Essential Oils as Green Pesticides: Potential and Constraints

OPENDER KOUL*, SURESH WALIA[1] AND G. S. DHALIWAL
Insect Biopesticide Research Centre, 30 Parkash Nagar, Jalandhar 144003, India; [1]Division of Agricultural Chemicals, Indian Agricultural Research Institute, New Delhi 110012, India

Biopestic. Int. 4(1): 63–84 (2008)

ABSTRACT Many plant essential oils show a broad spectrum of activity against pest insects and plant pathogenic fungi ranging from insecticidal, antifeedant, repellent, oviposition deterrent, growth regulatory and antivector activities. These oils also have a long tradition of use in the protection of stored products. Recent investigations indicate that some chemical constituents of these oils interfere with the octopaminergic nervous system in insects. As this target site is not shared with mammals, most essential oil chemicals are relatively non-toxic to mammals and fish in toxicological tests, and meet the criteria for "reduced risk" pesticides. Some of these oils and their constituent chemicals are widely used as flavoring agents in foods and beverages and are even exempt from pesticide registration. This special regulatory status combined with the wide availability of essential oils from the flavor and fragrance industries, has made it possible to fast-track commercialization of essential oil-based pesticides. Though well received by consumers for use against home and garden pests, these "green pesticides" can also prove effective in agricultural situations, particularly for organic food production. Further, while resistance development continues to be an issue for many synthetic pesticides, it is likely that resistance will develop more slowly to essential-oil-based pesticides owing to the complex mixtures of constituents that characterize many of these oils. Ultimately, it is in developing countries which are rich in endemic plant biodiversity that these pesticides may ultimately have their greatest impact in future integrated pest management (IPM) programmes due to their safety to non-target organisms and the environment.

KEY WORDS : Essential oils, green pesticides, monoterpenes, phytochemicals, antifeedants, repellents, fumigants, commercialization

INTRODUCTION

The environmental problems caused by overuse of pesticides have been the matter of concern for both scientists and public in recent years. It has been estimated that about 2.5 million tons of pesticides are used on crops each year and the worldwide damage caused by pesticides reaches $100 billion annually. The reasons for this are two fold: (1) the high toxicity and nonbiodegradable properties of pesticides and (2) the residues in soil, water resources and crops that affect public health. Thus, on the one hand, one needs to search the new highly selective and biodegradable pesticides to solve the problem of long term toxicity to mammals and, on the other hand, one must study the environmental friendly pesticides and develop techniques that can be used to reduce pesticide use while maintaining crop yields. Natural products are an excellent alternative to synthetic pesticides as a means to reduce negative impacts to human health and the environment. The move toward green chemistry processes and the continuing need for developing new crop protection tools with novel modes of action makes discovery and commercialization of natural products as green

* Corresponding author: E-mail: okoul@airtelmail.in; okoul@koulresearch.org
0973-483X/08/63-84©2008 (KRF)

pesticides an attractive and profitable pursuit that is commanding attention. The concept of "Green Pesticides" refers to all types of nature-oriented and beneficial pest control materials that can contribute to reduce the pest population and increase food production. They are safe and ecofriendly. They are more compatible with the environmental components than synthetic pesticides (Isman and Machial, 2006).

Thus in the present concept of green pesticides, some rational attempts have been made to include substances such as plant extracts, hormones, pheromones and toxins from organic origin and also encompass many aspects of pest control such as microbial, entomophagous nematodes, plant-derived pesticides, secondary metabolites from microorganisms, pheromones and genes used to transform crops to express resistance to pests. More recently, the encouragement of use of products from natural resources and even the extremely biodegradable synthetic and semisynthetic products in pest management, has been considered to constitute the umbrella of green pesticides (Koul *et al.*, 2003; Koul 2005; Dhaliwal and Koul, 2007; Koul, 2008). However, it will be beyond the scope of any article to discuss all of them at one place. Here we shall like to emphasize on some recent developments where essential oils have been projected as safe and commercially viable green pesticides with some recent commercial developments along with their potential and constraints.

Essential oils are defined as any volatile oil(s) that have strong aromatic components and that give distinctive odour, flavour or scent to a plant. These are the by-products of plant metabolism and are commonly referred to as volatile plant secondary metabolites. Essential oils are found in glandular hairs or secretory cavities of plant-cell wall and are present as droplets of fluid in the leaves, stems, bark, flowers, roots and/or fruits in different plants. The aromatic characteristics of essential oils provide various functions for the plants including (i) attracting or repelling insects, (ii) protecting themselves from heat or cold; and (iii) utilizing chemical constituents in the oil as defence materials. Many of the essential oils have other uses as food additives, flavourings, and components of cosmetics, soaps, perfumes, plastics, and as resins.

Typically these oils are liquid at room temperature and get easily transformed from a liquid to a gaseous state at room or slightly higher temperature without undergoing decomposition. The amount of essential oil found in most plants is 1 to 2%, but can contain amounts ranging from 0.01 to 10%. For example, orange tree produce different composition of oils in their blossoms, citrus fruits, and/or leaves. In certain plants, one main essential oil constituent may predominate while in others it is a cocktail of various terpenes. In *Ocimum basilicum* (basil), for example, methyl chavicol makes up 75% of the oil, β-asarone amounts to 70–80% in *Acorus calamus* rhizomes, linalool , in the range of 50–60%, occurs in coriander seed and leaf oils procured from different locations at different time intervals and is by far the most predominant constituent followed by *p*-cymene, terpinene, camphor and limonene. Interestingly 2-decenol and decanal were the most predominant constituents in leaf oil (Lawrence and Reynolds, 2001). However, in other species there is no single component which predominates.

Most essential oils comprise of monoterpenes - compounds that contain 10 carbon atoms often arranged in a ring or in acyclic form, as well as sesquiterpenes which are hydrocarbons comprising of 15 carbon atoms. Higher terpenes may also be present as minor constituents. The most predominant groups are cyclic compounds with saturated or unsaturated hexacyclic or an aromatic system. Bicyclic (1,8-cineole) and acyclic (linalool, citronellal) examples also make the components of essential oils. However, intraspecific variability in chemical composition does exist, which is relative to ecotypic variations and chemotypic races or populations.

ESSENTIAL OILS AS GREEN PESTICIDES

Naturally green concept suggests the avoidance of use of any pesticide via public education and awareness-raising program, developed to inform public about the potential risk of pesticide use and alternatives that are available. In fact, such programs support the policy of "prudent avoidance". Various steps suggested in these programs are overseeding, high mowing, grass cycle, compost spread, deep root watering, core aeration, slow release soil feeding, use of beneficial organisms, etc. This concept is very useful for kitchen garden, lawn and other domestic pest control strategy. Use of essential oils or their components add to this natural concept owing to their volatility, limited persistence under field conditions and several of them having exemption under regulatory protocols.

Essential oils are usually obtained via steam distillation of aromatic plants, specifically those used as fragrances and flavourings in the perfume and food industries, respectively, and more recently for aromatherapy and as herbal medicines. Plant essential oils are produced commercially from several botanical sources, many of which are members of the mint family (Lamiaceae). The oils are generally composed of complex mixtures of monoterpenes, biogenetically related phenols, and sesquiterpenes. Examples include 1,8-cineole, the major constituent of oils from rosemary and eucalyptus; eugenol from clove oil; thymol from garden thyme; menthol from various species of mint; asarones from calamus; and carvacrol and linalool from many plant species. A number of source plants have been traditionally used for protection of stored commodities, 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

Table 1. Mammalian toxicity of some essential oil compounds

Compound	Animal tested	Route	LD_{50} (mg/kg)
2-Acetonaphthone	Mice	Oral	599
Apiol	Dogs	Intravenous	500
Anisaldehyde	Rats	Oral	1510
trans-Anethole	Rats	Oral	2090
(+) Carvone	Rats	Oral	1640
1,8-Cineole	Rats	Oral	2480
Cinnamaldehyde	Guinea pigs	Oral	1160
	Rats	Oral	2220
Citral	Rats	Oral	4960
Dillapiol	Rats	Oral	1000–1500
Eugenol	Rats	Oral	2680
3-Isothujone	Mice	Subcutaneous	442.2
d-Limonene	Rats	Oral	4600
Linalool	Rats	Oral	> 1000
Maltol	Rats	Oral	2330
Menthol	Rats	Oral	3180
2-Methoxyphenol	Rats	Oral	725
Methyl chavicol	Rats	Oral	1820
Methyl eugenol	Rats	Oral	1179
Myrcene	Rats	Oral	5000
Pulegone	Mice	Intraperitoneal	150
γ-terpinene	Rats	Oral	1680
Terpinen-4-ol	Rats	Oral	4300
Thujone	Mice	Subcutaneous	87.5
Thymol	Mice	Oral	1800
	Rats	Oral	980

Source: Dev and Koul (1997); FAO (1999); Koul (2005) neuromodulator octopamine (Kostyukovsky *et al.*, 2002) by some oils and with GABA-gated chloride channels by others (Priestley *et al.*, 2003). The purified terpenoid constituents of essential oils are moderately toxic to mammals (Table 1), but, with few exceptions, the oils themselves or products based on oils are mostly nontoxic to mammals, birds, and fish (Stroh *et al.*, 1998), therefore, justifying their placement under "green pesticides". Owing to their volatility, essential oils have limited persistence under field conditions; therefore, although natural enemies are susceptible via direct contact, predators and parasitoids reinvading a treated crop one or more days after treatment are unlikely to be poisoned by residue contact as often occurs with conventional insecticides. In fact, effects on natural enemies have yet to be evaluated under field conditions. 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.

There are several examples of essential oils like that of rose (*Rosa damascene*), patchouli (*Pogostemon patchouli*), sandalwood (*Santalum album*), lavender (*Lavendula officinalis*), geranium (*Pelargonium graveolens*), etc. that are well known in perfumery and fragrance industry. Other essential oils such as lemon grass (*Cimbopogon winteriana*), *Eulcalyptus globulus*, rosemary (*Rosemarinus officinalis*), vetiver (*Vetiveria zizanoides*), clove (*Eugenia caryophyllus*) and thyme (*Thymus vulgaris*) are known for their pest control properties. While peppermint (*Mentha piperita*) repels ants, flies, lice and moths; pennyroyal (*Mentha pulegium*) wards off fleas, ants, lice, mosquitoes, ticks and moths. Spearmint (*Mentha spicata*) and basil (*Ocimum basilicum*) are also effective in warding off flies. Similarly, essential oil bearing plants like *Artemesia vulgaris*, *Melaleuca leucadendron*, *Pelargonium roseum*, *Lavandula angustifolia*, *Mentha piperita*, and *Juniperus virginiana* are also effective against various insects and fungal pathogens (Kordali *et al.*, 2005). Studies conducted on the effects of volatile oil constituents of *Mentha* species are highly effective against *Callosobruchus maculatus* and *Tribolium castanum*, the common stored grain pests (Tripathi *et al.*, 2000). Essential oils derived from eucalyptus and lemongrass have also been found effective as animal repellents, antifeedants, insecticides, miticides and antimicrobial products; thus finding use as disinfectants, sanitizers, bacteriostats, microbiocides, fungicides and some have made impact in protecting household belongings.

Essential oil from *Cinnamomum zeylanicum*, *Cymbopogon citratus*, *Lavandula angustifolia* syn. *L. officinalis*, *Tanacetum vulgare*, *Rabdosia melissoides*, *Acorus calamus*, *Eugenia caryophyllata*, *Ocimum* spp., *Gaultheria procumbens*, *Cuminum cymium*, *Bunium persicum*, *Trachyspermum ammi*, *Foeniculum vulgare*, *Abelmoschus moschatus*, *Cedrus* spp. and *Piper* species are also known for their varied pest control properties.

Citronella (*Cymbopogon nardus*) essential oil has been used for over fifty years both as an insect repellent and an animal repellent. Combining few drops each of citronella, lemon (*Citrus limon*), rose (*Rosa damascena*), lavender and basil essential oils with one litre of distilled water is effective to ward off indoor insect pests. The larvicidal activity of citronella oil has been mainly attributed to its major monoterpenic constituent citronellal (Zaridah *et al.*, 2003).

Vetiver (*Vetiveria zizanioides*) essential oil obtained by steam distillation of aromatic roots contains a large number of oxygenated sesquiterpenes. This oil is known to protect clothes and other valuable materials from insect attack when placed in closets, drawers, and chests.

Catnip (*Nepeta cateria*) essential oil is highly effective for repelling mosquitoes, bees and other flying insects. The most active constituent in catnip has been identified as nepetalactone. It repels mosquitoes ten times more than DEET. It is particularly effective against *Aedes aegypti* mosquito, a vector for yellow fever virus. Oil of *Trachyspermum* sp. is also larvicidal against *A. aegypti* and southern house mosquito, *Culex quinquefasciatus* Say (LC_{50} = 93.19–150.0 ppm) (Vrushali *et al.*, 2001).

Similalrly, essential oils of *Ocimum sanctum* caused 20% mortality to 3rd instar *S. litura* larvae (Sharma *et al*., 2001). At a topical dose of 100 µg/ larvae, > 90% larval mortality has been reported when essential oil of *Satoreja hortensis*, *Thymus serpyllum* and *Origanum creticum* (LD_{50} = 48.4–53.4) were applied to 3rd instars *S. litura* (Isman *et al*., 2001). Similar studies were reported by Sharda *et al*. (2000) where essential oil of *Ageratum conyzoides* caused 43.0–68.75% mortality at 0.025–0.25 µl concentration. Tripathi *et al*., (2003) has reported toxicity of essential oil of *Aegle marmelos* by topical application to *S. litura* larvae with LD_{50} = 116.3 µg/ larvae. Essential oil of *Lippia alba* induces growth inhibition (GI_{50} = 6.9–11.0 mg/g diet), where both relative growth and feeding consumption rates of *S. litura* were conspicuously reduced (Tripathi *et al*., 2003)

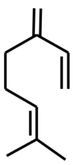
Dill oil obtained from dill plant (*Anethum sowa*) as by-product of dill industry is also a rich source of carvone. The other major constituent of *A. sowa* namely dillapiole is well known for its insecticide synergistic properties. It also occurs to the extent of about 40–60% in *Anethum graveolens* seed oil and more than 51% in spearmint oil (*Mentha spicata*). The turmeric (*Curcuma longa*) leaves, the unutilized part of turmeric plant, on hydrodistillation yields oil rich in α-phellandrene (70%). This oil induces growth inhibition and larval mortality against *Spilosoma obliqua* (Agarwal *et al*., 1999). The leaf oil is also ovicidal and nymphicidal against *Dysdercus koenigii* and induces moderate knockdown effect against *T. castaneum*. Curcumene and ginger oil at 0.2% concentration induces 86% inhibition of the mycelial growth of the test fungus *Rhizoctonia solani*. Thus, collective assessment of essential oil efficacy as green pesticides suggests that some oils are significantly more active than others. However, more empirical evaluation of active components using wide array of pest species would reveal valuable and specific biological activities as discussed in next section.

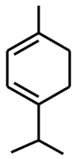
ESSENTIAL OIL CONSTITUENTS AND THEIR EFFICACY

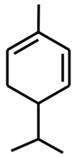
As mentioned above essential oils are complex mixtures of natural organic compounds which are predominantly composed of terpenes (hydrocarbons) such as myrecene, pinene, terpinene, limonene, *p*-cymene, α- and β- phellandrene etc.; and terpenoids (oxygen containing hydrocarbons) such as acyclic monoterpene alcohols (geraniol, linalool), monocyclic alcohols (menthol, 4-carvomenthenol, terpineol, carveol, borneol,), aliphatic aldehydes (citral, citronellal, perillaldehyde), aromatic phenols (carvacrol, thymol, safrol, 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), sulphur containing constituents, methyl anthranilate, coumarins, etc. Zingiberene, curcumene, farnesol, sesquiphellandrene, termerone, nerolidol, etc. are examples of sesquiterpenes (C_{15}) 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 essential oils but are sometimes encountered as by-products. Chemical structures of some of the essential oil constituents are given in Fig. 1 and many among them possess potent biological activity and are responsible for the bitter taste and toxic properties.

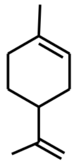
Insecticides and Growth Inhibitors

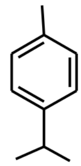
Essential oil constituents are primarily lipophilic compounds that act as toxins, feeding deterrents and oviposition deterrents to a wide variety of insect-pests. Insecticidal properties of several monoterpenoids to the housefly, red flour beetle and southern corn root-worm have been reported (Rice and Coats, 1994). Although many monoterpenoids have insecticidal properties, the degree of toxicity of different compounds to one species differs considerably. Cornelius *et al.* (1997) evaluated toxicity of monoterpenoids against *Coptotermes formosanus* (a subterranean termite) of which eugenol was found most effective as termiticide. It was also effective as a fumigant and as feeding deterrent. Eugenol is also reported as toxic to asian armyworm, *Spodoptera litura* Fabricius, granary weevil, *Sitophilus grana-*

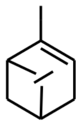

Myrcene

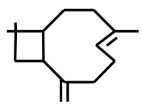

α-Terpinene

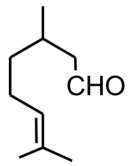

α -Phellandrene

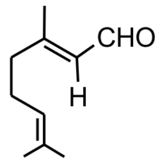

Limonene

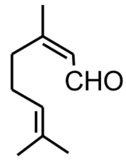

p- Cymene

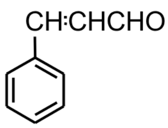

α-Pinene

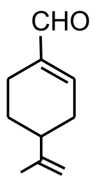

Caryophyllene

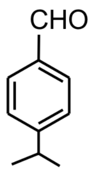

Citronellal

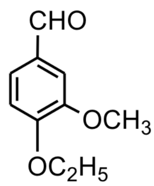

Citral (Geranial)

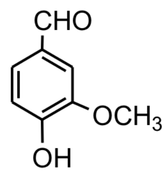

Citral (Neral)

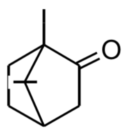

Cinnamaldehyde

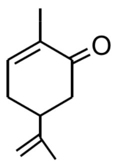

Perillaldehyde

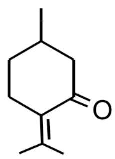

Cuminaldehyde

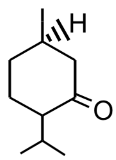

Ethyl vanillin

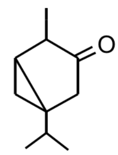

Vanillin

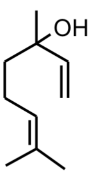

Camphor

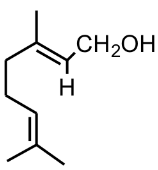

Carvone

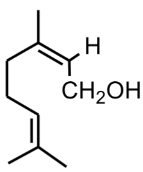

Pulegone

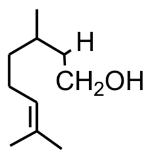

Menthone

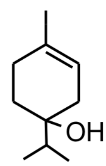

Thujone

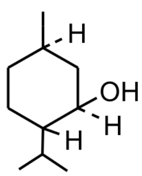

Linalool

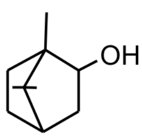

Geraniol

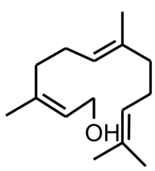

Nerol

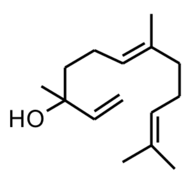

Citronellol

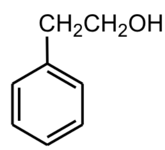

Terpine-4-ol

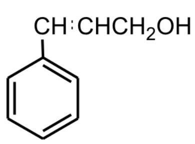

Menthol

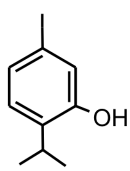

Borneol

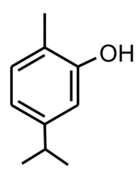

Farnesol

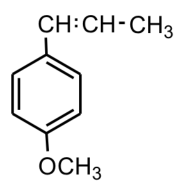

Nerolidol

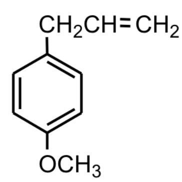

Phenylethyl alcohol


Cinnamic alcohol


Thymol


Carvacrol


Anethole


Estragol

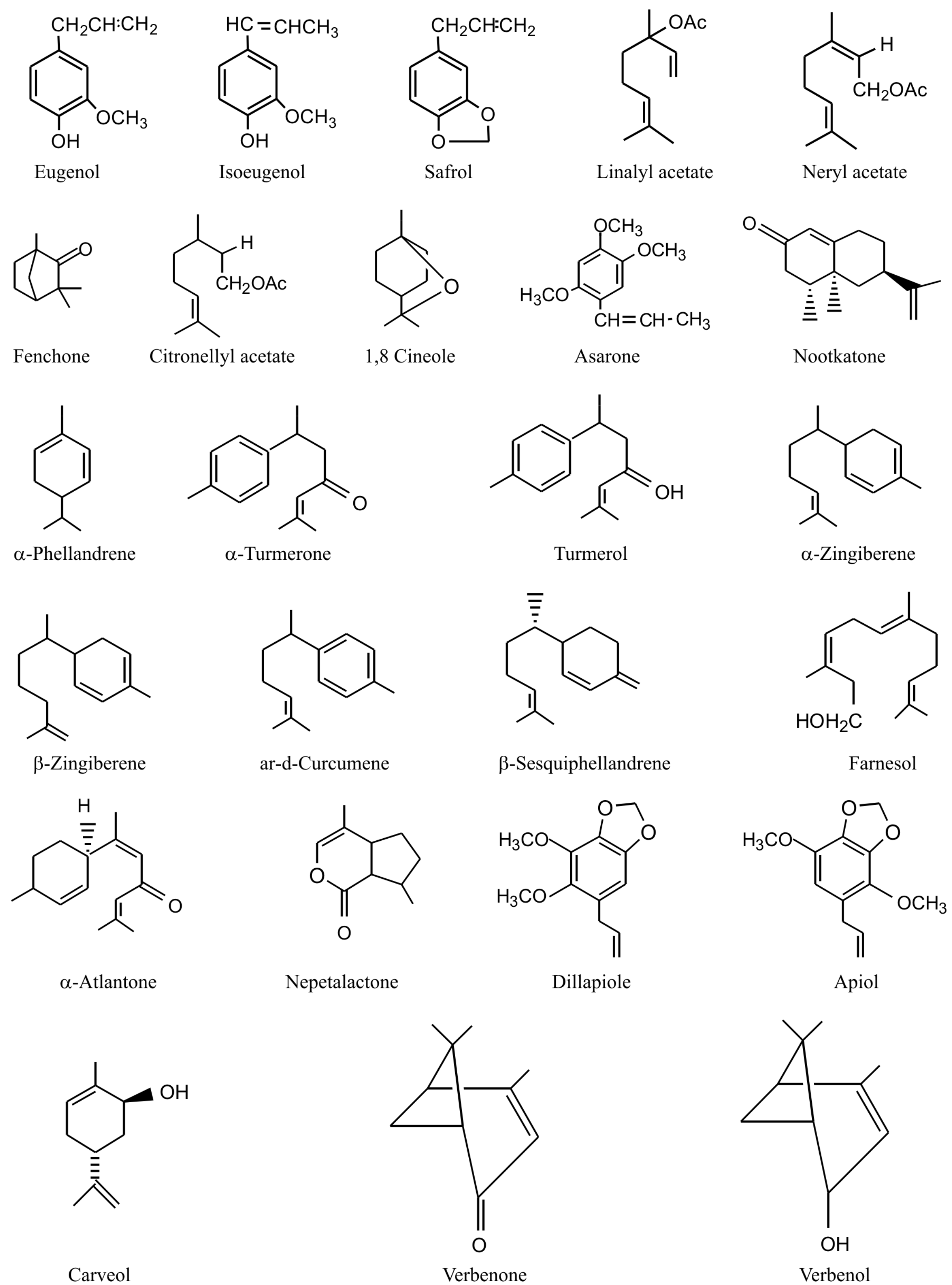


Fig. 1. Chemical structures of essential oil constituents

ries (Linnaeus), common house fly, *Musca domestica* Linnaeus and western corn root worm, *Diabrotica virgifera* Lee Conte, (LD_{50} = 2.5–157.6 µg/insect) (Hummelbrunner and Isman, 2001; Obeng-Ofori and Reichmuth, 1997; Lee *et al.*, 1997). Eugenol is also active against *Drosophila melanogaster* Meigen, yellow fever mosquito, *Aedes aegypti* (Linnaeus) and American cockroach, *Periplanata americana* (Linnaeus) (Bhatnagar *et al*., 1993; Ngoh *et al*., 1998). Similarly, thymol induces toxicity in *M. domestica* and *S. litura* (LD_{50} = 25.4–29.0 µg/insect) (Lee *et al*., 1997; Hummelbrunner and Isman, 2001) and is also toxic to *D. melanogaster* and northern house mosquito, *Culex pipiens* Linnaeus (Franzios *et al*., 1997; Traboulsi *et al*., 2002). Citronellal is toxic to *S. litura, M. domestica* (LD_{50} = 66.0–111.2 µg/insect; Hummelbrunner and Isman, 2001; Lee *et al*., 1997), cowpea weevil, *Callosobruchus maculatus* (Fabricius) and *D. melanogaster* (Don-Pedro, 1996). *d*-Limonene in the range of 50–273.7 µg/insect 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; Lee *et al*., 2001; Coats *et al*., 1991). Similarly, limonene found in the essential oil of various citrus leaves and fruit peels have exhibited significant insect control properties (Karr and Coats, 1988). Menthone, *trans*-anethole and cinnamaldehyde are well known anti-insect compounds that have been studied against variety of insects with wide range of dosage required to kill 50% population (65–1735 µg/insect) (Marcus and Lichtenstein, 1979; Harwood *et al*., 1990; Lee *et al*., 1997; Franzios *et al*., 1997; Hung and Ho, 1998; Hummelbrunner and Isman, 2001; Chang and Ahn, 2001; Lee *et al*., 2001; Chang and Cheng, 2002). Meepagala *et al.* (2006) found that apiol isolated from *Ligusticum hultenii* exhibited high termiticidal activity of 100% within 11 days after treatment and similar effect was shown by vulgarone B, isolated from *Artemisia douglasiana*, where as cnicin isolated from *Centaurea maculosa* showed mortality of 81% within 15 days after treatment when applied at 1.0% (w/w) concentration to these termites. Citral **(**3,7-dimethyl 2,6-octadienal), the most important member of acyclic monoterpenoids is a liquid which has smell of lemon and occurs to an extent of 60–80% in lemon grass oil. Due to the presence of one α, β -unsaturated moiety, it occurs as a mixture of *E* (*trans*) and *Z* (*cis*) geometric isomers. These isomers are referred as geranial and neral, respectively but do not show much potential in pest control.

Lichtenstein *et al.* (1974) have reported that carvone isolated from aerial parts of dill plants (*Anethum graveolus* Linnaeus) was insecticidal to *Drosophilla* and *Aedes* spp. It also suppressed larval and adult survival (Ouden *et al.*, 1993). Lee *et al.* (1997) evaluated acute toxicity of 34 naturally occurring monoterpenoids against three insect species. They reported that citronellic acid and thymol were the most toxic against house fly, while citronellol and thujone were most effective against the western corn root worm. Hierro *et al.* (2004) has reported the action of different monoterpenic compounds against *Anisakis simplex* larvae and found that geraniol, citronellol, citral, carvacrol and cuminaldehyde were active at 12.5 µg/ml concentration.

Eugenol from cloves, *Eugenia cryophyllus*; 1,8-cineole from *Eucalyptus globules*; citronellal from lemon grass, *Cymbopogon nardus*; pulegone from *Mentha pulegium*, and thymol and carvacrol from *Thymus vulgaris* are among the most active constituents against insects. Eugenol shows variable LD_{50} values which are purely species specific. Pulegone is shown to be effective against *M. domestica, D. virgifera, P. saucia* and, *S. litura* in the range of LD_{50} = 38–753.9 µg/insect (Lee *et al.*, 1997; Harwood *et al.*, 1990; Hummelbrunner and Isman, 2001). Pulegone containing diet at 0.1% retarded development and inhibited reproduction of last instar of southern armyworm, *Spodoptera eridania* (Cramer) (Gunderson *et al.*, 1985). Pulegone has also been observed to be more toxic than *l*-menthol against european corn borer, *Ostrinia nubilalis* (Hubner) 1st instar, where as reverse toxicity was observed against 2nd instar (Lee *et al*., 1999).

Substituted phenols such as eugenol, methyl eugenol, isoeugenol, safrole, isosafrole are better toxicants and repellents than monoterpenes, such as limonene, cineole and p-cymene. The essential oil from root of sweet flag, *Acorus calamus* is also known for its insecticidal and antigonadal actions associated with its most abundant constituent β - asarone (Koul *et al*., 1990; Koul, 1995). *A. calamus* has been shown to induce mortality of 80.87% in 3rd instars of *Spilarctia obliqua* (Walker) in laboratory and 74.26% under field conditions at 2.0% concentration (Dubey *et al.,* 2004).

According to Raina *et al*., (2007) orange oil extracted from citrus peel (containing ~92% *d*-limonene) caused 96 and 68% mortality to formosan subterranean termite, *Coptotermes formosanus* Shiraki within 5 days and there was significant reduction in feeding as compared to controls at 5 ppm concentration (v/v), also the termites did not tunnel through glass tubes fitted with sand treated with 0.2–0.4% orange oil extract. Catnip oil derived from *Nepeta cataria* and its two major components *E, Z*- nepetalactone, *Z, E*-nepetalactone monoterpenes at 40 mg/cm^2 caused 100% mortality to formosan subterranean termite, *C. formosanus* after one day, where as at 20 mg/cm^2, 97% mortality was achieved by *E, Z*- nepetalactone within 7 days which also determined its repellent action by preventing termites to tunnel through a 60 mm glass tube filled with sand treated at 200 ppm (Chauhan and Raina, 2006).

Acaricidal activities of various essential oils have been assessed and found toxic to honey bee mite, *Acarapis woodi* (Rennie), (Ellis and Baxendale, 1997), varroa mite, *Varroa jacobsoni* Oudemans (Calderone and Spivak, 1995), northern fowl mite, *Ornithonyssus sylviarum* (Canestrini and Fanzago) (Carroll, 1994), grain mite, *Tyrophagus longior* Gervais, (Perrucci, 1995), scab mite, *Psoroptes cuniculi* (Delafond), (Perrucci *et al*., 1995), two spotted spider mite, *Tetranychus urticae* Koch (Chiasson *et al.,* 2001), *Dermatophagoides pteronyssinus* (Trouessart) and American house dust mite, *Dermatophagoides farinae* Huges, (Yatagi *et al*., 1997) and *T. urticae* (Lee *et al*., 1997). Choi *et al*. (2004) has evaluated 53 plant essential oils against *T. urticae* and *Phytoseilus persimilis*. Among pure constituents citronellal, eugenol, menthol, pulegone, and thymol are moderately active against various mites (Calderone and Spivak, 1995; Perrucci *et al*., 1995; Ellis and Baxendale, 1997). Essential oils rich in 1,8-cineole are also effective against house dust mites (Miresmailli *et al*., 2006). These studies indicate that such compounds can make substantial impact as commercial products, if suitable delivery systems are developed.

Beninger *et al*., (1993) has shown that diterpene 3-epicaryotin reduced growth of european corn borer larvae when incorporated into artificial diet and pupal deformities and time to pupation also increased. Menthol reduced growth and inhibited pupation of the variegated cutworm, *Peridroma saucia* (Hubner) (Harwood *et al*., 1990). *d*- Limonene, linalool, α-myrcene and α-terpineol significantly increased the nymphal duration in German cockroach, *Blattella germanica* (Linnaeus) when fed through artificial diet (Karr and Coats, 1992). 1, 8 Cineole isolated from *Artemisia annua* is also a potential insecticidal allelochemical that could reduce the growth rate, food consumption and food utilization in some post harvest pests and house hold insects (Jacobson and Halber, 1947; Klocke *et al.,* 1989; Obeng and Reichmuth, 1997). Similar effects against *O. nubilali*s (reared from 1st instars on diet) have been recorded with carveol, 4-carvomenthenol, *l*-carvone, citronellal, geraniol, isopulegol, limonene, linalool, *l*-menthol, perillaldehyde, peril alcohol, α-pinene, pulegone, α-terpineol, thujone, thymol, 2-fluoro ethyl thymol ether (a fluorinated thymol derivative MTEE-25), MTEE-35, MTEE-76, MTEE-90, MTEE-99 and MTEE-P in the concentration range of 0.02–20.0 mg/g diet (Lee *et a*l., 1999). The LC_{50} value of MTEE-25 was 6 times more than its parent compound thymol to 1st instars of *O. nubilalis.*

Turmeric plant oil is also very useful in pest control. The turmeric leaves and unutilized parts of turmeric plant, on hydrodistillation yields oil rich in 2-phellandrene (70%) that inhibits growth of *S. obliqua* and diamond back moth, *Plutella xylostella* (Linnaeus) at 1.0 % concentration (Govindaraddi, 2005; Walia, 2005).

Fumigants

Monoterpenes being volatile are more useful as insect fumigants. Several studies have been undertaken in the past to explore the potential of essential oils and their constituents as insect fumigants. Pulegone, linalool and limonene are known effective fumigants against rice weevil, *Sitophilus oryzae*. While *Mentha citrata* oil containing linalool and linalyl acetate exhibit significant fumigant toxicity to these rice weevils (Singh *et al.,* 1989), *l*-carvone has been reported to cause 24 times more fumigant toxicity than its contact toxicity to lesser grain borer, *Rhizopertha domestica* (Tripathi *et al.,* 2003). Carvone was similarly effective as adulticide while menthol was most effective as fumigant against *T. castaneum* and *C. maculatus.* 1,8-cineole on the other hand exhibits both contact and fumigant toxicity when tested against *T. castaneum* (Tripathi *et al.,* 2001). The adults were more susceptible than the larvae to both contact and fumigant toxicity. Number of compounds has been evaluated as fumigants against *Musca domestica* and *T. castaneum.* LC_{50} (µg/l) values have been determined for carvacrol, carveol, geraniol, linalool, menthol, terpineol, thymol, verbenol, carvones, fenchone, menthone, pulegone, thujone, verbenone, cinnamaldehyde, citral, citronellal, and cinnamic acid (Rice and Coats, 1994). These studies reveal that ketones were more effective as fumigants.

Trans-anethole, thymol, 1,8-cineole, carvacrol, terpineol, and linalool have been evaluated as fumigants against *T. castaneum*. Only compound to show significant effect against this insect species was *trans*-anethole and red flour beetles seemed to be least susceptible to most of the other compounds up to 300 µl/l fumigation. Anethole has shown significant effect on population from 20 µl/l concentration (66% reduction in population), which touched to 98% at 80 µl/l level and beyond this there was absolute control of population generation. For improving the mortality effect of anethole, minimum heat treatment (45˚C) device was used that enhanced the toxicity of adults by 2-fold at 50.0 µl/l and 100.0 µl/5l treatment, respectively. Among various combinations of compounds used anethole combined with 1,8-cineole (1:1) was the best. This combination reduced the population by 100% at 50µl/l concentration and at the same time was toxic to adults as well. As *T. castaneum* was resistant to most of the compounds, a workable gelatin capsule formulation (IBRC-TACT) based on combination of four compounds has been developed, which reduced the progeny by 100%. A significant observation has been that when treatment was continued for larvae in 5-litre jars (with feeding medium) and insects were allowed to complete life cycle under treated conditions the freshly emerged adults coming to the surface of the feeding medium were dead within 12 h. This suggests that freshly emerged adults were highly susceptible to the treatment of anethole or IBRC-TACT and could not withstand the effect of compounds. One of the plausible explanations for such an effect could be the interference during the sclerotization immediately after the emergence from pupae, which ultimately leads to the death of beetles within 12 h of their emergence (Koul *et al.,* 2007).

Antifeedants

Antifeedant chemicals may be defined as being either repellent without making direct contact to insect, or suppressant or deterrent from feeding once contact has been made with insects. Essential oil constituents such as thymol, citronellal and α-terpineol are effective as feeding deterrent against tobacco cutworm, *S. litura* and synergism or additive effects of combination of monoterpenoids from essential oils have been reported against *S. litura* larvae (Hummelbrunner and Isman, 2001). Bioefficacy of *Eucalyptus camaldulensis* var. *obtusa* and *Luvanga scandans* essential oils has also been determined against *S. litura* larvae. Biogenically related monoterpenoids, the 1,8-cineole from *Eucalyptus camaldulensis* var. *obtusa* and linalool from *Luvanga scandans* species were found to be most active isolates from these plants via topical application. Linalool was more active (LD_{50} = 85.5 µg/larva) than 1,8-cineole (LD_{50} = 126.6 µg/larva). Various known monoterpenoids have been used as binary mixtures and tested for synergy, using toxicity and feeding inhibition parameters. The data suggests that thymol and *trans*-anethole synergized the effects of linalool (at 18 µg/larva dose, combined in 1:1 ratio) but thymol with 1,8-cineole exhibited only additive effect and so was the case with terpineol and linalool combination. A definite synergism was also observed in case of isolated compounds from two different plant species, i.e. linalool with 1,8-cineole (Singh *et al.*, 2008).

Antifeedant activity of 1,8- cineole has also been demonstrated against *T. castaneum* (Tripathi *et al.*, 2001). In another study (Paruch *et al.*, 2000), a terpenoid lactone exhibited antifeeding activity against granary weevil, *Sitophilus granarium*; the khapra beetle, *Trogoderma granarium*; and confused flour beetle, *T. confusum*. The activity was comparable to the neem biopesticide. Feeding deterrence activities of leaf essential oil of *Curcuma longa* against adult and larvae of grain borer, *R. domestica*; rice weevil, *S. oryzae*; and red flour beetle, *T. castaneum* has been attributed to the presence of monoterpenes, carvone and dihydrocarvone (Tripathi *et al.*, 2003). Products isolated/derived from *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger) have also been found effective as insect antifeedant and insect growth regulators (Chowdhury *et al*., 1999; Agarwal *et al*., 2000; Agarwal and Walia, 2003).

Koschier and Sedy, (2001) studied the antifeedant effect of essential oil of majoram and rosemary oil (*Rosemarinum officinalis*) at 0.1–1.0% concentration against onion thrips, *Thrips tabaci* Lindeman. Essential oils of *Ocimum sanctum*, *O. basilicum*, *Cymbopogon winterianus*, *Callistemon lanceolatus* and *Vitex negundo* caused 100% feeding deterrence at 10% concentration. Considerable feeding inhibition (70.21–80.21%) was recorded for 3rd instars of *S. obliqua* when treated with 0.4% concentration of *Artemisia nilagarica* and *Juglans regia* var. *kumaonica* oils, while at 0.3% these oils induced feeding deterrence of 63.12–83.76% among 5th instars of *S. litura* (Chowdhury *et al.*, 2000). Essential oils from *Elsholtzia densa, E. incise and E. piulosa* also showed significant antifeedant activity against 3rd instars of *S. litura* (Shishir *et al.*, 2004). Highest feeding deterrence of 76.4% was observed in *H. armigera* with essential oil of *Aegle marmelos* (Tripathi *et al*., 2003). These oils are rich in 1,8-cineole, linalool, eugenol, carvacrol and thymol, which are known compounds to show effects against various insect species and fumigant activity in above cases could be attributed to them in the respective essential oils.

Repellents

Vector-borne diseases caused by *A. aegypti* and other mosquitoes have become global health problem. Though thousands of plants have been tested as potential sources of insect repellents, only a few plant-derived chemicals tested to date demonstrate the broad effectiveness and duration as good as DEET (Cockcroft *et al.*, 1998). Recently, a review of botanical phytochemicals with mosquitocidal potential has been published (Shaalan *et al*., 2005), demonstrating identification of novel effective mosquitocidal from botanicals containing active phytochemicals. The review gives current state of knowledge on larvicidal plant species, extraction processes, growth and reproduction inhibiting phytochemicals, botanical ovicides, synergistic, additive and antagonistic joint action effects of mixtures, residual capacity, effects on non-target organisms, resistance, screening methodologies, and discuss promising advances made in phytochemical research for vector control.

Similarly, laboratory bioassays were conducted to determine the activity of 15 natural products isolated from essential oil components extracted from the heartwood of Alaska yellow cedar, *Chamaecyparis nootkatensis* (D. Don) Spach., against *Ixodes scapularis* Say nymphs, *Xenopsylla cheopis* (Rothchild), and *Aedes aegypti* (L.) adults. Four of the compounds from the essential oil have been identified as monoterpenes, five as eremophilane sesquiterpenes, five as eremophilane sesquiterpene derivatives from valencene and nootkatone, and one as a sesquiterpene outside the eremophilane parent group. Carvacrol was the only monoterpene that demonstrated biocidal activity against ticks, fleas, and mosquitoes with LC_{50} values of 0.0068, 0.0059, and 0.0051% (w/v), respectively after 24 h. Nootkatone from Alaska yellow cedar was the most effective of the eremophilane sesquiterpenes against ticks (LC_{50} = 0.0029%), whereas the nootkatone from grapefruit extract exhibited the greatest biocidal activity against fleas (LC_{50} = 0.0029%). Mosquitoes were most susceptible to one of the derivatives of valencene, valencene-13-aldehyde (LC_{50} = 0.0024%), after 24 h. Bioassays to determine residual activity of the most effective products were conducted at 1, 2, 4, and 6 wk after initial treatment. Residual LC_{50} values for nootkatone did not differ significantly at 4 wk post-treatment from the observations made at the initial 24 h treatment. The ability of these natural products to kill arthropods at relatively low concentrations also represents an alternative to the use of synthetic pesticides for control of disease vectors (Panella *et al*., 2005; Dietrich *et al.*, 2006). Repellency of oils of lemon, eucalyptus, geranium, and lavender have also been recorded against *Ixodes ricinus* (Acari: Ixodidae) in the laboratory and field (Jaenson *et al*., 2006).

However, plants whose essential oils have been reported to have repellent activity include citronella, cedar, verbena, pennyroyal, geranium, lavender, pine, cinnamon, rosemary, basil, thyme, and peppermint. Most of these essential oils provided short-lasting protection usually lasting less than 2 h. Many essential oils and their monoterpenic constituents are known for their mosquito repellent activity against *Culex* species (Choi *et al*., 2002; Traboulsi *et al*., 2002). The mosquito repellent activity of 38 essential oils was screened against the mosquito *A. aegypti* under laboratory conditions using human subjects (Trongtokit *et al*., 2005). The oils of *Cymbopogon nardus* (citronella), *Pogostemon cablin* (patchuli), *Syzygium aromaticum* (clove) and *Zanthoxylum limonella* were the most effective and provided 2 h of complete repellency. Among three essential oil constituents namely eugenol, cineole and citronellal, the later was found to be most effective against *A. aegypti* mosquito (Coats *et al.*, 1991). Lemon grass oil ointment containing 15% v/w citral exhibited 50% repellency which lasted for 2–3 h (Oyedela *et al.*, 2002). It has now been reported that a component of the essential oil of the catnip plant (*Nepeta cateria*), the nepetalactone repels mosquitoes 10 times more effectively than DEET as it takes about one-tenth as much nepetalactone as DEET to have the same effect. *Tagetes erecta* is a potential plant whose essential oil from flowers has been effective repellent against insects (Ray *et al*., 2000). Accordingly ocimene from *T. minuta* has also repellent properties which need to be exploited in detail.

Cinnamaldehyde, eugenol, cinnamyl acetate and essential oils from different *Cinnamomum* species are effective mosquito larvicides (Huang and Ho, 1998; Cheng e*t al.*, 2004). Several monoterpenoidal constituents evaluated for their insect repellent activity show that linalool and nerol in linear monoterpenoids and carvone, pulegol, pulegone and isopulegol in monocyclic monoterpenoids are the most effective space repellents; some others have been found effective as repellents against the German cockroach, *B. germanica* (Inazuka, 1983). Two monoterpenes namely menthol and citral have been reported to be toxic against tracheal mites (Ellis and Baxendale, 1997). Thus such essential oil compounds may play a pivotal role in the control of mosquito driven dengue and malaria outbreaks through lure and kill technique. In recent years, several monoterpenoids have been considered potential alternatives to conventional insecticides as a natural means of pest control. Since oxygenated essential oil constituents are more active, efforts have been made to improve bioefficacy of one such oxygenated essential oil constituent fenchone (LC_{50} = 3.8 mg/l for house flies and 14.2 mg/l for red flour beetles; Rice and Coats, 1994) by its chemical modification and structure-activity relationship studies.

Turmerone and *ar*-turmerone (dehydroturmerone), the major constituents of turmeric rhizome powder oil are strong repellents to stored grain pests. The turmeric oil has been reported to provide protection to wheat grains against red flour beetle, *T. castaneum* (Herbst) (Chahal *et a*l., 2005). The fruit oil of *Piper retrofractum* has also shown high repellency (52–90%) against *T. castaneum* at 0.5–2% concentration.

Oviposition Inhibitors and Ovicides

Application of 1, 8 cineole and majoram reduced ovipopsition rate by 30–50% at concentration of 1.0%, as compared to untreated controls (Koshier and Sedy, 2001). In Egypt, *A. calamus* oil at 0.1% prevented oviposition of *C. maculatus* (Dimetry *et* *al.*, 2003). Garlic oil which is also an oviposition deterrent has been found to be highly toxic to eggs of *P. xylostella* (Govindaraddi, 2005) and 99.5% reduction in egg hatching has been recorded in *S. obliqua* at 250 mg oil/50 eggs using essential oil of *Aegle marmelos* (Tripathi *et al*., 2003). l-Carvone also completely suppresses the egg hatching of *T. castaneum* at 7.22 mg/cm^2 surface treatment (Tripathi *et al*., 2003). Carvacrol, carveol, geraniol, linalool, menthol, terpineol, thymol, verbenol, carvones, fenchone, menthone, pulegone, thujone, verbenone, cinnamaldehyde, citral, citronellal, and cinnamic acid have been evaluated as ovicides against *M. domestica* eggs (Rice and Coats, 1994). Inhibition of hatching ranged from 33–100%. These studies demonstrate that monoterpenoid ketones are significantly more effective than structurally similar alcohols (like menthone versus menthol; verbenone versus verbenol, etc.)

Attractants

Geraniol and eugenol are effective attractants and are used as lures in traps for the Japanese beetle, *Popillia japonica* Newman, and methyl-eugenol has been used to trap oriental fruit fly, *Dacus dorsalis* Hendel (Vargas *et al*., 2000). Cinnamyl alcohol, 4-methoxy-cinnamaldehyde, cinnamaldehyde, geranylacetone and α-terpineol are also attractive to adult corn rootworm beetles, *Diabrotica* sp. (Hammack, 1996; Petroski and Hammack, 1998). The essential oil and a number of extracts of *Rosmarinus officinalis* L. in solvents of increasing polarity have been isolated, and their components identified and tested as pest control agents. Ethanol and acetone extracts attract grape berry moth, *Lobesia botrana*. However, none of the extracts had a significant effect on western flower thrips, *Frankliniella occidentalis*, which is attracted by 1,8-cineole, a major essential oil component (Katerinopoulos *et al*., 2005).

Lemon essential oil is distilled from the peels of *Citrus limonum*. It has a light yellow color and a characteristic lemon aroma. Lemon essential oil contains several terpenes and geraniol, which have all been shown to attract thrips, fungus gnats, mealybugs, scale, and Japanese beetles. Adding this oil to the insect-a-peel, thrips/leafminer blue trap, or the yellow aphid/whitefly sticky trap will attract these unwanted pests and capture them on the trap (http://www.arbico-organics.com/1610075.html).

Compositions of cis-jasmone were found to effectively attract adult Lepidoptera. The cis-jasmone may be used alone or in combination with one or more other volatiles of the Japanese honeysuckle flower, particularly linalool and/or phenylacetaldehyde. By attracting the adult Lepidoptera to attracticidal baits and/or field traps, the attractants are useful for the control and monitoring of these agricultural pests (Pair and Horvat, 1997). Similarly, natural essential oils have shown a high attractiveness for greenhouse whitefly, *Trialeurodes vaporariorum* Westwood. Greenhouse whitefly reacted particularly intensively to sandalwood oil, basil oil, and grapefruit oil. After the application of aromatic substances on yellow sticky traps, the number of insects caught increased significantly amounting to 487.64, 483.20, and 333.09%, respectively (Górski, 2004). Thus, natural essential oils or their constituents could be useful in the monitoring of pests, at least greenhouse whitefly in the present case.

Antifungal Agents

Antifungal activities of certain essential oils or their components have also been assessed and found effective for *Botrytis cinerea* (Wilson *et al*., 1997), *Monilinia fructicola* (Taso and Zhou, 2000), R*hizoctonia solani*, *Fusarium moniliforme* and *Sclerotinia sclerotiorum* (Muller *et al.*, 1995), *F. oxysporum* (Bowers and Locke, 2000), *Cymbopogon nardus* (De-Billerbeck *et al*., 2001), *Aspergillus niger* (Paster *et al.*, 1995), *A. flavus* (Montser and Carvajal, 1998), *Penicillium digitatum* (Daferera *et al.*, 2000) and *F. solani*, *R. solani*, *Pythium ultimum* and *Colletotrichum lindemuthianum* (Zambonelli *et al.*, 1996), *Alternaria padwickii*, *Bipolaris oryzae*, and peanut fungi (Nguefack *et al*., 2007; Krishna and Pande, 2007). Unlike insects, different fungal species show more consistent results. Thymol and carvacrol are definitely active against most fungal species tested (Kurita *et al*., 1981; Muller-Riebau *et al*., 1995; Tsao and Zhou, 2000). The mechanism of action of these compounds against fungi is unknown but may be related to their general ability to dissolve or otherwise disrupt the integrity of cell walls and membranes (Isman and Machial, 2006).

Greenhouse experiments have been conducted to determine the effectiveness of plant essential oils as soil fumigants to manage bacterial wilt (caused by *Ralstonia solanacearum*) in tomato. Pottin-gmixture ("soil") infested with *R. solanacearum* was treated with the essential oils at 400 mg and 700 mg per liter of soil in greenhouse experiments. *R. solanacearum* population densities were determined just before and 7 days after treatment. Populations declined to undetectable levels in thymol, palmarosa oil, and lemongrass oil treatments at both concentrations, whereas tea tree oil had no effect. Tomato seedlings transplanted in soil treated with 700 mg/liter of thymol, 700 ml/liter of palmarosa oil, and 700 ml/liter of lemongrass oil were free from bacterial wilt and 100% of plants in thymol treatments were free of *R. solanacearum* (Pradhanang *et al*., 2003).

Antiviral Agents

The plant volatile oils and pure isolates have been mentioned as containing substances which interfere with or inhibit infection of viruses. The essential oil of *Melaleuca alternifolia* in concentration of 100, 250, 500 ppm has been found to be effective in decreasing local lesions of TMV on host plant *Nicotiana glutinosa* (Bishop, 1995). Similarly, essential oils of *Ageratum conyzoides*, *Callistemon lanceolatus*, *Carum copticum*, *Ocimum sanctum* and *Peperomia pellucida* have been evaluated for inhibitory activity against cowpea mosaic virus (CPMV), mung bean mosaic virus (MBMV), bean commonil mosaic virus (BCMV) and southern bean mosaic virus (SBMV). *Ocimum sanctum* at 3000 ppm gave the best inhibition of 89.6, 90, 92.7, 88.2% against CMV, MBMV, BCMV, and SBMV respectively. The other oils also showed inhibitory activity against other viruses (Rao *et al*., 1986) Another report has shown 62% inhibition against tobacco mosaic virus. The fresh hydrodistilled carrot leaves yielded 0.07% essential oil, analysed by GLC and TLC. Constituents were identified by IR, NMR and mass spectra. Twenty nine compounds were identified and the major constituents were Sabinene (10.93%), linalool (14.90%), linalyl acetate (8.35%), and Carvone (8.77%) (Khanna *et al*., 1990)

Tagetes minuta oil has been found to be active against carnation ring spot (CaRSV) and carnation vein mottle viruses (CaVMV). The ingredients present in the oil namely dihydrotagetone and ocimene when tested individually in pure form, were found to have enhanced antiviral activity against two carnation viruses (US Patent 6444458, 2002). The oil as such and the bioactive consitituent present in oil can be commercially used as natural and eco-friendly antiviral products.

Thrips-vectored Tomato spotted wilt virus is one of the most devastating pest complexes affecting tomato. Field trials were conducted over 2 years to determine the effects of volatile plant essential oils and kaolin-based particle films on the incidence of tomato spotted wilt and population dynamics of *Frankliniella* thrips. The essential oils compound, geraniol, lemongrass (*Cymbopogon flexuosus*) oil, and tea tree (*Melaleuca alternifolii*) oil, were compared with a standard insecticide treatment and an untreated control. All treatments were applied with and without kaolin, in a 5 × 2 factorial design. When combined with kaolin, the three essential oils reduced tomato spotted wilt virus incidence by 32 to 51% in 2005 and by 6 to 25% in 2006 compared with the control. When applied with kaolin, the three essential oils produced yields similar to the insecticide standard (Reitz *et al*., 2008). Therefore, naturally occurring products, such as essential oils and kaolin, could be used successfully to control viruses and reduce insecticide use on tomatoes.

COMMERCIAL PRODUCTS AND USES

In spite of considerable research effort in many laboratories throughout the world and an ever-increasing volume of scientific literature on the pesticidal properties of essential oils and their constituents, surprisingly few pest control products based on plant essential oils have appeared in the market place. This may be a consequence of regulatory barriers to commercialization (i.e. cost of toxicological and environmental evaluations) or the fact that efficacy of essential oils toward pests and diseases is not as apparent or obvious as that seen with currently available products. In the United States, commercial development of insecticides based on plant essential oils has been greatly facilitated by exemption from registration for certain oils commonly used in processed foods and beverages (Quarels, 1996). This opportunity has spurred the development of essential oil-based insecticides, fungicides, and herbicides for agricultural and industrial applications and for the consumer market, using rosemary oil, clove oil, and thyme oil as active ingredients. Interest in these products has been considerable, particularly for control of greenhouse pests and diseases and for control of domestic and veterinary pests. Nonetheless, some U.S. companies have introduced essential-oil-based pesticides in recent years. Mycotech Corporation produced an aphidicide/miticide/fungicide for greenhouse and horticultural use and for bush and tree fruits based on cinnamon oil with cinnamaldehyde (30% in the EC formulation) as the active ingredient, however, this product is no longer being sold. EcoSMART Technologies has introduced insecticides containing eugenol and 2-phenethyl propionate aimed at controlling crawling and flying insects, under the brand name EcoPCO® for pest control professionals. An insecticide/miticide containing rosemary oil as the active ingredient has recently been introduced for use on horticultural crops under the name EcoTrol™. Another product based on rosemary oil is a fungicide sold under the name Sporan™, while a formulation of clove oil (major constituent: eugenol), sold as Matran™, is used for weed control. All of these products have been approved for use in organic food production. The primary active ingredients in EcoSMART products are exempt from Environmental Protection Agency registration and are approved as direct food additives or classifies as GRAS (generally recognized as safe) by the Food and Drug Administration.

Several smaller companies in the U.S. and the U.K. have developed garlic-oil based pest control products and in the U.S. there are consumer insecticides for home and garden use containing mint oil as the active ingredient. Menthol has been approved for use in North America for control of tracheal mites in beehives, and a product produced in Italy (Apilife VAR™) containing thymol and lesser amounts of cineole, menthol and camphor is used to control Varroa mites in honeybees (Canadian Honey Council; http://www.saskatchewanbeekeepers.ca/users/folder.asp@FolderID=5317.htm).

The humble marigold could be the key to organic, renewable and cost-effective pest control, according to researchers at De Montfort University (DMU) in Leicester. *Tagetes patula*, the French marigold species most common to gardens, has the ability to destroy attackers beneath the soil and it is this property that researchers believe could be harnessed to help protect crops.

Israel startup Botanocap, founded on oil encapsulation knowledge created at the Ben Gurion University of the Negev, is developing a slow release technology for essential oils, to make relatively environmentally friendly pesticides. The company has developed a patented technology for the gradual release of essential etheric oils and natural components. It possesses patents on capturing essential oils in capsules, to achieve the delayed release effect. Etheric oils can be produced from some 3000 plants. Controlled slow release with protecting the active components until release are the main point of Botanocap (http://www.ivc-online/ivcWeeklyItem.asp?articleID=5313).

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

CONCLUSIONS AND CONSTRAINTS

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

In terms of specific constraints, the efficacy of these materials falls short when compared to synthetic pesticides although there are specific pest contexts where control equivalent to that with conventional products has been observed. Essential oils also require somewhat greater application rates (as high as 1% active ingredient) and may require frequent reapplication when used out-of-doors.

Additional challenges to the commercial application of plant essential-oil-based pesticides include availability of sufficient quantities of plant material, standardization and refinement of pesticide products, protection of technology (patents) and regulatory approval (Isman, 2005). Although many essential oils may be abundant and available year round due to their use in the perfume, food and beverage industries, large-scale commercial application of essential-oil-based pesticides could require greater production of certain oils. In addition, as the chemical profile of plant species can vary naturally depending on geographic, genetic, climatic, annual or seasonal factors, pesticide manufacturers must take additional steps to ensure that their products will perform consistently. All of this requires substantial cost and smaller companies may not be willing to invest the required funds unless there is a high probability of recovering the costs through some form of market exclusivity (e.g. patent protection). Finally, once all of these issues are addressed, regulatory approval is required. Although several plant essential oils are exempt from registration in the United States, many more oils are not, and few countries currently have such exemption lists. Accordingly, regulatory approval continues to be a barrier to commercialization and will likely continue to be a barrier until regulatory systems are adjusted to better accommodate these products (Isman and Machial, 2006).

In fact, pesticides derived from plant essential oils do have several important benefits. Due to their volatile nature, there is a much lower level of risk to the environment than with current synthetic pesticides. Predator, parasitoid and pollinator insect populations will be less impacted because of the minimal residual activity, making essential-oil-based pesticides compatible with integrated pest management programs. It is also obvious that resistance will develop more slowly to essential-oil-based pesticides owing to the complex mixtures of constituents that characterize many of these oils. Ultimately, it is in developing countries where the source plants are endemic that these pesticides may ultimately have their greatest impact in integrated pest management strategy. It is expected that these pesticides will find their greatest commercial application in urban pest control, public health, veterinary health, vector control vis-à-vis human health and in protection of stored commodities. In agriculture, these pesticides will be most useful for protected crops (e.g. greenhouse crops), high-value row crops and within organic food production systems where few alternative pesticides are available. There are thus the opportunities like (i) changing consumer preferences towards the use of 'natural' over synthetic products; (ii) existence of and growth in niche markets, where quality is more important than price; (iii) strong growth in demand for essential oils and plant extracts; (iv) potential to extend the range of available products including new product development through biotechnology; (v) production of essential oils and plant extracts from low cost developing countries.

Acknowledgements. Authors are thankful to Gurmeet Singh, Rajwinder Singh and Anshu Middha for rendering suitable help during the compilation of this review. This review article contains information gathered from numerous published resources, and thus we would like to extend our appreciation to all authors of the references used in this manuscript.

REFERENCES

Agarwal, M. and Walia, S. (2003) Pest control potential of phytochemicals derived from *Curcuma longa* and *Zingiber officinale*. *In* P. Dureja, D.B. Saxena, J. Kumar, S.B. Singh, M. Gopal and R.S. Tanwar (eds.), *Proc. Int. Conf. Pesticides, Environment, Food Security*, Society of Pesticide Science, New Delhi, pp 110–119.

Agarwal, M., Walia, S. and Dhingra, S. (1999) Pest control properties of turmeric leaf oil against *Spilosoma obliqua*, *Dysdercus koenigii* and *Tribolium castaneum*. *Proceed. 2nd All India People's Congress*, Calcutta, pp l–7.

Agarwal, M., Walia, S. and Dhingra, S. (2000) Insect growth inhibition, antifeedant and antifungal activity of compounds isolated/derived from *Zingiber officinale* rhizomes. *Pest Manag. Sci.*, **37**, 289–300.

Beninger, C.W., Ndyiragije, P. and Arnason, J.T. (1993) Diterpene 3-epicaryoptin affects growth and development of the European corn borer (Lepidoptera: Pyrallidae). *J. Econ. Entomol*., **86,** 1559–1602.

Bhatnagar, M., Kapur, K.K., Jalees, S. and Sharma, S.K. (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. *Entomol. Res.*, **17,** 21–29.

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

Bishop, C.D. (1995) Antiviral activity of the essential oil of *Melaleuca alternifolia* (Maiden & Betche) cheel (Teatree) against Tobacco Mosaic Virus. *J. Essen. Oil Res*., **7**, 641–648.

Bowers, J.H. and Locke, L.C. (2000) Effect of botanical extracts on the population density of *Fusarium oxisporum* in soil and control of Fusarium wilt in the green house. *Plant Dis.*, **84,** 300–305.

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

Carroll, J.F. (1994) Feeding deterrence in northern fowl mites (Acari: Macronyssidae) by some naturally occurring plant substances. *Pestic. Sci*., **41,** 203–207.

Chahal, K.K., Arora, M., Joia, B.S. and Chhabra, B.R. (2005) Bioefficacy of turmeric oil against *Tribolium castaneum* (Herbst) under laboratory conditions. *In* V.K. Dilawari, G.S. Deol, B.S. Joia and P.K. Chuneja (eds.), *Proc. 1st Congress on Insect Science*: *Contributed Papers*, PAU Ludhiana, pp. 147–148.

Chang, K.S. and Ahn, Y.T. (2001) Fumigant activity of (*E*) - anethole identified in *Illicium verum* fruit against *Blattella germanica*. *Pest Manage. Sci.*, **58,** 161–166.

Chang, S.T. and Cheng, S.S. (2002) Antitermitic activity of leaf essential oils and components from *Cinnamomum osmophleum*. *J. Agric. Food Chem.*, **50,** 1389–1392.

Chauhan, K.R. and Raina, A.K. (2006) Effect of catnip oil and its major compounds on the formosan subterranean termite (*Coptotermes formosanus*). *Biopestic. Int*., **2,** 137–143.

Cheng, S.S., Liu, J.Y., Tsai, K.H., Chen, W.J. and Chang, S.T. (2004) Chemical composition and mosquito larvicidal activity of essential oils from leaves of different *Cinnomomum osmophloeum* provenances. *J. Agric. Food Chem.*, **52**, 4395–4400.

Chiasson, H., Belanger, A., Bostanian, N., Vincent, C. and Poliquin, A. (2001) Acaricidal properties of *Artemisia absinthium* and *Tanacetum vulgare* (Asteraceae) essential oils obtained by three methods of extractions. *J. Econ. Entomol*., **94,** 167–171.

Choi, W.I., Lee, S.G., Park, H.M. and Ahn, Y.J. (2004) Toxicity of plant essential oils to *Trialeuroides vaporariorum* (Homoptera:Aleyrodidae). *J. Econ. Entomol*., **96**, 1479–1484.

Choi, W.S., Park, B.S., Ku, S.K. and Lee, S.K. (2002) Repellent activities of essential oils and monoterpenes against *Culex pipiens*. *J. Am. Mosq. Cont. Assoc*., **18**, 348–351.

Chowdhury, H., Singh, R.D., Mandal, P. and Dutta, A. (2000) Antifeedant activity of two essential oils on lepidopteran insects. *Pestic. Res. J.*, **12**, 137–140.

Coats, J.R., Karr, L.L. and Drewes C.D. (1991) Toxicity and neurotoxic effects of monoterpenoids in insects and earthworms. *In* P. A. Hedin (ed.), *Naturally Occurring Pest Bioregulators*, ACS Symposium Series 449, American Chemical Society, Washington DC, pp. 306–316.

Cockcroft, A., Cosgrove, J.B. and Wood, R.J. (1998) Comparative repellency of commercial formulation of deet, permethrin and citronellal against the mosquito *Aedes aegypti*, using a collagen membrane technique compared with human arm tests. *Med. Vet. Entomol.*, **12**, 289–294.

Cornelius, M.L., Grace, J.K. and Yates III, J.R. (1997) Toxicity of monoterpenoids and other natural products to the Formosan subterranean termite (Isoptera: Rhinotermitidae). *J. Econ. Entomol.*, **90**, 320–325.

Daferera, D.J., Ziogas, B.N. and Polissiou, M.G. (2000) GC-MS analysis of essential oils from some Greek aromatic plants and their fungi toxicity on *Penicillium digitatum*. *J. Agric. Food Chem.*, **48,** 2576–2581.

Dhaliwal, G.S. and Koul, O. (2007) *Biopesticides and Pest Management: Conventional and Biotechnological Approaches*. Kalyani Publishers, New Delhi.

De-Billerbeck, V.G., Roques, C.G., Bessiere, J.M., Fonvieille, J.L. and Dargent, R. (2001) Effects of *Cymbopogon nardus* (L) essential oil on the growth and morphogenesis of *Aspergillus niger*. *Can. J. Microbiol.*, **47,** 9–17.

Dev, S. and Koul, O. (1997) *Insecticides of Natural Origin*. Harwood Academic Publishers, Amsterdam, Netherlands.

Dietrich, G., Dolan, M.C., Peralta-Cruz, J., Schmidt, J., Piesman, J., Eisen, R.J. and Karchesy, J.J. (2006) Repellent activity of fractioned compounds from *Chamaecyparis nootkatensis* essential oil against nymphal *Ixodes scapularis* (Acari: Ixodidae). *J. Med. Entomol.*, **43**, 957–961.

Dimetry, N.Z., Hafez, M. and Abbass, M.H. (2003) Efficiency of some oils and neem formulations against the cow pea beetle, *Callosobruchus maculatus* (Fabricius) Coleoptera: Bruchidae). *In* O. Koul, G.S. Dhaliwal, S.S. Marwaha and J. K. Arora (eds.), *Biopesticides and Pest Management*, Vol. 2, Campus Books International, New Delhi, pp. 1–10.

Don-Pedro, K.M. (1996) Investigation of single and joint fumigant insecticidal action of citrus peel oil components. *Pestic. Sci.*, **46,** 79–84.

Dubey, A., Gupta, R. and Chandel, B.S. (2004) Efficacy af *Acorus calamus, Vitex negundo* and *Ageratum conyzoides* against tobacco caterpillar, *Spilarctia obliqua* Walker. *Indian J. Entomol.*, **66**, 238–240.

Ellis, M.D. and Baxendale, F.P. (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.

FAO (1999) The use of spices and medicinals as bioactive protectants for grains. *Agriculture Service Bulletin*, **137**, 201–213.

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

Górski, R. (2004) Effectiveness of natural essential oils in the monitoring of greenhouse whitefly (*Trialeurodes vaporariorum* Westwood). *Folia Hort.*, **16**, 183–187.

Govindaraddi, K. (2005) Antifeedant and insecticidal properties of essential oils of turmeric (*Curcuma longa* L.) and garlic (*Allium sativum* L.) against diamond back moth, *Plutella xylostella* (L). M.Sc thesis,CCS Haryana Agricultural University, Hisar.

Gunderson, C.A., Samuelian, J.H., Evans, C.K. and Bratisten, L. (1985) Effects of the mint monoterpene pulegone on *Spodoptera eridania* (Lepidoptera: Noctuidae). *Environ.Entomol.*, **14,** 859–863.

Hammack, L. (1996) Corn volatiles as attractants for northern and western corn rootworm beetles (Coleopteran: Chrysomelidae: *Diabrotica* sp.). *J. Chem. Ecol.*, **22,** 1237–1253.

Harwood, S.H., Modenke, A.F. and Berry, R.E. (1990) Toxicity of peppermint monoterpenes to the variegated cutworm (Lepidoptera: Noctuidae). *J. Econ. Entomol.*, **83,** 1761–1767.

Hierro, I., Valero, A., Perez, P., Gonzalex, P., Cabo, M.M. and Navarro, M.C. (2004) Action of different monoterpenic compounds against *Anisakis simplex* S.l.L_3 larvae. *Phytomedicine*, **11,** 77–82.

Huang, Y. and Ho, S.H. (1998) Toxicity and antifeedant activities of cinnamaldehyde against the grain storage insects *Tribolium castaneum* (Herst) and *Sitophillus zeamais* Motsch. *J. Stored Prod. Res.*,

34, 11–17.

Hummelbrunner, A. L. and Isman, M.B. (2001) Acute, sublethal, antifeedant and synergistic effects of monoterpenoid essential oil compounds on the tobacco cut worm (Lepidoptera: Noctuidae). *J. Agric. Food Chem.*, **49**, 715–720.

Inazuka, S. (1983) Monoterpenoids as repellents against the German cockroach (*Blattela germanica* L.). *J. Pestic. Sci.*, **8,** 293–299.

Isman, M.B. (2000) Plant essential oils for pest and disease management. *Crop Prot.*, **19**, 603–608.

Isman, M.B. (2005) Problems and opportunities for the commercialization of botanical insecticides. *In* C. Regnault-Roger, B.J.R. Philog'ene and C. Vincent (eds.), *Biopesticides of Plant Origin*, Lavoisier, Paris, pp. 283–291.

Isman, M.B. and Machial, C.M. (2006) Pesticides based on plant essential oils: from traditional practice to commercialization. *In* M. Rai and M.C. Carpinella (eds.), *Naturally Occurring Bioactive Compounds*, Elsevier, BV, pp 29–44

Jacobson, M. and Halber, L. (1947) *The Chemistry of Organic Medicinal Plants*, Chapman and Hall, New York.

Jaenson, T.G.T., Garboul, S. and Pålsson, K. (2006) Repellency of oils of lemon, eucalyptus, geranium, and lavender and the mosquito repellent MyggA natural to *Ixodes ricinus* (Acari: Ixodidae) in the laboratory and field. *J. Med. Entomol.*, **43**, 731–736.

Karr, L.L. and J.R. Coats (1988). Insecticidal properties of d- limonene. *J. Pestic. Sci.*, **13**, 2287–2290.

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

Katerinopoulos, H., Pagona, G, Afratis, A., Stratigakis, N. and Roditakis, N. (2005) Composition and insect attracting activity of the essential oil of *Rosmarinus officinalis*. *J. Chem Ecol*., **31**, 111-122.

Khanna, R.K., Sharma, O.S., Singh, A., Battacharya, S.C., Sen, N. and Sethi, K.L. (1990) The essential oil from leaves of *Dacus carota* Linn. var sa*tiva. Chem. Anal. Struc.*, **14**, 173–176.

Klocke, J.A., Balandrin, M.F. and Yamasaki, R.B. (1989) Limonoids, phenolics and furano-coumarins as insect antifeedants, repellants and growth inhibitory components. *In* J.T. Arnason, P. Morand and B.J.R. Philogene (eds.), *Insecticides of Plant Origin*, American Chemical Society, Washington DC, pp. 136–149.

Kordali, S., Cakir, A., Mavi, A., Kilic, H. and Yildirim, A. (2005) Screening of chemical composition and antifungal activity of essential oils from three Turkish *Artemisia* species. *J. Agric. Food Chem*., **53**, 1408–1416.

Kostyukovsky, M., Rafaeli, A., Gileadi, C., Demchenko, N. and Shaaya, E. (2002) Activation of octopaminergic receptors by essential oil constituents isolated from aromatic plants: possible mode of action against insect pests. *Pest Manag. Sci.*, **58**, 1101–1106.

Koschier, E.L. and Sedy, K.A. (2001) Effects of plant volatiles on the feeding and oviposition of *Thrips tabaci*. *In* R. Marullo and L. Mound (eds.), *Thrips and Tospoviruses*, CSIRO, Australia, pp. 185–187.

Koul, O. (1995) Acorus allelochemical: Chemistry and bioefficacy against insects. *In* B.S. Parmar and S. Walia (eds.), *Pesticides, Crop Protection and Environment*, Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, pp. 99–113.

Koul, O. (2005) *Insect Antifeedants*. CRC Press, Bota Racon, FL.

Koul, O. (2008) Phytochemicals and insect control: An antifeedant approach. *Crit. Rev. Plant Sci.*, **27**, 1–24.

Koul O, Smirle MJ and Isman MB (1990). Asarones from *Acorus calamus* L. oil, their effect on feeding behavior and dietary utilization in *Peridroma saucia. J. Chem. Ecol.* **16**: 1911–1920.

Koul, O., Dhaliwal, G.S. , Marwaha, S.S. and Arora, J.K. (2003) Future perspectives in biopesticides. *In* O. Koul, G.S. Dhaliwal, S.S. Marwaha and J.K Arora (eds.), *Biopesticides and Pest Management.*, Vol.1, Campus Books International, New Delhi, pp. 386–388.

Koul, O., Singh, G., Singh, R. and Singh, J. (2007) Mortality and reproductive performance of *Tribolium castaneum* exposed to anethole vapours at high temperature. *Biopestic. Int*., **3**, 126–137.

Krishna Kishore, G., Pande, S. and Harsha, S. (2007) Evaluation of essential oils and their components for broad-spectrum antifungal activity and control of late leaf spot and crown rot diseases in peanut. *Plant Dis.*, **91**, 375–379.

Kurita, N., Miyaji, M., Kurane, R. and Trakahara, Y. (1981) Antifungal activity of components of essential oils. *Agric. Biol. Chem*., **45**, 945–952.

Lawerence, B.M. and Reynolds, R.J. (2001) Progress in essential oils. *Perf. Flavour.*, **26**, 44–52.

Lee, B.H., Choi, W.S., Lee, S.E. and Park, B.S. (2001) Fumigant toxicity of essential oils and their constituent compounds towards the rice weevil, *Sitophilus oryzae* (L.). *Crop Prot*., **20,** 317–320.

Lee, S., Tsao, R. and Coats, J.R. (1999). Influence of dietary applied monoterpenoids and derivatives on survival and growth of the European corn borer (Lepidoptera: Pyrallidae). *J. Econ. Enomol.*, **92**, 56–67.

Lee, S., Tsao, R., Peterson, C. and Coats, J.R. (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.

Lichtenstien, E.P., Liang, T.T., Shulz, K.R., Schnoes, H.K. and Carter, G.T. (1974). Insecticide and synergistic components isolated from dill plant. *J. Agric. Food Chem.*, **22,** 658–664.

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

Meepagala, K.M., Osbrink, W., Sturtz, G. and 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. and Isman, M.B. (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 Manag. Sci*., **62**, 366–371.

Montser, B.R. and Carvajal, M. (1998) Control of *Aspergillus flavus* in maize with plant essential oils and their components. *J. Food Prot.*, **61,** 616–619.

Muller, R.F., Berger, B. and Yegen, O. (1995) Chemical composition and fungi toxic properties to phyto pathogenic fungi of essential oils of selected aromatic plants growing wild in Turkey. *J. Agric. Food Chem.*, **43,** 2262–2266.

Ngoh, S.P., Cho, L.E.W., Pang, F.Y., Huang, Y., Kini, M.R. and Ho, S.H. (1998) Insecticidal and repellent properties of nine volatile constituents of essential oils against the American cockroach, *Periplanata americana* (L.). *Pestic. Sci.*, **54,** 261–268.

Nguefack, J., Nguikwie, S.K., Fotio, D., Dongmo, B., Zollo, P.H. Amvam, Leth, V., Nkengfack, A.E., Poll, L. (2007). Fungicidal potential of essential oils and fractions from *Cymbopogon citratus*, *Ocimum gratissimum* and *Thymus vulgaris* to control *Alternaria padwickii* and *Bipolaris oryzae*, two seed-borne fungi of rice (*Oryza Sativa* L). *J. Essen. Oil Res.*, **19**, 581–587.

Ning, J., Kong, F., Lin B. and Lei, H. (2003) Large-scale preparation of the phytoalexin elicitor glucohexatose and its application as a green pesticide. *J. Agric. Food Chem.*, **51**, 987–991.

Obeng-Ofori, D. and Reichmuth, C.H. (1997) Bioactivity of eugenol, a major component of essential oil of *Ocimum suvae* (wild) against four species of stored product coleopteran. *Int. J. Pest Manag.*, **43,** 89–94.

Ouden, H.D., Visser, J.H., Alkena, D.P.W., Dei, J.J. and Derk, P.S.M. (1993). Experiments with volatile substances in slow release formulations causing repellency for oviposition by the cabbage root fly, *Phorbia brassicae* (Diptera : Anthomydae). *J. Appl. Entomol.*, **115**, 307–312.

Oyedela, A.O., Gbolade, A.A., Sosan, M.B., Adewoyin, F.B., Soyely, O.L. and Orafidiya, O.O. (2002). Formulation of an effective mosquito repellent topical product from lemon grass oil. *Phytomedicine*, **9,** 259–262.

Pair, S.D. and Horvat, R.J. (1997) Volatiles of Japanese honeysuckle flowers as attractants for adult Lepidopteran insects. US Patent 5665344.

Paster, N., Menasherou, M., Ravid, U. and Juven, B. (1995) Antifungal activity of oregano and thyme essential oils applied as fumigants against fungi attacking stored grain. *J. Food Protect*., **58,** 81–85.

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.

Perrucci, S., Macchioni, G., Gioni, P.L., Flamini, G. and Morelli, I. (1995) Structure toxicity relationship of some natural monoterpenes as acaricides against *Psoroptes cuniculi*. *J. Nat. Prod.*, **58,** 1261–1264.

Panella, N.A., Dolan, M.C., Karchesy, J.J., Xiong, Y., Peralta-cruz, J., Mohammad Khasawneh, M., Montenieri, J.A. and Maupin, G.O. (2005) Use of novel compounds for pest control: Insecticidal and acaricidal activity of essential oil components from heartwood of alaska yellow cedar. *J. Med. Entomol.*, **42**, 352–358.

Paruch, E., Ciunik, Z., Nawrot, J. and Wawrzenczyk, C. (2000) Lactones: Synthesis of terpenoids lactones active insect antifeedants. *J. Agric. Food Chem.*, **48**, 4973–4977

Petroski, R.J. and Hammack, L. (1998) Structure activity relationships of phenyl alkyl alcohols, phenyl alkyl amines and cinnamyl alcohol derivatives as attractants for adult corn root worm (coleopteran:Chrysomelidae: *Diabrotica* sp.). *Environ. Entomol.*, **27,** 688–694.

Pradhanang, P.M., Momol, M.T., Olson, S.M. and Jones, J.B. (2003) Effects of plant essential oils on *Ralstonia solanacearum* population density and bacterial wilt incidence in tomato. *Plant Dis.*, **87**, 423–427.

Priestley, C.M., Williamson, E.M., Wafford, K.A. and Sattelle, D.B. (2003) Thymol, a constituent of thyme essential oil, is a positive allosteric modulator of human GABA receptors and a homo-oligomeric GABA receptor from *Drosophila melanogaster*. *Br. J. Pharmacol.*, **140**, 1363–1372

Quarles, W. (1996) EPA exempts least-toxic pesticides. *IPM Pract.*, **18**, 16–1779.

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

Ray, D.P., Walia, S., Dureja, P and Singh, R.P. (2000) Composition and repellent activity of the essential oil of marigold (*Tagetes erecta*) flower. *Ind. Perf.*, **44**, 267–270.

Rao, G.P., Pandey, A.K. and Shukla, K. (1986) Essential oils of some higher plants vis-a-vis some legume viruses. *Indian Perf.*, **30**, 483–486.

Reitz, S.R., Maiorino, G., Olson, S., Sprenkel, R., Crescenzi, A. and Momol, M.T. (2008) Interesting plant essential oils and kaolin for the sustainable management of thrips and tomato spotted wilt on tomato. *Plant Dis.*, **92**, 878–886.

Rice, P.J. and Coats, J.R. (1994) Insecticidal properties of several monoterpenoids to the housefly (Diptera : Muscidae), red flour beetle (Coleoptera : Tenebrionidae) and southern corn root-worm (Coleoptera : Chrysomelidae). *J. Econ. Entomol.*, **87,** 1172–1179.

Shaalan, E.A., Canyon, D., Younes, M.W.F., Abdel-Wahab, H and Mansour, A. (2005) A review of botanical phytochemicals with mosquitocidal potential. *Environ. Int.*, **31**, 1149–1166.

Sharda, S. and Rao P.J. (2000) Effect of *Ageratum conyzoides* on development and reproduction of *Spodoptera litura*. *Indian J. Entomol.*, **62**, 231–238.

Sharma, S.S., Gill, K., Maliok, M.S. and Malik, O.P. (2001). Insecticidal, antifeedant and growth inhibitory activities of essential oils of some medicinal plants. *In* K. Sushil, S.A. Hasan, D. Samresh, A.K. Kukreja, S. Ashok, A.K. Sharma, S. Srikant and T. Rakesh (eds.), *Proceedings of the National Seminar on the Frontiers of Research and Development in Medicinal Plants*, CIMAP, Lucknow, pp. .

Shishir, T., Mittal, A.K., Kasana, V.K., Pant, A.K. and Tandon, S. (2004) Antifeedant activity of Elsholtzia essential oils against *Spodoptera litura. Ann. Plant Prot. Sci.*, **12**, 197–198.

Singh, D., Siddiqui, M.S., Sharma, S. (1989) Reproductive retardant and fumigant properties in essential oils against rice weevil in stored wheat. *J. Econ. Entomol.*, **82**, 727–733.

Singh, R., Rup, P.J. and Koul, O. (2008) Bioefficacy of 1,8-cineole from *Eucalyptus camaldulensis* var. *obtusa* and linalool from *Luvanga scandans* against *Spodoptera litura* (Lepidoptera: Noctuidae) and combination effects with some other monoterpenoids. *J. Pest Sci.*, (in press)

Stroh, J., Wan, M.T., Isman, M.B. and Moul, D.J. (1998) Evaluation of the acute toxicity to juvenile Pacific coho salmon and rainbow trout of some plant essential oils, a formulated product, and the carrier. *Bull. Environ. Contam. Toxicol.*, **60**, 923–930.

Traboulsi, A.F., Taoubi, K., El-Haj, S., Bessiere, J.M. and Rammal, S. (2002) Insecticidal properties of essential plant oils against the mosquito *Culex pipi-*

ens molesters (Diptera : culicidae). *Pest Manag. Sci.*, **58**, 491–495.

Tripathi, A.K., Prajapati, V. and Kumar, S. (2003) Bioactivity of l-carvone, d-carvone and dihydro-carvone towards three stored product beetles. *J. Econ. Entomol.*, **96**, 1594–1601.

Tripathi, A.K., Prajapati, V., Aggarwal, K.K., Sushil Kumar, Prajapti, V., Kumar, S. Kukreja, A.K. Dwivedi, S. and Singh, A.K. (2000) Effects of volatile oil constituents of *Mentha species* against stored grain pests, *Callosobrunchus maculatus* and *Tribolium castanum. J. Med. Arom. Plant Sci.*, **22**, 549–556.

Tripathi, A.K., Prajanpati, V., Aggarwal, K.K. and Kumar, S. (2001) Toxicity, feeding deterrence, and effect of activity of 1, 8-cineole from *Artemisia annua* on progeny production of *Tribolium castanaeum* (Coleoptera : Tenebrionidae). *J. Econ. Entomol.*, **94**, 979–983.

Tripathi, A.K., Prajapathi, V., Verma, N., Bhal, J.R., Bansal, R.P., Khanuja, S. P.S and Kumar, S. (2002) Bioactivities of the leaf essential oils of *Curcuma longa* (Var. Ch.66) on three species of stored product beetles (Coleoptera). *J. Econ. Entomol.*, **95**, 183–189.

Trongtokit,Y., Rongsrivam, Y., Komalamisra, N. and Apiwathnasorn, C. (2005) Comparative repellency of essential oils against mosquito bites. *Phytother. Res.*, **19**, 303–309.

Tsao, R. and Zhou, T. (2000) Antifungal activity of monoterpenoids against postharvest pathogens *Botrytis cinerea* and *Monilinia fructicola. J. Essential Oil Res.*, **12**, 113–121.

Vargas, R.I., Stark, J.D., Kido, M.H., Ketter, H.M. and Whitehand, L.C. (2000) Methyl-eugenol and cuelure traps for suppression of male oriental fruit flies and melon flies (Diptera:Tephritidae) in Hawaii: Effects of lure mixtures and weathering. *J. Econ. Entomol.*, **93,** 81–87.

Vrushali, T., Tare, V. and Shushil, K. (2001) Bioactivity of some medicinal plants against chosen insect pests/vectors. *In* K. Sushil, S.A. Hasan, D. Samresh, A.K. Kukreja, S. Ashok, A.K. Sharma, S. Srikant and T. Rakesh (eds.), *Proceedings of the National Seminar on the Frontiers of Research and Development in Medicinal Plants*, CIMAP, Lucknow, pp. .

Walia, S. (2005) Allelochemicals as Biopesticide. *In* O. Koul, G.S. Dhaliwal, A. Shankar, D. Raj and V.K. Koul (eds.), *Souvenir Conference on Biopesticides: Emerging Trends*, Society of Biopesticide Sciences, India, Jalandhar, pp. 19–32.

Wilson, C.L., Solar, J.M., Ghaouth, A. and Wisniewski, M.E. (1997) Rapid evaluation of plant extracts and essential oils for antifungal activity in *Botrytis cinerea. Plant Dis.*, **81,** 204– 210.

Yatagi, M. (1997) Miticidal activity of tree terpenes. *Curr. Top. Phytochem.*, **1,** 85–97.

Zambonelli, A., D"Aulerjo, A.Z., Bianchi, A. and Albasini, A. (1996) Effects of essential oils on phyto pathogenic fungi *in vitro. J. Phytopathol.*, **144,** 491–494.

Zaridah, M.Z., Nor Azah, M.A., Abu Said, A. and Mohd. Faridz, Z.P. (2003) Larvicidal properties of citronellal and *Cymbopogon nardus* essential oils from two different localities. *Trop. Biomed.*, **20**, 169–174.

Accepted 01 March 2008