (31.2)	*Coptotermes curvignathus* (Holmgren)	No-choice test	Soldier & worker		10% ethanolic extract resulted in 53 and 72.7% mortality after 1 & 2 weeks, respectively		Adfa et al. (2017)
Lamiaceae	*Nepeta cataria* L.	NS[c]	Z,E-nepetalactone (64)	*Reticulitermes flavipes* (Kollar) *R. virginicus* (Banks)	Topical Contact Contact	Worker Worker Worker		After 7 d, LD; 8200 µg^{-1} LC; 44.4 µg cm^{-2} LC; 21.1 µg cm^{-2}		Peterson and Ems-Wilson (2003)
	Mentha arviensis L.	Leaf	Menthol (63.2)	*C. heimi* (Wasmann)	Fumigant	Soldier Worker		100% mortality after 3 hr for both at 25 mg		Qureshi et al. (2012)
Rutaceae	*Citrus latifolia* Tanaka	Wax	Limonene (59.6)	*Cryptotermes brevis* Walker	Antifeedant	Worker		Antiffedant index = 100 at 100 mg cm^{-3} EC[b]; 24.69 mg cm^{-3}		Sbeghen-Loss et al. (2011)
Cuppressaceae	*Cryptomeria fortunei* Hooibrenk	Leaf	α-Terpineol (NS[c])	*R. chinensis* (Snyder)	Impregnated filter-paper	Worker		LC; 2.8 mg ml^{-1}		Xie et al. (2013)
	Cunninghamia konishii Hayata	Wood chip Leaf	α-Cedrol (53) α-Pinene (34.9)	*C. formosanus* Shiraki	No-choice	Worker Worker		100% mortality at 10 mg g^{-1} after 4 d for leaf and wood oil		Cheng et al. (2014)
Myrtaceae	*Eucalyptus camaldulensis* Dehnh.	Leaf	γ-Terpinene (75.5)	*C. formosanus*	Contact Noncontact	Worker Worker		LC after 7 d, 15.4 mg g^{-1} of filter paper 17.5 mg/Petri dish		Siramon et al. (2009)
	E. camaldulensis	Leaf	ND[d]	*C. gestroi* (Wasmann)	Impregnated filter-paper	Worker		LC; 3.2%	At 10%, 0.4 hr	Mikola et al. (2017)
	E. citriodora.	Leaf	ND	*C. gestroi*	Impregnated filter-paper	Worker		0.6%	At 10%, <1 hr	
	*E. maidenii*F. Muell.	Leaf	ND	*C. gestroi*	Impregnated filter-paper	Worker		3.1%	At 10%, 7 hr	
	E. pseudoglobulus (Naudin)	Leaf	ND	*C. gestroi*	Impregnated filter-paper	Worker		3.7%	At 10%, 11.1 hr	
	E. tereticornis Sm.	Leaf	ND	*C. gestroi*	Impregnated filter-paper	Worker		3.0%	At 10%, <1 hr	

Table 8. Continued

							Insecticidal effect			
Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knock-down (LT_{50})[e]	References
Zingiberaceae	*Alpinia galangal* (L.) Willd.	Rhizome	1,8-Cineole (61.9)	*C. gestroi* *C. curvignathus*	Antifeedant Toxicity Antifeedant Toxicity	Worker		At 2,000 ppm, mean consumption = 3.3 mg LD; 5407 mg kg^{-1} At 2,000 ppm = 3.3 mg LD; 3456 mg kg^{-1}		Abdullah et al. (2015)
Asteraceae	*Eclipta protasta* L.	Leaf	ND	*C, formosanus*	No-choice	Worker		LD 292 ppm at 24 hr		Elango et al. (2012)
Verbenaceae	*Lantana camara* L.	Growing plant	ND	*C. formosanus* *R. flavipes*	Barrier (plant + soil) Barrier (plant tissue + soil)	Soldier Soldier	No effect on termites foraging in 3 wk Greater repellent effect on C. *formosanus* than *R. flavipes*			Ding and Hu (2010)
	L. camara	Leaf	ND	*R. flavipes*	Antifeedant Toxicity (no-choice paper test)	78% feeding reduction at 0.21 mg cm^{-2}	>90% mortality at 0.21 mg cm^{-2}			Yuan and Hu (2011)
Fabaceae	*Enterolobium cyclocarpum* (Jacq) Griseb	Heart wood	D-limonene (17.8)	*Incisitermes marginipennis* (Latreille)	Oral toxicity	Worker		After 5 wk., survival rate = 38% and feeding rate was 26% at 56.63 mg		Raya-Gonzalezet al. (2013)
Moraceae	*Morus alba* L.	Heart wood	Resorcinol (40.5)	*R. flavipes*	Filter-paper Antifeedant Repellency	Worker Worker Worker	70% at 10 mg ml $^{-1}$	LC; 1.71 mg ml $^{-1}$ 62% at 10 mg ml $^{-1}$		Hassan et al. (2018)
Acanthaceae	*Andrographis lineate* Wallich ex Nees.	Leaf	ND	*C. formosanus*	No-choice	Worker		At 24 hr; LD; 358 ppm		Elango et al. (2012)
	A. paniculata (Burm.f)	Leaf	ND	*C. formosanus*	No-choice	Worker		371 ppm		
Papaveraceae	*Argemone Mexicana*	Leaf	ND	*C. formosanus*	No-choice	Worker		253 ppm		
Aristolochiaceae	*Aristolochia bracteolate* Lam.	Leaf	ND	*C. formosanus*	No-choice	Worker		363 ppm		
Solanaceae	*Datura metel* L.	Leaf	ND	*C. formosanus*	No-choice	Worker		317 ppm		
Fibaceae	*Sesbania grandiflora* (L.)	Leaf	ND	*C. formosanus*	No-choice	Worker		289 ppm		
Compositae	*Tagetes erecta* L.	Leaf	ND	*C. formosanus*	No-choice	Worker		409 ppm		

Table 8. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knock-down (LT_{50})[e]	
Commercial products/ EOC				*C. formosanus*						
Limonene				*C. brevis*	Antifeedant	Worker		Antiffedant index = 100 at 100 mg cm^{-3} EC; 44.43 mg cm^{-3}		Sbeghen-Loss et al. (2011)
α-Terpineol				*R. chinensis*	Impregnated filter-paper test	Worker		LC; 0.9 mg ml^{-1}		Xie et al. (2013)
				C. formosanus	Contact	Worker		LC after 7 d, 1.5 mg g^{-1} of filter paper		Siramon et al. (2009)
					Noncontact	Worker		0.8 mg/Petri dish		
p-Cymene				*C. formosanus*	Contact	Worker		3.8 mg g^{-1} of filter paper		Siramon et al. (2009)
					Noncontact	Worker		92.2 mg/Petri dish		
γ-Terpinene				*C. formosanus*	Contact	Worker		5.9 mg g^{-1} of filter paper		Siramon et al. (2009)
					Noncontact	Worker		92,542 mg/Petri dish		
1,8-Cineole				*C. formosanus*	Contact	Worker		6.7 mg g^{-1} of filter paper		Siramon et al. (2009)
					Noncontact	Worker		52 mg/Petri dish		
				C. gestroi	Repellent	Worker	At 250 ppm, 50%	LD; 1,102 mg kg^{-1}		Abdullah et al. (2015)
				C. curvignathus	Toxicity	Worker	At 750 ppm, 56%	LD; 945 mg kg^{-1}		
					Repellent	Worker				
					Toxicity	Worker				
α-Pinene				*C. formosanus*	Contact	Worker		44.9 mg g^{-1} of filter paper		Siramon et al. (2009)
					Noncontact	Worker		21.3 mg/Petri dish		
Terpinen-4-ol				*C. formosanus*	Contact	Worker		3.3 mg g^{-1} of filter paper		Siramon et al. (2009)
					Noncontact	Worker		1.7 mg/Petri dish		
Cederene				*C. formosanus*	Consumption	Worker		72.1 mg		Maistrello et al. (2001)
					Survival	Worker		43.8%		
Nootkatone				*C. formosanus*	Consumption	Worker		7.3 mg		
					Survival	Worker		15.3%		
Vetiver oil				*C. formosanus*	Consumption	Worker		15 mg		
					Survival	Worker		11.4%		

Table 8. Continued

Family	Plant species	Plant part	Major component (%)	Species	Bioassay type	Life-stage (condition)	Insecticidal effect			References
							Repellency (%)	Mortality (LD_{50} or LC_{50})[a]	Knock-down (LT_{50})[e]	
2-Phenyl-2-propanol				*C. formosanus*	Contact	Worker		% mortality after 7 d, 93.7		Raina et al. (2012)
					Vapor	Worker		98.4 after 3 d		
Citral				*C. formosanus*	Contact	Worker		56.5		
l-Carvone				*C. formosanus*	Contact	Worker		73.9		
					Vapor	Worker		95.3 after 3 d		
l-Linalool				*C. formosanus*	Contact	Worker		59.4		
					Vapor	Worker		69.6 after 3 d		
Patchouli Oil				*C. formosanus*	Repellency	Worker	50 μg g^{-1} of sand after 24 hr	11.6 μg/termite		Zhu et al. (2003)
					Mortality	Worker		10 cm at 50 μg g^{-1} of sand		
					Tunneling length	Worker				
Vetiver Oil				*C. formosanus*	Mortality	Worker		13% at 10 μg g^{-1}		Zhu et al. (2001)
					Tunneling length	Worker		19.87 at 10 μg g^{-1}		

[a] LC_{50} or LD_{50} = lethal concentration or lethal dose required to kill 50% of the population.
[b] EC_{50} = effective concentration required to cause 50% repellency against termite
[c] NS = not stated by authors.
[d] ND = not done by the authors
[e] Knockdown time is expressed as LT_{50}; LT_{50} = lethal time required to kill 50% of the population.

barrier to insect infestation and (2) controlled release of the EO over an extended period (Kim et al. 2016). In short, the exploration of materials that can deliver and retain EOs and EOCs, without interfering with bioactivity should be sought.

Lack of Theoretical Framework and Hypotheses in Studies

One of the fundamental reasons that stimulated the search/research for alternatives to currently used synthetic insecticides is the development of insecticide resistance and the realization that EOs could be sustainable alternatives. Resistance typically occurs due to increased application pressure. Hence, it follows that with EOs and EOCs, it might be a question of when. It may be relevant to integrate the exploration of EOs and EOCs with synergistic studies. This may be necessary to slow down the heritable change in the sensitivity of urban insects to EOs. For example, the repeated exposure of *Myzuz persicae* Sulzer to azadirachtin culminated in the development of resistance (Feng and Isman 1995). And there is no reason not to expect otherwise with any other toxicant. Hence, it might be relevant to approach EO research cautiously and explore possible synergistic combinations, additives, mixtures, and nanoformulations that hold promising results. An example of such would be those formulated by Tak and Isman (2017). The study explored a 1:1 (w:w) binary combination of carvacrol, trans-cinnamaldehyde, α-terpineol, and thymol against noninsect arthropods and reported that thymol had the most synergistic interaction. The synergist, piperonyl butoxide, was used to synergize EOCs such as carvacrol, limonene, eugenol, and thymol, against the German cockroach (Oladipupo et al. 2020a). Additionally, essential oils could be used to synergize under nonchemical control methods. For example, Perry and Choe (2020) described the potentiality of using essential oils to improve the efficacy of heat treatments against drywood termites.

Inherent Variability of Essential Oils Data

There is little or no information among the relative potencies of essential oils vis-à-vis plant family or EOCs. It is possible that regardless of where the plant is cultivated, specific components would be abundant. For example, eugenol is routinely associated with the genus *Syzygium*, *trans*-cinnamaldehyde with *Cinnamonum*, and thymol with Thymus (Cheng et al. 2008, Kim et al. 2016, Yones et al. 2016, Lambert et al. 2020). Yet there are substantial variations in compositions of EOCs within other genera like *Cuppresus* and *Piper* (Marsaro et al. 2004, Kuo et al. 2007, Souto et al. 2012, Xie et al. 2013, Wagan et al. 2017). Interestingly, the relative abundance of an EOC in a plant does not necessarily correlate with bioactivity. For example, the most abundant EOC of *R. officinalis*, 1,8-cineole, had lower toxicity when compared to *R. officinalis* EO blend (Miresmailli et al. 2006). Even more intriguing is the inherent variation of the components of an EO across plant families and seasonal variability in EOC in the same plants. Hence, estimating the structural-activity relationship could be a tool to assess, compare, and optimize insecticidal effects across groups. In other words, there should be less emphasis on screening a given plant (i.e., EO or plant extract) for its insecticidal activity to assess the relative potencies of established EOCs. At best, the former generates data that answers the question of 'who', 'what', 'when' and 'where', while the latter is certain to provide knowledge (i.e., 'how') and mechanism (i.e., 'why') that is central to the commercialization of EOs.

Even more concerning is the variabilities across studies. The nonuniformity of bioassays across studies precludes any straightforward comparison and makes it difficult to distill results across studies. Such variabilities make it challenging to compare studies directly. In the interim, a meta-analysis could help overcome such a hurdle. In short, there is a forest of publications describing the potential effects of EOs and EOCs against urban pests and a desert of relevant data from these studies. This is why we plea to authors to include relevant data that can be used. For example, many authors cite mortality and do not report the dose. Their results are therefore of little use. The way forward is to at a minimum include the concentration of a toxicant (EOC) per body weight in topical or mg liter^{-1} in fumigant bioassays. For contact bioassays, accurate information on the type of surface, species, sex, age, stage, insect mass, and EOC formulation should be provided.

Disconnect Between Laboratory and Field Studies

The contrast between laboratory and field efficacy is arguably one of the major impediments to the commercialization of EOs (Benelli et al. 2016, Isman 2020). First, the design of laboratory bioassays is not reflective enough of field conditions. For example, topical application of cockroaches or bed bugs cannot be repeated in the field. The delivery of EOs through superabsorbent polymer gels or nanoformulations against cockroaches might not work in homes due to other sources of food and water that would distract cockroaches unless attractants are used. Second, the rapid biodegradation/volatilization of EOs, paradoxically, make them unusable in the field. Thus, frequent reapplication or specialized (and expensive) formulations may be required to achieve a satisfactory level of control. Economically, this is disadvantageous. Third, academics test pure or highly concentrated EOs/EOCs in specific ways while the industry makes formulations/combinations of EOs. So, the laboratory results show pure/concentrated compounds are effective. When academics test commercialized formulations/combinations, most combination/commercialized formulations are not effective as residuals even at the highest label rate (Ajibefun et al. unpublished, Gaire et al. 2021). This could be because in certain cases, these formulations are further diluted down or the EOC's completely evaporate.

Further, the variability in response to a given EO or EOC is worrisome. Essentially, the 'all or none' response to almost 'no dose-response'. These contrasts create a vacuum for the investigation and design of formulations that increases the persistence and stabilizations of EOs without interrupting bioactivity.

Conclusions

In developing this review, it was clear that there was a lack of testable hypotheses and predictions guiding most investigations. Most studies seem to report the toxicity of EOs and EOCs rather than fit their insecticidal activity into a theoretical framework. This is also reflected in the number of papers summarized. Authors should realistically ask, 'What data do I need to provide' to advance the scholarship on essential oils or 'Does my study address broader impacts?'. Clear methodology detailing approaches might be more useful to everyone. If everyone uses at least one common methodology, we would have a better basis to compare the performance of EOs and EOCs. Additionally, we advocate the use of EOs/EOCs in laboratory-based bioassays that are relevant to potential field applications. In short, to truly advance the scholarship on essential oils, authors should be more focused on studies that advance both theoretical and practical knowledge.

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