

Current Status of Botanical Pesticides for Crop Protection

Quang Le Dang, Chi Hwan Lim¹ and Jin-Cheol Kim*

Eco-friendly Research Group, Division of Convergence Chemistry, Korea Research Institute of Chemical Technology,
Daejeon 305-600, Korea

¹College of Agriculture and Life Science, Chungnam National University, Daejeon 305-764, Korea

(Received on June 11, 2012; Revised on July 16, 2012; Accepted on September 3, 2012)

The problems caused by synthetic pesticides have led the need for effective biodegradable pesticides with greater selectivity. Botanical pesticides are generally recognized as safe in agriculture systems. Thus, they have been regarded as attractive alternatives to synthetic chemical pesticides for the pest management. Both lower efficacy and higher costs of production make botanicals more expensive to use than conventional pesticides. Moreover, only a small portion of plant-derived metabolites among a number of bioactive metabolites are in use because commercialization of botanicals is inhibited by several problems such as toxicity, or high production cost. However, with the growing acceptance of botanical pesticides as an efficient crop protection alternative resulting in increasing demand, plant-based pesticides will play a significant role in achieving sustainable agriculture in future.

Keywords : Botanical pesticides, Plant-derived metabolites, Sustainable agriculture, Synthetic pesticides

Introduction

The agents that cause disease in plants are known to include pathogenic microorganisms such as viruses, bacteria, fungi, protozoa and nematodes. Plants also suffer from competition with weeds and are often damaged by attacks of insects. It is conservatively estimated that diseases, insects and weeds together annually interfere with the production of, or destroy, between 31 and 42% of all crops produced worldwide. Out of 36.5% average of total losses, 14% are caused by diseases, 10.2% by insects, and 12.2% by weeds. Oerke and Dehne (2004) reported that the actual losses were estimated at 26–30% for sugar beet, barley, soybean, wheat and cotton, and 35%, 39% and 40% for maize, potatoes and rice, respectively, for the period 1996–1998. The total annual worldwide crop loss from plant diseases is about \$ 220 billion (2002 prices) (Agrios, 2005).

After World War II, the agrochemical industry with discoveries of the major classes of synthetic pesticides (organochlorines, organophosphates and carbamates) provided agriculture with a vast array of crop protection chemicals such as fungicides, insecticides, nematicides,

and herbicides (Jespers and De Waard, 1993). Crop growers have mainly used such synthetic agrochemicals to control plant diseases. However, overuse of these synthetic pesticides has led to resistance in plant pathogens and other numerous problems unforeseen at the time of introduction such as acute and chronic pollution, negative effects on wildlife (fish, birds), disruption of biological control and pollination, and groundwater contamination. Governments responded to these problems with regulatory action, banning or restricting the most damaging products and creating policies to make more stringent pesticide registration procedures and replace such chemicals and to pose fewer or lesser risk to human health and the environment (Gonzalez-Coloma *et al.*, 2010; Isman, 2006).

New pesticides including botanical pesticides are being discovered and developed to replace the active compounds that are lost due to the new registration requirements. Botanical products have long been considered as crop protectants. A lot of plant derived-compounds with pesticidal activities such as essential oil, terpenoids, lipids, sterols, alkaloids, flavanones and polyketides have been discovered and registered as biopesticides (Copping and Duke, 2007; Copping and Menn, 2000). Phytochemicals have been interested in controlling plant diseases because they are specific to target species, have often unique modes of action and little toxicity to human and are rapidly degraded into non-toxic substances under environmental conditions.

*Corresponding author

Phone) +82-42-860-7436, Fax) +82-42-861-4913

Email) kjinc@kriict.re.kr

Some of them possess modes of action different from introduced chemicals and are, therefore, lack cross-resistance (Vidhyasekaran, 2004). Thus, botanical pesticides have been long recommended as attractive alternatives to synthetic chemical insecticides for pest management. The number of scientific literature documenting pesticidal activity of plant metabolites continues to increase, yet only a minority of botanical pesticides are currently used in agriculture over the world. In this paper, we reviewed plant-derived metabolites showing potent fungicidal, insecticidal, and nematocidal activities.

Botanical fungicides

Numerous phytochemicals have the potentials to control fungal diseases of crops (Copping and Duke, 2007; Engelmeier and Hadacek, 2006; Isman, 2000b). Jojoba (*Simmondsia californica*) oil, rosemary (*Rosemarinus officianalis*) oil, thyme (*Thymus vulgaris*) oil, clarified hydrophobic extract of neem (*Azadirachta indica*) oil, and cottonseed (*Gossypium hirsutum*) oil with garlic (*Allium sativum*) extract are several botanical extracts and essential oils marketed as botanical fungicides for organic farmers (Dayan *et al.*, 2009).

Cinnamaldehyde (Fig. 1) is used in mushrooms, row crops, horticultural crops, turf and pine forests to control diseases such as dry bubble (*Verticillium fungicola*), and pitch canker disease (*Fusarium moniliforme* var *subglutinans*) (Copping and Duke, 2007). Its mode of action is apparently through inhibition of synthesis of the fungal cell wall component chitin (Bang *et al.*, 2000). Thymol and carvacrol (Fig. 1) from essential oil of *Thymbra spicata* show strong antifungal activity against *F. moniliforme*, *Rhizoctonia solani*, *Sclerotinia sclerotiorum*. They efficiently inhibited all of the fungi with concentrations ranging from 50–100 µg/ml (Muller-Riebau *et al.*, 1995). β-Thujaplicin and γ-thujaplicin (Fig. 1) are monoterpenes from *Calocedrus macrolepis* var. *formosana* heartwood, exhibiting a broad antifungal spectrum against white rot fungi and brown rot fungi (Yen *et al.*, 2008). The MIC values of β-thujaplicin and γ-thujaplicin were in the range of 5.0–50 µg/ml. β-Caryophyllene oxide and α-terpineol (Fig. 1) of *Hypericum hyssopifolium* and *H. heterophyllum* were strongly inhibitory to the growth of *Fusarium* species and *R. solani* at 1,000 µg/ml (Cakir *et al.*, 2004). T-muurolol and α-cadinol (Fig. 1) exhibited activity against *R. solani* and *F. oxysporum* with the highest antifungal indexes ranging from 60% to 85% (Chang *et al.*, 2008). Asaroaldehyde and α-asarone (Fig. 1) derived from *Acorus gramineus* rhizome were active against *Phytophthora infestans* and *R. solani* with control

values of 50–100% at 1,000 µg/ml (Lee, 2007).

Singh *et al.* (2008) reported that securinine and allosecurinine (Fig. 1) isolated from *Phyllanthus amarus* completely inhibit spore germination of *Alternaria* spp., *Heterosporium* spp. and *Curvularia* spp. at 200 µg/ml. Nor-securinine (Fig. 1) was fungicidal to *H. frumentacei* at 1,000 µg/ml (Sahni *et al.*, 2005). Alkaloids neoveratalines A and B (MICs about 200 µg/ml), veramilaline, stenophylline B, stenophylline B-3-O-β-D-glucopyranoside, veramiline-3-O-β-D-glucopyranoside, jervine, and jervine-3-O-β-D-glucopyranoside (Fig. 1) isolated from rhizomes of *Veratrum taliense* exhibited strong antifungal activity to *Phytophthora capsici* and *Rhizoctonia cerealis* (Zhou *et al.*, 2003).

Emodin, physcion, and rhein (Fig. 1) isolated from *Cassia tora* showed fungicidal activities against *Botrytis cinerea*, *Blumeria graminis* f. sp. *hordei*, *P. infestans*, and *R. solani* with IC₅₀ values in a range of 46–375 µg/ml. Aloe-emodin had an apparent IC₅₀ value of 177 and 275 µg/ml against *R. solani* and *B. cinerea*, respectively (Kim *et al.*, 2004a, b). Chrysophanol, parietin (physcion), and nepodin (Fig. 1) isolated from roots of *Rumex crispus* showed activity against *B. graminis* f. sp. *hordei* and synergistic activity against fungus *Sphaerotheca fuliginea*. They controlled *B. graminis* f. sp. *hordei* with IC₅₀ values of 4.7, 0.48 and 20 µg/ml, respectively (Choi *et al.*, 2004; Yang *et al.*, 2007). Dehydro-α-lapachone (Fig. 1) from stems of *Catalpa ovata* completely inhibited the mycelial growth of *B. cinerea*, *Colletotrichum* spp., *Magnaporthe oryzae* and *Pythium ultimum* over a range of 0.4–33.3 µg/ml (Cho *et al.*, 2006b). Cho *et al.* (2006a, c) also demonstrated an antifungal activity of curcumin, demethoxycurcumin and bisdemethoxycurcumin (Fig. 1) against red pepper anthracnose in a range of 0.4–100 µg/ml. Curcumin was fungicidal to *P. infestans*, *Puccinia recondita*, and *R. solani* with 100%, 100%, and 63% control values at a concentration of 500 µg/ml (Kim *et al.*, 2003).

Lignans erythro-austrobailignan-6, meso-dihydroguaiaretic acid and nectandrin-B (Fig. 1) from *Myristica fragrans* efficiently suppressed *A. alternata*, *B. cinerea*, *Colletotrichum coccodes*, *Colletotrichum gloeosporioides*, *F. oxysporum*, *R. solani* and *M. oryzae* with IC₅₀ from 24 to 100 µg/ml (Cho *et al.*, 2007). Four neolignans from *Magnolia obovata* such as magnolol, honokiol, 4-methoxyhonokiol and obovatol (Fig. 1) showed potent mycelial growth inhibition with IC₅₀ from 7.1 to 95 µg/ml against *Alternaria alternata*, *C. coccodes*, *F. oxysporum*, *M. oryzae*, *P. capsici*, *P. infestans*, *P. ultimum* and *R. solani* (Choi *et al.*, 2009).

Saponinoids including spirostanol saponins dioscin, prosapogenin of dioscin and gracillin (Fig. 1) isolated from *Dioscorea collettii* var. *hypoglauca* rhizomes induced

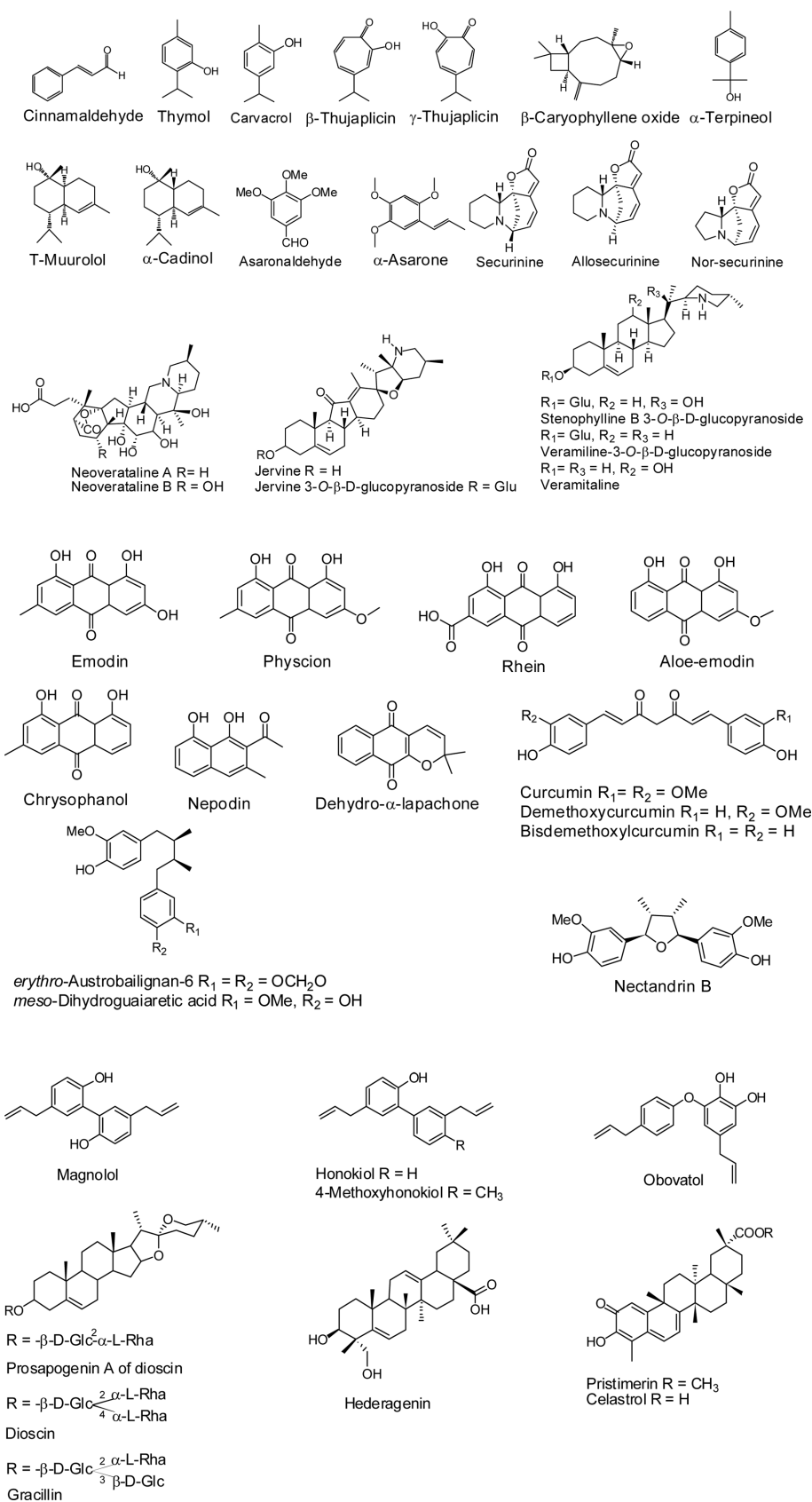


Fig. 1. Phytochemicals with antifungal activity against phytopathogenic fungi.

morphological deformation of mycelia and conidia of *M. oryzae* with MMDC (minimum morphological deformation concentration) 2.3, 5.5 and 9.0 μM , respectively (Hu *et al.*, 2003). Hederagenin aglycone (Fig. 1) was reported to be active against *Rhizoctonia bataticola* (ED_{50} 1636.0 $\mu\text{g/ml}$) and *Sclerotium rolfsii* (ED_{50} 412.5 $\mu\text{g/ml}$) (Saha *et al.*, 2010; Saniewska *et al.*, 2006). Quinonoid triterpenes pristimerin and celastrol (Fig. 1) from the roots of *Celastrus hypoleucus*, inhibited the mycelial growth of *Glomerella cingulata*, *B. cinerea*, *R.*

solani and *M. oryzae* (Luo *et al.*, 2005).

In the case of commercialized phytochemicals L-glutamic acid and γ -aminobutyric acid, they are introduced as active ingredients of AuxiGro used as a fungicide and plant growth regulator for fungal managements of fruits and vegetables, tree nuts, peanuts, grains, turf grasses and for preventing powdery mildew on grapes. They are not toxic to mammals or other organisms tested and they are not likely to be toxic to plants (Copping and Duke, 2007).

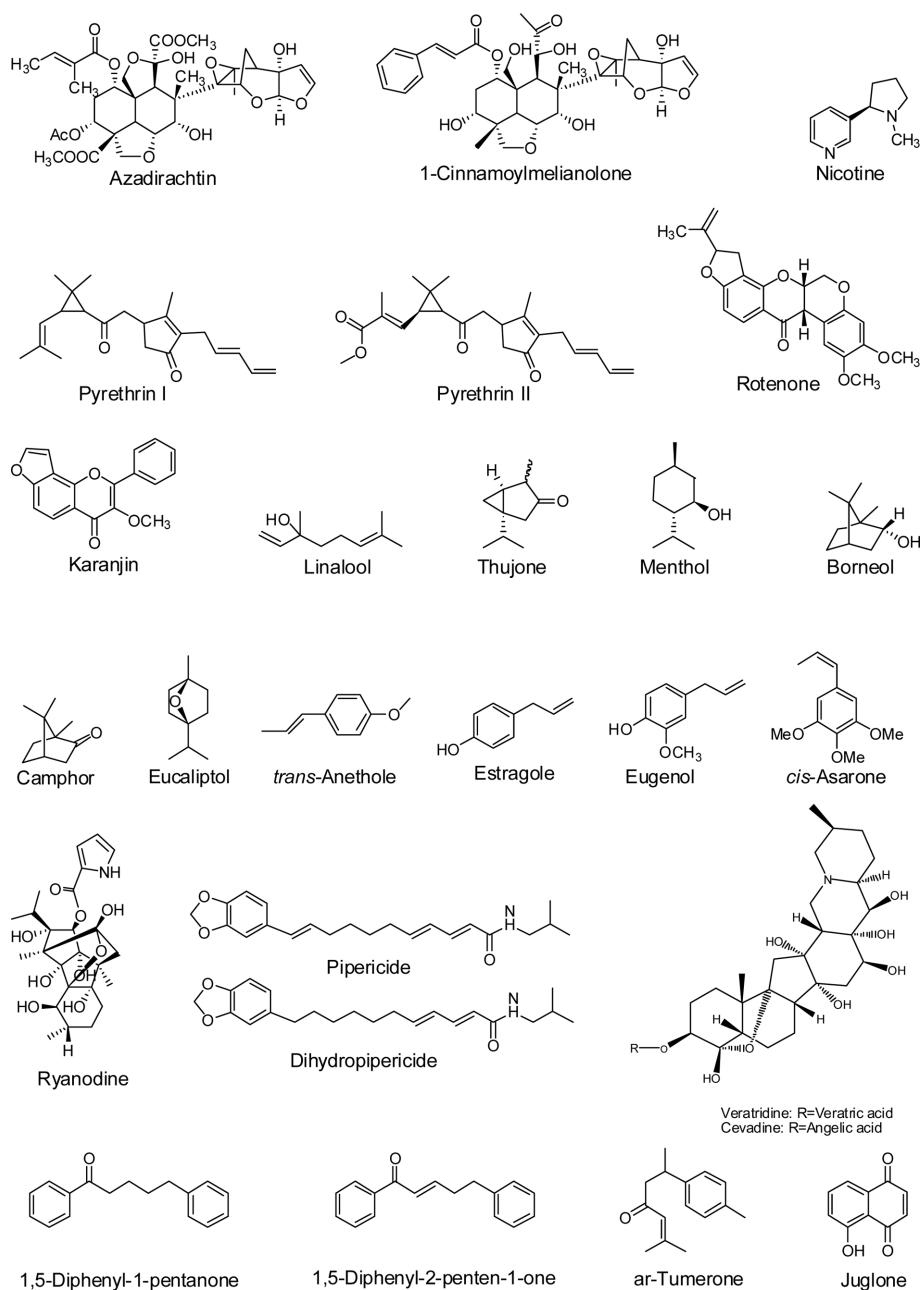


Fig. 2. Phytochemicals with insecticidal activity against insects.

Botanical insecticides

Botanical insecticides from phytochemical resources being used currently include azadirachtin, nicotine, pyrethrins, rotenone, and numerous essential oils. Neem seeds (*A. indica*) contain 0.2 to 0.6% azadirachtin (Fig. 2) and numerous minor azadirachtin analogs (Isman, 2006). Azadirachtin has two effects on phytophagous insects; it disrupts insect molting by blocking the synthesis and release of ecdysteroids hormones, and is a potent antifeedant to many insects (Gonzalez-Coloma *et al.*, 2010). Azadirachtin is effective against whitefly, thrips, leaf miners, caterpillars, aphids, jassids, beetles and mealybugs (Copping and Duke, 2007). Lepidoptera were extremely sensitive to the chemical and show effective antifeedancies from below 1 to 50 µg/ml, depending on species (Mordue and Nisbet, 2000). Azadirachtin is sold with a wide range of trade names such as Azatin, Align, Bio-neem, Bollwhip, Neem, Neemazad, Neemix, and so on (Copping and Duke, 2007).

Seeds of chinaberry tree (*Melia azedarach*), the most closely related genus of neem, contain a number of remarkable insecticidal triterpenoids (meliatoxins) such as 1-cinnamoylmelianolone (Fig. 2) (Isman, 2000a). The meliatoxins are abundant in chinaberry tree in Asia and toxic to mammals. However, the seeds of *M. azedarach* growing in Argentina lacked meliatoxins, but produced a notably triterpenoid meliartenin that is a strong feeding deterrent to insects (Isman, 2006).

Nicotine (Fig. 2) is the main bioactive component of the tobacco plants *Nicotiana tabacum* (Copping and Duke, 2007). Nicotine is a nonsystemic insecticide that binds to the cholinergic acetylcholine nicotinic receptor. Nicotin and its semi-synthetic derivatives are used for the control of a wide range of insects, including aphids, thrips and whitefly, on protected ornamentals and field-grown crops, including orchard fruit, vines, vegetables and ornamentals (Addor, 1995; Copping and Duke, 2007).

Pyrethrins I (Fig. 2) and II are most abundant in pyrethrum of *Tanacetum cinerariaefolium* and account for most of the insecticidal activity (Isman, 2006; Gonzalez-Coloma *et al.*, 2010). Pyrethrins block voltage-gate sodium channels in nerve axons, resulting in a neurotoxic action. Technical grade pyrethrum (20 to 25% pyrethrins) controls a wide range of insects and mites on fruit, vegetables, field crops, ornamentals, glasshouse crops and house plants (Copping and Duke, 2007).

Rotenone (Fig. 2) has been used for more than 150 years and is found in *Derris*, *Lonchocarpus* and *Tephrosia* species. It is used to control a wide range of arthropod

pests, including aphids, thrips, suckers, moths, beetles and spider mites in fruit and vegetable cultivation. Rotenone is mitochondrial poison, which blocks the electron transport chain and prevents energy production. It is considered as a stomach poison because it must be ingested to be effective (Isman, 2006).

Karanjin (Fig. 2) is a furanoflavonol, a type of flavonoid. It is obtained from the seeds of the karanjin tree (*Millettia pinnata* = *Derris indica*), a tree growing wild in south India. Karanjin is an acaricide and insecticide. It suppresses the effects of ecdysteroids and thereby acts as an insect growth regulator (IGR) and antifeedant. It also inhibits cytochrome P-450 in susceptible insects and mites (Gonzalez-Coloma *et al.*, 2010).

Plant essential oils disrupt the endocrinologic balance of insects. They may be neurotoxic or may act as insect growth regulators, disrupting the normal process of morphogenesis. Several volatile substances of essential oils such as linalool (Fig. 2) have been shown as inhibitors of acetylcholinesterase (AChE) against different insect species. Thujone, thymol, menthol and borneol (Fig. 2) have been classified as a neurotoxic insecticide, which acts on GABA receptors (Rameshwar Singh, 2010). Camphor and eucalyptol (Fig. 2) are used for control the honeybee parasite varroa (*Varroa jacobson* and *V. destructor*). *trans*-Anethole, estragole, eugenol (Fig. 2) and carvacrol showed topical activity to insects (Addor, 1995). Eugenol is effective on arthropod, armyworms, thrips, aphids and mites (Isman, 2000b). Cinnamaldehyde is toxic to corn rootworm and other pest of animals (Copping and Duke, 2007; Gonzalez-Coloma *et al.*, 2010). Two asarones, *a*-asarone and *cis*-asarone (Fig. 2), caused high mortalities for *Sitophilus oryzae*, *Callosobruchus chinensis* and *Lasioderma serricorne* adults (Park *et al.*, 2003).

Ryanodine (Fig. 2) and related alkaloids are poisonous alkaloids found in the stem of Caribbean shrub *Rynia speciosa*. It controls codling moth (*Cydia pomonella*), citrus thrips in maize, apples, pears and citrus. It has extremely high affinity to the open-form ryanodine receptor, a group of calcium channels found in skeletal and heart muscle cells. It affects muscles by binding to the calcium channels in the sarcoplasmic reticulum and cause rapidly death. The effect of the nanomolar-level binding is that ryanodine causes release of calcium from calcium stores in the sarcoplasmic reticulum leading to massive muscular contractions (Copping and Duke, 2007; Isman, 2006).

Pipericide, dihydropipericide (Fig. 2) of black pepper *Piper nigrum* was active to adzuki bean weevil (*Callosobruchus chinensis*). Pipericide and dihydropipericide

caused LD₅₀ values 0.56 and 0.23 µg/insect, respectively (Isman, 2006).

Sabadilla is a botanical insecticide from the seeds of the South American lily (*Schoenocaulon officinate*). The plant contains a (2:1) mixture of cevadine and veratridine (Fig. 2), which account for the insecticidal activity of the plant (Isman, 2006). They act on the voltage-sensitive sodium channels of nerve, heart, and skeletal muscle cell membranes (Gonzalez-Coloma *et al.*, 2010). The compounds were effective against thrips (*Frankliniella* spp. and *Thrips* spp.) in citrus and avocados (Copping and Duke, 2007).

Another aphicide, 1,5-diphenyl-2-penten-1-one and 1,5-diphenyl-1-pentanone (Fig. 2) isolated from the

roots of *Stellara chamaejasme* caused aphicidal activity against *A. gossypii* and *Schizaphis graminum* (Ping *et al.*, 2001). *ar*-Turmerone (Fig. 2) caused 100 and 64% mortality for *Nilaparvata lugens* female adults at 1000 and 500 µg/ml, respectively (Lee *et al.*, 2001). 5-Hydroxy-1,4-naphthoquinone (Juglone, Fig. 2) isolated from *Diospyros kaki* roots was effectively active against *N. lugens* and *Laodelphax striatellus* (Jeon *et al.*, 2011).

Botanical nematicides

Phytochemicals with nematicidal activities have been also known as botanical nematicides. Most of secondary metabolites are responsible for the nematicidal activities.

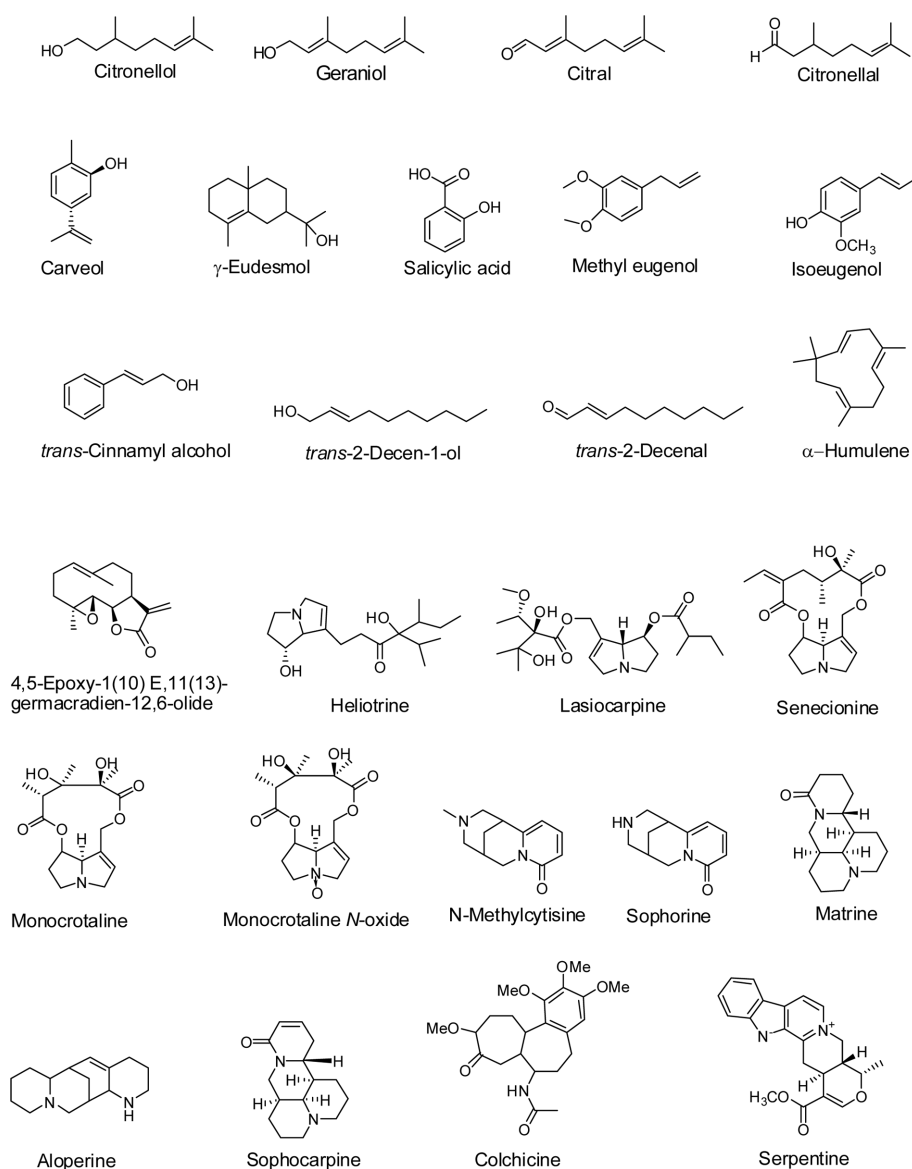


Fig. 3. Phytochemicals with nematicidal activity against phytoparasitic nematodes.

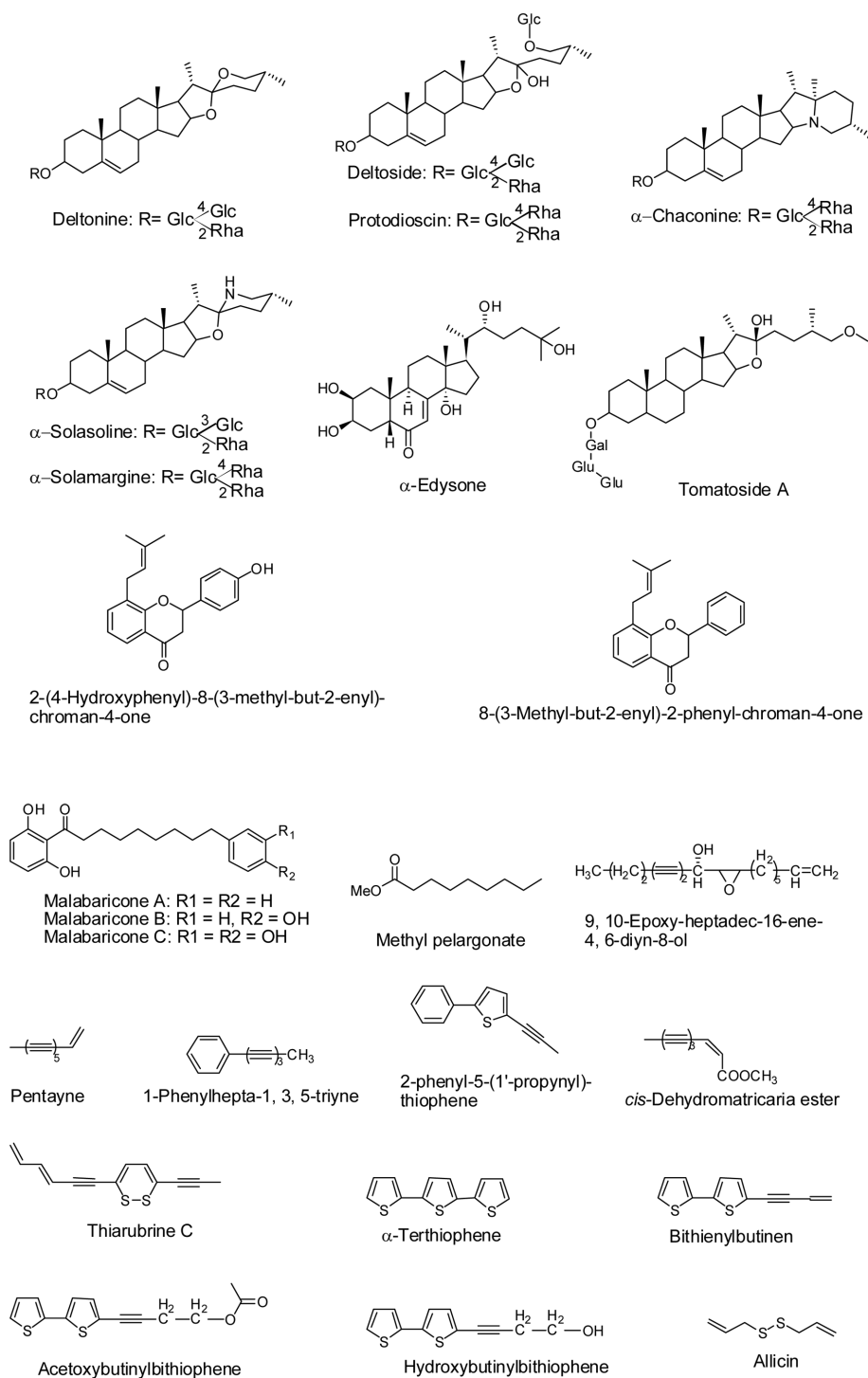


Fig. 3. Continued.

The volatile constituents of plant essential oils are promising remarkable nematocides (Choi *et al.*, 2007a, b; Kim *et al.*, 2008; Kong *et al.*, 2006, 2007a, b; Park *et al.*, 2007). Monoterpenes presented in Fig. 3 such as citronellol (Fig. 3), geraniol, menthol, thymol, citral and

cintronellal (Fig. 3) have shown noteworthy nematocidal activity against J2s pine wood nematode (PWN; *Bursaphelenchus xylophilus*) (Choi *et al.*, 2007a; Kim *et al.*, 2008; Park *et al.*, 2007). Borneol, carveol (Fig. 3), citral, geraniol and α -terpineol are potential nematocides

against root knot nematode (RKN); the effects of soil treatment on galling of tomato caused by *Meloidogyne incognita* are significant (Echeverrigaray *et al.*, 2010; Oka *et al.*, 2000). The EC_{50} values at 96 h after treatment against *M. incognita* of benzaldehyde, γ -eudesmol (Fig. 3) and estragole are 9, 50 and 180 $\mu\text{g/ml}$, respectively. The synergistic nematicidal interactions of terpene pairs *trans*-anethole/geraniol, *trans*-anethole/eugenol, carvacrol/eugenol and geraniol/carvacrol were the most potent (Ntalli *et al.*, 2011).

Salicylic acid (Fig. 3) and cinnamaldehyde were effective against RKN and provided control of galling on tomato plants (Chitwood, 2002). Eugenol (LD_{50} 0.48 $\mu\text{g/ml}$), methyl eugenol (LD_{50} 0.517 $\mu\text{g/ml}$), isoeugenol (LD_{50} 0.2 $\mu\text{g/ml}$) and methyl isoeugenol (LD_{50} 0.21 $\mu\text{g/ml}$) affected on PWN (Park *et al.*, 2007). *cis*-Asarone, *trans*-cinnamyl alcohol, *trans*-2-decen-1-ol, *trans*-2-decenal (Fig. 3), decanol, undecanal and benzaldehyde caused mortalities (77–100%) for PWN (Kim *et al.*, 2008).

Sesquiterpenes α -humulene (Fig. 3) (Suga *et al.*, 1993) from barks of *Pinus* species and 4,5-epoxy-1(10) *E*,11(13)-germacradien-12,6-olide from *Magnolia grandiflora* (Hong *et al.*, 2007) were active against PWN. Thoden *et al.* (2009a, b) reported nematicidal activity of pyrrolizidine alkaloids heliotrine, lasiocarpine, senecionine, monocrotaline and monocrotaline *N*-oxide (Fig. 3) against RKNs *M. hapla* and *M. incognita*. Quinolizidine alkaloids from *Sophora flavescens* and *S. alopecuroides* including *N*-methylcytisine, cytisine (sophorine), matrine, aloperine and sophocarpine (Fig. 3) were significantly nematicidal PWN (Chitwood, 2002; Matsuda *et al.*, 1989, 1991; Zhao, 1999). Among of those alkaloids, aloperine are the most effective alkaloid (Zhao, 1999). Colchicine (Fig. 3) isolated from *Gloriosa superb* seeds, at concentration of 1% and 2%, showed nematotoxicity of 32% and 85% to J2s of *M. incognita*, respectively (Nidiry *et al.*, 1993). Serpentine (Fig. 3) from *Catharanthus roseus* induced death and inhibited hatching of *M. incognita* (Chandravadana *et al.*, 1993).

Saponins from top and root tissues of *Medicago sativa* showed 86–91% mortality against *M. incognita* (D'Addabbo *et al.*, 2010). Furostanol glycosides and glycoalkaloids such as deltonine, deltoside, protodioscin, α -chaconine, α -solasonine, α -solamargine, α -ecdysone and tomatoside (Fig. 3) reduced moderately the number and size of root knots on tomato (Udalova *et al.*, 2004). Two prenylated flavanones of *Phyllanthus niruri* have been evaluated their efficacy against *M. incognita*, and *Rotylenchulus reniformis*. The nematicidal activity against *M. incognita* of 8-(3-methyl-but-2-enyl)-2-phenyl chroman-4-one (LD_{50} 70.9 $\mu\text{g/ml}$) and 2-(4-hydroxyphenyl)-8-(3-

methyl-but-2-enyl)-chroman-4-one (LD_{50} 14.5 $\mu\text{g/ml}$) (Fig. 3) was dose-dependent (Shakil *et al.*, 2008).

Miscellaneous compounds such as fatty acid derivatives, polyynes, dithiins, and furans are considered to possess the nematicidal activity (Ghisalberti, 2002). Three diarylnonanoids malabaricones A, B and C (Fig. 3) from *Myristica malabarica* caused mortalities from 31–75% for PWN (Choi *et al.*, 2008). Methyl pelargonate (Fig. 3) was active to *M. incognita* on soybean at concentrations less than 1.6 $\mu\text{g/ml}$ (Davis *et al.*, 1997).

Two polyynes pentayne and 9, 10-epoxy-heptadec-16-ene-4, 6-diyn-8-ol (Fig. 3) from the roots of *Cirsium japonicum* inhibited reproduction of PWN. 1-Phenylhepta-1, 3, 5-triyn-2-ene and 2-phenyl-5-(1'-propynyl)-thiophene (Fig. 3) from *Coreopsis lanceolata* and *cis*-dehydromatricaria ester from *Solidago altissima* also inhibited the propagation of PWN at a dose of 110 $\mu\text{g/ball}$ (Kawazu *et al.*, 1980).

Thiarubrine C (Fig. 3) from the roots of *Rudbeckia hirta* was toxic to *M. incognita* and *Pratylenchus penetrans* at LC_{50} of 12.4 $\mu\text{g/ml}$ and 23.5 $\mu\text{g/ml}$, respectively. Thiarubrine C was also effective in reducing plant infection when mixed with soil 24 hours prior to or at planting, unlike other related compounds such as α -terthienyl (Sánchez Deviala *et al.*, 1998).

Marigold (*Tagetes* spp.) was reported to contain nematicidal principles such as α -terthiophene, bithienylbutinen, acetoxylbutinylbithiophene and hydroxybutinylbithiophene (Fig. 3) (Chitwood, 2002; Ploegn, 1999). Allicin (Fig. 3) from garlic *Allium sativum* caused inhibition on hatching of *M. incognita* at concentrations less than 0.5 $\mu\text{g/ml}$ (Gupta and Sharma, 1993).

Conclusions

Sustainable agricultural development is consistently considered for most of countries to sustain the growing population. Currently, integrated crop management is playing an important role in organic farming. Biopesticides are key components of integrated crop disease management. Moreover, interest in phytochemical based-pesticides for crop protection is increasing because in public perception they are regarded as environmentally safe and less toxic to humans than synthetic chemicals. Additionally, it has been suggested that botanical extracts are more complex in comparison to synthetic pesticides and therefore, they may delay the development of resistance of phytopathogens.

Many natural product based-pesticides have been discovered up to now. Nevertheless, only about 30 different biopesticides are registered and currently marketed (Copping and Duke, 2007; Copping and

Menn, 2000). This is mainly due to high cost, low activity, or phytotoxic effects to crops. These factors have hindered commercialization of botanical pesticides. Despite this situation, however, efforts related to botanical pesticides have increased to develop commercial products that would abate the negative effects of inappropriate and intensive use of synthetic agrochemicals. With the growing acceptance of botanical pesticides as next generation of pest control products, the major companies as well as small companies will include botanical pesticides in their portfolio. Botanical pesticides can play an important role in the production of organic food and postharvest disease protection of food as well as in achieving sustainable agriculture.

Acknowledgement

This study was carried out with the support of Cooperative Research Program for Agricultural Science & Technology Development (Project No.: 200901OFT102966197), Rural Development Administration, Republic of Korea.

References

- Addor, R. W. 1995. Insecticides. In: Agrochemicals from natural products, ed. by Godfrey, C.R.A., pp. 1–63, Marcel Dekker, New York, USA.
- Agrios, G. N. 2005. Plant Pathology. 5th ed. Elsevier Academic Press, Burlington, Mass., USA.
- Bang, K. H., Lee, D. W., Park, H. M. and Rhee, Y. H. 2000. Inhibition of fungal cell wall synthesizing enzymes by *trans*-cinnamaldehyde. *Biosci. Biotechnol. Biochem.* 64: 1061–1063.
- Cakir, A., Kordali, S., Zengin, H., Izumi, S. and Hirata, T. 2004. Composition and antifungal activity of essential oils isolated from *Hypericum hyssopifolium* and *Hypericum heterophyllum*. *Flavour Fragr. J.* 19: 62–68.
- Chandravadana, M. V., Nidiry, E. S. J., Khan, R. M. and Rao, M. S. 1993. Nematicidal activity of serpentine against *Meloidogyne incognita*. *Fundam. Appl. Nematol.* 17: 185–192.
- Chang, H. T., Cheng, Y. H., Wu, C. L., Chang, S. T., Chang, T. T. and Su, Y. C. 2008. Antifungal activity of essential oil and its constituents from *Calocedrus macrolepis* var. *formosana* Florin leaf against plant pathogenic fungi. *Bioresource Technol.* 99: 6266–6270.
- Chitwood, D. J. 2002. Phytochemical based strategies for nematode control. *Annu. Rev. Phytopathol.* 40: 221–249.
- Cho, J.-Y., Choi, G. J., Lee, S.-W., Lim, H. K., Jang, K. S., Lim, C. H., Cho, K. Y. and Kim, J.-C. 2006a. *In vivo* antifungal activity against various plant pathogenic fungi of curcuminoids isolated from the rhizomes of *Curcuma longa*. *Plant Pathology J.* 22: 94–96.
- Cho, J.-Y., Kim, H. Y., Choi, G. J., Jang, K. S., Lim, H. K., Lim, C. H., Cho, K. Y. and Kim, J.-C. 2006b. Dehydro-alpha-lapachone isolated from *Catalpa ovata* stems: activity against plant pathogenic fungi. *Pest Manag. Sci.* 62: 414–418.
- Cho, J.-Y., Choi, G. J., Lee, S.-W., Jang, K. S., Kim, H. K., Kim, C. H., Cho, C. H., Lee, S. O., Cho, K. Y. and Kim, J.-C. 2006c. Antifungal activity against *Colletotrichum* spp. of curcuminoids isolated from *Curcuma longa* L. rhizomes. *J. Microbiol. Biotechnol.* 16: 280–285.
- Cho, J.-Y., Choi, G. J., Son, S. W., Jang, K. S., Lim, H. K., Lee, S. O., Sung, N. D., Cho, K. Y. and Kim, J.-C. 2007. Isolation and antifungal activity of lignans from *Myristica fragrans* against various plant pathogenic fungi. *Pest Manag. Sci.* 63: 935–940.
- Choi, G. J., Lee, S. W., Jang, K. S., Kim, J. S., Cho, K. Y. and Kim, J.-C. 2004. Effects of chrysophanol, parietin, and nepodin of *Rumex crispus* on barley and cucumber powdery mildews. *Crop Prot.* 23: 1215–1221.
- Choi, I. H., Kim, J., Shin, S. C. and Park, I. K. 2007a. Nematicidal activity of monoterpenoids against the pine wood nematode *Bursaphelenchus xylophilus*. *Russ. J. Nematol.* 15: 35–40.
- Choi, I. H., Park, J. Y., Shin, S. C., Kim, J. and Park, I. K. 2007b. Nematicidal activity of medicinal plant essential oils against the pine wood nematode *Bursaphelenchus xylophilus*. *Appl. Entomol. Zool.* 42: 97–401.
- Choi, N. H., Choi, G. J., Min, B. S., Jang, K. S., Choi, Y. H., Kang, M. S., Park, M. S., Choi, J. E., Bae, B. K. and Kim, J.-C. 2009. Effects of neolignans from the stem bark of *Magnolia obovata* on plant pathogenic fungi. *J. Appl. Microbiol.* 106: 2057–2063.
- Choi, N. H., Kwon, H. R., Son, S. W., Choi, G. J., Choi, Y. H., Jang, K. S., Lee, S. O., Choi, J. E., Ngoc, L. H. and Kim, J.-C. 2008. Nematicidal activity of malabaricones isolated from *Myristica malabarica* fruit rinds against *Bursaphelenchus xylophilus*. *Nematology* 6: 801–807.
- Copping, L. G. and Duke, S. O. 2007. Natural products that have been used commercially as crop protection agents. *Pest Manag. Sci.* 63: 524–554.
- Copping, L. G. and Menn, J. J. 2000. Biopesticides: a review of their action, applications and efficacy. *Pest Manag. Sci.* 56: 651–676.
- D’Addabbo, T., Carbonara, T., Leonetti, P., Radicci, V., Tava, A. and Avato, P. 2010. Control of plant parasitic nematodes with active saponins and biomass from *Medicago sativa*. *Phytochem. Rev.* DOI: 10.1007/s11101-010-9180-2.
- Davis, E. L., Meyers, D. M., Dullum, C. J. and Feitelson, J. S. 1997. Nematicidal activity of fatty acid esters on soybean cyst and root nematodes. *J. Nematol.* 29: 677–684.
- Dayan, F. E., Cantrell, C. L. and Duke, S. O. 2009. Natural products in crop protection. *Bioorg. Med. Chem.* 17: 4022–4034.
- Echeverrigaray, S., Zacaria, J. and Beltrão, R. 2010. Nematicidal

- activity of monoterpenoids against the root-knot nematode *Meloidogyne incognita*. *Phytopathology* 100: 199–203.
- Engelmeier, D. and Hadacek, F. 2006. Antifungal natural products: assays and applications. In: *Advances in Phytomedicine, Naturally Occurring Bioactive Compounds*, Vol. 3, ed. by Rai, M. and Carpenella, M. C., pp. 423–467. Elsevier Science B.V., Netherlands.
- Ghisalberti, E. L. 2002. Secondary metabolites with antinematodal activity. In: *Studies in Natural Products Chemistry*, Vol. 26, ed. by Atta-ur-Rahman, pp. 425–506. Elsevier Science B.V., Netherlands.
- Gonzalez-Coloma, A., Reina, M., Diaz, C. E. and Fraga, B. M. 2010. Natural product-based biopesticides for insect control. In: *Comprehensive Natural Products II*, ed. by L. Mander and H.-W. Liu, pp. 237–268. Elsevier Science B.V., Oxford, UK.
- Gupta, R. and Sharma, N. K. 1993. A study of the nematocidal activity of allicin-an active principle in garlic, *Allium sativum* L., against root-knot nematode, *Meloidogyne incognita* (Kofoid and White, 1919) Chitwood, 1949. *Int. J. Pest Manag.* 39: 390–392.
- Hong, L., Li, G., Zhou, W., Wang, X. and Zhang, K. 2007. Screening and isolation of a nematocidal sesquiterpene from *Magnolia grandiflora* L. *Pest Manag. Sci.* 63: 301–305.
- Hu, K., Dong, A., Kobayashi, H., Iwasaki, S. and Yao, X. 2003. Antifungal agents from traditional chinese medicines against rice blast fungus *Pyricularia oryzae* Cavara. In: *Plant-derived antimycotics: current trends and future prospects*, ed. by M. Rai and D. Mares, pp. 525–549. The Haworth Press, Inc., Binghamton, NY, USA.
- Isman, M. B. 2000a. Biopesticides based on phytochemicals. In: Koul, O. and Dhaliwal, G. S. (Eds.), *Phytochemical Biopesticides*. Harwood Academic, Amsterdam, Netherlands, pp. 1–12.
- Isman, M. B. 2000b. Plant essential oils for pest and disease management. *Crop Prot.* 19: 603–608.
- Isman, M. B. 2006. Botanical insecticides, deterrents and repellents in modern agriculture and an increasingly regulated world. *Annu. Rev. Phytopathol.* 51: 45–66.
- Jeon, J.-H., Kim, Y.-K., Lee, S.-G., Lee, G.-H. and Lee, H.-S. 2011. Insecticidal activities of a *Diospyros kaki* root-isolated constituent and its derivatives against *Nilaparvata lugens* and *Laodelphax striatellus*. *J. Asia Pacific Entomol.* 14: 449–453.
- Jaspers, A. and De Waard, M. 1993. Natural products in plant protection. *Neth. J. Plant. Pathol.* 99: 109–117.
- Kawazu, K., Nishii, Y. and Nakajima, S. 1980. Two nematocidal substances from roots of *Cirsium japonicum*. *Agric. Biol. Chem.* 44: 903–906.
- Kim, M.-K., Choi, G. J. and Lee, H.-S. 2003. Fungicidal property of *Curcuma longa* L. rhizome-derived curcumin against phytopathogenic fungi in a greenhouse. *J. Agric. Food Chem.* 51: 1578–1581.
- Kim, J.-C., Choi, G. J., Lee, S.-W., Kim, J.-S., Chung, K. Y. and Cho, K. Y. 2004a. Screening for antifungal extracts against various plant pathogenic fungi and control of powdery mildew with extracts of *Achyranthes japonica* and *Rumex crispus*. *Pest Manag. Sci.* 60: 803–808.
- Kim, Y. M., Lee, C. H., Kim, H. G. and Lee, H. S. 2004b. Anthraquinones isolated from *Cassia tora* (Leguminosae) seed show an antifungal property against phytopathogenic fungi. *J. Agric. Food Chem.* 52: 6096–6100.
- Kim, J., Seo, S. M., Lee, S. G., Shin, S. C. and Park, I. K. 2008. Nematicidal activity of plant essential oils and components from coriander (*Coriandrum sativum*), oriental sweetgum (*Liquidambar orientalis*), and valerian (*Valeriana wallichii*) essential oils against pine wood nematode (*Bursaphelenchus xylophilus*). *J. Agric. Food Chem.* 56: 7316–7320.
- Kong, J. O., Lee, S. M., Moon, Y. S., Lee, S. G. and Ahn, Y. J. 2006. Nematicidal activity of plant essential oils against *Bursaphelenchus xylophilus* (Nematoda: Aphelenchoididae). *J. Asia-Pacific Entomol.* 9: 173–178.
- Kong, J. O., Lee, S. M., Moon, Y. S., Lee, S. G. and Ahn, Y. J. 2007a. Nematicidal activity of cassia and cinnamon oil compounds and related compounds toward *Bursaphelenchus xylophilus* (Nematoda: Parasitaphelenchidae). *J. Nematol.* 39: 31–36.
- Kong, J. O., Park, I. K., Choi, K. S., Shin, S. C. and Ahn, Y. J. 2007b. Nematicidal and propagation activities of thyme red and white oil compounds toward *Bursaphelenchus xylophilus* (Nematoda: Parasitaphelenchidae). *J. Nematol.* 39: 237–242.
- Lee, H. S. 2007. Fungicidal property of active component derived from *Acorus gramineus* rhizome against phytopathogenic fungi. *Bioresource Technol.* 98: 1324–1328.
- Lee, H.-S., Shin, W.-K., Song, C., Cho, K.-Y. and Ahn, Y.-J. 2001. Insecticidal activities of *ar-turmerone* identified in *Curcuma longa* rhizome against *Nilaparvata lugens* (Homoptera: Delphacidae) and *Plutella xylostella* (Lepidoptera: Yponomeutidae). *J. Asia Pacific Entomol.* 4: 181–185.
- Luo, D. Q., Wang, H., Tian, X., Shao, H. J. and Liu, J. K. 2005. Antifungal properties of pristimerin and celastrol isolated from *Celastrus hypoleucus*. *Pest Manag. Sci.* 61: 85–90.
- Matsuda, K., Kimura, M., Komai, K. and Hamada, M. 1989. Nematicidal activities of (-)-N-methylcytisine and (-)-anagryne from *Sophora flavescens* against pine wood nematodes. *Agric. Biol. Chem.* 53: 2287–2288.
- Matsuda, K., Yamada, K., Kimura, M. and Hamada, M. 1991. Nematicidal activity of matrine and its derivatives against pine wood nematodes. *J. Agric. Food Chem.* 39: 181–191.
- Mordue, A. J. and Nisbet, A. J. 2000. Azadirachtin from the neem tree *Azadirachta indica*: its actions against insects. *An. Soc. Entomol. Bras.* 29: 615–632.
- Muller-Riebau, F., Berger, B. and Yegen, O. 1995. Chemical composition and fungitoxic properties to phytopathogenic fungi of essential oils of selected aromatic plants growing wild in Turkey. *J. Agric. Food Chem.* 43: 2262–2266.
- Nidiry, E. S. J., Khan, R. M. and Reddy, P. P. 1993. *In vitro*

- nematicidal activity of *Gloriosa superba* seed extract against *Meloidogyne incognita*. *Nematol. Medit.* 21: 127–128.
- Ntalli, N. G., Ferrari, F., Giannakou, I. and Menkissoglu-Spiroudi, U. 2011. Synergistic and antagonistic interactions of terpenes against *Meloidogyne incognita* and the nematicidal activity of essential oils from seven plants indigenous to Greece. *Pest Manag. Sci.* 67: 341–351.
- Oerke, E. C. and Dehne, H.-W. 2004. Safeguarding production-losses in major crops and the role of crop protection. *Crop Prot.* 23: 275–285.
- Oka, Y., Nacar, S., Putievsky, E., Ravid, U., Yaniv, Z. and Spiegel, Y. 2000. Nematicidal activity of essential oils and their components against the root-knot nematode. *Phytopathology* 90: 710–715.
- Park C., Kim S.-I. and Ahn Y.-J. 2003. Insecticidal activity of asarones identified in *Acorus gramineus* rhizome against three coleopteran stored-product insects. *J. Stored Prod. Res.* 39: 333–342.
- Park, I. K., Kim, J., Lee, S. G. and Shin, S. C. 2007. Nematicidal activity of plant essential oils and components from ajowan (*Trachyspermum ammi*), allspice (*Pimenta dioica*) and litsea (*Litsea cubeba*) essential oils against pine wood nematode (*Bursaphelenchus xylophilus*). *J. Nematol.* 39: 275–279.
- Ping, G., Taiping, H., Rong, G., Qiu, C. and Shigui, L. 2001. Activity of the botanical aphicides 1,5-diphenyl-1-pentanone and 1,5-diphenyl-2-penten-1-one on two species of Aphididae. *Pest Manag. Sci.* 57: 307–310.
- Ploegn, A. T. 1999. Greenhouse studies on the effect of Marigolds (*Tagetes* spp.) on four *Meloidogyne* species. *J. Nematol.* 31: 62–69.
- Rameshwar Singh, R. 2010. Mechanism of action of insecticidal secondary metabolites of plant origin. *Crop Prot.* 29: 13–920.
- Saha, S., Walia, S., Kumar, J. and Parmar, B. S. 2010. Structure-biological activity relationships in triterpenic saponins: the relative activity of protobassic acid and its derivatives against plant pathogenic fungi. *Pest Manag. Sci.* 66: 825–831.
- Sahni, S., Maurya, S., Singh, U. P., Singh, A. K., Singh, V. P. and Pandey, V. B. 2005. Antifungal activity of nor-securinine against some phytopathogenic fungi. *Mycobiology* 33: 97–103.
- Sánchez Deviala, S., Brodie, B. B., Rodríguez, E. and Gibson, D. M. 1998. The potential of thiarubrine C as a nematicidal agent against plant-parasitic nematode. *J. Nematol.* 30: 192–200.
- Saniewska, A., Jarecka, A., Bialy, Z. and Jurzysta, M. 2006. Antifungal activity of saponins originated from *Medicago hybrida* against some ornamental plant pathogens. *Acta Agrobot.* 59: 51–58.
- Shakil, N. A., Pankaj Kumar, J., Pandey, R. K. and Saxena, D. B. 2008. Nematicidal prenylated flavanones from *Phyllanthus niruri*. *Phytochemistry* 69: 759–764.
- Singh, A. K., Pandey, M. B., Singh, S., Singh, A. K. and Singh, U. P. 2008. Antifungal activity of securinine against some plant pathogenic fungi. *Mycobiology* 36: 99–10.
- Suga, T., Ohta, S., Munesada, K., Ide, N., Kurokawa, M., Shimizu, M. and Ohta, E. 1993. Endogenous pine wood nematocidal substances in pines, *Pinus massoniana*, *P. strobus* and *P. palustris*. *Phytochemistry* 33: 1395–1401.
- Thoden, T. C., Boppré, M. and Hallmann, J. 2009a. Effects of pyrrolizidine alkaloids on the performance of plant-parasitic and free-living nematodes. *Pest Manag. Sci.* 65: 823–830.
- Thoden, T. C., Hallmann, J. and Boppré, M. 2009b. Effects of plants containing pyrrolizidine alkaloids on the northern root-knot nematode *Meloidogyne hapla*. *Europ. J. Plant Pathol.* 123: 27–36.
- Udalova, Z. V., Zinov'eva, S. V., Vasil'eva, I. S. and Paseshnikchenko, V. A. 2004. Correlation between the structure of plant steroids and their effects on phytoparasitic nematodes. *Appl. Biochem. Microbiol.* 40: 93–97.
- Vidhyasekaran, P. 2004. Concise Encyclopedia of Plant Pathology. Food Products Press, New York, USA.
- Yang, X., Yang, L., Wang, S., Yu, D. and Ni, H. 2007. Synergistic interaction of physcion and chrysophanol on plant powdery mildew. *Pest Manag. Sci.* 63: 511–515.
- Yen, T. B., Chang, H. T., Hsieh, C. C. and Chang, S. T. 2008. Antifungal properties of ethanolic extract and its active compounds from *Calocedrus macrolepis* var. *formosana* (Florin) heartwood. *Bioresource Technol.* 99: 4871–4877.
- Zhao, B. G. 1999. Nematicidal activity of quinolizidine alkaloids and the functional group pairs in their molecular structure. *J. Chem. Ecol.* 25: 2205–2214.
- Zhou, C.-X., Liu, J.-Y., Ye, W.-C., Liu, C.-H. and Tan, R.-X. 2003. Neoverataline A and B, two antifungal alkaloids with a novel carbon skeleton from *Veratrum taliense*. *Tetrahedron* 59: 5743–5747.