Plant Essential Oils and Pest Management

7

Saeid Moharramipour and Maryam Negahban

Abstract

Insect pest management in agriculture is facing challenge in several problems of using synthetic pesticides and toxic fumigants including environmental contamination, pesticide resistance, and destruction of nontarget organisms. So, public and environmental pressure can support environmentally safe pesticide alternatives to the use of synthetic pesticides. In recent years, a new field is developing on the use of botanical pesticide origin in the pest management practices. Botanicals have been considered as potential pest management agents, because they demonstrate to have a wide range of bioactivity and possess contact and fumigant toxicity and repellent, oviposition, and feeding deterrence. In addition, the main advantages of many plant-based pesticides lie in their low mammalian toxicity and rapid degradation with broad-spectrum activity. Botanical insecticides composed of essential oils may prove to be a reasonable alternative to the more persistent synthetic pesticides. The essential oils obtained by the distillation of aromatic plants can be utilized to protect agricultural product pests. Recently, the essential oils and their constituents have received a great deal of attention as pest control agents.

They are volatile and can function as fumigants and, in some instances, are comparable to methyl bromide in laboratory tests with insects. Their action against stored product insects has been extensively studied. Moreover, these natural oil and new formulations are considered to be an alternative means of controlling harmful larvae of field crop insects. Recent research has demonstrated their larvicidal and antifeeding effects, their capacity to delay

S. Moharramipour (✉) • M. Negahban
Department of Entomology, Faculty of Agriculture,
Tarbiat Modares University, P. O. Box 14115-336,
Tehran, Iran
e-mail: moharami@modares.ac.ir

K. Sahayaraj (ed.), *Basic and Applied Aspects of Biopesticides*,
DOI 10.1007/978-81-322-1877-7_7,

development and adult emergence and cause egg mortality, their deterrent effects on oviposition, and their arrestant and repellent action. Also the combined effects of gamma radiation or diatome with essential oil on some stored product insect have been reported. Despite these most promising properties, problems related to their volatility, poor water solubility, aptitude for oxidation, and high sorption are the important limiting factors for the application of natural compounds in large-scale commodity fumigations, and it might lead to more residue-treated commodities. In view of the problem, it is necessary to do a kind of research such as work on new formulations of the oil components and their effects on sorption, tainting, and residues in food commodities. Nowadays, using new technologies such as nanoencapsulated formulation can overcome the constraints of plant essential oils. It seems that the findings of research could be promising to make practical use of plant essential oils. As the new technology in nanoencapsuled essential oil through the control release of active ingredients overcome the restrictions of plant essential oils usage in storage and farms. Finally, most of the natural pest control measures using botanicals are becoming important tools by the development of their use in pest management, because they could be economical and eco-friendly for both the public health and the environment.

Keywords
Botanicals • Biopesticides • Nanocapsule • Plant essential oil • Stored-product pests • Field crop insects

7.1 Introduction

Widespread insecticide resistance has been a major problem in a sustainable and cost-effective biointensive integrated pest management (BIPM) strategy. In addition, the increasing public concern over pesticide safety and possible damage to the environment has resulted in increasing attention being given to natural products for the control of agricultural pests (Rajendran and Sriranjini 2008; Zapata and Smagghe 2010). The coevolution of plants along with insects has compelled the use of natural chemical defenses for the management of insect pests. Several studies have focused on the potential use of botanical applications in biological control of different insect pests, since some are selective, biodegrade to nontoxic products, and have few effects on nontarget organisms and the environment (Singh and Upadhyay 1993; Isman 2000; Kim et al. 2010). Apart from all the advantages and safety aspects of botanicals as compared to synthetics, it will also give farmers the necessary psychological satisfaction. At the same time, it will be helpful in reducing the present excessive use of synthetic insecticides, which are not compatible with many biological and microbial components of an IPM package (Rattan 2010). In the past few decades, several studies have focused on the potential use of the essential oil applications in biological control of different economically important insect pests.

The essential oils may be more rapidly degraded in the environment than synthetic compounds, and some have increased specificity that favors beneficial insects, and the pesticides of plant origin are gaining increased attention and interest among those concerned with environment-friendly, safe, and integrated crop management approaches. In addition, they are playing a vital role in organic food production globally (Pillmoor et al. 1993; Rattan 2010). Their action against stored product insects has been extensively studied (Negahban et al. 2007a; Sahaf et al. 2008a, b, c; Rastegar et al. 2008; Saeidi and Moharramipour 2008; Sahaf and Moharramipour 2007; Arabi et al. 2008a, b; Ghasemi et al. 2009). Moreover, these natural derivatives are considered to be an alternative means of controlling pestiferous larvae of Lepidoptera (Jamal et al. 2011; Hasheminia et al. 2011; Yi et al. 2007; Vanichpakorn et al. 2010; Lee et al. 2001a, b). That is to say that recent research has demonstrated their larvicidal and antifeeding effects (Negahban and Moharramipour 2007a; Negahban and Moharramipour 2008; Sahaf and Moharramipour 2008), their capacity to delay development and adult emergence and cause egg mortality, their deterrent effects on oviposition (Negahban and Moharramipour 2007b; Shakarami et al. 2004; Sahaf et al. 2008b), and their arrestant and repellent action (Negahban et al. 2007b; Moharramipour et al. 2008; Sahaf et al. 2008a). In view of the various activities of the essential oils against agriculture product pests as reported by various workers, plant extracts contain compounds that show ovicidal, repellent, and antifeedant properties and can combine with other methods such as gamma radiation (Ahmadi et al. 2008a,b).

The insecticidal constituents of many plant extracts and the essential oils are monoterpenoids. Camphor, camphene, 1,8-cineol and α-pinene, linalool, methyl acetate, limonene, menthone, geraniol, citral, citronellal, thymol, carvacrol, eugenol, geraniol, and *trans*-anethole are well-known examples of pesticide compounds (Phillips et al. 2010; Negahban et al. 2007a; Isman and Machial 2006; Isman 2000). Additionally, monoterpenoid compounds have been considered as potential pest control agents because they are acutely toxic to insects and possess repellent (Mediouni-Ben Jemaa and Tersim 2011; Kim et al. 2010) and antifeedant properties (Sbeghen-Loss et al. 2011; Shukla et al. 2012) and ovicidal, larvicidal, pupicidal, and adulticidal activities (Yang et al. 2004; Waliwitiya et al. 2009; Murugan et al. 2012).

Finally, mostly the work has been carried on studying the effects of the essential oils, their lethal doses, and the time to achieve lethal effects, but their formulations especially as a form of micro- or nanoencapsules are in general not fully elucidated. Nanotechnology of the essential oils may act through the control release of active ingredients and overcome the restrictions of plant essential oils usage in storage and farms. Nanoencapsulation is a process in which tiny particles or droplets are surrounded by a coating to give small capsules many useful properties. In a relatively simplistic form, a nanocapsule is a small sphere with a uniform wall around it. The material inside the nanocapsule is referred to as the core, internal phase, or fill, whereas the wall is sometimes called a shell, coating, or membrane. Most nanocapsules have dimensions measured in nanometers. Nanocapsules have a polymeric shell; the active substances are usually dissolved in the inner core but may also be adsorbed at their surface (Khoee and Yaghoobian 2009).

Nanoencapsulation technique can serve as new model formulations for the development of the essential oils and their compound derivatives with enhanced activity or environmental friendliness. However, their functions and clarity on the specificity of the metabolites responsible for proclaimed insecticidal activity is lacking. Worthwhile for us, the plant origin nanoinsecticides could be exploited for the development of novel formulations with highly precise target for sustainable insect pest management in agriculture. In this chapter, we review the essential oil sources of insecticidal activity, their constituents, and mode of action and discuss the few botanical materials with potential action and their development of formulation with encapsulation for producing nanoinsecticidal products.

7.2 Potential and Improvement of Plant Essential Oils as New Insecticides

The use of the essential oils extracted from aromatic plants to control pests has been investigated and is well documented (Isman 2006). As a result, most essential oils come from highly aromatic species such as those in the Asteraceae, Myrtaceae, Apiaceae, Verbenaceae, and Lamiaceae plant families. Many aromatic plant species are indigenous to Iran (Naghibi et al. 2005). Iran is situated in arid and semiarid areas and has many endemic aromatic plants from different families. It therefore seems very worthwhile to mount a comprehensive screening program to determine the insecticidal efficacy of such plants. Additional research from our laboratory shows that several essential oils possess insecticidal activity effects (Table 7.1). The genus *Artemisia* is a member of the large and evolutionary advanced plant family (Asteraceae). More than 300 different species comprise this diverse genus which is mainly found in arid and semiarid areas of Europe, America, and North Africa as well as in Asia (Heywood and Humphries 1977). Many *Artemisia* species are used medicinally and hence to be of more commercial values. It has been reported that *Artemisia herba-alba* Asso. (Asteraceae) inhibits the asexual reproduction of *Aspergillus niger* Tiegh (Eurotiales: Trichocomaceae), *Penicillium italicum* Wehmer (Eurotiales: Trichocomaceae), and *Zygorhychus* sp. Vuillemin (Tantaoui-Elaraki et al. 1993). *Artemisia scoparia* Waldst et Kit (Asteraceae) is used as a choleretic, anti-inflammatory, and diuretic agent in the treatment of hepatitis (Hikino 1985).

Table 7.1 Examples of essential oils and insects which are known to be affected by these oils

Plant source	Insect species[a]	Action[b]	Selected references
Perovskia atriplicifolia	*T. castaneum*	F, SG, MFO	Ahmadi et al. (2008a, b, c, d, e), (2009a, b), (2011a, b)
	C. maculatus	F, SG, MFO	
Rosmarinus officinalis	*T. castaneum*	F, SG, MFO	
	C. maculatus	F, SG, MFO	
Artemisia sieberi	*C. maculatus*	F, R, OD, O	Negahban et al. (2006a, b), Negahban and Moharramipour (2008), (2007a, b)
	S. oryzae	F, R	
	T. castaneum		
Artemisia scoparia	*C. maculatus*	F, R, FD	Negahban et al. (2006a), Negahban and Moharramipour (2007a, b)
	S. oryzae	F, R, OD, O	
	T. castaneum	F, R	
		F, R, FD	
Thymus kotschyanus	*C. maculatus*	F, R, OD, O	Akrami et al. (2011)
Mentha longifolia	*C. maculatus*	F, R, OD, O	
Perovskia abrotanoides	*T. castaneum*	F, R, FD	Arabi et al. (2008a, b)
	S. oryzae	F, R	
Tanacetum polycephalum	*T. castaneum*	F	
Thymus kotschyanus	*V. destructor*	F	Ghasemi et al. (2009, 2011)
Ferula assa-foetida	*V. destructor*	F	
Mentha longifolia	*V. destructor*	F	
Artemisia annua	*P_i. rapae*	FD	Hasheminia et al. (2011)
Achillea millefolium	*P_i. rapae*	FD	
Ruta graveolens	*C. maculatus*	F	Hosseinpour et al. (2011)
Ferula gummosa	*C. maculatus*	F	
Carum copticum	*P_l. xylostella*	F, R, FD	Jamal et al. (2012)
Eucalyptus leucoxylon	*C. maculatus*	F	Kambouzia et al. (2009)
	S. oryzae	F	
	T. castaneum	F	
Vitex pseudo-negundo	*B. brassicae*	F	Moharramipour and Sahaf (2006)
Salvia mirzayanii	*C. maculatus*	F	Nikooei et al. (2011)
	T. confusum	F	
Zhumeria majdae	*T. confusum*	F, R, FD	

(continued)

Table 7.1 (continued)

Plant source	Insect species[a]	Action[b]	Selected references
Achillea wilhelmsii	*P. interpunctella*	F, R, FD, O	Rafiei Karahroodi et al. (2008, 2009, 2011)
Achillea millefolium	*P. interpunctella*	F, R, FD, O	
Artemisia dracunculus	*P. interpunctella*	F, R, FD, O	
Salvia multicaulis	*P. interpunctella*	F, R, FD, O	
Thymus vulgaris	*P. interpunctella*	F, R, FD, O	
Ziziphora clinopodioides	*P. interpunctella*	F, R, FD, O	
Rosmarinus officinalis	*P. interpunctella*	F, R, FD, O	
Lavandula angustifolia	*P. interpunctella*	F, R, FD, O	
Mentha piperita	*P. interpunctella*	F, R, FD, O	
Hyssopus officinalis	*P. interpunctella*	F, R, FD, O	
Salvia officinalis	*P. interpunctella*		
Anethum graveolens	*P. interpunctella*		
Foeniculum vulgare	*P. interpunctella*		
Carum carvi	*P. interpunctella*		
Petroselinum sativum	*P. interpunctella*		
Artemisia absinthium	*P. interpunctella*		
Santolina chamaecyparissus	*C. maculatus*	F	Saeidi et al. (2011), Saeidi and Moharramipour (2008)
Citrus reticulata	*C. maculatus*	F, R, OD, O	
Citrus limon	*C. maculatus*	F, R, OD, O	
Citrus aurantium	*C. maculates*	F, R, OD, O	
	C. maculatus		
Carum copticum	*C. maculatus*	F, R, OD, O	Sahaf and Moharramipour (2007, 2008, 2009), Sahaf et al. (2007, 2008a, b, c)
Vitex pseudo-negundo	*S. oryzae*	F, FD	
	T. castaneum	F, R, FD	
Salvia bracteata	*C. maculatus*	F, R, OD, O	Shakarami et al. (2004, 2005)
	S. oryzae	F, R	
	T. castaneum	F, R, FD	
	S. granarius	F, R	
Thymus persicus	*C. maculatus*	F, R, OD, O	Taghizadeh Saroukolai (2008a, b), (2009), (2010), Taghizadeh Saroukolai and Moharramipour (2011)
Prangos acaulis	*S. oryzae*	F, R	
	T. castaneum	F, R, FD	
	C. maculatus	F, R, OD, O	
	S. oryzae	F, R	
	T. castaneum	F, R, FD	

[a]Genus; *B*, *Brevicoryne; C*, *Callosobruchus; P*, *Plodia; P_i*, *Pieris; P_l*, *Plutella; S*, *Sitophilus*; *T*, *Tribolium*
[b]Action, *F* fumigant, *R* repellent, *FD* feeding deterrence, *OD* oviposition deterrence, *O* ovicide, *SG* synergism with gamma radiation, *MFO* micronuclei formation in ovaries induced by gamma radiation and oil

Artemisia is a genus that grows in many areas of Iran. There are several reports showing that species of this genus are highly toxic to stored product insects such as *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae), *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), and *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) (Negahban et al. 2006b, 2007a). The effects of *Artemisia annua* L. (Asteraceae) crude leaf extracts on the toxicity, development, feeding efficiency, and chemical activities of small cabbage *Pieris rapae* L. (Lepidoptera: Pieridae) have been evaluated (Hasheminia et al. 2011). *Artemisia vulgaris* L. (Asteraceae) has been reported to be repellent and toxic to *T. castaneum* (Wang et al. 2006). The fumigant toxicity of the essential oils extracted from two plants of the Iran flora, *Ruta graveolens* L. (Rutaceae) belonging to Rutaceae and *Ferula gummosa* Boiss from Apiaceae, was investigated on *C. maculatus* (Hosseinpour et al. 2011). Also the toxicity of 42 essential oils extracted from Myrtaceae has been tested against *S. oryzae* and *T. castaneum* (Lee et al. 2004). Negahban and Moharramipour (2007c) reported the fumigant toxicity of three Myrtaceae species oil, *Eucalyptus intertexta* R.T. Baker (Myrtaceae), *Eucalyptus sargentii* Maiden (Myrtaceae), and *Eucalyptus camaldulensis* Dehnh (Myrtaceae), against three major stored-product beetles, *C. maculatus*, *S. oryzae*, and *T. castaneum*.

Lamiaceae family is best known for their essential oils common to many members of the family. These plants have been used by human since prehistoric times and are one of the major sources of culinary, vegetable, and medicinal plants all over the world (Naghibi et al. 2005). From this family, the genus *Thymus* (Lamiaceae) consists of 14 species in Iranian flora, four of which including *Thymus persicus* (Ronniger ex Rech. f.) are indigenous to Iran (Rechinger 1982; Nickavar et al. 2005). *Thymus* species have strong antifungal, antibacterial, and insecticidal activity (Stahl-Biskup and Saez 2002; Rasooli et al. 2006). These plant species and their extracts are known to have various effects on insect pests, including stored-product insects. Several studies have assessed the ability of the *Thymus* essential oils and their constituents as fumigants and repellents against a number of insect pests. The insecticidal and repellent activities of *Thymus vulgaris* L. have been reported against *T. castaneum* (Clemente et al. 2003), *S. oryzae* (Lee et al. 2001a), *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) (Passino et al. 2004), *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae) (Hori 2003), *Spodoptera litura* (F.) (Lepidoptera: Noctuidae) (Hummelbrunner and Isman 2001) and mushroom sciarids (*Lycoriella mali* Fitch, Sciaridae) (Choi et al. 2006). Other plant essential oils with biological activity include *Thymus mandschuricus* Ronniger against *S. oryzae* (Kim et al. 2003) and *Thymus mastichina* (L.) against *T. castaneum* (Pascual-Villalobos and Robledo 1998). Moreover, *Thymus serpyllum* L. which is rich in the phenols thymol and carvacrol has fumigant effect against the bean weevil *Acanthoscelides obtectus* (Say) (Coleoptera: Bruchidae) (Regnault-Roger et al. 1993; Regnault-Roger and Hamraoui 1995). The fumigant effect of the essential oil extracted from aerial part of the *T. persicus* has been investigated against the red flour beetle, *T. castaneum,* and rice weevil *S. oryzae* (Taghizadeh Saroukolai et al. 2010). *Salvia mirzayanii* (Rech. F. and Esfand) (Lamiaceae) is a wild-growing flowering plant belonging to the family Lamiaceae and is found in the southern area of Iran (Yamini et al. 2008). Many studies indicated antioxidant, antimicrobial, and antiviral activities of some *Salvia* species (Sivropoulou et al. 1997; Javidnia et al. 2002). Soleimannejad et al. (2011) has reported the high-toxicity effects of *S. mirzayanii* essential oil on nutritional indices of the *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae) adults.

Perovskia abrotanoides Karel (Lamiaceae), the Caspian Russian sage, is a perennial silvery white spicy foliage plant with long-lasting dark blue flowers. Despite its common name, *P. abrotanoides* is native to Iran, Afghanistan, Pakistan, Tajikistan, Turkmenistan, and Tibet China province (Xizang region) (Rechinger 1982; USDA 2007). The efficiency of the essential oil from *P. abrotanoides* has been reported as a fumigant in the management of *S. oryzae* and *T. castaneum* (Arabi et al. 2008a). Also, the oviposition deterrence and repellent activity of *Thymus kotschyanus* Boiss and Hohen and *Mentha longifolia* L. (Lamiaceae) was reported on *C. maculatus* (Akrami et al. 2011). Ajwain, *Carum copticum* C. B. Clarke (Apiaceae), is a medicinal plant, and its oil is used as pharmaceutical and in flavoring. It is an annual plant which grows in the Iran, Pakistan, and Egypt with white flowers and small brownish fruits (Zargari 1991). Chaste tree, *Vitex pseudo-negundo* Hand I. MZT (Verbenaceae), naturally grows around seasonal rivers in Iran. Medicinal properties of this species caused to introduce *V. pseudo-negundo* as a familiar drug (Filekesh et al. 2005). The insecticidal activity of *C. copticum* (Sahaf et al. 2007) and *V. pseudo-negundo* (Sahaf et al. 2008a, b) has been determined against *T. castaneum*, *S. oryzae*, and *C. maculatus* (eggs, larvae and adults), as an important storage pest of legume seeds in Iran (Sahaf and Moharramipour 2008).

Repellency effect, oviposition deterrency, and ovicidal activity of several essential oils of medicinal plant species growing in Iran have been investigated by Rafiei Karahroodi et al. (2008; 2009; 2011). In recent years, some commercial plant extracts have been introduced to varroa control. Acaricidal activity of the essential oils of *T. kotschyanus*, *Ferula assa-foetida* L. (Apiaceae), and *E. camaldulensis* has been demonstrated against *Varroa destructor* Anderson (Mesostigmata: Varroidae) (Ghasemi et al. 2011). In addition, combined application of the essential oils and gamma radiation is an ecologically safe method which could be used in the management of stored-product pests (Ahmadi et al. 2008a, b). Under in vitro experimental conditions, the essential oil had no significant direct effect on frequency of micronucleus induced in *T. castaneum* ovaries. However, using gamma radiation alone and in combination with *Rosmarinus officinalis* L. (Lamiaceae) has significantly increased the induced micronucleus. They indicated that gamma radiation can induce significant cytogenetic effects and in combination with *R. officinalis* could show synergistic effect (Ahmadi et al. 2009b).

In spite of these hopeful properties, problems related to their volatility, poor water solubility, and oxidation potentiality have to be resolved before use as an alternative pest control system, in the hope that using encapsulated formulations of the essential oil components seems to be the best choice (Clancy et al. 1992; Moretti et al. 2002). Controlled release by nanoencapsulated formulations allows the essential oil to be used more effectively over a given time interval, suitability to mode of application, and minimization of environmental damage. Our studies indicated a postingestive toxicity of the essential oil from *Artemisia sieberi* Besser (Asteraceae) using the nanoencapsulated formulation as potential insecticide for the control of *Plutella xylostella* (L.), (Lepidoptera: Plutellidae), and *T. castaneum* (Negahban et al. 2011b; 2013a). Also, ovicidal activity of nanoencapsulated essential oil of *C. copticum* on diamondback moth *P. xylostella* was evaluated by Jamal et al. (2012). Consequently, our results showed higher repellency rates in nanocapsule than in pure essential oil due to controlled-release formulations allowing smaller quantities of the essential oil to be used more effectively over a given time interval. The reasons for nanocapsulating the essential oil have been to improve its stability to reduce side effects or to reduce dosing frequency and total dosing amount, to obtain better repellent activity, and for sustained (long-lasting) release. Therefore, the nanocapsulation of the essential oil might provide a new method for the management of pests (Negahban et al. 2013a, b). Also, persistence or half-life time of the nanoencapsulated essential oil of *A. sieberi* was significantly longer than *A. sieberi* oil against stored product insect, such as *T. castaneum*. These results elucidate the suitability of nanoencapsulated essential oil as an insect control agent in organic food protection (Negahban et al. 2010). Despite fundamental differences in biology, physiology, and feeding behavior of tested insects, the general response of insect's toxicity, repellency, and antifeedant activities of nanoencapsuled essential oil was similarly effective in many aspects compared to pure essential oil. Overall, it seems that the findings of research could be promising to make practical use of plant essential oils, as the new technology in nanoencapsuled essential oil through the control release of active ingredients overcome the restrictions of plant essential oils usage in storage and farms. Nevertheless, more studies are necessary to economize these novel technologies in natural environments such as warehouses, greenhouses, and farms.

7.3 Essential Oils: Extraction Methods, Constituents, and Their Efficacy

Methods used for extracting the essential oil include traditional press extraction (Chen et al. 2008), steam distillation extraction (Mostafa et al. 2010; Xavier et al. 2011), organic solvent extraction (Sarikurkcu et al. 2009), subsequent ultrasound-assisted solvent extraction (Sereshti et al. 2011), supercritical CO2 extraction (Akgun et al. 2009; Zizovic et al. 2007), microwave-assisted steam distillation (Chemat et al. 2006; Sahraoui et al. 2008), and so on. On the other hand, some known disadvantage factors, such as lower extraction rate, loss of active composition, residual of organic solvents, and higher production cost, limit their application in industrial process. Compared with others, hydrodistillation is the most commonly used method due to its advantages: easy to operate, lower cost, and good quality. However, because of involvement of higher temperatures and long time in the extraction process, some thermal-sensitive compounds in the essential oil are destroyed (Liu et al. 2009). Thus, reduction of distillation time in hydrodistillation process will provide a promising extraction method for the essential oil. If the distillation time could be reduced significantly under the premise of full extraction, the advantages of hydrodistillation are retained, while the quality of the resulting oil can be improved. Extracting the essential oil by hydrodistillation can be described as several steps. First, the essential oil molecules exist initially in plant cells in contact with water molecules, then the total pressure of mixture will reach the amount of partial pressure of each component at same temperature, finally the essential oil is brought out by water vapor. Ultrasonic processing technology is the most effective method for mixing liquid material currently. It is reasonable to believe that ultrasonic processing has positive effects on reducing distillation time through promoting contact of the two molecules. Additionally, it has been reported that the extraction rate of the essential oil can be enhanced by adding an appropriate amount of inorganic salts during the extraction process (Ji et al. 2008).

The essential oils are complex mixtures of 20–60 organic compounds and hundreds of different constituents (Bakkali et al. 2008; Rajendran and Sriranjini 2008). Depending on its chemistry, an essential oil can have widely different therapeutic and insecticidal actions. The ingredients found in the essential oils are organic due to their molecular structure which is based on carbon atoms held together by hydrogen atoms. Oxygen atoms and sometimes nitrogen and sulfur atoms are also present. Chemical structures of some of the essential oil constituents possess potent biological activity (Fig. 7.1) and are responsible for the bitter taste and toxic properties. Essential oil constituents are primarily lipophilic compounds that act as toxins, feeding deterrents, and oviposition deterrents to a wide variety of insect pests. Insecticidal properties of several monoterpenoids have been reported on housefly, red flour beetle, and southern corn rootworm (Rice and Coats 1994; Lee et al. 2004; Wang et al. 2006, Kim et al. 2010). As mentioned above, the essential oils are complex mixtures of natural organic compounds which are predominantly composed of terpenes (hydrocarbons), such as myrcene, pinene, terpinene, limonene, phellandrene, etc., and terpenoids (oxygen containing hydrocarbons), such as acyclic monoterpene alcohols (geraniol, linalool), monocyclic alcohols (menthol, 4-carvomenthenol, terpineol, carveol, borneol), aliphatic aldehydes (citral, citronellal, perillaldehyde), aromatic phenols (carvacrol, thymol, safrole, eugenol), bicyclic alcohol (verbenol), monocyclic ketones (menthone, pulegone, carvone), bicyclic monoterpenic ketones (thujone, verbenone, fenchone), acids (citronellic acid, cinnamic acid), and esters (linalyl acetate). Some essential oils may also contain oxides (1,8- cineole), sulfur-containing constituents, methyl anthranilate, and coumarins. Zingiberene, curcumene, farnesol, sesquiphellandrene, termerone, and nerolidol are examples of sesquiterpenes (C15) isolated from essential oils. Mono and sesquiterpenoidal essential oil constituents are formed by the condensation of isopentenyl pyrophosphate units. Diterpenes usually do not occur in the essential oils but are sometimes encountered as by-products (Koul et al. 2008). The eight main chemical components found in the essential oils are as follows.

7.4 Monoterpene Alcohols

They contain 10 carbon atoms often arranged in a ring or in acyclic form. They are colorless and highly volatile. They can deteriorate very quickly

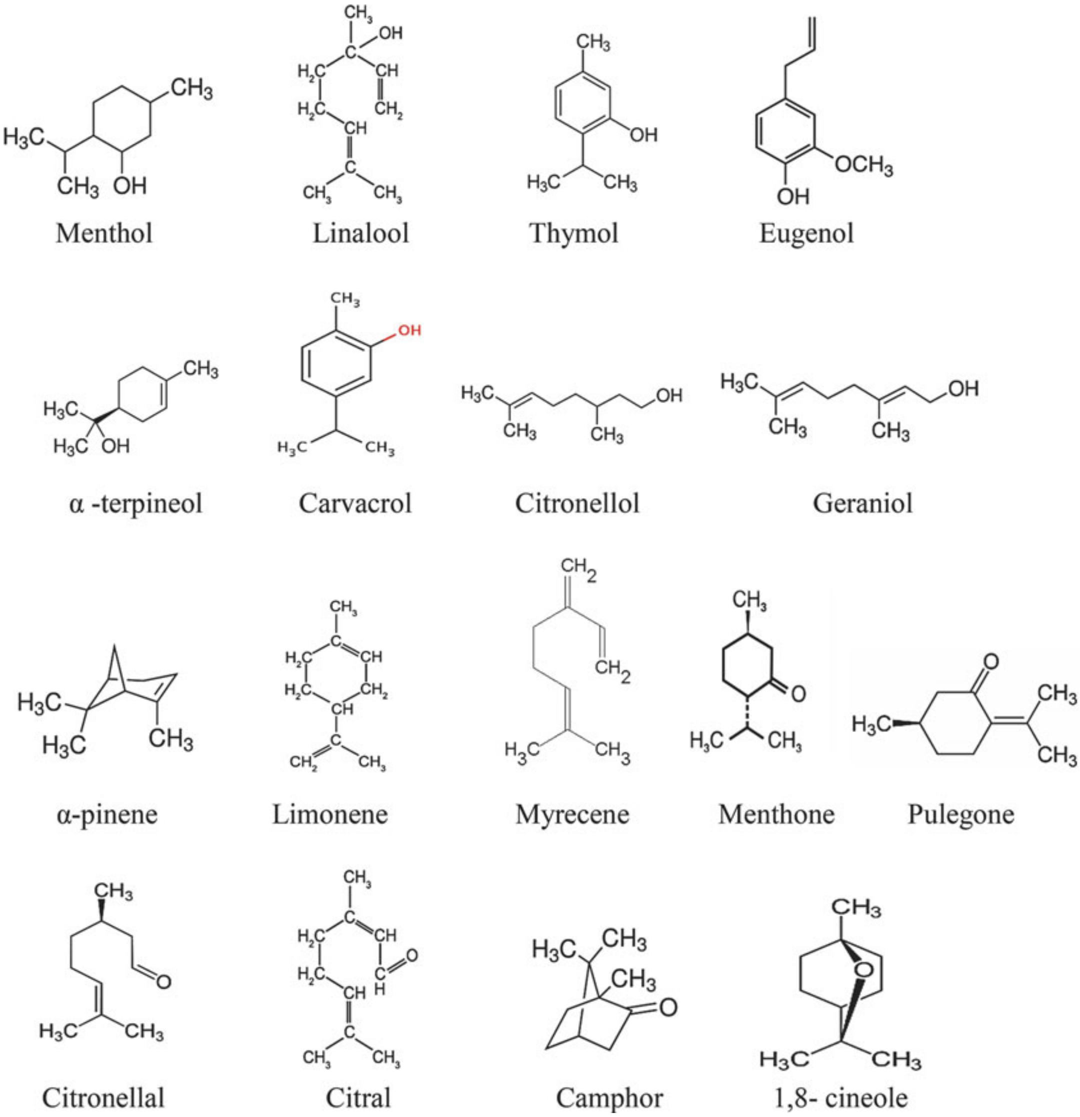

Fig. 7.1 Chemical structure of some plant essential oil components with insecticidal activities

and therefore need to be kept at cool temperatures and to be antiviral, antibacterial, and antifungal. Being typically volatile and rather lipophilic compounds, they can rapidly penetrate into insects and interfere with their physiological functions (Lee et al. 2002) and have insecticidal properties. Eugenol is reported as toxic to *S. litura*, *Sitophilus granarius* (L.) (Coleoptera: Curculionidae), *Musca domestica* L. (Diptera: Muscidae), and *Diabrotica virgifera* Lee Conte (Coleoptera: Chrysomelidae) (Hummelbrunner and Isman 2001; Obeng-Ofori et al. 1997; Lee et al. 1997). Eugenol is also active against *Drosophila melanogaster* Meigen (Diptera: Drosophilidae), *Aedes aegypti* (L.) (Diptera: Culicidae), and American cockroach, *Periplaneta americana* (L.) (Blattodea: Blattidae) (Bhatnagar et al. 1993, Ngoh et al. 1998). Cornelius et al. (1997) evaluated toxicity of monoterpenoids against *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae) (a subterranean termite) of which eugenol was found most effective as termiticide. Moreover, Meepagala et al. (2006) found that apiol isolated from *Ligusticum hultenii* Fernald (Apiaceae) exhibited high termiticidal activity and similar effect was shown by vulgarone B, isolated from *Artemisia douglasiana* Besser (Asteraceae). According to Raina et al. (2007) and Chauhan and Raina (2006) *d*-limonene, *E*, *Z*- nepetalactone, and *Z*, *E*-nepetalactone caused mortality to formosan subterranean termite, *C. formosanus*, and there was significant reduction in feeding. It was also effective as a fumigant and as feeding deterrent. Similarly, thymol has shown to have direct contact toxicity to larvae of *Agriotes obscurus* (L.) (Coleoptera: Elateridae) (Waliwitiya et al. 2000). Varying concentrations of the essential oil of red thyme having thymol are toxic to *A. aegypti* and *Aedes albimanus* Wiedemann (Barnard 1999). Thymol was also found to repel mosquitoes (Kalemba et al. 1991, Chokechaijaroenporn et al. 1994). According to Taghizadeh Saroukolai et al. (2010), the insecticidal activity of *T. persicus* could be related to these constituents.

Citronellal is toxic to *S. litura*, *M. domestica* (Hummelbrunner and Isman 2001; Lee et al. 1997), and *C. maculatus* (Don-Pedro 1996). There are several reports on insecticidal activity of camphor (Negahban et al. 2007a) in some species of *Artemisia*, and 1,8-cineole was the most toxic fumigant found in eucalyptus, rosemary, and *Perovskia* essential oils (Lee et al. 2003; Negahban and Moharramipour 2007c, Lee et al. 2001a; Negahban et al. 2007a; Arabi et al. 2008a). Coats et al. (1991) found the fumigant toxicity effect of myrcene and a-terpineol against *S. oryzae* after 24 h. α-Pinene is reported to be toxic to *T. confusum* (Ojimelukwe and Alder 1999). Hierro et al. (2004) have reported the toxicity activity of geraniol, citronellol, citral, carvacrol, and cuminaldehyde against *Anisakis simplex* Rudolphi (Ascaridida: Anisakidae). Menthone, trans-anethole, and cinnamaldehyde are well-known anti-insect compounds (Marcus and Lichtenstein 1979, Harwood et al. 1990, Lee et al. 1997, Franzios et al. 1997, Huang and Ho 1998; Hummelbrunner and Isman 2001; Chang and Ahn 2001; Chang and Cheng 2002). *d*- Limonene, linalool, myrcene, and terpineol significantly increased the nymphal duration in German cockroach, *Blattella germanica* (L.) (Blattodea: Blattellidae), when fed through artificial diet (Karr and Coats 1992). Also, *d*-limonene is toxic to *M. domestica*, *D. virgifera*, *S. litura* (Lee et al. 1997; Hummelbrunner and Isman 2001), and some stored grain pests and cockroaches (Don-Pedro 1996, Coats et al. 1991). Similarly, limonene found in the essential oil of various citrus leaves and fruit peels has exhibited significant insect control properties (Karr and Coats 1988). Acaricidal activity of thymol and 1,8-cineole from the essential oils of *T. kotschyanus*, *F. assa-foetida*, and *E. camaldulensis* against *V. destructor* was evaluated (Ghasemi et al. 2011). Essential oils rich in 1,8-cineole are also effective against house dust mites (Miresmailli et al. 2006). Among pure constituents, citronellal, eugenol, menthol, pulegone, and thymol are moderately active against various mites (Calderone and Spivak 1995; Perrucci 1995; Ellis and Baxendale 1997).

7.5 Sesquiterpene Alcohols

Which hydrocarbons comprise of 15 carbon atoms. These terpenes are not as volatile as monoterpenes and having a calming effect as well as being anti-inflammatory and anti-infectious. Varying properties include anti-inflammatory, antiviral, and anticarcinogenic. New insecticidal sesquiterpene extracts of the root bark of *Celastrus angulatus* M. have been reported (Wei et al. 2011).

7.6 Other Compounds

Aldehydes: antimicrobial, anti-inflammatory, disinfectant, and sedative

Esters: antispasmodic, anti-inflammatory, antifungal, calming, and sedative

Ethers: antispasmodic and analgesic

Ketones: anticatarrhal, regenerative, and analgesic

Oxides: expectorant and stimulant

Phenols: Strongly antimicrobial, stimulants to the immune and nervous system, and irritating to mucous membranes.

The essential oils work as the chemical defense mechanism of the plant. They ward off insects and play a role in initiating the regeneration process for the plant. They have a chemical structure that is similar to that found in human and animal cells and tissues. This makes the essential oils compatible with human and animal protein and enables them to be readily identified and accepted by the body. Diffused essential oils can increase atmospheric oxygen and provide negative ions that inhibit bacterial growth and can break down and render potentially harmful chemicals nontoxic. Some benefits of pure therapeutic grade essential oils are as follows: regenerating, oxygenating, and immune defense properties of plants, also containing oxygen molecules, which help to transport nutrients to the starving human cells. Because a nutritional deficiency is an oxygen deficiency, disease begins when the cells lack the oxygen for proper nutrient assimilation. By providing the needed oxygen, the essential oils also work to stimulate the immune system, very powerful. Antioxidants create an unfriendly environment for free radicals. They prevent all mutations, work as free radical scavengers, prevent fungus, and prevent oxidation in the cells, removing metallic particles and toxins from the air.

Plant essential oils are produced commercially from several botanical sources. Examples include 1,8-cineole, eugenol, thymol, menthol, asarones, carvacrol, and linalool from many plant species. A number of source plants have been traditionally used for protection of stored commodities (Koul et al. 2008), especially in the Mediterranean region and in Southern Asia, but interest in the oils was renewed with emerging demonstration of their fumigant and contact insecticidal activities to a wide range of pests in the 1990s (Isman 2000). The rapid action against some pests is indicative of a neurotoxic mode of action, and there is evidence for interference with the neuromodulator octopamine (Kostyukovsky et al. 2002) by some oils and with GABA-gated chloride channels by others (Priestley et al. 2003). Recent evidence for an octopaminergic mode of action for certain monoterpenoids (Bischof and Enan 2004; Kostyukovsky et al. 2002), combined with their relative chemical simplicity, may yet find these natural products useful as lead structures for the discovery of new neurotoxic insecticides with good mammalian selectivity. The knowledge on the mode of action of available insecticides will help to determine the chemical properties of novel compounds that may be ideally suited for modification of insect behavior at doses that can be used safely and economically in agriculture (Haynes 1988). The plant origin insecticides could be exploited for the development of novel molecules with highly precise target for sustainable insect pest management in agriculture (Rattan 2010). Given these encouraging results, further experiments are in progress to assess the suitability of natural active principle formulations for application as a new tool in integrated control of different pest.

7.7 Fumigant Properties of Essential Oils

More current research shows that the essential oils and their constituents may have the potential as alternative compounds to currently used fumigants (Nattudurai et al. 2012; Kim et al. 2010; Suthisut et al. 2011). Major constituents from aromatic plants, mainly monoterpenes, are of special interest to industrial markets because of other potent biological activities in addition to their toxicity to insects (Kubo et al. 1994; Isman 2000; Weinzierl 2000). Several studies have been undertaken in our laboratory to explore the potential of the essential oils and their constituents as insect fumigants. Table 7.2 provides examples of bioassay test to determine the LC_{50} values of insecticidal activity of a few of the better-known essential oils. Their action against stored product insects has been extensively studied. Moreover, these natural derivatives are considered to be an alternative means of controlling harmful larvae of field crop insect pests. The optimum use of the essential oils with maintaining their active ingredients by developing applicable methods is the essential way to control insects. For taking into account the limitations and the physicochemical characteristics of the essential oils, nanoencapsulated formulations of the essential oil components seem to be the best choice. To get the best out of our

Table 7.2 Fumigant toxicity of some selected plant essential oils on insects and mites

Plant source	Insect species[a]	Stage	LC_{50} (μL/L air) (95 % fiducial limits)	Selected references
Artemisia scoparia	*C. maculatus*	Adult	1.46 (1.29–1.68)	Negahban et al. (2006a)
	S. oryzae	Adult	1.87 (1.70–2.11)	
	T. castaneum	Adult	2.05 (1.72–2.37)	
Artemisia sieberi	*C. maculatus*	Adult	1.45 (1.23–1.66)	Negahban et al. (2007a)
	S. oryzae	Adult	3.86 (3.49–4.28)	
	T. castaneum	Adult	16.76 (14.64–18.61)	
Eucalyptus intertexta	*C. maculatus*	Adult	2.55 (2.24–2.84)	Negahban and Moharramipour (2007c)
	S. oryzae	Adult	6.93 (6.45–7.34)	
	T. castaneum	Adult	11.59 (11.28–11.90)	
Eucalyptus camaldulensis	*C. maculatus*	Adult	3.97 (3.64–4.31)	
	S. oryzae	Adult	12.06 (11.63–12.43)	
	T. castaneum	Adult	33.50 (30.47–36.51)	
Eucalyptus sargentii	*C. maculatus*	Adult	3.87 (3.56–4.19)	
	S. oryzae	Adult	12.91 (12.47–13.33)	
	T. castaneum	Adult	18.38 (17.65–19.07)	
Carum copticum	*S. oryzae*	Adult	12.30 (6.42–42.74)	Sahaf et al. (2007)
	T. castaneum	Adult	150.36 (102.69–284.81)	
Vitex pseudo-negundo	*C. maculatus*	Egg	2.20 (1.81–2.94)	Sahaf and Moharramipour (2008)
		Larvae	8.42 (6.87–10.06)	
		Adult	9.39 (6.63–14.22)	
Vitex pseudo-negundo	*S. oryzae*	Adult	31.96 (26.60–39.25)	Sahaf et al. (2008a)
	T. castaneum	Adult	47.27 (42.31–52.70)	
Carum copticum	*C. maculatus*	Egg	1.01 (0.88–1.12)	Sahaf and Moharramipour (2008)
		Larvae	2.50 (1.95–3.17)	
		Adult	0.90 (0.08–1.03)	
Perovskia abrotanoides	*S. oryzae*	Adult	18.75 (16.59–21.26)	Arabi et al. (2008a)
	T. castaneum	Adult	11.39 (9.35–13.56)	
Thymus vulgaris	*C. maculatus*	Egg	1.99 (1.40–2.95)	Dezfouli et al. (2010)
		Larvae	6.14 (5.47–6.88)	
Eucalyptus leucoxylon	*C. maculatus*	Adult	2.76 (2.29–3.18)	Kambouzia et al. (2009)
	S. oryzae	Adult	8.48 (8.02–8.88)	
	T. castaneum	Adult	13.15 (12.83–14.09)	
Thymus persicus	*S. oryzae*	Adult	3.34 (2.62–4.28)	Taghizadeh Saroukolai et al. (2009)
	T. castaneum	Adult	236.9 (186.27–292.81)	
Salvia mirzayanii	*C. maculatus*	Adult	2.58 (2.00–3.20)	Nikooei and Moharramipour (2010)
Citrus reticulata	*C. maculatus*	Adult	8.70 (8.30–9.15)	Saeidi et al. (2011)
Citrus limon	*C. maculatus*	Adult	7.21 (6.79–7.71)	
Citrus aurantium	*C. maculatus*	Adult	6.33 (5.88–6.88)	
Thymus kotschyanus	*V. destructor*	Adult	1.07 (0.87–1.26)	Ghasemi et al. (2011)
Ferula assa-foetida	*V. destructor*	Adult	2.46 (2.10–2.86)	
Eucalyptus camaldulensis	*V. destructor*	Adult	1.74 (0.96–2.50)	
Artemisia annua	P_i. *rapae*	Larvae	9.38 (6.84–14.49)	Hasheminia et al. (2011)
Achillea millefolium	P_i. *rapae*	Larvae	4.19 (3.1–6.18)	
Ruta graveolens	*C. maculatus*	Adult	14.7 (12.3–17)	Hosseinpour et al. (2011)
Ferula gummosa	*C. maculatus*	Adult	29.2 (25.9–32.7)	
Carum copticum	P_l. *xylostella*	Larvae	3.50 (3.32–3.71)	Jamal et al. (2012)

[a]Genus; *C*, *Callosobruchus*; P_i, *Pieris*; P_l, *Plutella*; *S*, *Sitophilus*; *T*, *Tribolium*; *V*, *Varroa*

data, high fumigant toxicity and persistence of nanoencapsulated *A. sieberi* essential oil have been demonstrated as a new formulation against *C. maculatus* and *T. castaneum* (Negahban et al. 2011a; 2010). Also, preparation and characterization of nanoparticles containing *Cuminum cyminum* L. (Apiaceae) oil as a potential agriculture insecticidal application have been evaluated against insect pests (Zandi et al. 2010).

7.8 Antifeedant Properties of the Essential Oils

Antifeedant chemicals may be defined as being either repellent without making direct contact to insects or deterrent from feeding once contact has been made with insects (Koul et al. 2008).

7.8.1 Repellent Properties

One other great thing about the essential oils is that they have been tested as potential sources of insect repellents. Similarly, our laboratory bioassays have been conducted to determine the activity of some natural essential oils against some stored product and field crop pests. Repellency of *M. longifolia* and *T. kotschyanus* on *C. maculatus* was recorded at 90 % and 73.33 % At 800 ppm, respectively (Akrami et al. 2011). Also, at 1.5 ppm, the essential oil of *A. sieberi* was significantly more repellent to *T. castaneum* (65.90 %) than *S. oryzae* (59.70 %) and *C. maculatus* (55.80 %) (Negahban et al. 2007b), while *A. scoparia* strongly repelled *T. castaneum* (63.80 %) and *S. oryzae* (62.01 %) than *C. maculatus* (48.57 %) (Negahban et al. 2006a). Equally at 3 ppm, *S. mirzayanii* was significantly more repellent to *T. confusum* (86.66 %) than *C. maculatus* (70 %) (Nikooei and Moharramipour 2010). The strongest repellency has been shown in *Anethum graveolens* L. (Apiaceae) (100 %), *T. vulgaris* (100 %), and *R. officinalis* (93.33 %) and the weakest repellency in *Hyssopus officinalis* L. (Lamiaceae) (7.69 %) and *Petroselinum sativum* Hoffm. ex Gaudin (Apiaceae) (9.48 %) against *P. interpunctella* (Rafiei Karahroodi et al. 2009). Repellency of *C. reticulata* was significantly higher than *Citrus limon* (L.) Burm.f. (Rutaceae) and *Citrus aurantium* L. (Rutaceae). The adult insects were exposed to the concentration of 1, 3, 5, and 7 ppm of citrus peel essential oils to estimate repellent activities. Repellent values for *Citrus reticulata at the abovementioned concentrations* were estimated to be 26.66, 33.33, 33.66, and 40 %, respectively. *C. reticulata* essential oil was significantly more repellent to *C. maculatus* at 7 ppm (Saeidi et al. 2011).

Analysis of the data by Taghizadeh Saroukolai et al. (2009) has shown that the essential oil of *P. acaulis* strongly repelled adult insects and was significantly differed between insect species. The repellency of oil tested at the highest concentration (2 μl/ml acetone) was 83.6, 71.6, and 63.6 % on *S. oryzae*, *C. maculatus*, and *T. castaneum*, respectively. However, reverse observations have been made by several other studies concerning the strong repellent effects on *T. castaneum* rather than *S. oryzae* and *C. maculatus*. Therefore, further study is necessary to elucidate the mode of action of these essential oils. To the best knowledge of Negahban et al. (2013b), at 1.9 ppm, the nanocapsule of *Artemisia* oil was shown here to possess more repellent activity (80 %) to *P. xylostella* compared to *Artemisia* pure oil (62 %). The results showed higher repellent rates in nanocapsule than in the essential oil. The reasons for nanocapsulating the essential oil have been to improve its stability to reduce side effects or to reduce dosing frequency and total dosing amount, to obtain better repellent activity, and for sustained (long-lasting) release. These results showed that medicinal plants could be used as repellent of insects. These essential oils can be used for protecting agricultural products from pest injury.

Recent research has focused on insecticidal property of essential oil plants in biological control of insects. Nerio et al. (2010) reported that the increase in repellence activity for the essential oils is highly dependent on the product composition. Formulations based on creams, polymer mixtures, or microcapsules for controlled release resulted in an increase of repellency duration (Nentwig 2003;

Chang et al. 2006). For example, *Zanthoxylum limonella* oil was successfully microencapsulated in glutaraldehyde cross-linked gelatin (a polymer), in order to improve mosquito-repellent properties (Maji et al. 2007). Consequently, controlled release by nanoencapsulated essential oil seems to get the best out of the formulation for increasing the efficiency and providing a new method for the pest management.

7.8.2 Deterrent Properties

One of the significant aspects to the application of plant essential oils is that they have been considered as an important feeding deterrence in integrated pest management (IPM) programs. Needless to say, these are environmentally less harmful than synthetic pesticides and act in many insects in different ways. Several experiments have been designed to measure the nutritional indices such as relative growth rate (RGR), relative consumption rate (RCR), efficiency of conversion of ingested food (ECI), and feeding deterrence index (FDI). Bioefficacy of *A. sieberi* and *A. scoparia* exhibited antifeeding activity against *T. castaneum*, while *A. sieberi* oil was highly effective compared to *A. scoparia* and significantly decreased the RGR and RCR. Moreover, *A. sieberi* oil was more effective on FDI than *A. scoparia* (Negahban and Moharramipour 2007b). In another study (Sahaf and Moharramipour 2009), the efficacy of *C. copticum* and *V. pseudo-negundo* essential oils has also been determined against *T. castaneum* related to increase FDI.

Generally, antifeedant activity of *C. copticum* was more effective than *V. pseudo-negundo*. Soleimannejad et al. (2011) studied the effects of *Salvia mirzayanii* essential oil on nutritional indices of the *T. confusum* adults. *S. mirzayanii* showed a strong feeding deterrence action against adults of *T. confusum*. As there was an increase in the concentration of the essential oil, the growth rate (RGR), relative consumption rate (RCR), and efficiency of conversion of ingested food (ECI) were reduced significantly. However, there was a significant increase in feeding deterrence (FDI) action as increase in concentration of the essential oil. Therefore, the essential oil by fumigation could affect nutritional indices of the food by pre-ingestive and postingestive behavior. Reduction in growth and feeding rate may affect ECI and FDI, respectively. ECI indicates a sign of postingestive physiological effect. As in our experiments, food did not contaminated with the essential oil directly; therefore, it seems that indirect toxic properties of fumigation may have reduced growth and consequently ECI. Nevertheless, FDI shows pre-ingestive behavior of the insect. Consequently, the reduction in growth rate could be due to the feeding behavior of insect. It is possible that the reduction in feeding and growth rate of insects was mainly due to the feeding deterrent action. As in this study, strong feeding deterrent properties of the essential oils were observed. So, in addition to toxic effect of the essential oils, they have potential to affect growth and consumption rate of the insect.

7.9 Mechanism of Action of Essential Oils

As a matter of fact, the mode of action and site of effect for insecticidal activities from the essential oil is worthwhile for various authors (Enan 2001; Kostyukovsky et al. 2002; Priestley et al. 2003). Mostly the work has been carried on studying the effects of the essential oils, their lethal doses, and time to achieve lethal effects, but mode of action is in general not fully elucidated (Rattan 2010). Since large numbers of chemical defenses are present in the nature, very little is known about their mode of action at molecular level. The most striking thing to mention here is that the essential oils and their constituents disrupt the endocrinologic balance of insects (Rattan 2010). Toxicity from the essential oils in insects and other arthropods points to a neurotoxic mode of action; most prominent symptoms are hyperactivity followed by hyperexcitation leading to rapid knockdown and immobilization (Enan 2001).

Several essential oils from aromatic plants, monoterpenes, and natural products have been shown as inhibitors of acetylcholinesterase (AChE) against different insect species

(Kostyukovsky et al. 2002; Shaaya and Rafaeli 2007; Rajendran and Sriranjini 2008). Recently, it was found that azadirachtin (a tetraterpenoid) significantly inhibits the activity of AChE in *Nilaparvata lugens* Stal (Nathan et al. 2004). Furthermore, octopamine is a target for the essential oils activity in insects. The acute and sublethal behavioral effects of the essential oil compounds on insects are consistent with an octopaminergic target site in insects, which acts by blocking octopamine receptors (Enan 2001, 2005). Another possible target suggested for the essential oils is the interference with GABA-gated chloride channels in insects (Priestley et al. 2003). A case in point is that the thujone has been classified as a neurotoxic insecticide, which acts on GABA receptors (Hold et al. 2000; Ratra and Casida 2001). Koul et al. (2008) reported that the rapid action against some pests is indicative of a neurotoxic mode of action, and there is evidence for interference with the neuromodulator octopamine (Kostyukovsky et al. 2002) by some oils and with GABA-gated chloride channels by others (Priestley et al. 2003). On the whole, however, their functions on the specificity of the metabolites responsible for proclaimed insecticidal activity are lacking. Nevertheless the plant-based insecticides could be exploited for the development of novel molecules with highly precise target. For moving on the way to green chemistry processes and continuing need for developing new crop protection tools with novel modes of action makes discovery and commercialization of natural products as green pesticides with more empirical evaluation of active components for sustainable insect pest management in agriculture

7.10 Problems and Prospects

As a matter of fact, the essential oils and their components have certain advantages since they have been used in traditional medicine, in pharmaceutical preparations, and as natural flavorings. In addition to insecticidal activity, some of the essential oils have the advantage of showing fumigant, repellent, and contact and antifeedant action against agricultural product pests. Nonetheless, fumigants from plant sources lack the most important property of an ideal fumigant, i.e., sufficient vapor pressure for diffusion and penetration into commodities to kill the pests. Evidently, compounds of plant origin can be used only for small-scale applications or for space treatments. They require some carrier gases (e.g., CO_2) for even distribution and penetration into the commodities or they can act as adjuvant for conventional fumigants. Sometimes it has been claimed that monoterpenoids have comparable fumigant action to that of methyl bromide (Rajendran and Sriranjini 2008). However, this has not been established in large-scale trials with mixed-age cultures of target insects. The stability of the essential oils and their components is very important for toxic action. Negahban et al. (2006a) noted that the fumigant action of *A. sieberi* leaves decreased after processing over a period.

Very few studies have been conducted on the stability of promising the essential oils and their constituents. High sorption is one of the important limiting factors for the application of natural compounds in large-scale commodity fumigations, and it might lead to more residues; treated commodities will require longer aeration period. The most striking thing to mention here is that the nanoencapsulation process is a really helpful method for entrapping the essential oils of a very different chemical composition. In order to take full advantage of the essential oils, nanoencapsulated formulation reduces loss of the active principles, leading to high-loaded nanoparticles that offer protection against environmental agents; it also offers the possibility of controlled oil release. These effects appear maximized by nanocapsule adhesion to the hair structures typically present in some of the main defoliator families. Negahban et al. (2011a, b) reported that the fumigant toxicity of nanoencapsules was significantly higher than non-formulated oil at sublethal doses after 7 days exposure. When the nanoencapsulated oil is sprayed on the insect body, because of suspension capability in water, it completely wets all organs of the insect which is covered with fuzz.

Low viscosity of suspension resulted in uniform coatings, and the presence of surfactant in nanoformulation suspension causes a decrease in surface tension which increases stability of minute droplets of the essential oil in the suspension. Lai et al. (2006) have investigated the formulation of emulsion of *Artemisia arborescens* L. (Asteraceae) essential oil with solid lipid and its toxic effect on *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae). They showed that the type and amount of the essential oil did not alter fast during the period after being sprayed. The evaporation rate of the essential oil in the formulation is extremely low in comparison with control samples. Nanoformulation can be an up-to-date asset for pest control in agriculture. Moretti et al. (2002) reported the highest larval mortality occurred by microparticle adhesion to the hair structures of insects. Besides, the mortality rate was significantly high in experiment in closed condition in all fumigant, contact, and feeding nanoencapsulated treatments. This could be as a result of high volatility of the toxic mono- and sesquiterpene compounds which likely delivered fumigant toxicity by vapor action via the respiratory system, leading to more influence of complex and higher amount of active principles (Phillips et al. 2010, Kim et al. 2010). It can be concluded that mortality caused by nanoformulations is mainly wrought by contaminating the diet with the active principles released from the capsules and is a consequence of ingestion (Passino et al. 2004).

In general, the results show that the toxicity of various formulations besides chemical components depends on different factors such as application method as fumigant or contact toxicity or feeding repellent effects. Nanoencapsulation protects the quality and durability of active ingredients and thus increases the contact toxicity of the essential oil (Ziaee et al. 2014a, b). Moretti et al. (2002) and Passino et al. (2004) reported that insects' mortality due to nanoencapsulation is higher than non-formulated oil as the release rate of active ingredients can be controlled by loading them into nanocapsules over time. Therefore, according to researches, the appropriate application of nanoformulations can increase the insecticidal potential of the essential oils. Nevertheless, more studies are necessary to economize these novel technologies in the IPM.

The results of repellency tests indicate that although the non-formulated oil was more effective than nanoformulation in short time period (maximum 6 h after exposure), it is a strong repellent after 24-h exposure. In addition to feeding deterrency, the possibility of postingestive toxicity of nanoformulations is clearly increased.

7.11 Conclusion

Plant essential oils and their individual metabolites have demonstrated optimal potential for insecticidal activity against several species, not only insects, but other kinds of arthropods. However, its high volatility decreases the times of protection. What it does is that the major inconvenience of the use of this oil and, in general, of the essential oils is their chemical instability in the presence of air, light, moisture, and high temperatures that can determine the rapid evaporation and degradation of some active components. It was concluded that essential oils could be encapsulated successfully. All studied formulations demonstrated a high physical stability and a good capability to reduce the essential oil evaporation. The best results were obtained with nanoencapsulated formulation, which did not vary in size even after the spraying procedure. A central feature is that nanocapsules can be generally applied over large areas with conventional spray equipment, and numerous variables can be manipulated to control the release characteristics, e.g., capsule wall thickness, capsule size, capsule wall composition, and internal composition. Given these encouraging results, further experiments are in progress to assess the suitability of natural active principle formulations for application as a new tool in integrated control of different pests. Therefore, encapsulating the essential oils has a considerable potential as commercial insecticide products. Incorporation of the essential oils in controlled release with nanocapsule formulations could solve their problems and offer several advantages. Following an extensive literature review of the existing nanocapsulation technology, we concluded that several nanocapsulation applications would bloom if a low-cost continuous polymerization process for high-performance nanocapsules became available.

The essential oils have the ability to control a wide range of insects. Unfortunately, this broad-spectrum nature can adversely affect many nontarget beneficial species such as bees and parasitoid wasps along with the pest. Effectiveness of the essential oils can vary depending on where the chemicals are being applied. For instance, they may kill a large percentage of the target pest because it is a controlled environment, but in a real-life situation, the number may be much smaller. Evaluating uses of new formulations in similar situations as that of natural conditions may help in estimating the kind of effect it will have.

The essential oils are considered as a shorter-lived, fast-acting, and more acutely toxic material. But encapsulation technologies may modify them to longer-lasting, slow-acting, and less toxic materials that may be better for chronic pest problems. As essential oils are reported to be often the most phytotoxic, this property requires serious attention when formulating products. Other constraints such as lack of data for the essential oils on sorption, tainting, and residues in food commodities are included. Therefore, implementation of essential oil-based control systems will require more knowledge about their side effects in pest management systems. Because the knowledge of essential oils in this area is very limited, considerably more research will be required to develop and implement these new growing technologies. Acquiring this knowledge base will necessitate coordinated efforts among many scientific disciplines.

The main objective in future work is to achieve reactive polymerization of nanocapsule compositions to be used in controlled-release applications. These new nanocapsule formulations will achieve a high selectivity, specificity, and accuracy in delivering the optimum dose of the active ingredient to the desired site at the appropriate time. It will also seek to obtain a maximum activity on the target while producing minimal effect on the non-target materials. A secondary goal to the main objective is to extend this research by improving the understating of the released mechanisms. Therefore, it is time to focus the attention of the researchers toward the development and application of known essential oils and their constituents by advanced formulation technologies.

Plant essential oils and their individual metabolites have demonstrated optimal potential for insecticidal activity against several species, not only insects, but other kinds of arthropods. However, its high volatility decreases the times of protection. There are likely several reasons for encapsulating method that are good potential carrier to bring into being the biopesticides of the essential oil in agriculture:

1. What it does is that the major inconvenience of the use of this oil and, in general, of the essential oils is their chemical instability in the presence of air, light, moisture, and high temperatures that can determine the rapid evaporation and degradation of some active components. It was concluded that the essential oils could be encapsulated successfully. All studied formulations demonstrated a high physical stability and a good capability to reduce the essential oil evaporation. The best results were obtained with nanoencapsulated formulation, which did not vary in size even after the spraying procedure. A central feature is that nanocapsules can be generally applied over large areas with conventional spray equipment, and numerous variables can be manipulated to control the release characteristics, e.g., capsule wall thickness, capsule size, capsule wall composition, and internal composition. Given these encouraging results, further experiments are in progress to assess the suitability of natural active principle formulations for application as a new tool in integrated control of different pests. Therefore, encapsulating the essential oils has a considerable potential as commercial insecticide products. Incorporation of the essential oils in controlled release with nanocapsule formulations could solve their problems and offer several advantages. Following an extensive literature review of existing nanocapsulation technology, we concluded

that several nanocapsulation applications would bloom if a low-cost continuous polymerization process for high-performance nanocapsules became available.

2. The essential oils have ability to control a wide range of insects. Unfortunately, this broad-spectrum nature can adversely affect many nontarget beneficial species such as bees and parasitoid wasps along with the pest. Effectiveness of the essential oils can vary depending on where the chemicals are being applied. For instance, they may kill a large percentage of the target pest because it is a controlled environment, but in a real-life situation, the number may be much smaller. Evaluating uses of new formulations in similar situations as that of natural conditions may help in estimating the kind of effect it will have.
3. The essential oils are considered as a shorter-lived, fast-acting, and more acutely toxic material. But encapsulation technologies may modify them to longer-lasting, slow-acting, and less toxic materials that may be better for chronic pest problems.
4. As essential oils are reported to be often the most phytotoxic, this property requires serious attention when formulating products.
5. Other constraints such as lack of data for the essential oils on sorption, tainting, and residues in food commodities are included. Therefore, implementation of the essential oil-based control systems will require more knowledge about their side effects in pest management systems. Because the knowledge of essential oils in this area is very limited, considerably more research will be required to develop and implement these new growing technologies. Acquiring this knowledge base will necessitate coordinated efforts among many scientific disciplines.

7.12 Future Focus of the Work

The main objective in future work is to achieve reactive polymerization of nanocapsule compositions to be used in controlled-release applications. These new nanocapsule formulations will achieve a high selectivity, specificity, and accuracy in delivering the optimum dose of the active ingredient to the desired site at the appropriate time. It will also seek to obtain a maximum activity on the target while producing minimal effect on the non-target materials. A secondary goal to the main objective is to extend this research by improving the understating of the released mechanisms. Therefore, it is time to focus the attention of the researchers toward the development and application of known essential oils and their constituents by advanced formulation technologies.

References

Ahmadi M, Moharramipour S, Mozdarani H, Negahban M (2008a) Combination of medicinal plant essential oils with gamma radiation in management of *Tribolium castaneum*. The 1st international symposium on medicinal plants, their cultivation and aspects of uses, Jordan, Petra, 15–16 Oct 2008, M. A. Ateyyat, p 50

Ahmadi M, Moharramipour S, Zolfagharieh HR (2008b) Comparative fumigant toxicity of *Rosmarinus officinalis* and *Artemisia sieberi* against *Tribolium castaneum*. Integr Prot Stored Prod IOBC/WPRS Bull 40:243–247

Ahmadi M, Moharramipour S, Mozdarani R (2008c) Combined effect of gamma radiation and *Perovskia atriplicifolia* essential oil on the formation of micronuclei in genital cells of *Callosobruchus maculatus*. In: Proceedings of the 18th Iranian plant protection congress, 24–27 Aug 2008, Hamedan, Iran, p 119

Ahmadi M, Moharramipour S, Ardakani M, Negahban M, Fathollahi H (2008d) Integrated effect of *Perovskia atriplicifolia* and gamma radiation for the control of *Callosobruchus maculatus*. In: Proceedings of the 18th Iranian plant protection congress, 24–27 Aug 2008, Hamedan, Iran, p 118

Ahmadi M, Moharramipour S, Zolfagharieh HR, Babaii M (2008e) Toxicity of *Rosmarinus officinalis* on gamma irradiated adults of *Callosobruchus maculatus*. In: Proceedings of the 18th Iranian plant protection congress, 24–27 Aug 2008, Hamedan, Iran, p 123

Ahmadi M, Moharramipour S, Ardakani MR, Mozdarani H (2009a) Effect of combination of gamma radiation and essential oil from *Perovskia atriplicifolia* on mortality of *Tribolium castaneum*. J Nucl Sci Tech 49:50–56

Ahmadi M, Moharramipour S, Mozdarani H, Babaii M (2009b) Induction of micronuclei in ovaries of *Tribolium castaneum* exposed to gamma radiation and *Rosmarinus officinalis* essential oil. In: Athaniassou C, Termaterra P (eds) Conference of the

IOBC WPRS (OILB SROP) working group on integrated protection of stored products, 29 June–2 July 2009, Compobasso, Italy

Ahmadi M, Moharramipour S, Negahban M (2011a) Synergistic effect of gamma radiation and *Rosmarinus officinalis* essential oil for control of cowpea weevil, *Callosobruchus maculatus*. Global conference on entomology 5–9 Mar 2011, Chiang Mai, Thailand, p 603

Ahmadi M, Moharramipour S, Mozdarani H, Babaii M (2011b) Micronuclei formation induced by gamma radiation and *Perovskia atriplicifolia* essential oil on ovaries of *Tribolium castaneum*. Global conference on entomology, 5–9 Mar 2011, Chiang Mai, Thailand, p 538

Akgun M, Akgun NA, Dincer S (2009) Extraction and modeling of lavender flower essential oil using supercritical carbon dioxide. Ind Eng Chem Res 39:473–477

Akrami H, Moharramipour S, Imani S (2011) Comparative effect of *Thymus kotschyanus* and *Mentha longifolia* essential oils on oviposition deterrence and repellency of *Callosobruchus maculatus* F. Iran J Med Aromat Plants 27:1–10

Arabi F, Moharramipour S, Sefidkon F (2008a) Chemical composition and insecticidal activity of essential oil from *Perovskia abrotanoides* (Lamiaceae) against *Sitophilus oryzae* (Coleoptera: Curculionidae) and *Tribolium castaneum* (Coleoptera: Tenebrionidae). Int J Trop Insect Sci 28(3):144–150

Arabi F, Moharramipour S, Sefidkon F (2008b) Fumigant toxicity of essential oil from *Tanacetum polycephalum* against *Tribolium castaneum* and *Callosobruchus maculatus*. Int Prot Stored Prod IOBC/WPRS Bull 40:249–252

Bakkali F, Averbeck S, Averbeck D, Idaomar M (2008) Biological effects of essential oils- a review. Food Chem Toxicol 46:446–475

Barnard D (1999) Repellency of essential oils to mosquitoes (Diptera: Culicidae). J Med Entomol 36:625–629

Bhatnagar M, Kapur KK, Jalees S, Sharma SK (1993) Laboratory evaluation of insecticidal properties of *Ocimum basilicum* Linnaeus and *O. sanctum* Linnaeus plant's essential oils and their major constituents against vector mosquito species. Bull Entomol Res 17:21–29

Bischof LJ, Enan EE (2004) Cloning, expression and functional analysis of an octopamine receptor from *Periplaneta americana*. Insect Biochem Mol Biol 34:511–521

Calderone NW, Spivak M (1995) Plant extracts for control of the parasitic mite *Varroa jacobsoni* (Acari: Varroidae) in colonies of the western honey bee (Hymenoptera: Apidae). J Econ Entomol 88:1211–1215

Chang KS, Ahn YT (2001) Fumigant activity of (*E*) – anethole identified in *Illicium verum* fruit against *Blattella germanica*. Pest Manage Sci 58:161–166

Chang ST, Cheng SS (2002) Antitermitic activity of leaf essential oils and components from *Cinnamomum osmophloeum*. J Agric Food Chem 50:1389–1392

Chang KS, Tak JH, Kim SI, Lee WJ, Ahn YJ (2006) Repellency of *Cinnamomum cassia* bark compounds and cream containing cassia oil to *Aedes aegypti* (Diptera: Culicidae) under laboratory and indoor conditions. Pest Manage Sci 62:1032–1038

Chauhan KR, Raina AK (2006) Effect of catnip oil and its major compounds on the Formosan subterranean termite (*Coptotermes formosanus*). Biopesticide Int 2:137–143

Chemat F, Lucchesi ME, Smadja J, Favretto L, Colnaghi G, Visinoni F (2006) Microwave accelerated steam distillation of essential oil from lavender: a rapid, clean and environmentally friendly approach. Anal Chim Acta 555:157–160

Chen F, Li Q, Sheng L, Qiu L (2008) Comparison study of different methods for extracting volatile oil from bergamot. J Chin Med 31:1242–1244

Choi WS, Park BS, Lee YH, Jang DY, Yoon HY, Lee SE (2006) Fumigant toxicities of essential oils and monoterpenes against *Lycoriella mali* adults. Crop Prot 25:398–401

Chokechaijaroenporn O, Bunyapraphatasara N, Kongschensis S (1994) Mosquito repellent activities of *Ocimum* volatile oils. Phytomedicine 1:135–139

Clancy KM, Foust RD, Huntsberger TG, Whtaker JG, Whitaker DM (1992) Technique for using microencapsulated terpenes in lepidopteran artificial diets. J Chem Ecol 18:543–560

Clemente S, Mareggiani G, Broussalis A, Martino V, Ferraro G (2003) Insecticidal effects of Lamiaceae species against stored products insects. Bol Sanidad Veg Plagas 29:1–8

Coats JR, Karr LL, Drewes CD (1991) Toxicity and neurotoxic effects of monoterpenoids in insects and earthworms. In: Hedin PA (ed) Naturally occurring pest bioregulators, ACS (American Chemical Society). American Chemical Society, Washington, DC, pp 305–316

Cornelius ML, Grace JK, Yates JR (1997) Toxicity of monoterpenoids and other natural products to the Formosan subterranean termite (Isoptera: Rhinotermitidae). J Econ Entomol 90:320–325

Dezfouli E, Moharramipour S, Goldasteh SH (2010) Ovicidal, larvicidal and oviposition deterrency effects of essential oil from Thymus vulgaris L. (Lamiaceae) on Callosobruchus maculatus (F.) (Col., Bruchidae). J Entomol Res 2: 73–84

Don-Pedro KN (1996) Fumigant toxicity of citrus peel oils against adult and immature stages of storage insect pests. J Pesticide Sci 47:213–223

Ellis MD, Baxendale FP (1997) Toxicity of seven monoterpenoids to tracheal mites (Acari: Tarsonemidae) and their honey bee (Hymenoptera: Apidae) hosts when applied as fumigants. J Econ Entomol 90:1087–1091

Enan EE (2001) Insecticidal activity of essential oils: octopaminergic sites of action. Comp Biochem Physiol C Toxicol Pharmacol 130(3):325–337

Enan EE (2005) Molecular response of *Drosophila melanogaster* tyramine receptor cascade to plant essential oils. Insect Biochem Mol Biol 35(4):309–321

Filekesh E, Tayebi R, Akhlaghi H (2005) Study of the essential oils in organ plant of *Vitex pseudo-negundo* in Sabzevar. In: Proceedings of the 2nd symposium medicinal plants, 26–27 Jan 2005, Faculty of Agriculture, Medicinal Plants Research Center, Shahed University, Shadnaghsh Printing House, Tehran, p 235

Franzios G, Mirotsou M, Hatziapostolou E, Kral J, Scouras ZG, Mauragani-Tsipidou P (1997) Insecticidal and genotoxic activities of mint essential oils. J Agric Food Chem 45:2690–2694

Ghasemi V, Moharramipour S, Tahmasbi G H (2009) Fumigant toxicity of essential oil from *Mentha longifolia* (Lamiaceae) against *Varroa destructor* (Acari: Varroidae) and its side effects on *Apis mellifera* (Hymenoptera: Apoidea). Iranian Students Congress of Agricultural Sciences and Natural Resources, May 2009, Guilan University, pp 135–136

Ghasemi V, Moharramipour S, Tahmasb G (2011) Biological activity of some plant essential oils against *Varroa destructor* (Acari: Varroidae), an ectoparasitic mite of *Apis mellifera* (Hymenoptera: Apidae). Exp Appl Acarol 55:147–154

Harwood SH, Modenke AF, Berry RE (1990) Toxicity of peppermint monoterpenes to the variegated cutworm (Lepidoptera: Noctuidae). J Econ Entomol 83:1761–1767

Hasheminia SM, Jalali Sendi J, Talebi Jahromi K, Moharramipour S (2011) The effects of *Artemisia annua* L. and *Achillea millefolium* L. crude leaf extracts on the toxicity, development, feeding efficiency and chemical activities of small cabbage *Pieris rapae* L. (Lepidoptera: Pieridae). Pesticide Biochem Physiol 99:244–249

Haynes KF (1988) Sublethal effects of neurotoxic insecticides on insect behaviour. Annu Rev Entomol 33:149–168

Heywood VH, Humphries GJ (1977) In: Heywood VH, Harbone JB, Turner B (eds) The biology and chemistry of the Compositae (Anthemideae -systematic review, vol 2). Academic, London/New York, pp 851–898

Hierro I, Valero A, Perez P, Gonzalex P, Cabo MM, Navarro MC (2004) Action of different monoterpenic compounds against *Anisakis simplex* S.l.L3 larvae. Phytomedicine 11:77–82

Hikino H (1985) Antihepatotoxic constituents of Chinese drugs. Essent China Pharm Bull 20:415–417

Hold MK, Sirisoma SN, Ikeda T, Narahashi T, Casida EJ (2000) Thujone (the active component of absinthe): aminobutyric acid type. A receptor modulation and metabolic detoxification. Proceedings of National Academy of Science USA, Washington, DC, vol 97, pp 3826–3831

Hori M (2003) Repellency of essential oils against the cigarette beetle, *Lasioderma serricorne* (Fabricius) (Coleoptera: Anobiidae). Appl Entomol Zoo 38:467–473

Hosseinpour MH, Askarianzadeh A, Moharramipour S, Jalali Sendi S (2011) Insecticidal activity of essential oils isolated from Rue (*Ruta graveolens* L.) and Galbanum (*Ferula gummosa* Bioss.) on *Callosobruchus maculatus* (F.). Integr Prot Stored Prod IOBC/WPRS Bull 69:271–275

Huang Y, Ho SH (1998) Toxicity and antifeedant activities of cinnamaldehyde against the grain storage insects *Tribolium castaneum* (Herst) and *Sitophilus zeamais* Motsch. J Stored Prod Res 34:11–17

Hummelbrunner LA, Isman MB (2001) Acute, sublethal, antifeedant and synergistic effects of monoterpenoid essential oil compounds on the tobacco cutworm, *Spodoptera litura* (Lep., Noctuidae). J Agric Food Chem 49:715–720

Isman MB (2000) Plant essential oils for pest and disease management. Crop Prot 19:603–608

Isman MB (2006) Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu Rev Entomol 51:45–66

Isman MB, Machial CM (2006) Pesticides based on plant essential oils: from traditional practice to commercialization. In: Rai M, Carpinella MC (eds) Naturally occurring bioactive compounds. Elsevier B.V., Amsterdam/Boston, pp 29–44

Jamal M, Moharramipour S, Negahban M (2011) Effect of fumigant toxicity of plant essential oils *Carum copticum* on diamondback moth larvae. In: 2nd Iranian pest management conference (IPMC). 14–15 Sept 2011, Kerman, Iran, pp 290–296

Jamal M, Moharramipour S, Zandi M, Negahban M (2012) Ovicidal activity of nano-encapsulated essential oil of *Carum copticum* on diamondback moth *Plutella xylostella*. The First National Congress of Monitoring and Forecasting in Plant Protection, Borujerd, Iran, 14–15 Feb, pp 128–129

Javidnia K, Miri R, Kamalinejad M, Nasiri A (2002) Composition of essential oil of *Salvia mirzayanii* Rech. F. & Esfand from Iran. Flavour Frag J 17:465–467

Ji L, Che Z, Huang W, Xian F (2008) Research of extraction orange peel oil by steam distillation, Food Research. Development 29:92–93

Kalemba D, Kurowska A, Gora J, Lis A (1991) Analysis of essential oils. influence of insects. Part V essential oils of berries of Juniper (*Juniperus communis* L.). J Pesticide Sci 2:31–34

Kambouzia J, Negahban M, Moharramipour S (2009) Fumigant toxicity of *Eucalyptus leucoxylon* against stored product insects. Am Eurasian J Sustain Agric 3(2):229–233

Karr LL, Coats JR (1988) Insecticidal properties of d-limonene. J Pestic Sci 13:287–290

Karr LL, Coats JR (1992) Effects of four monoterpenoids on growth and reproduction of the German cockroach (Blattodea: Blattellidae). J Econ Entomol 85:424–429

Khoee S, Yaghoobian M (2009) An investigation into the role of surfactants in controlling particle size of polymeric nanocapsules containing penicillin-G in double emulsion. Eur J Med Chem 44:2392–2399

Kim SI, Park C, Ohh MH, Cho HC, Ahn YJ (2003) Contact and fumigant activities of aromatic plant extracts and essential oils against *Lasioderma serricorne* (Coleoptera: Anobiidae). J Stored Prod Res 39:11–19

Kim S, Yoon JS, Jung JW, Hong KB, Ahn YJ, Kwon HW (2010) Toxicity and repellency of *origanum* essential oil and its components against *Tribolium castaneum* (Coleoptera: Tenebrionidae) adults. J Asia Pac Entomol 13:369–373

Kostyukovsky M, Rafaeli A, Gileadi C, Demchenko N, Shaaya E (2002) Activation of octopaminergic receptors by essential oil constituents isolated from aromatic plants: possible mode of action against insect pests. Pest Manage Sci 587:1101–1116

Koul O, Walia S, Dhaliwal GS (2008) Essential oils as green pesticides: potential and constraints. Biopesticide Int 4(1):63–84

Kubo I, Muroi H, Kubo A (1994) Naturally occurring antiacne agents. J Nat Prod 57:9–17

Lai F, Wissing SA, Muller RH, Fodda AM (2006) *Artemisia arborescens* L essential oil-loaded solid lipid nanoparticles for potential agricultural application: preparation and characterization. Am Assoc Pharm Sci Technol 7(1):1–9

Lee S, Tsao R, Peterson C, Coats JR (1997) Insecticidal activity of monoterpenoids to western corn root worm (Coleoptera: Chrysomelidae), two spotted spidermite (Acari: Tetranychidae) and Housefly (Diptera: Muscidae). J Econ Entomol 90:883–892

Lee SE, Lee BH, Choi WS, Park BS (2001a) Fumigant toxicity of essential oils and their constituents compounds towards the rice weevil, *Sitophilus oryzae* (L). Crop Prot 20:317–320

Lee SE, Lee BH, Choi WS, Park BS, Kim JG, Campbell BC (2001b) Fumigant toxicity of volatile natural products from Korean spices and medicinal plants towards the rice weevil, *Sitophilus oryzae* (L). Pest Manage Sci 57:548–553

Lee S, Peterson CJ, Coats JR (2002) Fumigation toxicity of monoterpenoids to several stored product insects. J Stored Prod Res 39:77–85

Lee S, Peterson CJ, Coats JR (2003) Fumigant toxicity of monoterpenoids to several stored product insects. J Stored Prod Res 39:77–85

Lee BH, Annis PC, Tumaalii F, Choi WS (2004) Fumigant toxicity of essential oils from the Myrtaceae family and 1,8-Cineole against 3 major stored grain Insects. J Stored Prod Res 40:553–564

Liu T, She W, Wang T, Fu W, Zheng Q, Li G, Ma C, Wang Z (2009) Study on the antioxidative activity of lavender oil extracted by steam distillation and supercritical extraction. Lishizhen Med Mater Med Res 20:3035–3037

Maji TK, Baruah I, Dube S, Hussain MR (2007) Microencapsulation of *Zanthoxylum limonella oil* (ZLO) in glutaraldehyde crosslinked gelatin for mosquito repellent application. Bioresour Technol 98:840–844

Marcus C, Lichtenstein EP (1979) Biologically active components of anise toxicity and interactions with insecticides in insects. J Agric Food Chem 27:1217–1223

Mediouni-Ben Jemaa J, Tersim N (2011) Composition and repellent efficacy of essential oil from *Laurus nobilis* against adults of cigarette beetle *Lasioderma serricorne* (Coleoptera: Anobiidae). Tunisian J Plant Prot 6:29–42

Meepagala KM, Osbrink W, Sturtz G, Lax A (2006) Plant derived natural products exhibiting activity against *formosan subterranean termites* (*Coptotermes formosanus*). Pest Manag Sci 62:565–570

Miresmailli S, Bradbury R, Isman MB (2006) Comparative toxicity of *Rosmarinus officinalis* L. essential oil blends of its major constituents against *Tetranychus urticae* Koch (Acari: Tetranychidae) on two different host plants. Pest Manage Sci 62:366–371

Moharramipour S, Sahaf BZ (2006) Insecticidal activity of essential oil from *Vitex pseudo-negundo* against *Brevicoryne brassicae*. Integrated Control in Protected Crops, Mediterranean Climate. IOBC/WPRS Bull 29(4):337–341

Moharramipour S, Taghizadeh A, Meshkatalsadat MH, Fathipour1 Y, Talebi AA (2008) Repellent activity and persistence of essential oil extracted from *Prangos acaulis* to three stored-product beetles. The 1st international symposium on medicinal plants, their cultivation and aspects of uses, Jordan, Petra, 15–16 Oct 2008, M. A. Ateyyat, p 50

Moretti MDL, Sanna-Passino G, Demontis S, Bazzoni E (2002) Essential oil formulations useful as a new tool for the insect pest control. Am Assoc Pharma Sci Technol 3(2):1–11

Mostafa K, Yadollah Y, Shahab S (2010) Comparison of essential oils compositions of Nepeta persica obtained by supercritical carbon dioxide extraction and steam distillation methods. Food Bioprod Process 88:227–232

Murugan K, Kumar PM, Kovendan K, Amerasan D, Subrmaniam J, Hwang JS (2012) Larvicidal, pupicidal, repellent and adulticidal activity of *Citrus sinensis* orange peel extract against *Anopheles stephensi*, *Aedes aegypti* and *Culex quinquefasciatus* (Diptera: Culicidae). Parasitol Res 111:1757–1769

Naghibi F, Mosaddegh M, Mohammadi Motamed S, Ghorbani A (2005) Labiatae family in folk medicine in Iran: from ethnobotany to pharmacology. Iranian J Pharm Res 2:63–79

Nathan SS, Chung PG, Murugan K (2004) Effect of botanicals and bacterial Toxin on the gut enzyme of *Cnaphalocrocis medinalis*. Phytoparasitica 32:433–443

Nattudurai G, Gabriel Paulraj M, Ignacimuthu S (2012) Fumigant toxicity of volatile synthetic compounds and natural oils against red flour beetle *Tribolium castaneum* (Herbst)(Coleoptera : Tenebrionidae). J King Saud Univ Sci 24:153–159

Negahban M, Moharramipour S (2007a) Efficiency of A*rtemisia sieberi* and A*rtemisia scoparia* essential oils on nutritional indices of T*ribolium castaneum* (Col: Tenebrionidae). Iranian J Med Aromat Plants 23:13–22

Negahban M, Moharramipour S (2007b) Efficiency of *Artemisia sieberi* Besser and *Artemisia scoparia* Waldst et kit essential oils on biological activity of *Callosobruchus maculatus* F. (Col.: Bruchidae). Iranian J Med Aromat Plants 23:146–156

Negahban M, Moharramipour S (2007c) Fumigant toxicity of *Eucalyptus intertexta, Eucalyptus sargentii* and *Eucalyptus camaldulensis* against stored-product beetles. J Appl Entomol 131(4):256–261

Negahban M, Moharramipour S (2008) Efficacy of essential oils of two species of *Artemisia* on nutritional indices of *Tribolium castaneum* Herbst. The 1st international symposium on medicinal plants, their cultivation and aspects of uses, Jordan, Petra, 15–16 Oct 2008, M. A. Ateyyat, p 52

Negahban M, Moharramipour S, Sefidkon F (2006a) Chemical composition and insecticidal activity of *Artemisia scoparia* essential oil against three coleopteran stored-product insects. J Asia Pac Entomol 9(4):381–388

Negahban M, Moharramipour S, Sefidkon F (2006b) Insecticidal activity and chemical composition of *Artemisia sieberi* Besser essential oil from Karaj, Iran. J Asia Pac Entomol 9(1):61–66

Negahban M, Moharramipour S, Sefidkon F (2007a) Fumigant toxicity of essential oil from *Artemisia sieberi* Besser against three stored-product insects. J Stored Prod Res 43:123–128

Negahban M, Moharramipour S, Sefidkon F (2007b) Repellent activity and persistence of essential oil from *Artemisia sieberi* on three stored-product insects. Iranian J Med Aromat Plants 22(4):293–302

Negahban M, Moharramipour S, Hashemi SA, Zandi M (2010) Insecticidal properties of nano capsule of essential oil from *Artemisia sieberi* Besser from red flour beetle insect. Online in: http://abstracts.csc2010.ca/00001347.htm

Negahban M, Moharramipour S, Sarbolouki MN (2011a) Nanocapsulation of *Artemisia sieberi* oil as a new formulation against *Callosobruchus maculatus*. Integr Prot Stored Prod IOBC/WPRS Bull 69:249

Negahban M, Moharramipour S, Zandi M, Hashemi SA (2011b) Insecticidal activity of nano capsules of essential oil on *Tribolium castaneum* (Herbst). Global conference on entomology, 5–9 Mar 2011, Chiang Mai, Thailand, p 605

Negahban M, Moharramipour S, Zandi M, Hashemi SA (2013a) Efficiency of nanoencapsulated essential oil of *Artemisia sieberi* on nutritional indices of *Plutella xylostella*. Iranian J Med Aromat Plants 29:692–708

Negahban M, Moharramipour S, Zandi M, Hashemi SA (2013b) Repellent activity of nanoencapsulated essential oil of *Artemisia sieberi* on *Plutella xylostella* larvae. Iranian J Med Aromat Plants 29:909–924

Nentwig G (2003) Use of repellents as prophylactic agents. Parasitol Res 90:40–48

Nerio LS, Oliver-Verbel J, Stashenko E (2010) Repellent activity of essential oils: a review. Bioresour Technol 101:372–378

Ngoh SP, Cho LEW, Pang FY, Huang Y, Kini MR, Ho SH (1998) Insecticidal and repellent properties of nine volatile constituents of essential oils against the American cockroach, *Periplaneta americana* (L.). J Pesticide Sci 54:261–268

Nickavar B, Mojab F, Dolat-Abadi R (2005) Analysis of the essential oils of two *Thymus* species from Iran. Food Chem 90:609–611

Nikooei M, Moharramipour S (2010) Fumigant toxicity and repellency effects of essential oil of *Salvia mirzayanii* on *Callosobruchus maculatus* (Col.: Bruchidae) and *Tribolium confusum* (Col.: Tenebrionidae). J Entomol Soci Iran 30(2):17–30

Nikooei M, Moharramiour S, Talebi AA (2011) Fumigant toxicity of essential oil from *Zhumeria majdae* against *Callosobruchus maculatus*. Integrated Protection of Stored Products. IOBC/WPRS Bull 69:277–280

Obeng-Ofori DCH, Reichmuth J, Bekele J, Hassanali A (1997) Biological activity of 1,8-Cineol, a major component of essential oil of *Ocimum kenyense* (Ayobangira) against stored product beetles. J Appl Entomol 121:237–243

Ojimelukwe PC, Adler C (1999) Potential of zimtaldehyde, 4- allyl-anisol, linalool, terpineol and other phytochemicals for the control of confused flour beetle (*Tribolium confusum* J.D.V) (Col: Tenebrionidae). J Pesticide Sci 72:81–86

Pascual-Villalobos MJ, Robledo A (1998) Screening for anti-insect activity in Mediterranean plants. Ind Crops Prod 8:183–194

Passino GS, Bazzoni E, Moretti MDL (2004) Microencapsulated essential oils active against indianmeal moth. Bol Sanidad Veg Plagas 30:125–132

Perrucci S (1995) Acaricidal activity of some essential oils and their constituents against *Tyrophagus longior*, a mite of stored food. J Food Prot 58:560–563

Phillips AK, Appel AG, Sims SR (2010) Topical toxicity of essential oils to the *German cockroach* (Dictyoptera: Blattellidae). J Econ Entomol 103:448–459

Pillmoor JB, Wright K, Terry AS (1993) Natural products as a source of agrochemicals and leads for chemical synthesis. J Pest Sci 39:131–140

Priestley C, Williamson EM, Wafford KA, Sattelle DB (2003) Thymol, a constituent of thyme essential oil, is a positive allosteric modulator of human GABA a receptors and homo-oligomeric GABAa receptor from *Drosophila melanogaster*. Br J Pharmacol 140:1363–1372

Rafiei Karahroodi Z, Moharramipour S, Rahbarpoor A, Zahabi P, Salehi Marzigarani M (2008) Presentation of an olfactometer model RZR to assess repellency of essential oils. In: Proceedings of the 18th Iranian plant protection congress, 24–27 Aug 2008, Hamedan, Iran, p 144

Rafiei Karahroodi Z, Moharramipour S, Rahbarpour A (2009) Investigated repellency effect of some essential oils of 17 native medicinal plants on adults *Plodia Interpunctella*. Am Eurasian J Sustain Agric 3(2): 181–184

Rafiei Karahroodi Z, Moharramipour S, Farazmand H, Karimzadeh-Esfahani J (2011) Oviposition deterrency and ovicidal activity of eighteen medicinal plant essential oils on *Plodia interpunctella* Hübner (Lepidoptera: Pyralidae). Iranian J Med Aromat Plants 27:460–470

Raina AK, Bland J, Dollittle M, Lax A, Boopathy R, Lolkins M (2007) Effect of orange oil extract on the formosan subterranean termite (Isoptera: Rhinotermitidae). J Econ Entomol 100:880–885

Rajendran S, Sriranjini V (2008) Plant products as fumigants for stored- product insect control. J Stored Prod Res 44:126–135

Rasooli I, Rezaei MB, Allameh A (2006) Growth inhibition and morphological alterations of *Aspergillus niger* by essential oils from *Thymus eriocalyx* and *Thymus x-porlock*. Food Control 17:359–364

Rastegar F, Moharramipour S, Shojaei M, Abbasipour H (2008) Insecticidal activity of *Salvia officinalis* and *Zataria multiflora* on *Callosobruchus maculatus*. In: Proceedings of the 18th Iranian plant protection congress, Hamedan, Iran, vol 1, p 174

Ratra GS, Casida JE (2001) GABA receptor subunit composition relative to insecticide potency and selectivity. Toxicol Lett 122(3):215–222

Rattan RS (2010) Mechanism of action of insecticidal secondary metabolites of plant origin. Crop Prot 29:913–920

Rechinger KH (1982) Flora Iranica. 152, Akademische Druck-und Verlagsanstalt, Graz

Regnault-Roger C, Hamraoui A (1995) Fumigant toxic activity and reproductive inhibition induced by monoterpenes on *Acanthoscelides obtectus* (Say) (Coleoptera), a bruchid of kidney bean (*Phaseolus vulgaris* L.). J Stored Prod Res 31:291–299

Regnault-Roger C, Hamraoui A, Holeman M, Theron E, Pinel R (1993) Primary Title: Insecticidal effect of essential oils from mediterranean plants upon *Acanthoscelides Obtectus* Say (Coleoptera, Bruchidae), a pest of kidney bean (*Phaseolus vulgaris* L.). J Chem Ecol 19:1233–1244

Rice PJ, Coats JR (1994) Insecticidal properties of several monoterpenoids to the house fly (Diptera: Muscidae), red flour beetle (Coleoptera: Tenebrionidae), and southern maize rootworm (Coleoptera: Chrysomelidae). J Econ Entomol 87:1172–1179

Saeidi M, Moharramipour S (2008) Insecticidal activity of essential oil from gray santolina (*Santolina chamaecyparissus* L.) against *Callosobruchus maculatus* (F.). In: Proceedings of 18th Iranian plant protection congress, vol I, pests, Hamedan, Iran, p 177

Saeidi M, Moharramipour S, Sefidkon F, Aghajanzadeh S (2011) Insecticidal and repellent activities of *Citrus reticulata Citrus limon* and *Citrus aurantium* essential oils on *Callosobruchus maculatus*. Integr Prot Stored Prod IOBC/WPRS Bull 69:289–293

Sahaf BZ, Moharramipour S (2007) Comparative investigation on oviposition deterrence of essential oils from *Carum copticum* C. B. Clarke and *Vitex pseudo-negundo* (Haussk) Hand. I. MZT. On *Callosobruchus maculatus* on laboratory. Iranian J Med Aromat Plants 23(4):523–531

Sahaf BZ, Moharramipour S (2008) Fumigant toxicity of *Carum copticum* and *Vitex pseudo-negundo* essential oils against eggs, larvae and adults of *Callosobruchus maculatus*. J Pest Sci 81:213–220

Sahaf BZ, Moharramipour S (2009) Comparative study on deterrency of *Carum copticum* C. B. Clarke and *Vitex pseudo-negundo* (Hausskn.) Hand.-Mzt. essential oils on feeding behavior of *Tribolium castaneum* (Herbst). Iranian J Med Aromat Plants 24:385–395

Sahaf BZ, Moharramipour S, Meshkatalsadat MH (2007) Chemical constituents and fumigant toxicity of essential oil from *Carum copticum* against two stored product beetles. Insect Sci 14:213–218

Sahaf BZ, Moharramipour S, Meshkatalsadat MH (2008a) Chemical constituents and fumigant toxicity of *Vitex pseudo-negundo* essential oils against *Tribolium castaneum* and *Sitophilus oryzae*. J Asia Pac Entomol 11:175–179

Sahaf BZ, Moharramipour S, Fathipour Y, Meshkatalsadat MH (2008b) Chemical constituents and fumigant toxicity of *Vitex pseudo-negundo* essential oil on eggs, first instar larvae and adults of *Callosobruchus maculatus* (Coleoptera: Bruchidae). The 1st international symposium on medicinal plants, their cultivation and aspects of uses, Jordan, Petra, 15–16 Oct 2008, M. A. Ateyyat, P. 51

Sahaf BZ, Moharramipour S, Meshkatalsadat MH, Filekesh E (2008c) Repellent activity and persistence of the essential oils from *Carum copticum* and *Vitex pseudo-negundo* on *Tribolium castaneum*. Integrated Protection of Stored Products, IOBC Bull 40:205–210

Sahraoui N, Vian MA, Bornard I, Boutekedjiret C, Chemat F (2008) Improved microwave steam distillation apparatus for isolation of essential oils: comparison with conventional steam distillation. J Chromatogr Anal 1210:229–233

Sarikurkcu C, Arisoy K, Tepe B, Cakir A, Abali G, Mete E (2009) Studies on the antioxidant activity of essential oil and different solvent extracts of *Vitex agnuscastus* L. fruits from Turkey. Food Chem Toxicol 47:2479–2483

Sbeghen-Loss AC, Mato M, Cesio MV, Frizzo C, Barros NMD, Henzen H (2011) Antifeedant activity of Citrus waste wax and its fractions against the dry wood termites *Cryptotermes brevis*. J Insect Sci 11 (159):1–7

Sereshti H, Izadmanesh Y, Samadi S (2011) Optimized ultrasonic assisted extraction–dispersive liquid–liquid microextraction coupled with gas chromatography for determination of essential oil of *Oliveria decumbens* Vent. J Chromatogr Anal 1218:4593–4598

Shaaya E, Rafaeli A (2007) Essential oils as biorational insecticides e potency and mode of action. In: Ishaaya I, Nauen R, Rami Horowitz A (eds) Insecticides design using advanced technologies. Springer-Verlag, Berlin, pp 240–261

Shakarami J, Kamali K, Moharramipour S, Meshkatalsadat M (2004) Effects of three plant essential oils on biological activity of *Callosobruchus maculatus* F. (Coleoptera: Bruchidae). Iranian J Agric Sci 35:965–972

Shakarami J, Kamali K, Moharramipour S (2005) Fumigant toxicity and repellency effect of essential oil of *Salvia bracteata* on four species of warehouse pests. J Entomol Soc Iran 24(2):35–50

Shukla P, Polana SPV, Yasagar V, Abdel-Azim M (2012) Antifeedent activity of tree essential oils against the red palm weevils *Rhynchophorus ferrugineus*. Bull Insectol 65(1):71–76

Singh G, Upadhyay RK (1993) Essential oils: a potent source of natural pesticides. J Sci Ind Res 52:676–683

Sivropoulou A, Nikolaou C, Papanikolaou E, Kokkini S, Lanaras T, Arsenakis M (1997) Antimicrobial, cytotoxic, and antiviral activities of *Salvia fruticosa* essential oil. J Agric Food Chem 45:3197–3201

Soleimannejad S, Moharramipour S, Fathipour Y, Nikooei M (2011) Efficiency of essential oil from *Salvia mirzayanii* against nutritional indices of *Tribolium confusum*. Integr Prot Stored Prod IOBC/WPRS Bull 69:299–302

Stahl-Biskup E, Saez F (2002) Thyme: the genus thymus. Taylor and Francis, London

Suthisut D, Fields PG, Chandrapatya A (2011) Fumigant toxicity of essential oils from three Thai plants (Zingiberaceae) and their major compounds against *Sitophilus zeamais*, *Tribolium castaneum* and two parasitoids. J Stored Prod Res 47:222–230

Taghizadeh Sarokolai A, Moharramipour S, Meshkatalsadar MH (2008a) Efficacy of essential oils from *Thymus persicus* and *Prangos acaulis* on nutritional indices of *Tribolium castaneum*. In: Proceedings of the 18th Iranian plant protection congress, 24–27 Aug 2008, Hamedan, Iran, p 173

Taghizadeh Sarokolai A, Moharramipour S, Meshkatalsadar MH (2008b) Fumigant toxicity of essential oil from *Prangos acaulis* against *Tribolium castaneum* and *Sitophilus oryzae*. In: Proceedings of the 18th Iranian plant protection congress, 24–27 Aug 2008, Hamedan, Iran, p 117

Taghizadeh Saroukolai A, Moharramipour S (2011) Oviposition deterrence and persistence of essential oils from Thymus persicus (Roniger ex Reach f.) compared to Prangos acaulis (dc.) Bornm against Callosobruchus maculatus F. in laboratory. Iranian J Med Aromat Plants 27:202–211

Taghizadeh Saroukolai A, Moharramipour S, Meshkatalsadat MH, Fathipour Y, Talebi AA (2009) Repellent activity and persistence of essential oil extracted from *Prangos acaulis* to three stored-product beetles. Am Eurasian J Sustain Agric 3(2):202–204

Taghizadeh Saroukolai A, Moharramipour S, Meshkatalsadat MH (2010) Insecticidal properties of *Thymus persicus* essential oil against *Tribolium castaneum* and *Sitophilus oryzae*. J Pest Sci 83:3–8

Tantaoui-Elaraki AF, Ferhout H, Errifi A (1993) Inhibition of the fungal asexual reproduction stages by three Moroccan essential oils. J Essent Oil 5:535–545

USDA (2007) National Genetic Resources Program. Germplasm Resources Information Network (GRIN). National Germplasm Resources Laboratory, Beltsville, Maryland. http://www.ars-grin.gov/cgi-bin/npgs/html/taxon.pl?27388

Vanichpakorn P, Ding W, Cen XX (2010) Insecticidal activity of five Chinese medicinal plants against *Plutella xylostella* L. larvae. J Asia Pac Entomol 13:169–173

Waliwitiya R, Isman M, Vernon B, Riseman A (2000) Insecticidal activity of thymol, citronellal, eugenol and rosemary oil to *Agriotes obscurus* (Coleoptera: Elateridae) in laboratory and greenhouse bioassays. Faculty of Agricultural Sciences, University of British Columbia, Canada

Waliwitiya R, Kennedy CJ, Lowenberger CA (2009) Larvicidal and oviposition-altering activity of monoterpenoids, trans-anethole and rosemary oil to the yellow fever mosquito *Aedes aegypti* (Diptera: Culicidae). Pest Manage Sci 65(3):241–248

Wang J, Zhua F, Zhoua XM, Niua CY, Leia CL (2006) Repellent and fumigant activity of essential oil from Artemisia vulgaris to *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). J Stored Prod Res 42:339–347

Wei SP, Ji ZQ, Zhang HX, Zang JW, Wang YH, Wu WJ (2011) Isolation, biological evaluation and 3D-QSAR studies of insecticidal/narcotic sesquiterpene polyol esters. J Mol Model 17(4):681–693

Weinzierl RA (2000) Botanical insecticides, soaps and oils. In: Jack ER (ed) Biological and biotechnological control of insect pests. Lewis Publishers, Boca Raton, pp 101–121

Xavier VB, Vargas RMF, Cassel E, Lucas AMM, Santos A, Mondin CA, Santarem ER, Astarita LV, Sartor T (2011) Mathematical modeling for extraction of essential oil from Baccharis spp. by steam distillation. Ind Crops Prod 33:599–604

Yamini Y, Khajeh M, Ghasemi E, Mirza M, Javidnia K (2008) Comparison of essential oil compositions of *Salvia mirzayanii* obtained by supercritical carbon dioxide extraction and hydrodistillation methods. Food Chem 108:341–346

Yang YC, Choi HC, Choi WS, Clark JM, Ahn YJ (2004) Ovicidal and adulticidal activity of *Eucalyptus globulus* leaf oil terpenoids against *Pediculus humanus* capitis (Anoplura: Pediculidae). J Agric Food Chem 52:2507–2511

Yi CG, Kwonl M, Hieu TT, Jang YS, Ahn YJ (2007) Fumigant toxicity of plant essential oil to *Plutella xylostella* (Lepidoptera: Plutellidae) and *Cotesia glomerata* (Hymenoptera: Braconidae). J Asia Pac Entomol 10:157–163

Zandi M, Negahban M, Moharramipour S, Hashemi SA (2010) Preparation and characterization of nanoparticles containing *Cuminum cyminum* L. oil for potential agriculture insecticidal application. Online in: http://abstracts.csc2010.ca/00001895.htm

Zapata N, Smagghe G (2010) Repellency and toxicity of essential oils from the leaves and bark of Laurelia sempervirens and Drimys winteri against *Tribolium castaneum*. Ind Crops Prod 32:405–410

Zargari A (1991) Medicinal plants, Tehran University Press, Tehran 2:942 pp (in Persian)

Ziaee M, Moharramipour S, Mohsenifar A (2014a) MA-chitosan nanogel loaded with *Cuminum cyminum* essential oil for efficient management of two stored product beetle pests. J Pest Sci. doi: 10.1007/s10340.014.0590.6

Ziaee M, Moharramipour S, Mohsenifar A (2014b) Toxicity of *Carum copticum* essential oil-loaded nanogel against *Sitophilus granarius* and *Tribolium confusum*. J Appl Entomol. doi: 10.1111/jen.12133

Zizovic I, Stamenic M, Orlovic A, Skala D (2007) Supercritical carbon dioxide extraction of essential oils from plants with secretory ducts: mathematical modeling on the micro-scale. J Supercrit Fluids 39:338–346