Chapter 6
Role of Plant Essential Oils in Pest Management

Lizzy A. Mwamburi

Abstract The growing concern over potential hazards from chemical pesticide safety among consumers and potential harm to the environment has culminated in consideration of natural management strategies of pests. Because they are complementary to most crop production systems, biopesticides based on plants can be integrated into pest management systems. Plant essential oils (EOs) can replace the more persistent non-natural pesticides in protecting the environment from the accumulation of chemicals reduce resistance and increase crop productivity. In addition, they possess low mammalian toxicity, broad-spectrum activity, and degrade rapidly in foodstuffs. In addition to exhibiting distinctive properties compared with synthetic pesticides, including high levels of pest toxicity and reduced toxicity toward non-target organisms, EOs possess contact, feeding deterrence, fumigant toxicity, oviposition, and repellent properties. In this chapter, we review the sources of EOs, their insecticidal activities, constituents, and mode of action and discuss their synergism and formulation with encapsulation for producing nanoinsecticidal products.

Keywords Essential oils · Arthropod pests · Insecticidal activity

6.1 Introduction

In spite of its importance in the region, agricultural yields in sub-Saharan Africa (SSA) are generally quite low, leading to food insecurity in the region. One major hindrance to food security in Africa is the insurgence of arthropod pests that are responsible for a huge magnitude of agricultural economic losses both in the field and in storage. Losses as a result of insect pests in SSA countries may result to about 10–88% (Kfir et al. 2002; Ogendo et al. 2004; Ojo and Omoloye 2012; Midega et al.

L. A. Mwamburi (✉)
Department of Biological Sciences, University of Eldoret, Eldoret, Kenya
e-mail: lizzy.mwamburi@uoeld.ac.ke

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2016). Losses in the field and during storage result from direct feeding and reproduction, indirectly by insects acting as carriers of other pathogens or raising the humidity and stimulating fungal growth in storage (Tefera et al. 2010; Midega et al. 2016). Furthermore, favorable tropical climatic conditions in the region often favor the rapid population growth of these pests (Bekele et al. 1997; Midega et al. 2016).

In order to overcome food insecurity, there has been need to increase crop production, resulting in escalated and intensified pesticide applications in the last decade. Furthermore, the use of non-moderated applications of pesticides has led to residues in foods above approved limits resulting in detrimental effects on human health. In addition to having widespread insecticide resistance in the field and storage (Georghiou 1990), synthetic insecticides have non-selective action resulting in accumulation and persistence in the environment and food chains, posing risks to human health and imbalance of ecosystems.

Considering that most chemicals are banned, some control methods are either not available or are too costly for most farmers and as the basic requirement to achieve food security, there is an urgent requirement for simple, affordable and effective pest management for the smallholder farmers in SSA who are the majority producers.

The growing concern over potential hazards from chemical pesticide safety among consumers and the possibility of environmental harm has amounted in much deliberation being shifted to the use of natural products for the management of pests in agriculture. Hence, there is a need to seek an array of safe and long-term alternatives to synthetic pesticides that can increase horticultural crop productivity, decrease resistance and protect the environment from insecticidal pollution.

6.2 Plant-Based Biopesticides

Plants are furnished with possible substitutes for insect-control because they contain copius amounts of a wide array of biological compounds, among which are essential oils (EOs) making the application of plant EOs for biological control of economically important insect a subject of interest. In addition, EOs are considered safer than other plant-derived chemicals. Contrary to the problems that arise as a result of using synthetic pesticides, EOs are biodegradable and non-pollutive to the environment, easily accessible, inexpensive, and have appropriately found a promising role as biopesticides in pest management. Furthermore, the utilization of EOs to manage arthropod pests has been used traditionally to protect stored cereals from insect pests and are, therefore, culturally acceptable (Koul et al. 2008). In addition, EOs may be used further to develop pesticidal molecules to target specific insects (Rattan 2010). Thus, the inquisitiveness in the EOs has been revived with recent observations of their bioactivities to a diversity of pests (Isman 2006). Examples of some of these bioactivities are summarized in Table 6.1. One of the advantages of EOs includes the fact that they degrade rapidly in the environment and are more specific, and therefore favor beneficial insects. There are approximately 2000 plant species from Anacardiaceae, Annonaceae, Apiaceae, Araliaceae, Asteraceae, Cannabinaceae, Chenopodiaceae, Cupressaceae, Dipsacaceae, Ericaceae, Euphorbiaceae, Fabaceae,

Table 6.1 Examples of essential oils and insects that are affected by these oils

Plant	EOs	Insect	Mechanism	Reference
Achillea biebersteinii	Cis-Ascaridol, *p*-cymene, camphor, 1,8-cineole	*Tribolium castaneum*	Contact toxicity, inhibits growth	Nenaah (2014)
Agastache foeniculum	Estragole, 1,8-cineole, 1-octen-3-ol, Germacrene D	*Tribolium castaneum* *Rhyzopertha dominica*	Fumigant toxicity	Ebadollahi (2011b)
Allium sativum	Methyl allyl disulfide Diallyltrisulfide	*Sitophilus zeamais* (Motschulsky) *Tribolium castaneum* (Herbst)	Antifeedant activity, contact toxicity, decreased growth, fumigant toxicity, reduced oviposition	Huang et al. (2000a)
Anethum graveolense	Carvone, limonene	*Callosobruchus chinensis* (L.)	Disturb oviposition, hatching, pupal formation, adult emergence	Sefidkon (2001) and Chaubey (2008)
Artemisia herba-alba	1,8-cineol, camphene, α-pinene, borneol	*Tribolium castaneum* *Oryzaephilus surinamensis* L.	Contact toxicity, fumigant toxicity	Bachrouch et al. (2015)
Artemisia nilagirica	Camphor, β-farnesene, β-bisabolene, caryophyllene oxide	*Rhynchophorus ferrugineus* (Oliver)	Antifeedant activity against adults	Shukla et al. (2012)
Artemisia princeps	Bornane, camazulene, 3-methyl-6-(1-methylethyl)-1,2-cyclohexanediol	*Sitophilus oryzae* L.	Repellent activity against adults	Liu et al. (2001, 2006)
Artemesia sieberi	Camphor, camphene, 1,8-cineol, thujone	*Callosobruchus maculatus* F. *Sitophilus oryzae* L.	Adulticidal	Negahban et al. (2007)
Baccharis salicifolia	β–pinene, α-pinene, Sabinene, α-thujene	*Tribolium castaneum* (Herbst)	Contact toxicity, repellency	Garcia et al. (2005)
Callistemon citrinus	1,8-cineole, α-pinene, α-terpineol	*Callosobruchus maculatus* F.	Insecticidal, repellency against adults	Zandi-Sohani et al. (2013)
Callistemon sieberi	1,8-cineole, α-terpineol, α-pinene	*Callosobruchus chinensis* L.	Contact toxicity, disturbance on oviposition, feeding behavior	Lee et al. (2002) and Shukla et al. (2011)

(continued)

Table 6.1 (continued)

Plant	EOs	Insect	Mechanism	Reference
Carum copticum	Thymol, α-terpinolene, *p*-cymene	*Callosobruchus maculatus* F.	Ovicidal, larvicidal, adulticidal	Sahaf et al. (2007) and Sahaf and Moharramipour (2008)
Cinnamomum osmophloem	Cinnamaldehyde, β-cubebene, Linalool	*Meligethes aeneus* (Fabricius)	Repellency, adulticidal	Pavela (2011)
Citrus aurantium	*Meligethes aeneus*	Linalool, limonene, linalool acetate β-pinene	Repellency toxicity	Pavela (2011)
Clausena anisata	α-Pinene, *trans*-β-ocimene, estragole, β-elemene	*Acanthoscelides obtectus* (Say)	Toxicity, decrease in F1 progeny	Ndomo et al. (2008) and Usman et al. (2010)
Cuminum cyminum	Caryophyllene oxide, acaryphyllene α-pinene, geranylacetate	*Callosobruchus chinensis* L.	Egg hatching, disturbance of oviposition, emergence of adults Pupa formation,	Chaubey (2008) and Romeilah et al. (2010)
Cupressus sempervirens	α-Pinene, terpinene, α-terpinene, Sabinene	*Callosobruchus maculatus* F.	Contact toxicity, negatively affects longevity and fecundity	Hedjah-Chehheb et al. (2013)
Cymbopogon citratus	Geranial, neral, neryl acetate	*Tribolium castaneum* (Herbst) *Sitophilus oryzae* L.	Contact toxicity, repellent, feeding deterrent	Stefanazzi et al. (2011)
Cymbopogon schoenanthus	Limonene, β-phellandrene, δ-terpinene	*Callosobruchus maculatus* F.	Inhibits development	Ketoh et al. (2005) and Khadria et al. (2008)
Drimys winteri	α-Pinene, β-pinene, germacrene, safrole	*Tribolium castaneum* (Herbst)	Repellent, contact toxicity	Zapata and Smagghe (2010) and Muñoz et al. (2011)
Etlingera yunnanensis	1,8-cineole, estragole,, α-pinene, β-caryophyllene, limonene	*Liposcelis bostrychophila* (Badonnel) *Tribolium castaneum* (Herbst)	Contact toxicity, repellency	Shan-Shan et al. (2015)
Eucalyptus benthamii	α-Pinene, viridiflorol, 1,8-cineole	*Sitophilus zeamais* (Motschulsky)	Insecticidal, repellent activity	Mossi et al. (2011)

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Table 6.1 (continued)

Plant	EOs	Insect	Mechanism	Reference
Eucalyptus globulus	1,8-cineole, 3,7-dimethyl-2-octen-1-ol, trans-3-caren-2-ol	*Lasioderma serricorne* (F.)	Contact toxicity, repellent activities on adult	Ebadollahi et al. (2010)
Eucalyptus staigerana	1,8-limonene, z-citral, E-citral	*Zabrotes subfasciantus* (Boheman) *Callosobruchus maculatus* F.	Disturbs oviposition, reduction in number of emerged insects	Brito et al. (2006) and Maciel et al. (2010)
Eugenia caryophyllus	Eugenol, eugenol acetate, methyl chavicol	*Leptinotarsa decemlineata* (Say)	Contact toxicity, Antifeedant activity	Taghizadeh-Saroukolai et al. (2014)
Foeniculum vulgare	Anethole, limonene, α-fenchone	*Sitophilus zeamais* (Motschulsky) *Tenebrio molitor* (L.)	Repellant activity on adults	Cosimi et al. (2009) and Ebadollahi et al. (2014)
Gomortega keule	Limonene, α-pinene, 1,8-cineol, α-terpinene,	*Acanthoscelides obtectus* (Say)	Contact toxicity on adults	Bittner et al. (2008)
Hypericum scabrum	α-Pinene, camphor, terpinen-4-ol, and δ-cadinene	*Bruchus dentipes* (Baudi)	Contact toxicity on adults	Tozlu et al. (2011)
Illicium fargesii	Carvone, α-terpineol, *trans*-carveol, D-limonene	*Sitophilus zeamais*	Contact, fumigant toxicity	Wang et al. (2011)
Juniperus oxycedrus	Germacrene-D, α-pinene, Myrcene	*Sitophilus oryzae* L.	Toxicity	Athanassiou et al. (2012)
Lantana camara	α-Curcumene, α-acoradiene, β-caryophyllene	*Trogoderma granarium* (Everts)	Repellent activity	Tripathi and Kumar (2007) and Zoubiri and Baaliouamer (2012)
Laurus nobilis	α-Terpinyl acetate, β-pinene 1,8-cineole, Sabinene	*Trobilium confusum*	Toxicity	Isikber et al. (2006) and Cosimi et al. (2009)
Lavandula angustifolia	Linalool, 1,8-cineole, 1-borneol	*Meligethes aeneus* (Fabricius)	Repellent activity, mortality of adults	Pavela (2011) and Ebadollahi et al. (2014)
Litsea cubeba	*E*-citral, D-limonene, neral	*Lasioderma serricorne*	Contact toxicity in adults	Yang et al. (2014)
Mentha piperita	Menthol, Menthofuran, Menthone	*Callosobruchus maculatus* F.	Fumigant toxicity, affects mating, oviposition	Bassole et al. (2010) and El Nagar et al. (2012)

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Table 6.1 (continued)

Plant	EOs	Insect	Mechanism	Reference
Mentha pulegium	Decane, Pulegone, Limonene, Piperitenone	*Alphis gossypii*	Contact toxicity on adults	Ebadollahi et al. (2017)
Mentha spicata	Carvone, *cis*-Dihydrocarvone, *trans*-piperitone epoxide	*Leptinotarsa decemlineata* (Say)	Antifeedant activity, contact toxicity	Taghizadeh-Saroukolai et al. (2014)
Micromelum minutum	9-epi-β-caryophyllene, Bicyclogermacrene, 1,8-cineole, Tricyclene	*Callosobruchus maculatus* F.	Contact toxicity, fumigant toxicity, repellent activity	Paranagama and Gunasekera (2011)
Nardostachys chinensis	β-Gurjunene, Jatamansome, Aristolemone	*Tribolium castaneum* (Herbst)	Repellent on adults	Paudyal et al. (2012) and Liang et al. (2013)
Nigella sativa	Carvone, trans-anethone, limonene, *p*-cymene	*Sitophilus oryzae* L.	Contact toxicity, repellent activity	Chaubey (2012)
Ocimum basilicum	Linalool, Euginol, α-cadinol, β-ocimene	*Meligethes aeneus* (Fabricius)	Repellent activity, Adulticidal	Pavela (2011)
Origanum vulgare	Thymol, *p*-cymene, Carvacol	*Anobium punctatum*	Toxicity	Palla et al. (2020)
Piper sarmentosum. Roxb	Myristine	*Brontispa longissima* (Gesturo)	Antifeedant activity, Contact toxicity, Fumigation toxicity, Growth and development inhibition	Qin et al. (2010)
Rosmarinus officinalis	α-Pinene, 1,8-cineole, limonene, camphene	*Supella longipalpa*	Contact, fumigant toxicity, Repellency activity	Caballero-Gallardo et al. (2011) and Sharififard et al. (2016)
Salvia leucantha	Bornyl acetate, Caryophyllene oxide, Spathulenol, Caryophyllene	*Aedes aegypti* *A. quadrimaculatus*	Larvicidal activity	Ali et al. (2015)
Tagetes lucida	Methylchavicol, β-myrcene, β-ocimene, linalool	*Sitophilus zeamais*	Repellent activity	Nerio et al. (2009) and Caballero-Gallardo et al. (2011)

(continued)

Table 6.1 (continued)

Plant	EOs	Insect	Mechanism	Reference
Tagetes ternifora	*Cis*-ocimene, Ocimene Tagetone	*Tribolium castaneum* (Herbst) *Sitophilus oryzae* L.	Toxic activity, repellent activity, antifeedant	Stefanazzi et al. (2011)
Thymus satureidoides	Borneol, α-terpineol, camphene, α-pinene	*Varroa destructor*	Acaricidal activity	Ramzi et al. (2017)
Zataria multifora Boiss.	Thymol, [illegible]-cymene, Carvacrol, Lonalool	*Tribolium castaneum, Callosobruchus maculatus* F., *Trogoderma granarium*	Fumigant toxicity on adults	Saei-Dehkordi et al. (2010) and Mahmoudvand et al. (2011)
Zingiber zerumbet	Camphene, a-humulene, camphor, 1,8-cineole	*Sitophilus zeamais Tribolium castaneum*	Fumigant toxicity	Suthisut et al. (2011)

Illiciaceae, Lamiaceae, Lauraceae, Meliaceae, Myrtaceae, Papaveraceae, Pedaliaceae, Piperaceae, Poaceae, Rutaceae, Schisandraceae, Scrophulariaceae, Verbenaceae, Vitaceae and Zingiberaceae plant families have been investigated for the insecticidal potential of their EOs have been found to exhibit lethal and sub-lethal effects such as adulticidal, feeding deterrent, growth and development inhibition, larvicidal, ovicidal, oviposition, progeny production, pupicidal and repellent (Grainge and Ahmed 1988).

6.2.1 *Essential Oils*

EOs are natural compounds that are volatile in nature and, have aromatic constituents characteristic in plants for various functions. They are synthesized via a combination of secondary metabolic pathways in plants and have a distinctive odour (Ebadollahi et al. 2020), may be composed of complex mixtures of aromatic compounds (Bakkali et al. 2008; Rajendran and Sriranjini 2008) and are present as droplets of fluid in the bark, flowers, fruits, leaves, stems and roots in different plants. Many EOs contain natural antioxidants and natural antimicrobial agents (Dorman et al. 2000). In Lamiaceae, they are produced by glandular trichomes, secretory cavities in Myrtaceae and Rutaceae and resin ducts in Asteraceae, Apiaceae (Fahn 1988). These structures burst open and the compounds are let out in copious amounts when herbivores feed or move on the surface of the plants (Duke et al. 2000).

In addition to their role in triggering the revitalization process for the plant through reproduction processes as attracts of pollinators and seed disseminators, and plant thermotolerance (Zhang et al. 2016), EOs also take part either directly or indirectly in plant defenses against arthropod pests (War et al. 2012).

Direct defense responses against insect pests target the biological systems for example the digestive and nervous systems, the endocrine organs of the insects and may be toxic and repellent, result in antinutrition and reduced digestibility, slowed growth and reduced reproduction (War et al. 2012). While indirect responses are insect-specific, and their compositions vary with the attacking insect. They may also involve the release of chemicals that lure the natural enemies of the herbivore by releasing aromatic compounds that lure or favour another organism(s) that reduce herbivore populations (War et al. 2012; Scholz et al. 2016).

6.2.2 Components of Essential Oils

The volatile compounds of EOs may be grouped into four: benzene derivatives, hydrocarbons, terpenes and other compounds (Haagen-Smit 1949; Ngoh et al. 1998). Terpenes and terpenoids are characterized by low molecular weight terpenes form the main group; C% hemiterpenes, the C10 monoterpenes, C15 sesquiterpenes, C20 diterpenes, C30 triterpenes and C40 tetraterpenes. Monoterpenoids constitute about 90% of the total EOs with a wide variety of functions and structures. Other related compounds are acids (e.g. chrysanthemic acid), acyclic alcohols (e.g. citronellol, geraniol), aldehydes (e.g. citronellal), bicyclic alcohols such as verbenol, cyclic alcohols such as menthol, ketones such as menthone, phenols such as thymol, and oxides (cineole) (Koul et al. 2008).

The chemical compounds of EOs vary within different species of the same genus and may also vary in various plant parts, geographical factors, time of harvest, season, climate and extraction method (Rocha et al. 2014). For instance, the concentration of 1,8-cineole was found to vary in the EOs of *Eucalyptus citriodora* (18.9%) (Karemu et al. 2013), *E. globulus* (31%) (Ebadollahi et al. 2010), *E. radiata* (63.3%) (Toudert-Taleb et al. 2014), and *E. saligna* (45.2) (Mossi et al. 2011). Similarly, limonene concentrations were reported to vary in *Citrus bergamia* (38.4%) (Cosimi et al. 2009), *C. limonum* (54.6%), (Bertuzzi et al. 2013), *C. reticulata* (64.1%) and *C. sinensis* (72.7%) (Kamal et al. 2011).

Camphor is well documented for its insecticidal properties (Singh et al. 2014; Tembo et al. 2018). In the same way, camphor concentrations were found to vary in different species of *Artemisia* (Kordali et al. 2006; Negahban et al. 2007; Shukla et al. 2012).

6.3 Pesticidal Properties of Essential Oils

EOs display a wide range of biopesticidal activities ranging from lethal to sublethal effects against Coleoptera, Diptera, Hemiptera Isoptera and Lepidoptera (Regnault-Roger et al. 2012; Pavela and Benelli 2016; Campos et al. 2019). Table 6.1 shows the pesticidal properties of some EOs from various plants. The differences in constituents of various EOs account for various mechanisms of action that range from antinutritional, developmental inhibitory, acute toxicity to repellency effects (Isman 2006; Pavela 2008; Hernández-Carlos and Gamboa-Angulo 2019). Other than the various patterns of phytochemical activties, toxic effects of EOs have been attributed to several other factors. One of which is the point at which the toxin penetrates the insect. The conventional modes of entry are through inhalation, ingestation or through skin absorption by the insect (Ozols and Bicevskis 1979).

EOs of *Artemisia spp*. are known to possess repellent and toxicity properties against coleopteran beetles. Examples of which include *Sitophilus spp*., *Tribolium castaneum,* and *Callosobruchus maculatus*. In a similar manner, Nyamador et al. (2010) found that the EOs of *Cinnamomum spp* possessed contact, fumigant and repellent activity against *C. maculatus*. The authors reported on adulticidal, antifeed, deterrent, ovicidal and oviposition activities towards *C. maculatus* and *C. subinnotatus* as a result of exposure of EO of *Cymbopogon giganteus* and *C. nardus* Similarly, Ketoh et al. (2005) reported on development inhibition towards *C. maculatus* using *C. schoenanthus*.

EOs of *Eucalyptus spp* were found to exhibit adulticidal, repellency, oviposition, contact toxicity and fumigant toxicity against coleopteran beetles (Mohan et al. 2011). For instance, *Eucalyptus* EOs with large amounts of cineole were shown to be insecticidal towards *Varroa jacobsoni* that is parasitic towards the honeybee (Calderone and Spivak 1995), *Tetranychus urticae* and *Phytoseiulus persimilis* (Choi et al. 2004) and *Dermatophagoides pteronyssinus* (El-Zemity et al. 2006). A similar study by Chagas et al. (2002) reported insecticidal activity against the tick *Boophilus microplus* using EOs from three *Eucalyptus* spp.*, E. citriodora, E. globulus* and *E. staigeriana*.

Taking into consideration the various activities of the EOs against pests of agriculture, and the fact that plant extracts contain compounds that exhibit various bioactivities including ovicidal, repellent, and antifeedant properties, it is feasible to combine the EOs with methods such as gamma radiation (Ahmadi et al. 2008a, b). Monoterpenoids account for a large percentage of the constituents of many plant extracts that display bioinsecticidal activities and the EOs. Citronella, camphor, citral, camphene, geraniol, methyi acetate, linalool, thymol, limonene, eugenol, menthone, carvacrol, trans- anethole 1,8-cineol and α -pinene, are well-known examples of biopesticide compounds (Phillips et al. 2010; Negahban et al. 2007; Isman and Machial 2006; Isman 2006). Furthermore, the fact that monoterpenoids possess antifeedant properties (Sbeghen-Loss et al. 2011; Shukla et al. 2012) acute toxicity repellent (Mediouni-Ben and Tersim 2011; Kim et al. 2010), larvicidal, adulticidal, ovicidal, and pupicidal activities (Yang et al. 2014; Waliwitiya et al. 2009; Murugan et al. 2012) make them potential pest control agents.

6.4 Mode of Activity of Essential Oils

Understanding the mode of activity of available EOs is of importance as it helps qualify the chemical characteristics of novel compounds that may be appropriate for insect pest control and dosage that can be safe and economical in agriculture (Haynes 1988). Given the encouraging results observed with EOs against insect pests, there has been rapid development to evaluate the appropriateness of the formulations of their active ingredient for application in integrated pest control programs.

Being distinctively lipophilic and volatile, EOs can permeate the insects' cuticle and disrupt their physiological processes (Lee et al. 2002) cause biochemical dysfunction and mortality. Furthermore, this fast action is a demonstration of the neurotoxicity nature of some EOs against some pests (Kostyukovsky et al. 2002). The mechanism of action, lethal doses, time taken to achieve lethal effects and site for bioactivities from plant EOs has been widely studied.

Plant EOs act at multiple levels of insects as fumigants, insect growth regulators, toxicants, repellents, phagodeterrents and synergists (Table 6.1). Neurotoxicity as a result of exposure to EOs in insects is characterized by hyperactivity, hyperexcitation and finally knockdown and immobilization (Enan 2001).

6.4.1 Fumigant Properties of Essential Oils

Current research has established that active ingredients from EOs may be possible alternatives to prevailing fumigants since they are easily changed to vapour at room temperature, including having various activities against a diversity of insects and fast penetrating. Various studies have investigated the probability of the use of components of plant EOs as insect fumigants. EOs of *Artemisia* spp., *Citrus* spp., *Eucalyptus* spp. *Lavalandula* spp., *Mentha* spp., have been well documented as fumigants. Table 6.1 shows fumigant activities of various plants.

The action of EOs as fumigants against stored product beetles *Sitophilus* spp. and *T. castaneum* has been a subject of immense interest (Fang et al. 2010; Ebadollahi et al. 2012; Franca et al. 2012; Germinara et al. 2017; Salem et al. 2017; Idouaarame et al. 2018; Devi et al. 2020). Findings of the various studies demonstrate that the mechanism of action for the oils is predominantly in the gaseous phase and through the respiratory system. Since most insects respire through the trachea, the vapour causes the spiracles to open. Suffocation occurs due of obstruction the tracheal respiration (Schoonhoven 1978) resulting in death of the insect (Pugazhvendan et al. 2012; Wafaa et al. 2017).

Studies by Huang et al. (2000a) reported that diallyl trisulfide and methyl allyl disulfide from garlic possessed fumigant and toxicity properties against the two beetles *Sitophilus zeamais* and *Tribolium castaneum* Likewise, Sahaf et al. (2007, 2008) demonstrated that the EOs of *Carum copticum* possessed fumigant properties against *S. zeamais* and *T. castaneum* The fumigant toxicity was accredited to the presence of monoterpenoids especially thymol. Monoterpenoids are basically volatile and induce toxic effects such as fumigants as a result of their ability to penetrate the insect cuticles.

Plant EOs obtained from Cymbopogon (Stefanazzi et al. 2011), *Myrtus communis* (Bertoli et al. 2012) anise, eucalyptus, cumin, rosemary and oregano were also demonstrated to have fumigant effects resulting in total mortality of the eggs of *Tribolium confusum* and *Ephestia kuehniella* (Tunç et al. 2000). *Ocimum* spp. extracts, and their active ingredients were found to possess insecticidal effects against a diversity of insects (Ebadollahi et al. 2020).

In a separate study, Singh and Pandey (2018) found that linalool, pulegone, limonene, linalayl acetate found in *Mentha* induced fumigant toxicity to *S. oryzae*. The apiaceae family have been found to have potential as fumigants agents for insects of stored products. For instance, Kim et al. (2003) reported significant mortalities using *Foeniculum vulgare* against *S. oryzae* and *Callosobruchus chinensis* using. While Chaubey (2008) reported fumigant toxicity using *Apium graveolens* and *Cuminum cyminum* against *C. chinensis*, Park et al. (2006) attributed toxicity of larvae of *Lycoriella ingenua* to the activie ingredient limonene, menthone and pulegone of *Schizonepeta tenuifolia*.

6.4.2 Antifeedant Properties

Antifeedant chemicals may deter feeding after contact or act as repellents without making direct contact with the insects (Koul et al. 2008). A significant aspect of the antifeed properties of the EOs of plants is that they have found use in pest management (Table 6.1). Nevertheless, their action on insects is varied and are generally not harmful to the environment .

Indices such as feeding deterrence index (FDI), efficiency of conversion of ingested food (ECI), relative growth rate (RGR) and relative consumption rate (RCR) and are used to determine feeding deterrence. For instance, while the EOs of *Artemisia sieberi* and *A. scoparia* displayed antifeeding activity against *Tribolium castaneum*, EOs of *A. sieberi* oil had higher efficacy in comparison to those from *A. scoparia* and significantly decreased RGR and RCR. *A. sieberi* oil displayed higher efficacy in terms FDI compared to oils from *A. scoparia* (Negahban et al. 2007). In a separate study by Sahaf and Moharramipour (2008), the efficacy of *Carum copticum* and *Vitex pseudonegundo* EOs against *C. maculatus* was found to increase FDI.

EOs in various plants may disrupt or hinder feeding by making the plant matter unappealing or unappetizing (Talukder 2006; Rajashekar et al. 2012). The insects linger on the plants and ultimately die from starvation. Ebadollahi (2011a) demonstrated antifeed activities of *Lavandula* against adults of *T. castaneum*. *Melaleuca alternifolia* and its constituent compounds manifested antifeedant activities against *Helicoverpa armigera* (Liao et al. 2017). Similarly, Taghizadeh-Sarikolaei et al. (2014) reported antifeed activities of *Thymus daenensis* towards *Leptinotarsa decemlineata* and the prominent constituents as thymol, ρ-cymene and γ-terpinene. Shukla et al. (2012) reported antifeed efficacy of oils of *Eupatorium adenophorum* aerial parts and the florescence of *Artemisia nilagirica* against adults of *Rhynchophorus ferrugineus*. The authors reported significantly higher antifeed activity from *E. adenophorum* and *A. nilagirica* from the aerial parts compared to those from *E. adenophorum* leaves. The differences in activity was attributed to the difference in chemical composition, with the major components in the oils from the florescence and leaves of *E. adenophorum* showing approximately 41% oxygenated sesquiterpenes and 64% sesquiterpene hydrocarbons, respectively. The principal class of compounds in EOs *A. nilagirica* aerial parts were composed of monoterpenes (32.92%) and sesquiterpenes (37.02%).

Similarly, the EO constituents citronellal, thymol and α –terpineol were reported to result in feeding deterrence in tobacco cutworm, *Spodoptera litura* (Hummelbrunner and Isman 2001). *Dictamnus dasycarpus* rootbark demonstrated feeding inhibition against *T. castaneum* and *S. zeamais* (Liu et al. 2002). The authors established that fraxinellone resulted in feeding deterrence in the adults and larvae of *T. castaneum* and adults of *S. zeamais*, while dictamnine was responsible for feeding deterrence in adults and larvae of *T. castaneum* and *S. zeamais*.

EOs of *Salvia mirzayanii* displayed a strong feeding deterrence activity towards adults of *T. confusum* (Soleimannejad et al. 2011). The authors observed an increase in the concentration of the EO, RGR, RCR, whereas ECI were reduced significantly. Therefore, nutritional indices may have been influenced by the EO by interfering with the pre-ingestive and post-ingestive process. Consequently, feeding behavior of an insect may result in a reduction in the consumption and consequently growth rate of the insect.

6.4.3 Repellent Properties

Several studies report on the activities of various plants' EOs as repellents (Table 6.1). Repellents provide plants with protection gainst insect pests with minimal harm to the ecosystem.

For example, the oils of *Laureliopsis philippiana* manifested repellent against *Sitophilus* weevils (Norambuena et al. 2016). Methyleugenol and safrole were established to the compounds responsible for the repellency. Other activities observed during the study were contact toxicity and reduced emergence.

Akrami et al. (2011) reported repellency of *Mentha longifolia* on *C. maculatus* and *T. castaneum*. The authors found significantly more repellency of the EO of *A. sieberi* at 1.5 ppm towards *T. castaneum* compared to *C. maculatus* and *S. oryzae*

(Negahban et al. 2007), and *A. scoparia* significantly repelled *T. castaneum* and *S. oryzae* compared to *C. maculatus* (Negahban et al. 2006). Strong repellency (100%) was also observed in *Anethum graveolens* and *T. vulgaris*, towards *P. interpunctella* (Rafiei et al. 2009). Repellency may differ between arthropods. For instance, Taghizadeh-Saroukolai et al. (2009) showed that EO of *P. acaulis* varied in its degrees of repellency against *S. oryzae* (83.6%), *C. maculatus* (71.6) and *T. castaneum* (63.6%).

Nerio et al. (2010) demonstrated that the composition of active components influenced the repellency of the EOs. For instance, feeding deterrence, repellency and toxic activities were exhibited against *T. castaneum* larvae and adults using EOs extracted from fruits and leaves of *Schinus areira* (Descamps et al. 2011). The authors reported repellency from the oils obtained from the leaves. The compostions of the EOs of the leaves were predominantly camphene, monoterpenoids, α-phellandrene and 3-carene, whereas 3-carene, α-phellandrene, and β-myrcene were the principal oils obtained from the fruits. All the oils caused mortality of larvae in fumigant and topical bioassays. However, the former was not observed in the adults. Furthermore, both EOs influenced the nutritional index.

6.4.4 Toxicants

The red flour beetle (*Tribolium species*), rice weevil (*S. oryzae*) and the maize weevil (*S. zeamais*) account for more than 60% losses of cereals and pulses during storage in tropical countries (Singh et al. 2012). The use of EOs from plants as toxicants is an attractive option as these are effective and have been used traditionally. Furthermore, studies on plant derivatives have demonstrated that many plant products are toxic to insects that infest stored products (Table 6.1).

Research shows that the efficacy of EOs towards most insects is associated to terpenes. Monoterpenoids and sesquiterpenes account for the major proportion of the major essential constituents (Table 6.1). For instance, carvacrol, 1,8-cineol, thymol, eugenol, α-pinene and limonene, have been reported to have toxic effects against storage insects. While linalool EO of coriander seed was reported to be toxic towards *S. oryzae* (Knio et al. 2008), limonene, carvone, and (E)-anethole were the principal active components found in the EO of caraway (Fang et al. 2010). High insecticidal toxicity of *Carum carvi* and *Coriandum sativum* against *Cryptolestes pusillus* and *Rhyzopertha dominica* has been attributed to linalool and camphor-rich fractions (Lopez et al. 2008).

Insecticidal toxicity against *Aphis craccivora* was observed when faba beans were treated with a neem oil formulation (neemix®) from *Azadirachta indica* and *Ocimum basilicum* (Sammour et al. 2011). In addition, the authors also reported cumulative adult mortality of up to 100% after 7 days. Geranial, linalool and methyl chavicol were established as the components for insecticidal activities in basil oil. Similarly, Aslan et al. (2004) reported that geranial, linalool and methyl chavicol were insecticidal towards *Tetranychus urticae* and *Bemisia tabaci*.

Insecticidal activity of terpenes (carvone, linalool, terpeniol, phellandrine and citronellol) from garlic and mint were observed on different growth stages of *Agrostis ipsilon* (Sharaby and El-Nujiban 2015). Similarly, high insecticidal efficacy of *Salvia officinalis* towards *A. ipsilon* was reported to result from the presence of sesquiterpenes and terpenes (Sharaby and Al-Dosary 2014). In a parallel study, Sharaby et al. (2012) demonstrated that garlic, eucalyptus, and mint EOs caused toxicity to grasshopper (*Heteracris littoralis*).

Similarly, toxic effects were observed when EOs from *Triaenops persicus* were assessed against adults *S. oryzae* and *T. castaneum* (Koul et al. 2008). Neurotoxic effects as a result of thymol in thyme were observed when *Thymus vulgaris* was assayed against *Nezara viridula* (Koul et al. 2008). Similarly, thymol induced high toxicity to *Lipaphis pseudobrasicae* (Sampson et al. 2005), *Spodoptera litura* (Hummelbrunner and Isman 2001) and *S. oryzae* (Rozman et al. 2006).

6.4.5 Growth Retardants and Inhibitors of Development

Several studies (Table 6.1) have reported effects of plant EOs and their components that disrupt the development and growth of insects, reducing the weight at various stages of growth prolonging the developmental stages (Talukder 2006; Athanassiou et al. 2014; Aziza et al. 2014). The survival rates of larvae, pupae, and adult emergence may also be affected (Koul et al. 2008).

Studies using EOs from azadirachtin and neem seed were reported to increase nymphal mortality of aphids at 80 and 77%, respectively, resulting in prolonged maturation time to adulthood (Kraiss and Cullen 2008). In a similar manner, some botanical biopesticides have been found to especially have dramatized effects during the development and maturation periods, including emergence of adults (Shaalan et al. 2005). Chaubey (2008) found that EOs from *Piper nigrum*, *Myristica Nigella sativa*, *fragrans,* and *Trachyspermum ammi* influenced changes in the reproduction and growth of *C. chinensis*. In a separate study, Abbas et al. (2012) found that *Citrus reticulata* EOs inhibited growth and caused decline in population of *Rhyzopertha domonica*. In a similar manner, EOs from citrus peels resulted in reduced oviposition of *C. maculatus* (Elhag 2000). Likewise, *Elettaria cardamomum* EOs were reported to exhibit deter the oviposition of *C. maculatus* (Abbasipour et al. 2011).

EOs have also been reported to prolong growth stages. For example, basil oil prolonged the duration of the nymph stage of *Aphis craccivora* causing a reduction in number of adults (Sammour et al. 2011). Similarly, Anshul et al. (2014) showed that *Artemisia annua* EOs reduced the weights of *Helicoverpa armigera* larvae while prolonging the larval stage.

6.4.6 Sterility/Reproduction Inhibitors

Sterility may happen as a consequence of induced insect sterility technique or by the use of a chemosterilant that hinders reproduction (Morrison et al. 2010). Chemosterilants may cause permanent or temporary sterility of either male or female insects or interfere with the development of sexual stages from the young to the adults (Wilke et al. 2009; Navarro-Llopis et al. 2011). Asawalam and Adesiyan (2001) and Shaalan et al. (2005) drew attention to the fact that grains mixed with different parts of plants, extracts, oils or powder had the effect of reducing insect eggs hatchability oviposition, postembryonic or progeny development. For example, Elango et al. (2009) reported on the ovicidal effects against *Anopheles subpictus* using extracts of *Andrographis paniculata, A. lineat,* and *Tagetes erecta*.

Use botanical insecticides as chemosterilants may be at the physiological level for instance azadirachtin has been found to interfere with the synthesis of hormones responsible for molting and release of the same from the prothoracic gland, resulting in incomplete ecdysis in young insects, and sterility in adult insects (Isman 2006).

Constituent compounds from garlic; diallyl disulfide and methyl allyl have been found to display toxicity towards *T. castaneum* and *S. zeamais* (Ho et al. 1996; Huang et al. 2000a) at various stages of development. Egg hatching was totally suppressed at 0.32 mg/cm^2 using diallyl trisulfide, while at 0.08 mg/cm^2 larval and adult emergence were repressed. The food consumption, food utilization and growth rate were significantly reduced by methyl allyl disulfide for adults in both insect species, with feeding deterrence indices of 1.52 mg/g food for *T. castaneum* and 44% at 6.08 mg/g food for *S. zeamais* (Huang et al. 2000b). Similarly, Plata-Rueda et al. (2017) demonstrated that the pupal stages of *Tenebrio molitor* were more susceptible to diallyl disulfide and diallyl sulfide compared to larvae and adult stages. The authors attributed the difference in the developmental stages to the fact that efficacy may have been influenced by the way garlic compounds penetrated of the insect body and the capability of the insect to break down these compounds. Furthermore, the insects exhited changes in movement, muscle contraction and paralysis were they came into contact to the EOs of garlic Muscle contractions and paralysis could have been been as a result of neutotoxicity, coupled with hyperextension and hyperactivity of the abdomen and legs and resulting in an instant knockdown effect or immobilization (Prowse et al. 2006; Zhao et al. 2013).

6.5 Synergistic Action of Essential Oils

Various studies have revealed that mixtures or combinations of various EOs compounds exhibit additive, synergistic, and/or antagonist toxicity effects in different groups of insects (Ntalli et al. 2011; Gallardo et al. 2015; Tak et al. 2016; Wu et al. 2017; Gaire et al. 2020). The synergy observed in EOs may be as a result of the different mechanisms of action of their chemical constituents. For example, using synergistically interacting groups of monoterpenoids found in products allows for the achievement of higher insecticidal activity by using smaller amounts of the active constituents (Tak and Isman 2015; Tak et al. 2016).

The rationale for using combinations of EOs is to produce a superior product with multiple mechanisms of action, bearing in mind that the product has a significant effect than the total effects of the known and unknown chemical components of the individual EOs. Earlier studies proposed that the synergistic role of constituents in the EOs with high camphor content (Gonzalez-Coloma et al. 2006; Nerio et al. 2010). For instance, Tak and Isman (2015) showed that a combination of camphor and 1,8-cineole displayed hightened penetration of the cuticle, resulting in a synergy toxic effect towards the larvae of the cabbage looper. The authors found that these changes increased the ability of the mixture of two oils to penetrate the cuticle, resulting in reduced surface tension and increased solubility. Similarly, Abbassy et al. (2009) demonstrated a higher synergistic insecticidal effect of terpien-4-ol and c-terpinene from EOs of *Majorana hortensis* against larvae of *Spodoptera littoralis* than either of the individual compounds.

Faraone et al. (2015) reported increased toxicity (16–20-fold) against *Myzus persicae* as a result of the synergistic action of imidacloprid and two EOs linalool and thymol of *Lavendula angustifolia* and *Thymus vulgaris,* respectively. Mixtures of EO ingredients particularly monoterpenoids exhibited toxic synergy effects against insects as a result of increased ability to penetrate the cuticle (Gaire et al. 2020). The authors observed heightened synergistic effect in toxicity against bed bugs using a mixture of eugenol, thymol and carvacrol. The authors further reported that the synergistic interaction displayed by the mixture was most likely influenced by factors associated to the target site. Including the capability of the monoterpenoids to be operate on various sites within the nervous system of insect.

6.6 Nanoencapsulation

Despite their promising properties, EOs possess problems related to potential for oxidation, solubility in water, volatility, that should be rectified before they can be used effectively (Martin et al. 2010). Turek and Stintzing (2013) explored the factors that influenced EO stability. Besides their being highly volatile, EOs easily decompose in direct heat, exposure to high humidity, light, and/or oxygen. Degradation of the constituents may be as a result of cyclization, oxidation, dehydrogenation or isomerization reactions stimulated chemically or enzymatically (Scott 2005) and may be affected by the conditions during distillation, processing, storage of the plant material, and handling of the final product (Schweiggert et al. 2007).

To achieve high efficacy and stability, EOs are encapsulated and used to deliver EOs in insect pest management programs. Nanoencapsulation uses an approach of encapsulating the active agent in a thin layer of protective membrane in order to cushion it from extreme environmental effects. Nanocapsules consist of a shell, active ingredients that may be adsorbed on the surface or dissolved in the inner core

(Khoee and Yaghoobian 2009). The carrier or envelope may be made up of natural polymers such as proteins or polysaccharides or synthetic polymers such as polyamides or melamineformaldehyde, lipids, phospholipids, or inorganic materials such as SiO_2 (Nagpal et al. 2001; Kumari et al. 2010), giving EOs high efficacy while cushioning them from the likelihood of evaporation or degradation.

An important characteristic of nanoencapsulated EOs is the controlled release, that is characterized by a a prolonged release that follows a preliminary burst (São Pedro et al. 2013). In addition to minimized evaporation and exposure to extreme environmental conditions, nanoencapsulation of EOs represents a practicable and logical approach that modulates drug release, increases the stability of the active ingredients, decreases their volatility, enhances their bioactivity, and reduces toxicity (Ravi Kumar 2000).

6.7 Essential Oil Nanoformulations and Insect Pest Control

Nanoformulated EOs exhibit distinctive properties including higher pest toxicity. For instance, nanopermethrin had higher larvicidal efficacy towards *Culex quinquefasciatus* compared to the non-formulated form of permethrin (Anjali et al. 2010). Studies also reveal that when transformed into nanoparticles novel non-precise and biological properties become part of EOs. They gain entry into epithelial and endothelial cells of the pest and move from one cell to another by transcytosis along the axons and dendrites, blood, and lymph, triggering oxidative stress and other reactions (Devi and Maji 2011). For example, geranium oil used as mosquito repellent when transformed into high-quality solid lipid nanoparticle-loading geranium oil (Asnawi et al. 2008). In separate studies by Yang et al. (2009) and Werdin-Gonzalez et al. (2014), EOs of garlic and geranium incorporated into nanoparticles of polyethylene glycol and tested against *Tribolium castaneum* and *Rhyzopertha dominica* produced an increase in contact toxicity as a result of the slow and sustained dissemination of the effective terpenes. Furthermore, the nanoformulations increased the ability of the EO contact toxicity and changed the feeding ability of both pests. While the nanoemulsion of EO citronella caused a higher release rate against mosquito (Nuchuchua et al. 2009; Solomon et al. 2012).

Encapsulation of EOs enhances their bioactivity. For instance, Ferreira et al. (2019) demonstrated the efficiency and prolonged activity of chitosan encapsulated EO of *Siparuna guianensis* against *Aedes aegypti* larvae as a result of increased contact and slow and controlled release conferred by chitosan nanoparticles. Similarly, chitosan and angico gum nanoparticles containing EOs of *Lippia sidoides* caused 92% mortality of larvae of the mosquito *Aedes aegypti* (Paula et al. 2010). Likewise, chitosan and cashew gum nanoparticles containing EO *L. sidoides* caused 75–100% mortality of *A. aegypti* after 48 and 72 h respectively (Paula et al. 2011). In a separate study, Christofoli et al. (2015) found that nanoencapsulated EOs from *Zanthoxylum rhoifolium* displayed great efficacy in reducing the egg numbers and nymphs of *Bemisia tabaci* populations. The *in vitro* release was chararacterized by an initial fast release, followed by second sustained slow release. Nanoencapsulated oils display more chemical activity compared to non-encapsulated material, more mobility, allowing entry into the tissues of the insect. This can be achieved by feeding and entry through digestive tract or contact through the insect's cuticle. The pest cells, Entry into the endothelial and epithelial, is by transcytosis (Devi and Maji 2011).

Campolo et al. (2017) demonstrated significant insecticidal activity against the invasive tomato pest *Tuta absoluta* using nanoformulations of EOs of citrus peel with polyethylene glycol. Khoobdel et al. (2017) demonstrated insecticidal activity of nanoformulations of EOs of *Rosmarinus officinalis* towards the red flour beetle, *Tribolium castaneum*. Louni et al. (2018), showed that nanoemulsion formulation of *Mentha longifolia* had enhanced contact toxicity on *Ephestia kuehniella*. Nanoencapsulation mechanism can, therefore serve as novel formulations for the establishment of the EOs and their chemical derivatives with improved functions.

6.8 Conclusion

The use of plant EOs as insecticides offers several advantages over synthetic chemicals. Moreover, their individual components have been determined to have potential for insecticidal activity against several arthropods of economic importance in agriculture. Furthermore, studies have shown that mixtures or combinations of several EO active ingredients exhibit additive, synergistic,and/or antagonist toxicity in various arthropod species. However, despite their promising properties, EOs face obstacles related to solubility in water, possibility of oxidation and volatility, due to exposure air, direct sunlight, high temperatures and moisture, resulting in possible degradation and evaporation of some active components. These setbacks have been solved by encapsulation of EOs resulting in controlled release characterized by a two-phase release; an first burst, then by a prolonged release, minimized evaporation and exposure to extreme environmental conditions, increased stability of the active ingredients, decreased volatility, and enhanced bioactivity.

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