7 Essential Oils against the Bio-Deteriorating Insect Pests of Stored Food Commodities

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Abstract

Plant-based essential oils (EOs) are emerging as promising alternatives to chemical insecticides worldwide against stored food insect pests. EOs are plant secondary metabolites containing a mixture of various aromatic and aliphatic compounds that play crucial role in plant defense and signaling processes. Coleoptera followed by Lepidoptera are the most destructing insect orders causing huge loss to stored food items worldwide. A plethora of research and review articles have been published reporting the efficacy of different EOs against them in various methods like contact toxicity, fumigation toxicity, repellent activity, oviposition deterrent activity, ovicidal activity, larvicidal activity, pupaecidal activity and antifeedant activity. However, most of the studies focused only on one or two insect pests or one or two methods. The present chapter aims to furnish short information on various important stored product insect pests as well as efficacy of different EOs against them in various ways as analyzed in different research studies. Further, future research studies concerning the use of EOs as insecticides should focus on detailed investigations in the real food system and their safety profile, an area that needs more research input.

Keywords

Essential oil · stored food · Coleoptera · Lepidoptera · Insecticide

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7.1 Introduction

Essential oils (EOs) are gaining increased interest to be developed as botanical insecticides for stored pest management in both developing and developed countries. The increased insect resistance, and eco-toxicological, environmental and social consequences of the commonly applied synthetic chemical insecticides in agriculture have led researchers to investigate EOs as viable eco-friendly alternatives of hazardous chemical insecticides. Further, the worldwide availability and relative cost-effectiveness of EOs make them a suitable alternative of synthetic insecticides.

EOs are plant secondary metabolites composed of a mixture of hundreds of aromatic and aliphatic compounds with the dominance of monoterpenes, sesquiterpenes and their oxygenated derivatives and they play very important roles in plant defense and signaling processes (Zuzarte and Salgueiro 2015). EOs are produced by different plant organs like leaves, flowers, buds, fruits, seeds, bark, wood, rhizomes and roots. Some angiospermic families such as Asteraceae, Cupressaceae, Lamiaceae, Lauraceae, Rutaceae, Myrtaceae, Piperaceae, Apiaceae and Poaceae show increased accumulation of EOs in their glandular trichomes, secretory cavities and resin ducts. The main components of EOs, monoterpenes and sesquiterpenes are synthesized via either the methylerythritol 4-phosphate (MEP) pathway or the mevalonate-dependent (MVA) pathway in the cytoplasm and plastid (Hüsnü and Buchbauer 2015). The most common methods for extraction of EOs from raw plant materials are hydro-distillation, steam distillation and mechanical processes as considered in the European Pharmacopoeia and the International Standard Organization on Essential oils (ISO 9235:2013) (Zuzarte and Salgueiro 2015). However, some other modern methods frequently used for extraction of EOs are solvent extraction, microwave-assisted extraction, ultrasonic extraction, Soxhlet extraction, subcritical or superheated water extraction (SCWE) and supercritical fluid extraction. The composition of EOs is strongly subjected to variations according to their geographic origin, physiological status (i.e., flowering, vegetative etc.) of the plants, the part of the plant from which EOs were extracted, method of extraction etc. that can significantly alter the quality and the quantity of EO components and thus the toxicity of the EOs (Campolo et al. 2018).

EOs have a huge potential to be developed as plant-based alternative insecticide against different stored product insects as supported by a plethora of literature, however, information of various storage insects as well as efficacy of EOs against them in a single article is limited. The aim of this chapter is to provide short information on various important stored product insect pests and to analyze research studies on the use of essential oils against them in various aspects.

Coleoptera (beetles) and Lepidoptera (moths and butterflies) are the two major groups of insects that are responsible for post-harvest deterioration of stored food commodities. They can infest the crops both in the field and in store. Crop damage by Coleoptera is done by both larvae and adults while Lepidoptera damage is done mainly by the larvae. These insect pests of storage food commodities not only cause serious damage to agricultural products worldwide during their storage but also provide suitable medium for other contaminants such as bacteria, fungi and mites.

The following is a short description of most common post-harvest storage insect pests causing significant damage to stored food commodities worldwide.

7.2 Coleoptera

This is the largest order of insects that contains the most common and important stored product insects. In adults, the front pair of wings is modified into hard elytra. They inhabit a wide variety of habitats and can be found almost everywhere. They can be primary, i.e., able to attack intact grains; while others are secondary pests, i.e., attack already damaged grains or grain products.

7.2.1 Curculionidae (Snout Beetles)

The adults of this family are characterized by the presence of elongated downward-curved snout (rostrum). This family contains world's most common and destructive stored grain pests comprising *Sitophilus oryzae* (L.) (rice weevil), *S. zeamais* Motsch. (maize weevil) and *S. granarius* (L.) (granary/wheat weevil). These are the major insect pests of stored wheat, rice, maize and barley; however, they are able to develop on all cereals, dried cassava and other processed food products. Adult females create a small hole in intact grain, lay eggs inside and seal the hole with a secretion. Pupation takes place inside the grain and adults chew their way out through the outer layer of the grain. An adult female can lay more than 500 eggs and live for 6 months or more (Mound 1989).

7.2.2 Bruchidae (Seed Beetles)

This family includes short, stout-bodied beetles with a short forewing not reaching the tip of the abdomen. Adults have relatively long antennae. Larvae feed inside stored dry grains, mainly legumes. This family contains several important field and stored crop pests. The most destructive insect pest from this family is *Callosobruchus* sp. Adults have a short life span of about 12 days and do not feed. They show the polyphenism, i.e., two life forms can be seen: the active (flying) form and the flightless form. The adult females lay about 100 eggs glued to the seed surface or pods. Larvae tunnel inside the seed where the entire development takes place. *C. maculatus* (Fabricius) (cowpea weevil or pulse beetle) and *C. chinensis* (Adzuki bean beetle) are the major field-to-storage insect pest of pulses with broad host range and may cause up to 100% destruction of seeds within 3–4 months (Kedia et al. 2015a, b). Other species such as *C. rhodesianus*, *C. subinnotatus*, *Acanthoscelides obtectus* Say (*Bruchus obtectus* Say) (American bean weevil), *Caryedon serratus* (Olivier) (groundnut borer) are also important pests of legume seeds.

7.2.3 Tenebrionidae (Darkling Beetles)

The adults of this family are black or dark brown and are characterized by the tarsi of the hind leg with only four segments. *Tribolium castaneum* Herbst. (red-rust flour beetle) and *T. confusum* J. du Val (confused flour beetle) from this family are probably the most serious secondary pests of all plant commodities in store (flour mills, grain bins, empty cargo containers, storage units and retail stores) throughout the world causing significant damage and weight loss of stored grains (Ismail 2018). Damage is done by both larvae and adults generally to broken grains rather than intact grains. The adult females lay small, cylindrical, white eggs scattered in the product. Larvae are yellowish with a pale brown head, and they live inside grains until pupation. Females can lay up to 1000 eggs and live for a year or more. Another important pest from this family is *Tenebrio molitor* (L.) (the yellow mealworm beetle). It has worldwide distribution and feeds on a wide range of cereal products, plant and animal materials.

7.2.4 Bostrichidae (Branch and Twig Borers)

Adults of this family are elongated with the head bent down ventrally to the thorax and contain rasp-like hooks on the pronotum. This family includes two serious stored grain pests: *Rhizopertha dominica* (Fabricius) (lesser grain borer) and *Prostephanus truncatus* (Horn) (larger grain borer). *R. dominica* attacks on a large number of cereal grains during storage including wheat, barley, rice, oats, cassava, flour and other cereal products (Filomeno et al. 2020). Females can lay up to 500 eggs on the grain surface. Larvae feed either externally or inside the grain and pupation takes place within the eaten grain. Both adults and larvae eat the endosperm resulting in powdered grains. *P. truncates* is a serious primary pest of maize and dried cassava.

7.2.5 Laemophloeidae (Lined Flat Bark Beetles)

This family contains one common pest of stored grains: *Cryptolestes ferrugineus* (Stephens) (rusty grain beetle). Adults are small with relatively big head and prothorax. This insect is a secondary pest of stored grains, usually attacks the germs of broken or cracked grains, thus reducing germination (Pantenius 1988). Other species such as *C. pusillus* (Schonherr) and *C. pusilloides* (Steel and Howe) can also cause significant damage particularly in humid areas of the tropics.

7.2.6 Silvanidae (Silvan Flat Bark Beetles)

This family includes two important species: *Oryzaephilus surinamensis* (L) (saw-toothed grain beetle) and *O. mercator* (Fauvel) (merchant grain beetle). They infest a wide variety of stored grains, processed foodstuff and almost every product of vegetable origin (Abd El-Salam et al. 2019). *O. surinamensis* prefers cereals, seeds and nuts while *O. mercator* is more frequent on oil-seed products all over the globe. They enter through damaged grains and feed on the germ.

7.2.7 Dermestidae (Skin Beetles)

One of the world's most serious destructive stored product pest of grain and seeds from this family is *Trogoderma granarium* Everts (khapra beetle). Adults are oval, red brown in color with dark thorax. Adult females may lay up to 120 eggs within the stored products. Larvae are very hairy and bore into undamaged stored seeds. The larvae have the ability to fall under facultative diapause for several years and are tolerant to insecticidal treatments (Kavallieratos et al. 2020).

7.2.8 Anobiidae (the Wood Borers)

This family includes two important widespread storage pests: *Lasioderma serricorne* (Fabricius) (cigarette beetle) and *Stegobium paniceum* (Linnaeus) (drugstore beetle). *L. serricorne* is a common pest of stored cereals, cocoa beans, tobacco, ground nut, peas, beans, flours and other food items. Adults create holes on grains to mate and lay eggs inside. Newly hatched larvae feed on them and are responsible for most of the damage (Zhou et al. 2018). *S. paniceum* is less common and larvae are active feeders of stored biscuits, macaroni, dry fruits and other products.

7.2.9 Trogossitidae (Bark Gnawing Beetles)

The common pest in storehouse and granary from this family is *Tenebroides mauritanicus* (L.) (the cadelle). It primarily attacks on cereals, oilseeds and their products. Both adults and larvae feed directly on stored food. The larvae may tunnel in wooden walls of the store to create a pupation chamber.

7.3 Lepidoptera

Lepidoptera is the second most important order of stored product insect pests after Coleoptera. Adults are active flyers with two pairs of scaly wings and larvae possess well-developed mandibles and pseudopods (false legs) on some of the abdominal segments. They can attack crops in both the field and store. Adults generally attack ripening crop while larvae can be found in recently harvested stored grains.

7.3.1 Pyralidae (Snout Moths)

This is a large family containing two important stored product insect pests: *Ephestia* sp. and *Plodia* sp. *E. cautella* (Walker) (tropical warehouse moth) is a serious cosmopolitan pest of stored maize, wheat, dried fruits, beans, nuts, banana, groundnut and other grains. Adult females create holes in bags and lay sticky eggs within the substrate. Larvae cause considerable damage from webbing in the grain and on the surface of bags forming large lumps. *E. elutella* (Hub.) (warehouse moth) can be found on stored cocoa beans, grains, pulses, nuts, tobacco, coconut and dried fruits. *E. kuehniella* (Zeller) (Mediterranean flour moth) is a major pest of flour mills, grout mills, corn milling plants, bakeries and flour products. *P. interpunctella* (Hübner) (Indian meal moth) prefers meals and flours but can be found on stored raisins, nuts, pulses and cereals. The larvae of these insects feed on the germinal part of the grains causing food contamination with dead bodies, frass, exuviae and silk webbing (Mound 1989).

7.3.2 Gelechiidae (Twirler Moths)

This family contains two serious post-harvest pests *Sitotroga cerealella* and *Phthorimaea operculella*. *S. cerealella* (Olivier) (Angoumois grain moth) is a serious primary pest of maize, wheat and sorghum, both in the field and in stores, particularly the warmer parts of the world. Larvae feed and spend their entire life inside one grain leaving a hole after emergence (Bushra and Aslam 2014). *P. operculella* (Zeller) (potato tuberworm) is a cosmopolitan pest of potatoes, tomatoes and eggplants, both in the field and stores.

7.3.3 Acaridae (the Mites)

This is the family of mites including *Acarus siro* L. (flour mite), the cosmopolitan mite in foodstuff. *A. siro* can be found in granaries, feed mixing plants, threshing floors, stacks of hay and straw, dead organic matter, soil or plant residues and almost all products of plant or animal origin. Adult females lay large clutches of sticky eggs. The grains lose nutrients and germination ability, give a musty smell and unpleasant taste after contamination.

7.4 Efficacy of Essential Oils against Stored Product Insect Pests

To control these losses, mainly synthetic pesticides (gray chemicals) have been widely used throughout the world. However, due to adverse effects on non-target organisms and environment, resistance development among pests and high cost of synthetic insecticides, natural plant-based insecticides are getting preferred and research is going on for their efficacy in large scale. Recently essential oil-based products are gaining momentum in view of their negligible persistence in the nature, multiple modes of action, low toxicity, large-scale availability, renewable source and less chances of resistance development in pests (Chaudhari et al. 2021). A plethora of research and review articles have been published reporting the efficacy of EOs against stored insect pests, however, most of them have focused only on one or two insect pests. The reports concerning bio-efficacy of various EOs against various stored product insect pests through various ways are compiled in Table 7.1. The following section deals with insecticidal activity of different EOs against various stored insect pests that have been reported time to time through various methods.

7.4.1 Contact Toxicity

Contact toxicity is a way to kill pests when they come in contact with a chemical. Different EOs have been analyzed by different workers to record their activity as contact toxicant against various stored product insect pests. The methods most commonly used were residual film assay, impregnated paper assay, dipping method, direct topical application method etc. Abdelgaleil et al. (2016) evaluated the contact toxicity of 20 plant EOs against *S. oryzae,* and found strong insecticidal contact activity for *Artemisia judaica* (Asteraceae), *Callistemon viminalis* (Myrtaceae) and *Origanum vulgare* (Lamiaceae) EOs with LD_{50} value of 0.08, 0.09 and 0.11 mg/cm^2, respectively. Similar result was also observed for *Syzygium aromaticum* (Myrtaceae) and *Lavandula officinalis* (Lamiaceae) EO (LD_{50} values 0.04 and 0.07 mg/cm^2, respectively) (El-Bakry et al. 2016) and for *Coriandrum sativum* (Apiaceae), *Eucalyptus obliqua* (Myrtaceae) and *Pinus longifolia* (Pinaceae) EOs (LD_{50} values 36.68, 52.77 and 77.30 μg/cm^2, respectively) against *S. oryzae* (Rani 2012). In another study, some EOs showed similar contact insecticidal activity against *S. zeamais* (LD_{50} values for *Aster ageratoides* (Asteraceae) and *Dracocephalum moldavica* (Lamiaceae) were 27.16 and 22.10 μg/cm^2, respectively) (Chu et al. 2011, 2013) suggesting the reliability of these EOs at very low dosages for curculionid insects. In a similar study, Upadhyay et al. (2019) investigated the contact toxicity of *Melissa officinalis* (Lamiaceae) EO against *T. castaneum* and observed strong toxicity after 48 h of exposure at 0.157 μl/cm^2 air concentration. In a laboratory bioassay, Emamjomeh et al. (2021) estimated the contact LC_{50} of *Eucalyptus globulus* (Myrtaceae) and *Zataria multiflora* (Lamiaceae) EOs as 13.07 and 1.47 μl/l, respectively, against *E. kuehniella*. Researches showed the toxicity difference of different EOs on different insects could be affected by the penetration ability of the EO components, ability of insect to metabolize these components, thickness and the composition of cuticle in insects.

Table 7.1 Bio-efficacy of various EOs against various stored product insect pests as analyzed through various methods

EO	Test insects	Results	Reference
Contact toxicity			
Cupressus lusitanica *Eucalyptus saligna*	*T. castaneum* *A. obtectus* *S. zeamais*	5.0–65.0% mortality at 0.20% v/w EOs and 120 days grain storage	Bett et al. (2017)
Liriope muscari	*T. castaneum* *L. serricorne*	LD_{50} values 13.36 and 11.28 μg/adult, respectively	Wu et al. (2015)
Aloysia citriodora	*R. Dominica*	LC_{50} value 26.6 mg/cm^2	Benzi et al. (2009)
Chenopodium ambrosioides	*C. chinensis* *C. maculatus* *A. obtectus* *S. granarius* *S. zeamais* *P. truncatus*	80–100% mortality at 0.2 μl/cm^2 dose within 24 h except *C. maculatus* and *S. zeamais* (20 and 5% mortality, respectively)	Tapondjou et al. (2002)
Cinnamomum *cassia* *Cocholeria aroracia* *Brassica juncea*	*L. serricorne*	Over 90% mortality at 3 days after treatment	Kim et al. (2003)
Hyptis suaveolens *Ocimum canum*	*T. mauritanicus*	100 and 20% mortality, respectively, at 0.5 μl EO/g of peanut after 24 h	Adjou et al. (2019)
Cymbopogon martinii	*P. interpunctella*	LD_{50} value 22.8 μg/cm ^{2}	Jesser et al. (2017)
Fumigation toxicity			
Eucalyptus globulus	*P. interpunctella*	KT_{50} value 8.34 min.	Jesser et al. (2017)
Mentha spicata	*L. serricorne* *S. paniceum*	97.63 and 97.76% mortalities, respectively, at 20% v/v concentration after 24 h	Karakoç et al. (2018)
Rosmarinus officinalis	*O. surinamensis*	100% mortality at 0.15 μl/ml EO	Kiran and Prakash (2015)
Lippia palmeri	*S. zeamais* *P. truncatus*	92–100% mortality at 72 h with 1000 μl/l EO concentration	Martínez-Evaristo et al. (2015)
Artemisia vulgaris	*T. castaneum* *C. maculatus* *R. Dominica*	LC_{50} in the range of 52.47 to 279.86 μl/l air after 24 h	Sharifian et al. (2013)
Cuminum cyminum	*C. chinensis* *S. oryzae*	LC_{50} value 3.52 and 104.07 μl/l, respectively	Kedia et al. (2015)
Menthalongifolia	*T. castaneum* *T. confusum* *T. molitor* *O. surinamensis* *A. siro*	84.4, 42.2, 100, 100 and 87.8 mortalities, respectively, at 1000 ppm of EO	Kavallieratos et al. (2022)

(continued)

Table 7.1 (continued)

EO	Test insects	Results	Reference
Repellent activity			
Cupressus lusitanica *Eucalyptus saligna*	*T. castaneum* *A. obtectus* *S. zeamais*	34–52.4% repellency at 0.20% v/w EOs after 120 days grain storage	Bett et al. (2017)
Cuminum cyminum	*C. chinensis* *S. oryzae*	100 and 53% repellency, respectively at 12.5 μl/l air EO concentration	Kedia et al. (2015)
Lippia palmeri	*S. zeamais* *P. truncatus*	Total repellency and repellency index 0.15 at 24 h with 20 μl/l EO	Martínez-Evaristo et al. (2015)
Premna quadrifolia *P. angolensis*	*S. Cerealella*	96.84 and 91.55% repellency, respectively at 1% EO concentration	Adjalian et al. (2015)
Oviposition deterrence and ovicidal activity			
Cuminum cyminum	*C. chinensis* *S. oryzae*	>95 and > 75% deterrence, respectively at 100 μl/l air EO concentration	Kedia et al. (2015)
Cinnamomum verum *Citrus hystrix* *Cymbopogon nardus* *Euodia suaveolens* *Syzygium aromaticum*	*C. ferrugineus*	LC_{50} values for eggs 17, 12, 11, 16 and 11 ppm, respectively	Ikawati et al. (2020)
Eucalyptus Rosemary Lemon grass	*E. Cautella*	60.2, 33.6 and 46.7% egg hatching inhibition, respectively, at 5–15% EOs concentration	Al-Taie and Sabr (2018)
Majorana hortensis	*P. Operculella*	100% eggs failed to hatch at 0.1 ml dose of EO through contact mode	Abd El-Aziz (2011)
Larvicidal and pupaecidal activity			
Cinnamomum verum *Citrus hystrix* *Cymbopogon nardus* *Euodia suaveolens* *Syzygium aromaticum*	*C. ferrugineus*	LC_{50} values for larvae 24, 17, 22, 22 and 24 ppm and for pupae 9, 8, 8, 10 and 7 ppm, respectively	Ikawati et al. (2020)
Laurus nobilis *Salvia officinalis*	*T. granarium*	LC_{50} values 37.9 and 50.7 μl/l, respectively, for larvae	Tayoub et al. (2012)
Zataria multiflora	*E. Kuehniella*	LC_{50} values 0.61 μl/cm^2 for larvae after 72 h	Emamjomeh et al. (2017)

(continued)

Table 7.1 (continued)

EO	Test insects	Results	Reference
Eucalyptus Rosemary Lemon grass	*E. Cautella*	29.33, 40 and 17.33% mortality of young larvae and 39.77, 21.67 and 32.20% mortality of late larvae, respectively, at 5–15% concentration of EOs	Al-Taie and Sabr (2018)
Majorana hortensis	*P. Operculella*	100, 100 and 11.3% mortality of larva, prepupa and pupal stages after 24 h at 0.2 ml/10 g dose	Abd El-Aziz (2011)
Menthalongifolia	*T. castaneum* *T. confusum* *T. molitor* *O. surinamensis* *A. siro*	100, 100, 34.4, 100 and 67.8% mortalities to larvae, respectively, at 1000 ppm EO	Kavallieratos et al. (2022)
Antifeedant activity			
Cuminum cyminum	*C. chinensis* *S. oryzae*	100 and 97% FDI, respectively, at 100 µl/l air EO concentration	Kedia et al. (2015a, b)
Acorus calamus	*P. truncatus*	Feeding lowered to 50% compared to the control at 0.01% oil concentration	Schmidt and Streloke (1994)
Rosmarinus officinalis	*O. surinamensis*	100% antifeedant activity at 0.15 µl/ml EO	Kiran and Prakash (2015)
Premna quadrifolia *P. angolensis*	*S. Cerealella*	0.07 and 0.15% grain damage, respectively, at 15 µl/ml dose of EO	Adjalian et al. (2015)

7.4.2 Fumigation Toxicity

Fumigants are insecticides that act in the vapor or gaseous phase on the target pests. Being volatile in nature, EOs are well suited to be developed as plant-based fumigants. Extensive work has been done to assess the fumigation toxicity of EOs against various storage insects. The most followed method for fumigation toxicity of EOs was impregnated paper assay by using filter papers inside closed containers. *Ocimum gratissimum* (Lamiaceae) EO showed prominent fumigation toxicity against *S. oryzae*, *C. chinensis*, *R. dominica* and *O. surinamensis* (LC_{50} values 0.50, 0.20, 0.20 and 0.19 µl/l, respectively) but less toxicity toward *T. castaneum* (LC_{50} 24.9 µl/l) (Ogendo et al. 2008). In another study, *Artemisia sieberi* (Asteraceae) EO showed pronounced fumigation toxicity against *C. maculatus*, *S. oryzae* and *T. castaneum* (LC_{50} values 1.45, 3.86 and 16.75 µl/l air, respectively, after 24 h) (Negahban et al. 2007). Similarly, Naseri et al. (2017) investigated the fumigant toxicity of *A. sieberi* and *A. khorassanica* EOs against adults of *S. cerealella* and recorded LC_{50} values as 9.26 and 7.38 µl/l air concentrations, respectively. Research showed pronounced fumigation toxicity of EOs against various insect pests favoring their application for managing insect pest population in closed spaces such as storage bins or buildings. Currently, through microencapsulation method, some EOs have been encapsulated and showed increased activity by improving their handling, stabilization and controlled delivery. The application of EOs in post-harvest protection of stored food commodities would be economical as very low dose of EO may uniformly fumigate the commodities kept in large containers.

7.4.3 Repellent Activity

Repellents are chemicals that act locally or at a distance by providing a vapor barrier, deterring an insect from coming into contact to or landing over a surface. Hundreds of plant EOs have been investigated as potential sources of insect repellents, however, the studies mainly focused on Dipteran insects; the insect pests of stored food commodities (Coleoptera and Lepidoptera) have been less researched. The most commonly used methods were filter paper method, choice bioassay and olfactometer assay. In a study, Caballero-Gallardo et al. (2011) tested the repellent activity of *Lippia alba*, *Rosmarinus officinalis*, *Lepechinia betonicifolia* (Lamiaceae), *Tagetes lucida* (Asteraceae) and *Cananga odorata* (Annonaceae) EOs against *T. castaneum* and observed 96 ± 2, 92 ± 4, 92 ± 4, 90 ± 3 and 98 ± 2% repellent activity, respectively, after 4 h of exposure at 0.2 μl/cm^2 concentration. Similarly, Fogang et al. (2012) observed the 100% repellent activity of *Zanthoxylum xanthoxyloides* (Rutaceae) EO against *A. obtectus* at 0.501 μl/cm^2 air concentration. Nattudurai et al. (2017) observed 85.24 and 75.24% repellency against *C. maculates* and *S. oryzae*, respectively, at 25 μl/l air concentration of *Atalantia monophylla* (Rutaceae) EO after 3 h of exposure using a Y-tube glass olfactometer. In an another study, Mahdi and Behnam (2018) observed 49.99 and 58.33% repellency of *Citrus sinensis* (Rutaceae) EO against *R. dominica* and *L. serricorne*, respectively, after 3 h of exposure. Similarly, Ogendo et al. (2008) observed 78–93% repellency of *Ocimum gratissimum* (Lamiaceae) EO at 0.05–0.2% v/w concentration after 24 h against *C. chinensis* through choice bioassay in Petri plates.

7.4.4 Oviposition Deterrent and Ovicidal Activity

Oviposition deterrent is the property by which a chemical does not allow the females to deposit eggs on a surface. Ovicidal activity is the property by which a chemical kills the eggs by disrupting embryonic development. Several EOs have been reported to have oviposition deterrent and ovicidal activities against various stored product insect pests, however, reports are more for the insects that lay eggs over the seed surface and are clearly visible. Papachristos and Stamopoulos (2004) investigated *Lavandula hybrida*, *Rosmarinus officinalis* (Lamiaceae) and *Eucalyptus globulus* (Myrtaceae) EOs against *A. obtectus* and observed 27.1–29.9% oviposition deterrent and ovicidal activity at 197.2 μl/l air concentration. The activity increased on increasing time period. Mondal and Khalequzzaman (2009) observed the ovicidal activity of five EOs on *T. castaneum* eggs and found the strongest effect for *Elettaria cardamomum* (Zingiberaceae) while the lowest impact for *Azadirachta indica* (Meliaceae). Kedia et al. (2014) observed 98% oviposition deterrence and 100%

ovicidal performance of *Mentha spicata* EO against *C. chinensis* at 0.1 and 0.0125 μl/ml concentrations, respectively. In a study, Ayvaz et al. (2009) tested the ovicidal activity of five EOs against *P. interpunctella* and *E. kuehniella*. The highest egg mortality was observed from *Satureja thymbra* (Lamiaceae) EO (100%) and the lowest from *Citrus limon* (Rutaceae) EO (25–30%) for both the insects. EOs exhibited oviposition inhibition either due to killing females before laying their eggs or due to the failure of live females to lay many eggs. Further, the EO components may enter into the eggs through chorion and suppress embryonic development exhibiting their ovicidal activity. These properties of checking the pest population at the beginning of their life cycle would be advantageous in view of development of resistance in pests and can be recommended in food safety programs.

7.4.5 Larvicidal and Pupaecidal Activity

Most of the EO toxicity studies refer to adults. Being internal feeders, the toxicity of EOs toward larvae and pupae has been less investigated and these stages seemed to be more resistant than the mature adult stage. Kedia et al. (2015a, b) tested *Cuminum cyminum* (Apiaceae) seed EO against *C. chinensis* and *S. oryzae* immature stages and observed the early embryonic stages (eggs and neonate larvae) as more susceptible than the older stages (mature larvae and pupae). The toxicity of the EO against *C. chinensis* was 92% for LI/LII larvae, 53% for LIII/LIV larvae and 41% for pupae at 50 μl/l air concentration. Similarly against *S. oryzae*, EO showed 59% toxicity to larvae and 44% mortality to pupae at the same concentration. In another study, Polatoğlu et al. (2016) tested *Crithimum maritimum* (Apiaceae) EO against the larva of *O. surinamensis*, *S. granarius* and *S. oryzae* in Petri plates and observed 100% mortality at 100 μl/ml dose. Papachristos and Stamopoulos (2009) observed the effects of *Lavandula hybrida*, *Rosmarinus officinalis* (Lamiaceae) and *Eucalyptus globules* (Myrtaceae) EOs on the development, longevity and fecundity of *A. obtectus*. All EOs caused increased larval and pupal developmental time and reduced longevity and fecundity of the newly emerged female adults. Studies showed that EOs can penetrate the chorion and/or vitelline membrane, facilitating their diffusion to affect vital physiological and biochemical processes of different developmental stages of insects. During storage conditions, all developmental stages are normally present at a single time and thus the products showing toxicity to immature stages as well has an additional merit to protect food commodities.

7.4.6 Antifeedant Activity

The chemicals which control insect feeding (mainly the active larval stage) and cause death by starvation are called feeding deterrents. Certain EOs have been reported to control grain damage by checking insect feeding in terms of feeding deterrence index (FDI), weight loss of treated seeds and total seed damage. Liu and Ho (1999) tested the antifeedant activity of *Evodia rutaecarpa* (Rutaceae) EO and observed strong antifeedant action against larvae than adults (at a concentration of 0.75 and 1.5 mg/disc for *T. castaneum* and 1.5 and 2.2 mg/disc for *S. zeamais*, respectively for growth and food consumption). Kiran and Prakash (2015) reported complete feeding deterrence of *Gaultheria procumbens* (Ericaceae) EO at 58.62 and 2.71 μl/l air concentration against *S. oryzae* and *R. dominica*, respectively. Similarly, Shukla et al. (2011) observed 100 and 96.82% FDI of *Lippia alba* (Lamiaceae) and *Callistemon lanceolatus* (Myrtaceae) Eos, respectively, even after 24 months of storage against *C. chinensis*. In a study, Satureja hortensis (Lamiaceae) oil significantly decreased the relative growth rate and relative consumption rate of *P. interpunctella* larvae. Further at 2 μl/disk concentration, efficiency of conversion of ingested food (9.843%) was significantly low (Shahab-Ghayoor and Saeidi 2015). Plant products having feeding deterrent activity in general show high adult mortality, less oviposition, increased larvae mortality and low adult emergence. These properties of EOs make them a suitable choice of alternative insecticide for stored food commodities.

7.5 Mode of Insecticidal Action

In most of the studies, the mode of insecticidal activity of EOs have been reported as neurotoxic by either inhibiting acetylcholine esterase (AChE) or by blocking γ-amino butyric acid (GABA) and octopamine receptors. Some other studies also report the EO toxicity by altering enzymatic and nonenzymatic antioxidant defense systems. AChE inhibition is one of the most researched mechanism as the insect AChE differs from the mammalian system by only a single residue and can be used as a selective marker. Various EO components bind the catalytic site of AChE, reduce its activity that lead to the accumulation of acetylcholine at neuromuscular junctions which again in turn induces neuronal excitation, hyperactivity, paralysis and finally death of the insects occur (Abdelgaleil et al. 2009; Kiran and Prakash 2015). Octopamine and GABA receptors are second important targets next to AChE for various EOs. EO components may also bind with octopamine receptors causing increased intracellular cAMP (cyclic adenosine monophosphate) concentration and subsequent death (Kostyukovsky et al. 2002). Some studies also suggested the blockage of GABA receptors as another targets of EOs mediated toxicity (Chaudhari et al. 2021). In a study, Kiran et al. (2017) reported that the toxicity of EO can be assigned to the increase in reactive oxygen species (ROS), superoxide dismutase (SOD) and catalase (CAT) and reduction in glutathione (GSH/GSSG) ratio upon treatment. The depletion in glutathione level can cause oxidative burden resulting into damage to nucleic acids and lipoproteins, and ultimately cell death. However, further research is needed to elucidate the exact mechanism of EOs against stored product insect pests.

7.6 Conclusion and Future Challenges

Due to multiple modes of action, eco-friendly nature, renewable source and favorable safety profile, EOs would be the better alternative to the hazardous chemicals fumigants. To assess their practical application and effective formulation, the large scale testing in storage is needed. Because of growing consumer awareness and negative concerns toward synthetic chemicals, the use of plant-based natural EOs is becoming more popular in food security. Further, these products must be standardized and registered before use to ensure product safety and efficacy. Some of the EO-based pesticides are already available in Western market; however, their use is limited due to higher volatility, low persistence and rapid oxidation. Recently, nanotechnology's booming research trends show that EOs are encapsulated into edible secondary wall materials such as chitosan, gelatin, alginate, carrageenan, cyclodextrins etc. using different nanoencapsulation techniques such as ionic-gelation, spray drying or chilling, coacervation, electrospinning, emulsification etc. This technique not only solved the low persistence of EO but also caused increased efficacy and controlled release of EO at low concentrations, making their application easy. Further, detailed investigations are required for the efficacy of these products in the real food system and their safety profile, an area that needs more research insight.

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