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Plant essential oils for pest and disease management

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Abstract

Certain essential plant oils, widely used as fragrances and flavors in the perfume and food industries, have long been reputed to repel insects. Recent investigations in several countries confirm that some plant essential oils not only repel insects, but have contact and fumigant insecticidal actions against specific pests, and fungicidal actions against some important plant pathogens. As part of an effort aimed at the development of reduced-risk pesticides based on plant essential oils, toxic and sublethal effects of some essential oil terpenes and phenols have been investigated using the tobacco cutworm (*Spodoptera litura*) and the green peach aphid (*Myzus persicae*) as model pest species. In this paper I review (i) the range of biological activities of essential oils and their constituents; (ii) their toxicity and proposed mode-of-action in insects; (iii) their potential health and environmental impacts as crop protectants; and (iv) commercialization of pesticides based on plant essential oils.

Keywords: Plant essential oils; Natural pesticides; Monoterpenoids

1. Introduction

In spite of widespread public concern for long-term health and environmental effects of synthetic pesticides, especially in Europe and North America, natural pesticides, both of microbial and plant origin, have yet to have much impact in the marketplace. Bioinsecticides, dominated by *Bacillus thuringiensis*-based products, and botanical insecticides, dominated by pyrethrum-based products, each command little more than 1% of the global insecticide market. However, recent government action in the United States, in the form of the Food Quality Protection Act of 1996, will dramatically restrict the use of many conventional insecticides upon which growers have depended for decades (e.g. organophosphates and carbamates). In turn, this will create a significant market opportunity for alternative products, in particular "reduced-risk" pesticides which are favored by the Environmental Protection Agency in the USA.

Against this backdrop, natural pesticides based on plant-essential oils may represent alternative crop protectants whose time has come. Essential oils, obtained by steam distillation of plant foliage, and even the foliage itself of certain aromatic plants (notably in the families Myrtaceae and Lamiaceae, but in other plant families as well) have traditionally been used to protect stored grain and legumes, and to repel flying insects in the home. Though some of the claims made for these crude preparations have yet to be substantiated through controlled experiments, scientific investigation into the biological activities of these materials proliferated in the past decade. The emerging picture is that certain, specific oils and their chemical constituents have demonstrable contact and fumigant toxicity to a number of economically important insect and mite pests, as well as to plant pathogenic fungi.

2. Biological activities of essential oils and their constituents

Contact and fumigant insecticidal actions of plant essential oils have been well demonstrated against stored product pests. Among 22 essential oils tested as fumigants against the bean weevil *Acanthoscelides obtectus* (Bruchidae), those of *Thymus serpyllum* (rich in the phenols thymol and carvacrol) and *Origanum majorama* (rich in terpinen-4-ol) were the most toxic (Regnault-Roger et al., 1993). In a more detailed study, Shaaya et al. (1991) evaluated the fumigant toxicity of 28 essential oils and 10 of their major constituents against four different

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species of stored product coleopterans. Most interestingly, there was little overlap among the insect species with respect to the most toxic oils and constituents, indicating that while these substances are generally active against a broad spectrum of pests, interspecific toxicity of individual oils and compounds is highly idiosyncratic. Sarac and Tunc (1995), investigating the fumigant action of four essential oils to three species of stored product pests, reached the same conclusion. A number of investigations by Ho and colleagues (Ho et al., 1994, 1995, 1997; Huang and Ho, 1998; Huang et al., 1998) have demonstrated contact, fumigant and antifeedant effects of a range of essential oil constituents (cinnamaldehyde, α-pinene, anethole, extracts of cloves, *Syzygium aromaticum*, and star anise, *Illicium verum*) against the red flour beetle *Tribolium castaneum* and the maize weevil *Sitophilus zeamais*. Eugenol, the major constituent of oil of cloves and also of the holy basil, *Ocimum suave*, was shown to be effective against these and two additional coleopterans, *S. granarius* and *Prostephanus truncatus* (Obeng-Ofori and Reichmuth, 1997).

Recent studies have also indicated efficacy against pests on plants. Essential oils of cumin (*Cuminum cyminum*), anise (*Pimpinella ansium)*, oregano (*Origanum syriacum* var. *bevanii)* and eucalyptus (*Eucalyptus camaldulensis*) were effective as fumigants against the cotton aphid (*Aphis gossypii*) and the carmine spider mite (*Tetranychus cinnabarinus*), two greenhouse pests (Tuni and Sahinkaya, 1998). Efficacy of basil (*Ocimum* spp.) against garden pests has recently been reviewed (Quarles, 1999). Lee et al. (1997) reported on the toxicity of a range of essential oil constituents to the western corn rootworm (*Diabrotica virgifera*), the two-spotted spider mite (*Tetranychus urticae*) and the housefly (*Musca domestica*), and dietary effects of a number of monoterpenoids against the European corn borer (*Ostrinia nubilalis*) have been recently reported (Lee et al., 1999). There is even evidence that certain essential oils and their constituents are effective against *Varroa jacobsoni*, an ectoparasite of the honey bee (Calderone et al., 1997).

However, systematic investigation of the antifungal activities of essential oils and their constituents predate those of the insecticidal properties. Kurita et al. (1981) screened 40 such compounds against seven species of fungi (primarily food spoilage organisms), and Singh et al. (1980) similarly screened five essential oils against 22 species of fungi, including both human and plant pathogenic types. More recently, Muller-Riebau et al. (1995) screened nine essential oils against four species of plant pathogenic fungi, whereas Wilson et al. (1997) screened 49 essential oils against the fruit pathogen *Botrytis cinerea*. In the former study, antifungal activity was strongly associated with monoterpenic phenols, especially thymol, carvacrol and eugenol, in the oils. Some of the essential oils and constituents found to be insecticidal (e.g. eugenol) were previously reported to be active against a range of plant pathogenic nematodes (Sangwan et al., 1990), and most recently some essential oils were shown to effectively inhibit plant germination, suggesting their potential use as bioherbicides (Dudai et al., 1999).

3. Toxicity to insects

The aforementioned studies with insects convincingly demonstrate the fumigant toxicity of essential oils and their constituents. Knockdown activity and lethal toxicity via contact has been demonstrated in the American cockroach (*Periplaneta americana*) (Ngoh et al., 1998), the German cockroach (*Blattella germanica*) and the housefly (*Musca domestica*) (Rice and Coats, 1994, Coats et al., 1991). These studies latter point to an obvious neurotoxic site-of-action. Certain essential oil monoterpenes are competitive inhibitors of acetylcholinesterase *in vitro* (Grundy and Still, 1985; Miyazawa et al., 1997), but this action may not be correlated with toxicity to insects in vivo.

A recent investigation by Enan et al. (1998) using the American cockroach points to the octopaminergic nervous system as the site-of-action in insects. The binding of ^{3}H-octopamine in a cockroach nerve cord protein preparation was significantly affected in the presence of a number of essential oil constituents. The lack of octopamine receptors in vertebrates likely accounts for the profound mammalian selectivity of essential oils as insecticides (i.e. they are toxic to insects but not to mammals), and thus the octopaminergic system of insects represents a biorational target for insect control. Investigation of the formamidine insecticides revealed interesting and potentially important sublethal behavioral and physiological effects, presumably mediated by the octopaminergic nervous system (Matsumura and Beeman, 1982). Sublethal effects observed with some of the essential oil compounds (viz., feeding deterrence, repellency) may be consistant with this mode-of-action.

To that end, the apparent correlation between the feeding deterrent effect of several monoterpenoids and their topical LD_{50} values in the tobacco cutworm (*Spodoptera litura*) (Noctuidae) is noteworthy (Fig. 1, Isman, unpublished data). Feeding deterrence was measured in early 5th instar larvae (avg. wt. = 103 mg) using a cabbage leaf disc choice bioassay ($n = 20$) (Bomford and Isman, 1996). Mortality was assessed following topical administration (1 μl acetone carrier) to the dorsum of 3rd instar larvae (avg.wt. = 18 mg; $n = 250$).

Green peach aphid nymphs (2nd instar) show both behavioral effects and toxicity in a laboratory bioassay where aphids are placed on mustard cabbage ("pak choi") leaf discs dipped in emulsions of an essential oil based insecticide (a proprietary mixture of eugenol, thymol and phenethylpropionate as active ingredients;

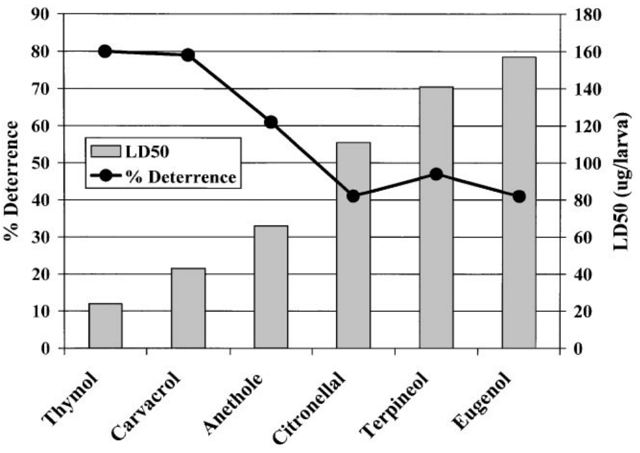

Fig. 1. Relationship between feeding deterrence and topical toxicity of selected monoterpenes and related phenols to the tobacco cutworm *Spodoptera litura*. Feeding deterrence determined for leaf discs treated with essential oil compounds at 150 μg cm^{-2}.

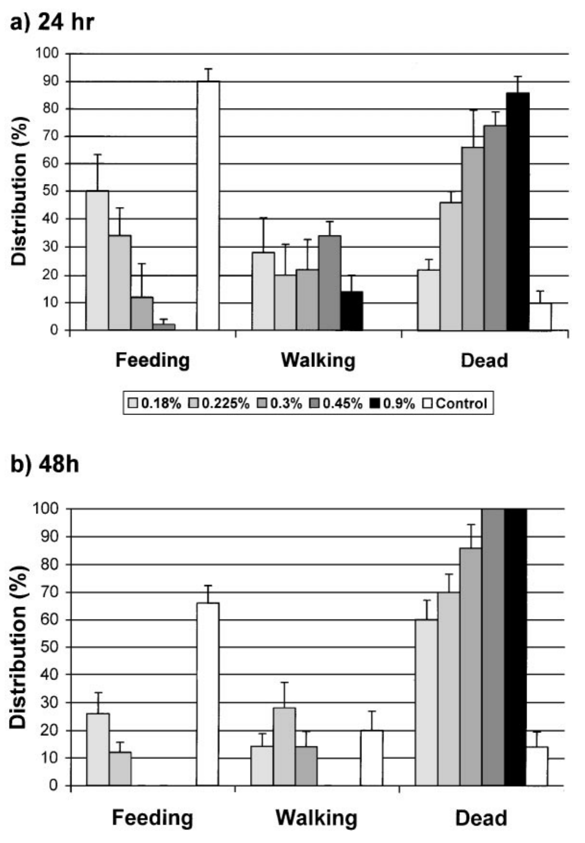

Fig. 2. Behavioral and toxic effects of an essential oil-based insecticide to the green peach aphid *Myzus persicae* in a laboratory leaf disc bioassay; (a) at 24 h, (b) at 48 h. Error bars represent standard error of the mean (n = 15–25 replicates with 10 insects per replicate).

EcoSMART Technologies Inc.) at various concentrations (Fig. 2). While 90% of nymphs placed on carrier-treated control leaf discs settled and were actively feeding after 24 h, 50% or fewer aphids fed on treated discs, and

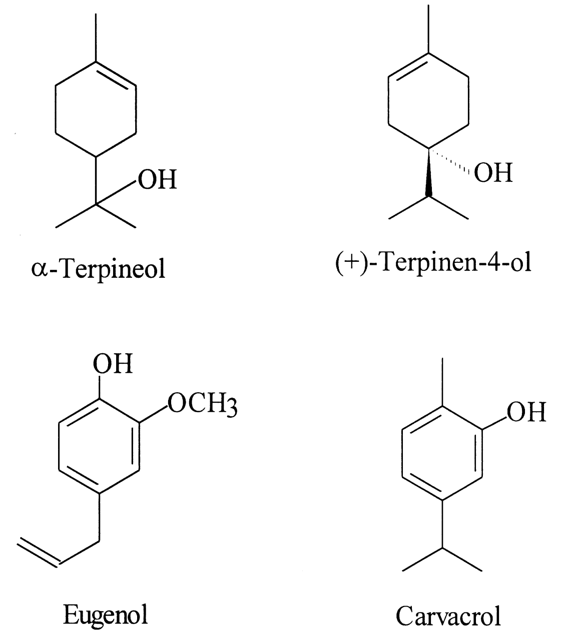

Fig. 3. Chemical structures of some monoterpenes and related phenols with insecticidal activities.

the frequency of aphids feeding was inversely concentration-dependent. Interestingly, approximately 20% of the aphids in all treatment groups (except controls) were found walking in the petri dish, off the leaf discs, after 24 h. Results were even more striking at the 48 h time of observation: at the lowest concentration tested (0.18%), the number of aphids feeding on discs declined from 50% at 24 h to 25%, and the number of dead aphids at this concentration increased from 22 to 60%.

Another important aspect of the toxicity of essential oil constituents, seen previously in studies with the intact oils themselves, are interspecific differences in susceptibility. Table 1 shows LD_{50} or LC_{50} values for two closely related monoterpenes (α-terpineol and terpinen-4-ol) and two monoterpenoid phenols (eugenol and carvacrol) (Fig. 3) tested against four species of insects and against the two-spotted spider mite. For the tobacco cutworm, the terpenes and eugenol are comparable in toxicity, whereas carvacrol is at least three times more active; in the case of the housefly, α-terpineol is about one-half as active as the other three which are similar in activity. In the fruit fly (*Drosophila melanogaster*), the terpenes are themselves equipotent, as are the phenols, but the phenols are about 3.5 times more active than the terpenes. Eugenol is 7–9 times more toxic than the two terpenes in the western corn rootworm beetle (*Diabrotica virgifera virgifera*), but in the two-spotted spider mite, terpinen-4-ol is more than twice as active as eugenol, and six times more active than carvacrol. The salient point is that these chemicals and other essential oil constituents can be *blended* to achieve a desired spectrum of activity and optimal efficacy against pests. However, investigations of

Table 1
Toxicity of selected essential oil monoterpenes and phenols to four species of insect and one species of mite[a]

Species (units)[b]	LD_{50} or LC_{50}			
	Eugenol	Carvacrol	α-terpineol	Terpinen − 4-ol
Spodoptera litura (μg larva^{-1})	157.6	42.7	141.3	130.4
Drosophila melanogaster (μg cm^{-2})	4.6	4.8	17.4	17.7
Musca domestica (μg fly^{-1})	77	92	173	79
Diabrotica virgifera (μg beetle^{-1})	12	NT[c]	112	90
Tetranychus urticae (ppm)	219	629	NT[c]	96

[a] Application methods: *S. litura* (3rd instar), *D. virgifera* (3rd instar), *M. domestica* (adult) — topical administration to the dorsum using 1 μl acetone; *D. melanogaster* (adult) — residue on inner walls of glass vials; *T. urticae* (adult) — bean leaves dipped in 5% aqueous acetone solutions.
[b] Data for *Spodoptera* and *Drosophila* unpublished; for *Musca*, *Diabrotica* and *Tetranychus* from, Lee et al. (1997).
[c] Not tested.

structure-activity relations among these compounds with respect to their toxicity to insects (e.g. Rice and Coats 1994) have not proven especially fruitful as far as predicting which compounds will be most efficacious to any particular type of pest.

4. Health and environmental impacts

Perhaps the most attractive aspect of using essential oils and/or their constituents as crop protectants (and in other contexts for pest management) is their favorable mammalian toxicity. Some of the pure essential oil compounds are slightly toxic, with rat acute oral LD_{50} values of 2–3 g kg^{-1} (viz. carvacrol, pulegone), but an essential oil insecticide consisting of a proprietary mixture of essential oil constituents (EcoSMART Technologies Inc.), resulted in no mortality when fed to rats at 2 g kg^{-1} (Enan, unpublished data), the upper limit required for acute toxicity tests by most pesticide regulatory agencies including the EPA. in the United States. In that many of the essential oils and their constituents are commonly used as culinary herbs and spices, pesticide products containing certain of these are actually exempt from toxicity data requirements by the EPA.

Static water toxicity tests using juvenile rainbow trout (*Oncorhynchus mykiss*) indicated that based on 96 h-LC_{50} values, eugenol is approximately 1500 times less toxic than the botanical insecticide pyrethrum, and 15,000 times less toxic than the organophosphate insecticide azinphosmethyl (Stroh et al., 1998; Table 2). In addition, eugenol and other essential oil constituents are non-persistent in fresh water, based on laboratory tests. These compounds are also non-persistent in soils: under aerobic conditions at 23°C, the half-life for α-terpineol ranges from 30–40 h, with complete degradation by 50 h (Misra and Pavlostathis, 1997). Eugenol is completely broken down to common organic acids by soil-borne *Pseudomonas* bacteria (Rabenhorst, 1996). Concerns for residues of essential oil pesticides on food crops should be mitigated by the growing body of evidence that some essential oil constituents acquired through the diet are actually *beneficial* to human health (Huang et al., 1994).

Table 2
Toxicity of some pesticide active ingredients to juvenile rainbow trout in static water tests (modified from Stroh et al., 1998)

Compound or product (% as active ingredient)	96 h LC_{50} (ppm)
Eugenol (90%)	60.8
Thyme oil (90%)	16.1
α-terpineol (90%)	6.6
Emulsifier[a]	18.2
Neem (3% azadirachtin)	4.0
Pyrethrum (20% pyrethrins)	0.04
Rotenone (44%)	0.03
Azinphosmethyl (94%)	0.004
Endosulfan (96%)	0.001

[a] Proprietary blend of anionic and nonionic emulsifiers.

5. Commercialization of essential oil-based pesticides

In a recent review paper on neem and other botanical insecticides, three barriers to the commercialization of new products of this type were identified: (i) the scarcity of the natural resource; (ii) the need for chemical standardization and quality control; and (iii) difficulties in registration. As the essential oils and their purified constituents have a long history of global use by the food and fragrance industries, and most recently in the field of aromatherapy, many of the oils and/or constituents that are pesticidal are readily available at low to moderate cost in quantity (USD 7–30 kg^{-1}). A number of constituents are available commercially in reasonable purity (95%), and essential oil producers and suppliers can often provide chemical specifications for even the most complex oils.

Of most importance, some of these materials are exempt from the usual data requirements for registration, if not exempt from registration altogether (at least in the USA.). Some American companies have recently taken advantage of this situation and have been able to bring essential-oil-based pesticides to market in a far shorter time period than would normally be required for a conventional pesticide. Mycotech Corporation produces Cinnamite™, an aphidicide/miticide/fungicide for glasshouse and horticultural crops, and Valero™, a miticide/fungicide for use in grapes, berry crops, citrus and nuts. Both products are based on cinnamon oil, with cinnamaldehyde (30% in EC formulations) as the active ingredient.

With over a dozen registered products by the end of 1999, EcoSMART Technologies is aiming to become a world leader in essential oil-based pesticides. They currently produce aerosol and dust formulations containing proprietary mixtures of essential oil compounds, including eugenol and 2-phenethyl propionate aimed at controlling domestic pests (cockroaches, ants, fleas, flies, wasps, etc.). These are marketed to pest control professionals under the brand name EcoPCO®, with less concentrated formulations for sale to the consumer under the name Bioganic™. Insecticides and miticides for horticultural crops and for glasshouse and nursery crops will be released shortly. Additional products (e.g. EcoVET™ for veterinary applications) are under development.

Commercial success with these products based on well-known chemistry will likely provide an impetus for the development and commercialization of future pesticides based on more exotic essential oils with even greater potency (e.g. Shaaya and Kostjukovsky, 1998).

6. Conclusions

Certain plant essential oils and/or their constituents have a broad spectrum of activity against insect and mite pests, plant pathogenic and other fungi, and nematodes. As such, they have considerable potential as crop protectants and for pest management in other situations (e.g. urban pest control). Current information indicates that they are safe to the user and the environment, with few qualifications. As a cautionary note, the essential oils that are most efficacious against pests are often the most phytotoxic; this latter property requires serious attention when formulating products for agricultural and landscape use. Also, selectivity among invertebrates is not well documented. Honeybees appear somewhat susceptible (Lindberg et al., 2000), and the susceptibility of various natural enemies has yet to be reported, although the lack of persistence of essential oils under field conditions could provide some measure of temporal selectivity favoring these non-target species.

Like other alternative pest management products, essential oil-based pesticides will not be a panacea for crop protection, but there should be substantial market niches, particularly where there is a premium on worker safety and environmental protection, in which these types of products will find wide acceptance among growers.

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