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The potential of botanical essential oils for insect pest control

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Today, Insect Pest management (IPM) has to face up to the economic and ecological consequences of the use of pest control measures. Fifty years of sustained struggle against harmful insects using synthetic and oil-derivative molecules has produced perverse secondary effects (mammalian toxicity, insect resistance and ecological hazards). The diversification of the approaches inherent in IPM is necessary for better environmental protection.

Among the alternative strategies, the use of plants, insecticidal allelochemicals appears to be promising. Aromatic plants, and their essential oils, are among the most efficient botanicals. Their activities are manifold. They induce fumigant and topical toxicity as well as antifeedant or repellent effects. They are toxic to adults but also inhibit reproduction. Although mechanisms depend on phytochemical patterns and are not yet well known, this widespread range of activities is more and more being considered for both industrial and household uses: essential oils are presently regarded as a new class of ecological products for controlling insect pests.

Keywords: Chemical ecology; plant-insect relationships; plant allelochemicals; toxicity; plant protection; insect pest management; damaged crops, food quality.

Introduction

Among the multitude of plant species, some are called aromatic because of the volatile compounds they contain, which give them an odour and a characteristic flavour. Abundant on the Mediterranean periphery, aromatic plants are closely associated with the origins of the western civilization. They have been mentioned from Antiquity for their uses as spices, pot herbs or medicinal plants: they enhanced that taste of foods and helped their preservation, served to embalm the dead or were incorporated into balms or curative ointments. Subsequently, they have known many industrial applications, particularly in perfumery, cosmetics and detergents, pharmacology and fine chemistry as well as aromatics for the food industry. A new field could be developed beside these traditional activities: insect pest management (Regnault-Roger, 1995). One of the fractions of aromatic plants, most frequently used for industrial applications, and which has shown promise for use in IPM, is the fraction of volatile fragrant compounds commonly called essential oils.

The wide complexity of essential oils

The volatility of essential oils allows them to be easily extracted by water vapours, in contrast to fixed lipid oils and essences (concrete, absolute, oleoresins and resinoids) which are extracted by solvents and alcohol. Guenther (1972) distinguished three kinds of water and steam distillation methods for obtaining essential oils. These methods are far more restrictive than more recent extraction and separation methods using supercritical fluids and do not allow the collection of all the aromatic molecules contained in the plant (Peyron, 1992; Richard and Loo, 1992; Pellerin, 1992) but it is nonetheless evident that essential oils appear to be very complex natural mixes. They generally consist of several tens or hundreds of constituents of which the great majority possess an isoprenoid skeleton. Most of the compounds have ten atoms of carbon (Monoterpenes), 15 atoms of carbon (Sesquiterpenes) or more rarely 20 atoms of carbon (Diterpenes). Aliphatic or benzenic molecules can be found as well. The majority of essential oils contain a limited number of main compounds but some of the minor compounds can play an important role as vectors of fragrance and make up the richness of an extract (Casanova, 1994). Improvements in the techniques of separation and identification in the course of the last 25 years have indisputably led to a better knowledge of the composition of essential oils. It is thus well established that essential oil composition is very variable and this has led the Pharmacy Academy to define norms. This inconsistency is due to the fact that all individuals in the same plant species do not always have an identical chemical composition: production can be directed or blocked at one of the stages of metabolism. These differences can be the result of the physiological development of the plant and its degree of maturity, of the choice of the organ, the climatic and soil conditions, seasonal variations and also of numerous chemotypes involving mendelian hereditary transmission.

Essential oils are particularly abundant in some families of plants: Conifers, Rutaceae, Umbelliferae, Myrtaceae and Labiatae, and are often localized in specialized histological structures (hairs, secretory canals of Labiatae or Conifers, schizogenous cavities of Myrtaceae).

The biological significance of essential oils has long been discussed. With regard to the first hypotheses which considered them as wastes of the phytometabolism, it appears today that they present multiple actions. They prevent plants from losing water by excessive evaporation. Their components react as donors of hydrogen in oxydation-reduction reactions. They also seem to be important agents of interspecific communication as they favour pollination by attracting insects and they also play a part in the defence of plants against herbivores, micro-organisms and fungi. Therefore, all these activities could be taken into account in the development of pest management strategies that include better protection of the environment.

Ecological and economic imperatives for the management of harmful insects

Insect control constitutes a major and ancient preoccupation of human beings. Insects form the largest class of the animal kingdom and include nearly 80% of known animal species. Among them, tens of thousands of species are considered as high risk species for Man. They have a double impact: (1) medical; insects are pathogenic agents or disease vectors for men and domestic animals and (2) agricultural; they devastate crops. Phytophagous insects damage rice crops (58% losses), cotton (47%), cause the loss of more than a third of corn and sugar-cane crops and nearly a fifth of wheat (Riba and Silvy, 1989).

Thus, the control of herbivorous insects still remains a great economic goal for a world population likely to double within the next 50 years according to the demographic predictions. Therefore, over the last 30 years, the market for pest management products for crop protection has shown a regular growth of 7–10% per year, a turnover of around 25 billion US dollars (Guillon, personal communication). This growth has been accompanied by a deep reorganization of the industrial sector, not only because of many takeovers and amalgamations of companies, but also because of modifications in the number and the nature of commercialized insecticidal molecules. Two factors contributed to this change: the expensive cost of commercialization licences and the numerous cases of ecotoxicity or toxicity to mammals which occurred in the past.

Even after half a century of sustained struggle against harmful insects, the ideal insecticide has not yet been found. All insecticides modify the ecological balance to varying degrees since they are intended to reduce the impact of insect species harmful to humans. However, since the second world war, the intensive utilization of synthetic or oil based insecticidal molecules has shown secondary effects which reduce the positive results and continue to cause increasing concern. Mammalian toxicity, disruption of the food chain and numerous cases of insect resistance to insecticides have been observed together with a phenomenon by which more harmful insects take the place of a decimated and sensitive species in a given ecological niche. So, diversifying approaches for a better control of harmful insects is now a major concern. This could be done by carrying out several kinds of treatment diversifying the biochemical targets in the insect and using genetic engineering, physical and chemical methods and entomophagous control. The combination of all these methods, used simultaneously or alternately, would certainly decrease the undesirable and secondary effects and also reduce the amounts of insecticide employed, as it is well known since Paracelse (16th century) that 'the dose makes the poison'. Today, insect pest management has to face ecological as well as economic costs.

An alternative strategy: ecochemical control

Among current alternative strategies aiming at decreasing the use of classical insecticides, ecochemical control based on plant-insect relationships is one of the most promising methods. For centuries, plants and insects have followed a parallel and interdependent evolution. Insects cannot live without plants and vice versa. Chemical mediators are used in interspecies communication, especially allelochemicals. These non-nutritional molecules, produced by an organism, modify the behaviour or the biology of an organism from another species. Consequently, plant allelochemicals exert a wide range of influences on insects: they can be repellent, deterrent or antifeedant; they may inhibit digestion, enhance pollination and capture with their attractive properties; they may increase oviposition or, contrarily, decrease reproduction by ovicidal and larvicidal effects. These molecules generally act at weak doses and have a specific action. Very few are toxic for mammals. Most of them are classed as secondary plant products and therefore have chemical structures that classify them as alkaloids, polyphenolics, terpenes and isoprenoids or cyanogenic glucosides (Strebler, 1989).

The use of plant extracts, including allelochemical compounds such as essential oils, with known affects on insects, could be a useful complementary or alternative method to the heavy use of classical insecticides. This could improve the biodegradability of insecticide treatments and therefore decrease the quantity of toxic insecticide residues, increase insecticide selectivity and develop a better respect for the environment.

This alternative strategy based on the identification of plant insecticidal molecules is not recent. Humans have been traditionally using plants in order to protect crops (Golob and Webley, 1980). In the 19th century, several active molecules were extracted from plants: nicotine, extracted from tobacco, appeared later to be toxic to mammals, rotenone from Papilionidae, and pyrethrum from *Chrysanthemum* (Compositeae) which were chemically very unstable. The second world war, by upsetting economic and commercial trades, reduced the utilization of this first generation of plant insecticides. Consequently, petroleum-derived and chemical insecticides (carbamates, organochlorides, organophosphorous) have been strongly developed and used and have led to considerable ecological hazards. In the 1970s new pyrethroids were synthesized, enhancing the stability of the molecules, but they provoked insect resistance. Hence, over the last 15 years, research has been devoted to find other insecticidal molecules which could be extracted from plants (Arnason *et al*., 1989). Azadirachtin extracted from the tropical tree: *Azadirachta indica* (Meliaceae) or neem, is one of the most representative compounds of this kind (Jacobson, 1986; Saxena, 1989). The most promising botanical groups are Meliaceae, Rutaceae, Asteraceae, Annonaceae, Labitae, Aristolochiaceae and Malvaceae (Jacobson, 1989; Schmutterer, 1990, 1992). Some of them are characterized as aromatic plants.

Consequently, these plant extracts including essential oils must have a great potential for pest management, which we shall review in light of recent literature. This work will complement previous reports on the biological and antimicrobial activities of essential oils as well as plant allelochemicals and their applications (Saxena and Koul, 1978; Gora *et al*., 1988; Brud and Gora, 1989; Inagaski, 1989; Klocke and Barnby, 1989; Sharma, 1993; Xu and Chiu, 1994).

The effect of essential oils on harmful insects

Among the first observations carried out in this field, two were particularly focused on the effect of essential oils on insect pests.

A relationship was established between plant resistance to insect pests and essential oil secretion. The resistance of conifers such as Scotch pine to flat bugs (Aradidae family) or violet long-horned beetle (*Callidium violaceum*, Coleoptera: Cerambycidae) was related to a high content of essential oils in the primary bark (Smelyanets and Khursin, 1973; Karasev, 1974). Chromatography fractions of Himalayan cedarwood oil (*Cedrus deodara*: Pinaceae) were bioassayed against the pulse beetle *Callosobruchus analis* (Coleoptera: Bruchidae) and the house fly *Musca domestica* (Diptera: Muscidea) to serve as suitable prototypes for the development of commercial insecticides (Singh and Agarwal, 1988). The toxicity of essential oils from willows and poplars on leaf insects was also pointed out (Rudnev *et al*., 1972). More recently, the wild tomato (*Lycopersicon hirsutum hirsutum*: Solanaceae) glandular trichome type VI was shown to secrete terpenes and essential oils that are associated with insect resistance (Gianfagna *et al*., 1992).

The second strand of research was looking at the use of plant material for worldwide crop protection. The most efficient plants were aromatic plants and therefore the activity of essential oils on stored-product insects was investigated. Patchouli, *Pogostenmon heyneanus* (Solanaceae) and *Ocimum basilicum* (Lamiaceae) essential oils showed insecticidal activity against *Sitophilus oryzae* (Coleoptera: Curculionidae), *Stegobium paniceum* (Coleoptera: Anobiidae), *Tribolium castaneum* (Coleoptera: Tenebrionidae) and *Bruchus chinensis* (Coleoptera: Bruchidae) (Deshpande *et al*., 1974; Deshpande and Tipnis, 1977). The goldenrod *Solidago canadensis* L. (Asteraceae) was strongly toxic to *Sitophilus granarius* (Coleoptera: Curculionidae) (Kalemba *et al*., 1990) and oils from *Eucalyptus* or *Thymus vulgaris* (Lamiaceae) were toxic to *Rhizopertha dominica* (Coleoptera: Bostrychidae) (Thakur and Sankhyan, 1992; Kurowska *et al*., 1991). Several essential oils extracted from various spices and pot herbs of the mediterranean area were active against *R. dominica, Oryzaephilus surinamensis* (Coleoptera: Cucujidae), *S. oryzae* and *T. castaneum* (Shaaya *et al*., 1991) and on the bruchid of kidney bean, *Acanthoscelides obtectus* (Coleoptera: Bruchidae) (Regnault-Roger and Hamraoui, 1993).

The toxic effect of essential oils was not only suitable for granary insects but also for flying insects: *Gaultheria* (Ericaceae) and *Eucalyptus* (Myrtaceae) oils exhibited very high killing power on insects such as the rice weevil *S. oryzae*, the beetles *Callosobruchus chinensis* (Coleoptera: Bruchidae) and *S. paniceum*, and also on *M. domestica* (Ahmed and Eapen, 1986). Actually, the activities of essential oils on species are manifold. *Mentha, Lavandula* (Lamiaceae) or *Pinus* (Pinaceae) essential oils were noted for their toxicity against *Myzus persicae* (Homoptera: Aphididae) and the greenhouse white fly *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae) as well as the Colorado beetle *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae) and the pear bug *Stephanitis pyri* (Hymenoptera: Stephanidae) (Mateeva and Karov, 1983). Mites (*Dermatophagoides farinae*, Acarina: Pyroglyphidae), termites (*Coptotermes formosanus*, Isoptera: Rhinotermitidae) and cockroaches (*Periplaneta fuliginosa*, Dictyoptera: Blattidae) were exterminated by the hinoki-asunaro (*Thujopsis dolabrata* hondai, Cupressaceae) leaf oil (Asada *et al*., 1989).

Insects vary enormously in their responses to secondary plants products and it is well known that the sensitivity of different insect species could be quite different for the same substance. Oils from *Cymbopogon nardus* (Graminae) which killed *A. obtectus* in a short time (Regnault-Roger *et al*., 1993) only knocked down and disabled *Sitotroga cereallela* (Lepidoptera: Gelichiidae) (Krishnarajah *et al*., 1985).

The toxic effect of essential oils, apart from the variability of phytochemical patterns, involves several other factors. The point of entry of the toxin is one of them. Commonly, essential oils can be inhaled, ingested or skin absorbed by insects. The fumigant toxicity of essential oils and their main components, the volatile monoterpenes, has been described (Smelyanets and Kuznetsov, 1968; Netzurubanza, 1991; Weaver *et al*., 1991; Regnault-Roger *et al*., 1993; Regnault-Roger and Hamraoui, 1995). Insects were also very sensitive to topical applications (*Sitophilus zeamaïs* (Coleoptera: Curculionidae), *T. castaneum* and *Prostephanus truncatus* (Coleoptera: Bostrychidae) reacted to *Citrus* (Rutacae) essential oils (Haubruge *et al*., 1989). *Pediculus capitis* (Anoplura: Pediculidae), *Anopheles funestus* (Diptera: Culicidae), *Cimex lectularius* (Hemiptera: Cimicidae) and *Periplaneta orientalis* (Dictyoptera: Blattidae) were killed by contact with *Eucalyptus saligna* (Myrtaceae) oil within 2 to 30 minutes (Kambu *et al*., 1982). *Dennettia tripetala* (Annonaceae) essential oil decimated adults and nymphs of the American cockroach *Periplaneta americana* (Dictyoptera: Blattidae) and the grasshopper *Zonocerus variegatus* (Orthoptera: Acrididae) (Iwuala *et al*., 1981). Antifeedant effects could decimate insects too. Some essential oils in sagebrush community plants: *Artemisia tridentata* (Asteraceae), *Purshia tridentata* (Boraginaceae) and *Chrysothamnus nauseosus* (Asteraceae) presented antifeeding properties against the Colorado potato beetle *L. decemlineata* (Jermy *et al*., 1981). Eugenols from *Laurus nobilis* (Lauraceae) essential oils decreased the feeding of *Mythimna unipuncta* (Lepidoptera: Noctuidae) (Muckensturm *et al*., 1982). The insects' decision to avoid feeding on a plant could be influenced by phagodeterrency of substances, post-consumption physiological stress or a repellent effect and it is not always easy to discriminate the different types of activity. A new bioassay had been created to discriminate between the phagodepressant and phagostimulant efficiency of *Sapindus saponaria* (Sapindaceae) extracts, *Minthostachis mollis* (Lamiaceae) and *Melaleuca quinquenervia* (Myrtaceae) essential oils on the flour beetle *T. castaneum* (Alonso-Amelot *et al*., 1994) and recently, a laboratory evaluated the antifeedant effect for the pales weevil, *Hylobius pales* (Coleoptera: Hylobiinae) of pine essential oils and terpenes extracted from plants by a choice test (Salom *et al*., 1994).

The repellent effect of essential oils was also observed: the *Adhatoda vasica* (Acanthaceae) essential oil exhibited repellent activity against *S. oryzae* and *B. chinensis* (Kokate *et al*., 1985); oil from *Ocimum suave* (Lamiaceae) repelled *S. zeamaïs* (Hassalani and Lwande, 1989) as well as *Lippia* (Verbenaceae) species of Kenya (Mwangi *et al*., 1992) and *Acorus calamus* (Araceae) essential oil repelled *T. castaneum* (Jilani *et al*., 1988). Essential oil from the berries of *Jupinerus communis* (Cupressaceae) is a very good mosquito repellent (Kalemba *et al*., 1991). Some essential oils both repelled the grain weevil *S. granarius* and inhibited its feeding (Nawrot, 1983) and *Absinthium* (Asteraceae) essential oils exerted both toxic and repulsive effects on this pest (Kalemba *et al*., 1993).

Essential oils are active against both adults and larvae and frequently act to inhibit reproduction. This action could be the result of female sensitivity: essential oils cause adult mortality and also repell carmine spider mite, *Tetranychus cinnabarinus* (Acarina: Tetranychidae) females, and reduce egg laying (Mansour *et al*., 1986). Reproductive inhibition can also affect the developmental stages of the pest. Leafhopper *Amrasca devastans* (Homoptera: Cicadellidae) oviposition was inhibited by volatiles of *Eucalyptus globulus* (Myrtaceae) and *Coriandrum sativum* (Umbelliferae) (Saxena and Basit, 1982), and a toxic effect of lavender oils on larvae of *T. vaporariorum* has been shown (Mateeva and Karov, 1983). The LD 50 of some volatiles extracted from the essential oils of *Parthenocissus quinquefolia* (Vitaceae), coniferous trees, *Citrus* and *Mentha* species, was tabulated using larvae of *L. decemlineata* and *Tribolium destructor* (Coleoptera: Tenebrionidae) (Vasechko *et al*., 1970). *A. calamus* oil and its active ingredients, asarone and its analogues, significantly reduced fecundity and hatchability of the kelp fly *Coelopa frigida* (Diptera: Coelopidae) (Ramos-Ocampo and Hsia, 1986a) and exerted an ovicidal action on *Oncopeltus fasciatus* (Hemiptera: Lygaeidae) (Ramos-Ocampo and Hsia, 1986b). They were also potent growth inhibitors and antifeedants to the variegated cutworm *Peridroma saucia* (Lepidoptera: Noctuidae) (Koul *et al*., 1990) and produced sterilizing effects on *P. truncatus* (Schmidt and Streloke, 1994). Citriodora, wintergreen and camphor oils also exhibited antifeedant activity against larvae and provoked a limited larval mortality (Dale and Saradamma, 1981). Essential oils extracted from common Greek aromatic plants, especially *Satureja, Origanum* and *Mentha* (Lamiaceae), prevented egg hatching and provoked prohibition or malformation of the puparium of the flies *Drosophila auraria* (Diptera: Drosophilidae) (Konstantopoulou *et al*., 1992). The inhibition of reproduction of *A. obtectus* by essential oils belonging to Labiatae, Umbelliferae, Lauraceae, Myristicaceae, Graminae, Rutacae, Myrtacae families was also observed. This beetle has been shown to be a convenient model to point out with accuracy which reproductive stage is targeted and the speed of the activity of essential oils (Regnault-Roger and Hamraoui, 1994).

Some essential oils and their components exhibited both a repellent and a larvicidal action: *Ocimum* volatile oils including camphor, cineole, methyl eugenol, limonene, myrcene and thymol, strongly repelled mosquitoes and *O. basilicum* exerted a larvicidal activity evaluated at $EC_{50} = 81$ ppm (Chokechaijaroenporn *et al*., 1994).

Nevertheless, not all essential oils are repellent; some have been found to be highly attractive. The use of pine and fir essential oils increased settling in trap trees by *Ips tyrographus* (Coleoptera: Scolytidae) (Ozols and Bicevskis, 1979). The essential oils including ionone and ionol-related compounds could be used to lure males of

Bactrocera latifrons (Diptera: Tephritidae) (Flath *et al*., 1994). However, some essential oils can exert quite opposite effects on different insect species: tansy essential oil was attractive and paralysing for *R. dominica*, toxic for *S. granarius* and repulsive for *T. confusum* (Kurowska *et al*., 1993).

In fact, the mechanisms of the toxic effect on insects are not presently well known. The neurotoxicity of several monoterpenoids (d-limonene, â-myrcene, Æ-terpineol, linalool and pulegone) which have been identified as important components of essential oils, were tested on the house fly as well as on the German cockroach (Coats *et al*., 1991) and linalool was identified as an inhibitor of acetylcholinesterase (Ryan and Byrne, 1988).

However, because of the chemical complexity of essential oils, several mechanisms being contingent on the phytochemical pattern of the oils and the sensitivity of the insect species could be involved. In these circumstances, the comparison of the toxicity of several essential oils in order to classify them, will be significant only if the evaluation involves experiments conducted with samples of known phytochemical pattern on identical insect populations (Table 1).

Also, the use of identical samples is necessary when the different kinds of toxicity of an essential oil are compared. In this way, the topical and fumigant toxicity of equal amounts of limepeel oil was recently tested on *Dermestes maculatus* (Coleoptera: Dermestidae) and this showed that the vapours were more toxic (Don Pedro, 1996).

To investigate the mechanisms of toxicity, a comparative study was conducted between larvae of a generalist insect, the fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) and a semispecialist, the velvetbean caterpillar *Anticarsia gemmatalis* (Lepidoptera: Noctuidae). The results showed that the midgut microsomes included cytochrome P_{450} monooxygenases, metabolized allelochemicals such as terpenes and that the monooxygenase activity towards these allelochemicals as generally higher in the generalist than in the semispecialist insect, and that this played an important role in the detoxication of plant toxins (Yu, 1987). In some cases essential oils could play a role as synergistic compounds. Contact with the free resin and essential oils of pine needles inhibited feeding in young caterpillars although the separate compounds were not very active on the needle-eating insects (Otto and Geyer, 1970). The residual toxicity of pyrethrins against *T. castaneum* adults was stabilized by essential oils such as Eucalyptus, Camphor, and Cedarwood (Ahmed and Gupta, 1976).

From all these observations, it could be deduced that essential oils present a widespread range of activities on insects and could be used for environmentally safer pest management. For this purpose, several patents utilizing essential oils were taken out during the last ten years to support the industrial approach.

Essential oils trends and development

Examination of some recent patents involving essential oils showed that a majority of the inventions focused on household uses. A cleaning solution including clove essential oils and pyrethroid would cleanse and destroy eggs and larvae, and leave a residue to prevent reinfestation by Blattaria (Heinmenberg, 1992). Several formulations were proposed to control mosquitoes and flies; some of them associated essential oils to pyrethroids (Liang, 1988; Kono *et al*., 1993) although Eucalyptus essential oil was used as a synergistic insecticide in addition to growth inhibitors (Narasaki *et al*., 1987). Spearmint, bitter almond and birch (*Betula lenta* (Betulaceae)) bark essential oils were incorporated into a mixture showing acaricide, insecticide and insect repellent properties (Matsumoto *et al*., 1987).

Some patents were devoted to the protection of domestic animals. A flea collar for pet dogs was manufactured by adding essential oils (Eucalyptus, Cedarwood, Citronella and Peppermint) to ethylene-vinyl acetate polymer in a mixture and demonstrated some usefulness (Seto, 1987). A systemic insect repellent composition with garlic essential oils could be eaten by animals to afford a continuous protection against fleas, ticks and other blood feeding pests; a sufficient blood level would ensure a continuous insect repellency (Weisler, 1987).

However, a large number of the patents have been assigned to the preservation of clothes from moths and beetles (such as *Anthrenus*: Coleoptera: Dermestidae), including: application of a solution containing clove essential oil on woollen cloth (Riedel *et al*., 1989), filter paper containing *Juniperus rigida* (Cupressaceae) essential oil (Okano, 1991) and tablets of p-dichlorobenzene added with essential oils (Okano *et al*., 1992) to be placed in a wardrobe. More recently, washfast insect-resistant fabrics have been created with partially or wholly hollow porous fibres coated with encapsulated insecticidal agents (among them, Eucalyptus oil) (Sano and Une, 1993).

Beside these domestic uses, essential oils present applications in agriculture and the food industry. Mustard essential oil was part of a sustained release formulation containing insecticide, microbicide and repellent substances absorbed onto silica and silane compounds used to prevent infestation of mites in feed (Saijo, 1989).

Essential oils can also be incorporated with polymers into sheets. Attractant adhesive films with essential oils were prepared to control insects in agriculture and horticulture (Klerk's Plastic Industrie B.V., 1990). Coating materials, useful in agricultural and livestock structures, include pine essential oils to enhance their insecticidal properties and repel harmful insects (Feliu Zamora, 1990). Adhesives containing acrylic polymers and high levels of essential oils showed a killing effect for *Blatella germanica* (Dictyoptera: Blatellidae) (Yamaguchi *et al*., 1989).

Table 1. Fumigant toxicity of some essential oils on *Acanthoscelides obtectus* (Coleoptera: Bruchidae)

Essential oil	Family	Main components (%)	LC 50 ($mg\,l^{-1}$) (24 h)	(48 h)
Thymus serpyllum L.	Labiatae	Thymol (30.4), carvacrol (28.9), p-cymene (10), citra (4.2)	2.0	1.5
Mentha piperita L.	Labiatae	Menthone (3.5), menthol (18.8), isomenthone (12.8)	22.4	8.7
Rosmarinus officianalis L.	Labiatae	Camphor (30.6), borneol (22.1), 1,8-cineole/â-phellandrene (10.6)	3.2	2.2
Satureia hortensis L.	Labiatae	Carvacrol (39.9), thymol (13.4), linalool (6.4)	5.7	2.5
Lavandula augustifolia P. Muller	Labiatae	Linalyl acetate (34.2), linalool (31.8), â-Caryophyllene (11.1)	12.6	5.7
Eucalyptus globulus Labill.	Myrtaceae	1.8-Cineole (86), *Æ*-pinene (3.9), *p*-cymene (2.4)	66.0	20.8
Laurus nobilis L.	Lauraceae	1.8-Cineole (48.6), sabinene (9.1), terpinyl acetate (8.2), *Æ*-pinene (7.1)	17.8	8.1
Origanum vulgare L.	Labiatae	Carvacrol (39.4), thymol (26.6), *p*-cymene (16.3)	10.0	3.3
Cymbopogon nardus Wats	Gramineae	Citronella (33.8), geraniol (21.6), citronellol (9.2), geranyl acetate (3.4)	60.4	24.0
Salvia officinalis L.	Labiatae	â & â-Thuyone (28), linalyl acetate (21.4), â-caryophyllerie and *Æ*-humulene (5)	7.1	4.9
Origanum majorana L.	Labiatae	Terpinene-1-ol-4 (20.6), linalool (15.3), [a]-terpinene (10.3)	1.9	1.5
Ocimum basilicum L.	Umbelliferae	Linalool (50), limonene (7.5), eugenol (3.6), estragole (3.2)	4.0	1.6
Cinnamomum verum Presl.	Lauraceae	Cinnamaldehyde (90), eugenol (3.6)	2.1	1.7
Petroselinum sativum L.	Umbelliferae	Apiole (43), thymol (10.2)	. 1000	. 1000
Cuminum cyminum L.	Umbelliferae	Cuminaldehyde (42.5), â-pinene (11.8), [a]-terpinene (11.4), nerol (11.4)	4.3	2.1
Apium graveolens Houtt	Umbelliferae	Limonene (73.2), sequiterpene (13)	302.0	263
Myristica fragrans L.	Myristicaceae	â Pinene (23.2), sabinene (22.6), myristicine (7.9)	125.8	112.2
Anethum graveolens	Umbelliferae	Limonene (35.9), carvone (34.8), â-myrcene (11.8)	50.0	22.4
Citrus limon (L.) Burm f	Rutacae	Limonene (63.9), â-pinene (12.2)	100.0	95.0
Verbena officinalis L.	Labiatae	Carvone (32.4), limonene (18.9), citral (17.6)	19.9	8.8
Coriandrum sativum L.	Umbelliferae	Linalool (68.2), *Æ*-pinene (5.5), [a]-terpinene (5.5)	19.9	8.8
Thymus vulgaris L.	Labiatae	Thymol (47.5), *p*-cymene (17.3), â-caryophyllene (6.1)	7.0	2.2
Thymus vulgaris L.	Labiatae	Thymol (26.5), *p*-cymene (18.4), â-caryophyllene (3.5)	13.5	4.5

Essential oils also showed some usefulness for building materials. A wood preservative solution mixed eucalyptus essential oils with pyrethroids and borax (Urabe, 1992). The resistance of veneer-faced panels to insects is improved by a deep impregnation of the polymer layer with hiba or kinoki essential oils (Akita, 1991; Tsubochi and Sugimoto, 1992).

All these examples demonstrate the wide range of uses of essential oils.

Conclusion

Today essential oils represent a market estimated at $700 million and a total world production of 45 000 tons. Nearly 90% of this production is focused on 15 products, particularly mints (*M. piperata, M. arvensis* and *M. spicata*) and citrus (orange, lemon, lime). Among the other important products are *E. globulus, Litsea cubera* (Lauraceae), clove, cedar and patchouli. In the course of the last few years, the utilization of essential oils has been modified. There has been a steady increase in production for the food aroma industry: citrus, rose, cedar, mints. On the contrary, the use of essential oils in hemisynthetic reactions (citronella, clove, eucalyptus, camphor, lemongrass) or in alcoholic perfumery (patchouli) has decreased (Verlet, 1994). So, a diversified use of essential oils by the development of their use in the pest management sector could be of both economic and ecological benefit.

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