Chapter

Essential Oil Nanoformulations as a Novel Method for Insect Pest Control in Horticulture

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Abstract

Eco-friendly biopesticides based on essential oils (EOs) appear to be a complementary or alternative method to chemically synthesized insecticides in integrated pest management programs. They have the advantage of reducing the adverse effects of chemical insecticides on human health and environment and at the same time increasing horticultural crop productivity and yield. Plant EOs exhibit toxic, repellent, and antifeedant effects on different insect species. However, the main problem in using plant EOs as biopesticides under field conditions is their chemical instability in the presence of air, light, moisture, and high temperatures which lead to the rapid evaporation and degradation of their active constituents. Incorporation of EOs into controlled-release nanoformulations may contribute to solve problems associated with their application; this kind of formulation is expected to be more effective than the bulk (free) substance.

Keywords: plant essential oils, biopesticides, nanoformulation, insect pest control, horticultural crops

1. Introduction

Horticultural crops are infested with numerous insect pests that cause tremendous economic losses including aphids (*Myzus persicae* and *Aphis gossypii*), beet armyworm (*Spodoptera exigua*), cabbage loopers (*Trichoplusia ni*), citrus mealybug (*Planococcus citri*), onion thrips (*Thrips tabaci*), and greenhouse whitefly (*Trialeurodes vaporariorum*) [1]. The use of synthetic chemical insecticides to control insect pests poses risks to human health and environment. For this reason, there is an urgent need to apply a range of modern strategies as alternatives for chemical pesticides in order to protect the environment from insecticidal pollution, decrease the regenerating resistance, and increase horticultural crop productivity.

Plant natural substances may provide potential alternatives to currently used insect-control agents because these materials constitute a rich source of bioactive chemicals. Plant-active substances may not only act as toxicants to insects but also as insect growth regulators, repellents, synergists, or phagodeterrents [2–4]. However, the major inconvenience of the use of essential oils is their chemical instability in the presence of air, light, moisture, and high temperatures that can lead to the rapid evaporation and degradation of some active components. Nanoformulations of the essential oils could solve these problems by protecting active components of essential oils from degradation and losses by evaporation, thereby enhancing their stability and maintaining the minimum effective dosage/application [5].

Nanoencapsulation or controlled delivery is a technique in which a membrane encloses small particles of active ingredient with the objective of offering protection to the core material from adverse environmental conditions, such as undesirable effects of light, moisture, and oxygen, and also avoiding drawbacks such as odor and volatility [6].

Nanoparticles (NPs) can be classified on the basis of the kind of material into metallic, semiconductor, and polymeric nanoparticles; the last ones are the most promising for essential oil nanoformulation. Furthermore, this kind of formulation is expected to be more effective than the bulk substances [7]. Controlled delivery technologies have emerged as an approach with promise not only to utilize resources in the maximum efficient way but also to reduce pollution. Moreover, if the resource is a natural or renewable polymer, then it will draw attention as a more new, more economical, and more eco-friendly source for use of humankind and a suitable approach for biological and integrated pest management (IPM) programs.

This chapter is describing the efficacy of essential oils as eco-friendly biopesticides and shedding light on the nanoformulations as biopesticides and their potential role in agriculture particularly in insect pest control. In order to reduce the negative impacts of chemical insecticides on environment and crop plants, and to protect crops from insect pests, nanoformulations are highly prospective to become an essential factor in integrated pest management programs.

2. Plant essential oils as biopesticides

Plants provide potential alternatives to currently used insect-control agents because they constitute a rich source of bioactive chemicals [8]; among these chemicals are plant essential oils. Essential oils, also known as aromatic oils, are volatile compounds produced naturally in plants for their own needs other than nutrition (i.e., protection or attraction) as secondary metabolites with distinctive odor [9, 10], most of them containing natural antioxidants and natural antimicrobial agents [11], and they are usually used in perfumery, in aromatherapy, in cosmetics, in incense, in medicine, in household cleaning products, and for flavoring food and drink [12].

Several essential oils have antiparasitic, bactericidal, fungicidal, virucidal, and insecticidal properties [2, 9]. Essential oils extracted from plants may act as toxicants, insect growth regulators [13], repellents and synergists [3, 14], and also as phagodeterrents [15]. Biopesticides based on essential oils (EOs) appear to be a complementary or alternative method in crop production and integrated pest management [16].

All chemicals produced by nature can be classified into two main groups; the first is the primary metabolites and constitutes the basic building blocks of living organisms such as proteins, carbohydrates, nucleic acids, and lipids. The second group is secondary metabolites that are simply classified into three main groups: terpenes (such as plant volatiles, cardiac glycosides, carotenoids, and sterols), phenolics (such as phenolic acids, coumarins, lignans, stilbenes, flavonoids, tannins, and lignin), and nitrogen-containing compounds (such as alkaloids and glucosinolates) [17]. Secondary metabolites play an important role in plant defense system against microorganisms and herbivorous insects [18].

According to [19] essential oils are lipophilic and thus can enter the insect and cause biochemical dysfunction and mortality. Several studies revealed that EOs from different plant families such as Asteraceae, Myrtaceae, Apiaceae, Lamiaceae, and Rutaceae are effective against different insect pests [19–22] (**Table 1**).

It has been shown that essential oils enter the insect body either by inhalation, ingestion, or skin absorption [23]. Essential oils may interfere with the biology, physiology, and nervous system of the insect [24, 25]. The biological and physiological effects of the botanical oils on insect pests may be attributed to their effect on the insect neuroendocrine system and juvenile hormone leading to hormone unbalance and insect malformation. A decrease in adult insect fecundity and egg fertility was observed [26] and may be caused by a decrease in periods and time of adults mating which leads to a reduction in ovulation [27]. Essential oils can also interfere with normal respiration of insects; it has been reported that essential oils can block the spiracles of insects leading to their suffocation [28–31].

Monoterpenes, the major components of plant essential oils, act as a neurotoxicant and act on acetylcholinesterase enzyme AChE, a key enzyme responsible for terminating the nerve impulse transmission through the synaptic pathway. Essential oil components also act on the octopaminergic system of insects, which is considered as a target for insect control. Insect paralysis and death

Plant family	Plant name	Insect pest	References
Tropaeolaceae	*Tropaeolum tuberosum*	*Premnotrypes vorax* (Coleoptera: Curculionidae)	[43]
Meliaceae Meliaceae Amaryllidaceae Anacardiaceae	*Melia azedarach* *Azadirachta indica* *Allium sativum* *Schinus molle*	*Phthorimaea operculella* (Lepidoptera: Gelechiidae)	[44]
Lamiaceae Rutaceae Tropaeolaceae Solanaceae Amaryllidaceae	*Minthostachys mollis* *Ruta graveolens* *Tropaeolum tuberosum* *Capsicum frutescens* *Allium cepa*	*Tecia solanivora* (Lepidoptera: Gelechiidae)	[45]
Poaceae	*Cymbopogon winterianus*	*Spodoptera frugiperda* (Lepidoptera: Noctuidae)	[46]
Myrtaceae Ericaceae	*Eucalyptus globulus* *Gaultheria procumbens*	*Agrotis ipsilon* (Lepidoptera: Noctuidae)	[47]
Amaryllidaceae	*Allium sativum*	*Tribolium castaneum* (Coleoptera: Tenebrionidae) *Sitophilus zeamais* (Coleoptera: Curculionidae)	[48]
Apiaceae Myristicaceae	*Athmanta haynaldii* *Myristica fragrans*	*Lymantria dispar* (Lepidoptera: Erebidae)	[49]
Poaceae	*Cymbopogon winterianus*	*Frankliniella schultzei* (Thysanoptera: Thripidae) *Myzus persicae* (Hemiptera: Aphididae)	[50]
Rutaceae	*Citrus sinensis*	*Ceratitis capitata* (Diptera: Tephritidae)	[51]
Myrtaceae Anacardiaceae	*Eucalyptus citriodora* *Schinus terebinthifolius*	*Bemisia tabaci* (Hemiptera: Aleyrodidae) *Trialeurodes ricini* (Hemiptera: Aleyrodidae)	[52]

Table 1.
Essential oils of some plant families with insecticidal efficacy against different insect pests.

predominantly occurred by disruption in octopamine, which is a neurotransmitter, neurohormone, and circulating neurohormone-neuromodulator, resulting in total breakdown of the nervous system [32–34].

The feeding efficiency is the ability of the insect species to use the food ingested to the best of their capabilities; antifeedant activity of the essential oils or extracts from different plants would be related to their effect on the chemoreceptors [35]. Plants containing alkaloids, steroids, flavonoids, terpenoids, and saponins possess high antifeedant activity against different insects; therefore these plants and different essential oils which exhibited antifeedant constituents could be developed into products suitable for using in integrated insect management programs [35]. The quality and quantity of food consumed may increasingly affect the growth, development, and reproduction of insects [36]; oil compounds can reduce ingestion or efficiency of conversion of assimilated materials and prevented nutrients from being available to own biomass [37, 38]. This positive effect of essential oils on insect-feeding efficiency may be attributed to the irreversible damage of some membranes related with the absorption in the gut; thus, large amount of energy is exerted by larvae to detoxify the essential oils [39].

Generally essential oils and their components have been considered safer than other plant-derived chemicals like rotenone and pyrethrum [40]. This could be attributed to existing detoxifying metabolism pathways and bio-rational mode of action of monoterpenoids as reported by [41]. It can be concluded that the essential oils act at multiple levels in the insects, so the possibility of generating resistance is a little probable [42] making them effective nontoxic agents in IPM programs.

3. Essential oil nanoformulations

Agricultural pests are usually controlled using chemical pesticides; 90% of applied pesticides are lost to the air and severely affecting the environment and increasing application costs to the farmer [53]. In addition, the use of pesticides increases pest resistance and reduces soil biodiversity [4, 53]. Recently, in many countries, integrated pest management systems which comprise both methods of traditional crop rotation and biological pest control are becoming favorable and preferred method to improve crop yields.

Biopesticides based on essential oils (EOs) appear to be a complementary or alternative method in IPM [54]. Essential oils showed toxic, repellent, and antifeedant effects on different insect species [2, 3, 55]. Despite these promising properties, problems related with the essential oils volatility, poor water solubility, and aptitude for oxidation have to be resolved before they can be used as an alternative pest control system [56].

Nanoemulsions and nanoencapsulation of the essential oils may solve these problems protecting them from degradation and losses by evaporation; this kind of formulation is expected to be more effective than the bulk (free) substance. On the other hand, it was found that pesticide nanoformulations showed less toxicity toward nontarget organisms compared with commercial formulations, and therefore a higher specificity was observed [57]; besides, that they reduce pesticide use and increase persistence of the active ingredient [58].

To achieve high stability and efficacy, essential oils are encapsulated in nanoemulsions, which are used as delivery systems and considered as a promising strategy to deliver essential oils in agriculture and particularly in insect pest management. Nanoemulsions are thermodynamically unstable systems that have small droplets (radius < 100 nm), which make them transparent or translucent [59], and could be used for both hydrophilic and hydrophobic pesticides; accordingly the use of toxic organic solvents can be eliminated. Nanoemulsion is usually produced either by high-energy emulsification or low-energy emulsification methods. In high-energy emulsification technique, mechanical devices such as high-pressure homogenizers, ultrasonic homogenizers, and microfluidizers are used to reduce droplet size by generating intense disruptive forces [60], while in low-energy emulsification technique, the physicochemical characteristics of surfactants and co-surfactants are involved [61]. It has been reported that using surfactant that blends in preparing nanoemulsions is usually more efficient than individual uses for various applications, using sufficient amounts of suitable surfactants and additionally protective colloids believed to make nanoemulsions more resistant to crystallization, agglomeration, and sedimentation [62].

Nanoencapsulation is a technique in which the active agent (solid, liquid, or gas) is surrounded or encapsulated by a thin layer or a membrane to protect the core active agent from severe and harmful environmental conditions such as light, moisture, and high temperature effects. The envelope or carrier could be natural polymers (polysaccharides, proteins), synthetic polymers (polyamides, melamine-formaldehyde, etc.), lipids, phospholipids, or inorganic materials (SiO_2) [63, 64].

Nanocarriers are structured in different designs with different materials; the main organic nanocarrier systems are polymeric and lipid-based particles. Polymeric nanoparticles are classified as nanocapsules (consist of polymeric wall and a core, which is commonly oily) and nanospheres (which are matrix systems) (**Figure 1**); these polymeric nanoparticles can be prepared using different techniques; one of them is known as nanoprecipitation or solvent displacement and based on an antisolvent procedure [65]. The other nanocarrier system is lipid nanoparticles which can be classified into liposomes, niosomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLC). To prepare these nanoparticles, several methods are used, for example, thin lipid film hydration method [66] and ethanol injection [67] to prepare liposomes, and solvent-in-water emulsion diffusion technique replacing liquid lipid of an o/w emulsion for a solid or a blend of solid lipids is used for the preparation of solid lipid nanoparticles [68].

A significant characteristic for nanoencapsulated system is controlled release, usually including an initial burst release, followed by a prolonged release [69]; obviously the main advantages of nanoencapsulation are its ability to reduce the amount of active ingredients needed, minimize evaporation, and control the release of active components. The use and application of nanoencapsulation in recent years

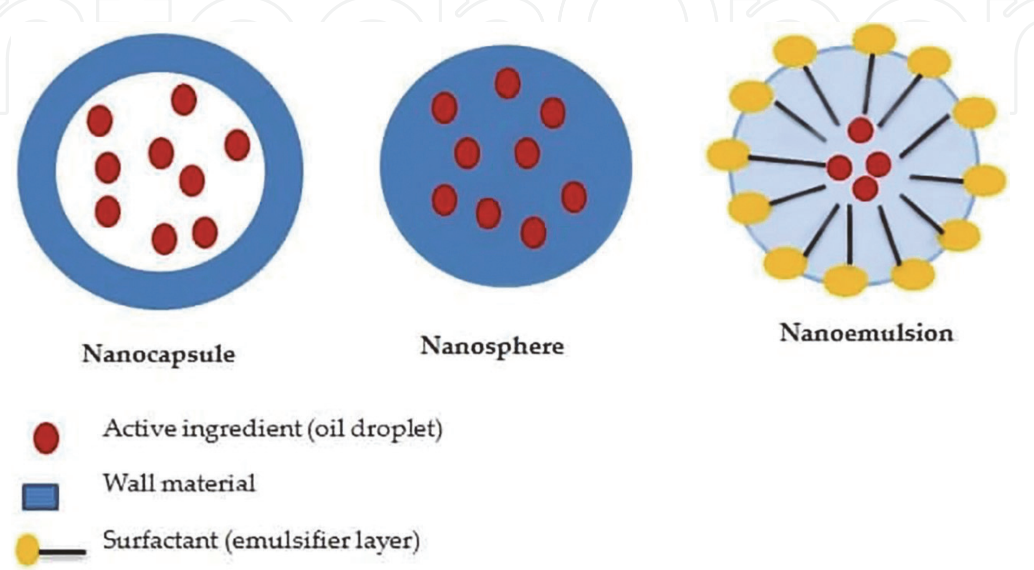

Figure 1.
Schematic representation of different nanoformulations.

have been increased. Manufactured nanoparticles exhibit a broad range of applications due to their unique properties compared with their bulk counterparts [70].

In prepared nanoencapsulated oil formulations, the encapsulation efficiency (% EE) can be expressed as a percentage of the total amount of oil found in the formulation at the end of the preparation procedure, or it is the ratio between the mass of entrapped essential oil and the total mass of the essential oil added, while the loading capacity (%LC) is the ratio between the mass of entrapped essential oil and the total mass of carrier (coating material) [71]. It was indicated by [72] that factors determining loading capacity and encapsulation efficiency are the solubility and miscibility of the active ingredient in the melted lipid phase, physiochemical structure of the lipid matrix, and the polymorphic state of the lipid material. A study by [71] mentioned that the potential of the particles depending on the nature of the coating nanoparticles also influenced the encapsulation efficiency and accordingly loading capacity. It has been reported that there are three variables that affect the encapsulation efficiency: stirring rate, oil loading, and the amount of cross-linking agent [73].

4. Essential oil nanoformulations and insect pest control

Nanoformulations exhibit unique properties compared with their bulk counterparts, including higher pest toxicity and less toxicity toward nontarget organisms. It was indicated that nanopermethrin has more larvicidal effect against *Culex quinquefasciatus* than the bulk form of permethrin [74]. Nanoformulation degrades rapidly with residual levels below the regulatory criteria in foodstuffs as concluded by [75] in their review dealing with applications of nanomaterials in agricultural production and crop protection.

Recent studies revealed the novel general and biological properties of the known materials, which they acquire when transformed into nanoparticles. They penetrate into the cells of the pest specially epithelial and endothelial cells by transcytosis. Moreover, they travel along the dendrites and axons, the blood, and lymphatic vessels provoking oxidative stress and other consequences [76].

In a previous study, geranium oil was incorporated into solid lipid nanoparticles using ultrasonic-solvent emulsification technique; the results indicated a production of high-quality solid lipid nanoparticle-loading geranium oil that was used as mosquito repellent [77]. While in other studies, polyethylene glycol (PEG) nanoparticles were used to incorporate garlic and geranium essential oils and were tested against *Tribolium castaneum* and *Rhyzopertha dominica* [16, 78], both essential oil-loaded nanoparticles produced a notable increase in the residual contact toxicity apparently due to the slow and persistence release of the active terpenes. In addition, the nanoformulation enhanced the essential oil contact toxicity and altered the nutritional physiology of both stored product pests. The essential oil citronella nanoemulsion prepared by high-pressure homogenization had resulted in a higher-release rate against mosquito [73, 79].

The variation in the amount of ingredient of curcuminoids and geranium oil affected the loading capacity and mean particle size of nanoformulation [71, 77]; they reported that 5.0% (w/w) stearic acid was found to be an optimum concentration for the formulation of solid lipid nanoparticles (SLNs). On the other hand, [78] showed that the oil-loading efficiency could reach 80% at the optimal ratio of garlic essential oil to 10% of polyethylene glycol (PEG) which was used as coated nanoparticles for the oil. The morphology and size of nanoparticles showed a round appearance and good dispersion, and its size was <240 nm in average diameter, likewise [16], determined the polydispersity index (PDI, which measures the size of distribution of nanoparticles) and loading efficiency for eight essential oil nanoparticles, and illustrated that the 10% ratio EO-polyethylene glycol showed the best relationship between a low polydispersion, narrow size distribution, and a high essential oil-loading efficiency; these nanoparticles had the biggest size in average diameter < 235 nm and a loading efficiency of >75%. In [71, 79], it is mentioned that the potential of the particles depending on the nature of the lipid matrix produced, which were used as coating nanoparticles, also influenced the encapsulation efficiency and accordingly loading capacity. In contrast, in [80], it is indicated that starch-coated encapsulation of neem oil nanoemulsion was found to be effective when compared to polyethylene glycol-coated encapsulation of neem oil nanoparticles.

The biological efficacy of geranium essential oil alone and in the form of nanoformulation was evaluated and compared against the potato tuber moth *Ph. operculella* first larval instar. This study showed that geranium oil-loaded solid lipid nanoparticles at different concentrations under laboratory conditions significantly affected the developmental process of immature stages and increased the percentage of mortality at all treatments and significantly reduced the adult's progeny and female fecundity and accordingly the percentage of hatchability. When this nanoformulated oil (geranium-loaded solid lipid nanoparticles) was applied under field conditions on potato crop, it exhibited longer residual efficacy than the free essential oil, suggesting that it may help to reduce insecticide application to control *Ph. operculella* [81].

It is known that nanoencapsulated oils have a much higher chemical activity than the bulk material, much more mobile, enabling penetration into insect tissues and enhancing insecticidal activity; this can be achieved by direct contact through the insects' cuticle or by ingestion and penetration through the digestive tract. They penetrate the cells of the pest especially epithelial and endothelial cells by transcytosis as confirmed by [76]. Nevertheless [79] concluded that the repellent effect of the obtained nanoemulsions composed of citronella oil, hairy basil, and vetiver oil could be attributed to the major difference in oil droplet size. The small nanoscale of droplet size of nanoemulsion prepared with high-pressure homogenization would play an important role on their efficacy besides physical stability. The prolonged mosquito protection time is probably due to the combination of these three essential oils. The lethal and sublethal activity of citrus peel essential oil as an emulsion and loading into polyethylene glycol nanoparticles was studied against the invasive tomato pest *Tuta absoluta* [82]. Their results showed that the essential oil nanoformulation tested had a significant insecticidal activity with higher mortality and significantly reduced the visible toxic effects on the plants suggesting that nanoformulated natural products could be successfully used in integrated pest management programs for *T. absoluta*. The insecticidal activity of *Rosmarinus officinalis* essential oil was enhanced in study by [83] for effective management of the red flour beetle, *Tribolium castaneum*, using nanoprecipitation method to prepare rosemary oil-loaded nanocapsules. In a research study done by [84], the contact toxicity of *Mentha longifolia* L. essential oil compared with its nanoemulsion on *Ephestia kuehniella* Zeller has been investigated; their results showed that the nanoemulsion formulation increased the effect of essential oil contact toxicity and its durability. The essential oil nanoformulations characterized by distinctive slow release property may represent a new category of biopesticide formulations that should be considered as a promising agent in the integrated pest management program.

5. Conclusion

The global population has been expanding rapidly for many years; in developing countries, it is expected that the food demand in 2050 will increase by 50–100% [85]; for this reason there is an urgent need to find safe alternative strategies that may contribute to the provision of food and at the same time protect the environment and human beings. To limit crop yield losses and increase the agricultural productivity, integrated pest management programs have implanted the application of effective, environmentally safe biopesticides.

Plant essential oils over the years were used as biopesticides to control insects; however, the difficulty in applying essential oils on large-scale and under severe environmental conditions required incorporation of these plant materials into new formulations through nanotechnology, such as nanoformulations that enhance the efficacy, increase stability, and prevent rapid evaporation of active compounds in plant oils. It is known that nanoencapsulated oils have a much higher chemical activity than the bulk material, are much more mobile, and are able to penetrate into insect tissues for efficient insecticidal activity.

The essential oil nanoformulations appear to be promising candidates to control the major pests of plants, due to their high volatility and stability. Before implementing the use of such oils, large-scale experiments are needed to evaluate their mammalian toxicity and to substantiate their efficacy under different conditions to validate their economic values as plant protectant; these nanoformulations require more in-depth studies to encourage the use of these natural substances in IPM programs and promote the development of sustainable crop-based systems that enhance crop yields, reduce ecological damage, and improve the quality of life for producers and consumers.

Conflict of interest

The author reports no conflicts of interest in this work.

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References

[1] Lindquist RK, Cloyd RA. Identification of Insects & Related Pests of Horticultural Plants: A Pictorial Guide. Columbus, Ohio: Ohio Florist Association; 2005

[2] Burfield T, Reekie SL. Mosquitoes, malaria and essential oils. International Journal of Aromatherapy. 2005;**15**:30-41

[3] El-Wakeil NE. Botanical pesticides and their mode of action (Review article). Gesunde Pflanzen. 2013;**65**: 125-149

[4] Ghormade V, Deshpande MV, Paknicar KM. Perspectives for nano biotechnology enabled protection and nutrition of plants. Biotechnology Advances. 2011;**29**(6):792-803

[5] Bertolini AC, Siani AC, Grosso CRF. Stability of monoterpenes encapsulated in gum Arabic by spray-drying. Journal of Agricultural and Food Chemistry. 2001;**49**:780-785

[6] Lai F, Sylvia AW, Rainer HM, Anna MF. Artemisia *arborescens L*. essential oil–loaded solid lipid nanoparticles for potential agricultural application: Preparation and characterization. AAPS PharmSciTech. 2006;7(1):E10-E18

[7] Rajendran S, Sriranjini V. Plant products as fumigants for stored-product insect control. Journal of Stored Products Research. 2008;**44**: 126-135

[8] Wink M. Production and application of phytochemicals from an agricultural perspective. In: van Beek TA, Breteler H, editors. Phytochemistry aned Agriculture. Vol. 34. Oxford, UK: Clarendon; 1993. pp. 171-213

[9] Bakkali F, Averbeck S, Averbeck D, Idaomar M. Biological effects of essential oils—A review. Food and Chemical Toxicology. 2008;**46**:446-475

[10] Chamorro ER, Zambón SN, Morales WG, Sequeira AF, Velasco GA. Study of the chemical composition of essential oils by gas chromatography. In: Salih B, editor. Gas Chromatography in Plant Science, Wine Technology, Toxicology and Some Specific Applications. Rijeka, Croatia: InTech; 2012. pp. 307-324. ISBN: 978-953- 51-0127-7

[11] Somesh M, Rupali S, Swati S, Jose M, Manish M. In-vitro comparative study on antimicrobial activity of five extract of few citrus fruit: Peel peel & pulp vs gentamicin. Australian Journal of Basic and Applied Sciences. 2015;**9**(1): 165-173

[12] Hesham HAR, Abdurahman HN, Rosli MY. Techniques for extraction of essential oils from plants: A Review. Australian Journal of Basic and Applied Sciences. 2016;**10**(16):117-127

[13] Bowers WS, Ohta T, Cleere JS, Marsella PA. Discovery of insect antijuvenile hormones in plants yield a potential fourth generation insecticides. Science. 1972;**193**:542-547

[14] Su HCF, Harvort R. Isolation identification and insecticidal properties of *Piper nigrumamides*. Journal of Agricultural and Food Chemistry. 1981; **29**:115-118

[15] Meisner J, Fleischerand A, Elzick C. Phagodeterrency induced by (−) Carvon in the larvae of *Spodoptera littoralis* (Boisd). Journal of Economic Entomology. 1982;**75**:462-466

[16] Werdin-Gonzalez JO, Gutiérrez MM, Ferrero AA, Band BF. Essential oils nanoformulations for stored-product pest control—Characterization and biological properties. Chemosphere. 2014;**100**:130-138

[17] Agostini-Costa TS, Vieira RF, Bizzo HR, Silveira D, Gimenes MA.

Chromatography and its applications. In: Dhanarasu S, editor. Plant Secondary Metabolites. Rijeka, Croatia: In Tech Publisher; 2012. pp. 131-164

[18] Bowsher C, Steer M, Tobin A. Plant Biochemistry. New York-Abigdon: Garland Science, Taylor and Francis Group. 2008. 446 pp. ISBN-0-8153-4121-0

[19] Lee BH, Annis PC, Tumaalii F, Choi W. Fumigant toxicity of essential oils from Myrtaceae family and 1, 8-cineol against 3 major stord—Grain insects. Journal of Stored Products Research. 2004;**40**:553-564

[20] Sharaby A. Effect of orange, *Citrus sinensis L.* peel oil on reproduction in *Phthorimaea operculella* (Zell.). Insect Science and Its Application. 1988;**9**(2): 201-203

[21] Al-Dhafer ZMA. Studies on the effect of natural products of some Saudi Arabian plants on the biology and behavior of the American bollworm *Helicovirpa armigera* (Hubn.) (Lepidoptera: Noctoidae) [thesis]. Fac. Sci; Girls College, Dammam, Saudi Arabia. 2001

[22] Al-Dosary MM. Sensory receptors and behaviour of the Red Palm Weevil *Rhynchophorus ferrugineus* (Oliv.) (Colioptera: Curculionidae) with reference to attractants, repellents and control [thesis]. Riyadh Girls College of Education Scientific Section, Department of Zoology. 2007

[23] Ozols G, Bicevskis M. Respects for the use of Ips tyrographus attractant. In: Shumakov EM, Chekmenev SY, Ivanova TV, editors. Biologia Aktualis Veshchestva Zashchiva Rastenij. Moscow: Izd. Kolos; 1979. pp. 49-51

[24] Mikhaiel AA. Potential of some volatile oils in protecting packages of irradiated wheat flour against *Ephestia kuheniella* and *Tribolium castaneum*. Journal of Stored Products Research. 2011;**47**(4):357-364. DOI: 10.1016/j.jspr.2011.06.002

[25] Mann RS, Kaufman PE. Natural product pesticides: Their development, delivery and use against insect vectors. Mini-Reviews in Organic Chemistry. 2012;**9**:185-202. DOI: 10.2174/157019312800604733

[26] Sharaby A, El-Nujiban A. Evaluation of some plant essential oils against the black cutworm *Agrotis ipsilon*. Global Journal of Advanced Research. 2015;**2**(4):701-711

[27] Huang Y, Ho SH, Lee HC, Yap YL. Insecticidal properties of eugenol, isoeugenol and methyleugenol and their effects on nutrition of *Sitophilus zeamais* Motsch. (Coleoptera: Curculionidae) and *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Journal of Stored Products Research. 2002;**38**: 403-412

[28] Schoonhoven AV. The use of vegetable oils to protect stored beans from bruchid attack. Journal of Economic Entomology. 1978;**71**(2): 254-256. DOI: 10.1093/jee/71.2.254

[29] Adedire CO, Obembe OM, Akinkurolere RO, Oduleye SO. Response of *Callosobruchus maculatus* Fabricius (Coleoptera: Chrysomelidae: Bruchinae) to extracts of cashew kernels. Journal of Plant Diseases Protection. 2011;**118**(2):75-79. DOI: 10.1007/BF03356385

[30] Ileke KD, Olotuah OF. Bioactivity of *Anacardium occidentals* and *Allium sativum* powders and oils extracts against cowpea bruchid, *Callosobruchus maculatus* (Fab) (Coleoptera: Bruchidae). International Journal of Biological Sciences. 2012;**4**(1):96-103

[31] Kaufmann C, Briegel H. Flight performance of the malaria vectors *Anopheles gambiae* and *Anopheles*

atroparous. Journal of Vector Ecology. 2004;**29**(1):140-153

[32] Hollingworth RM, Johnstone EM, Wright N. Pesticide synthesis through rational approaches. In: Magee PS, Kohn GK, Menn JJ, editors. ACS Symposium Series. Vol. 255. Washington, DC: American Chemical Society; 1984. pp. 103-125

[33] Enan EE. Molecular and pharmacological analysis of an octopamine receptor from american cockroach and fruit fly in response to plant essential oils. Archives of Insect Biochemistry and Physiology. 2005;**59**: 161-171. DOI: 10.1002/(ISSN)1520-6327

[34] Souguir S, Chaieb I, Ben Cheikh Z, Laarif A. Insecticidal activities of essential oils from some cultivated aromatic plants against *Spodoptera littoralis* (Boisd.). Journal of Plant Protection Research. 2013;**53**(4):388-391

[35] Schoonhoven L. Biological aspects of antifeedant. Entomologia Experimentalis et Applicata. 1982;**31**: 57-69

[36] Scriber JM, Slansky F. The nutritional ecology of immature insects. Annual Review of Entomology. 1981;**26**: 183-211

[37] Reese JC, Chan BG, Waiss AC. Effects of cotton condensed tannin, maysin (Corn) and pinitol (soybeans) on *Heliothis zea* growth and development. Journal of Chemical Ecology. 1982;**8**(12):1429-1436

[38] Sharaby A, Abdel Rahman H, Abdel-Aziz SS, Moawad SS. Natural plant oils and terpenes as protector for the potato tubers against *Phthorimaea operculella* infestation by different application methods. Ecologia Balkanica. 2014;**6**(1):45-59

[39] Zapata N, Budia F, Viñuela E, Medina P. Antifeedant and growth inhibitory effects of extracts and drimanes of Drimys winteri stem bark against *Spodoptera littoralis* (Lep., Noctuidae). Industrial Crops and Products. 2009;**30**:119-125

[40] Stroh J, Wan MT, Isman MB, Moul DJ. Evaluation of the acute toxicity to juvenile Pacific coho salmon and rainbow trout of some plant essential oils, a formulated product, and the carrier. Bulletin of Environmental Contamination and Toxicology. 1998; **60**:923-930

[41] Koul O, Singh R, Kaur B, Kanda D. Comparative study on the behavioral response and acute toxicity of some essential oil compounds and their binary mixtures to larvae of *Helicoverpa armigera*, *Spodoptera litura* and *Chilo partellus*. Industrial Crops and Products. 2013;**49**:428-436

[42] Gutiérrez L, Escudero A, Batlle R, Nerín C. The effect of mixed antimicrobial agents and flavours in active packaging films. Journal of Agricultural and Food Chemistry. 2009; **57**:8564-8571

[43] Calvache H. Efecto de barreras vegetales y qui’micas en el control del gusano blanco de la papa (*Premnotrypes vorax*). Revista Latinoamericana de la Papa. 1991;**4**:22-35

[44] Kroschel J, Koch W. Studies on the use of chemicals, botanicals and *Bacillus thuringiensis* in the management of the potato tuber moth in potato stores. Crop Protection. 1996;**15**(2):197-203

[45] Go’mez Jime’neza MI, Poveda K. Synergistic effects of repellents and attractants in potato tuber moth control. Basic and Applied Ecology. 2009;**10**: 763-769

[46] Labinas AM, Crocomo WB. Effect of Java grass (*Cymbopogon winterianus* Jowitt) essential oil on fall armyworm *Spodoptera frugiperda* (J. E. Smith, 1797)

(Lepidoptera, Noctuidae). Maringá. 2002;**24**(5):1401-1405

[47] Jeyasankar A. Antifeedant, insecticidal and growth inhibitory activities of selected plant oils on black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae). Asian Pacific Journal of Tropical Disease. 2012;**2**(1): S347-S351

[48] Ho SH, Koh L, Ma Y, Huang Y, Sim KY. The oil of garlic, *Allium sativum* L. (Amaryllidaceae), as a potential grain protectant against *Tribolium castaneum* (Herbst) and *Sitophilus zeamais* Motsch. Postharvest Biology and Technology. 1996;**9**:41-48

[49] Kosti'ca I, Petrovi'c O, Milanovi'c S, Popovi'c Z, Stankovi'c S, Todorovi'c G, et al. Biological activity of essential oils of *Athamanta haynaldii* and *Myristica fragrans* to gypsy moth larvae. Industrial Crops and Products. 2013;**41**:17-20

[50] Pinheiro PF, de Queiroz VT, Rondelli VM, Costa AV, Marcelino TP, Pratissoli D. Insecticidal activity of citronella grass essential oil on Frankliniella schultzei and Myzus persicae. Ciência e Agrotecnologia, Lavras. 2013;**37**(2):138-144

[51] Papachristos DP, Kimbaris AC, Papadopoulos NT, Polissiou MG. Toxicity of citrus essential oils against *Ceratitis capitata* (Diptera: Tephritidae) larvae. The Annals of Applied Biology. 2009;**155**:381-389

[52] Hussein HS, Salem ZMM, Soliman MA. Repellent, attractive, and insecticidal effects of essential oils from *Schinus terebinthifolius* fruits and *Corymbia citriodora* leaves on two whitefly species, *Bemisia tabaci*, and *Trialeurodes ricini*. Scientia Horticulturae. 2017;**216**:111-119

[53] Stephenson GR. Pesticide use and world food production: Risks and benefits. Environmental Fate and Effects of Pesticides. 2003:261-270. DOI: 10.1021/bk-2003-0853.ch015

[54] Tripathi AK, Upadhyay S, Bhuiyan M, Bhattacharya PR. A review on prospects of essential oils as biopesticide in insect-pest management. Journal of Pharmacognosy and Phytotherapy. 2009;**15**:52-63

[55] Isman MB. Plant essential oils for pest and disease management. Crop Protection. 2000;**19**:603-608

[56] Moretti MDL, Sanna-Passino G, Demontis S, Bazzoni E. Essential oil formulations useful as a new tool for insect pest control. AAPS PharmSciTech. 2002;**3**(2):1-11

[57] Frederiksen HK, Kristensen HG, Pedersen M. Solid-lipid nanoparticle formulations (SLN) of the pyrethroid gamma-cylalothrin (GCH): incompatibility of the lipid and the pyrethroid. Journal of Controlled Release. 2003;**86**:243-253

[58] Liu WT. Nanoparticles and their biological and environmental applications. Journal of Bioscience and Bioengineering. 2006;**102**:1-7

[59] McClements DJ. Nanoemulsions versus microemulsions: Terminology, differences, and similarities. Soft Matter. 2012;**8**:1719-1729

[60] McClements DJ. Food Emulsions: Principles, Practices, and Techniques. Boca Raton, London: CRC Press; 2004. ISBN: 0849320232

[61] Anton N, Benoit JP, Saulnier P. Design and production of nanoparticles formulated from nano-emulsion templates—A review. Journal of Controlled Release. 2008;**128**:185-199

[62] Vilasau J, Solans C, Gómez M, Dabrio J, Mújika-Garai R, Esquena J. Phase behaviour of a mixed ionic/ nonionic surfactant system used to

prepare stable oil-in-water paraffin emulsions. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2011;**384**:473-481

[63] Nagpal BN, Srivastava A, Valecha NA, Sharma VP. Repellent action of neem cream against *An. culicifacies* and *Cx. Quinquefasciatus*. Current Science. 2001;**80**:1270-1271

[64] Kumari A, Yadav SK, Yadav SC. Biodegradable polymeric nanoparticles based drug delivery systems. Colloids and Surfaces. 2010;**75**(1):1-18

[65] Reis CP, Neufeld RJ, Ribeiro AJ, Veiga F. Nanoencapsulation I. Methods for preparation of drug-loaded polymeric nanoparticles. Nanomedicine: Nanotechnology, Biology and Medicine. 2006;**2**:8-21

[66] Bangham AD. Physical structure and behavior of lipids and lipid enzymes. Advances in Lipid Research. 1963;**1**:65-104

[67] Batzri S, Korn ED. Single bilayer liposomes prepared without sonication. Biochimica et Biophysica Acta. 1973; **298**:1015-1019

[68] Pardeike J, Hommoss A, Müller RH. Lipid nanoparticles (SLN, NLC) in cosmetic and pharmaceutical dermal products. International Journal of Pharmaceutics. 2009;**366**:170-184

[69] São Pedro A, Santo IE, Silva C, Detoni C, Albuquerque E. The use of nanotechnology as an approach for essential oil-based formulations with antimicrobial activity. In: Méndez-Vilas A, editor. Microbial Pathogens and Strategies for Combating them: Science, Technology and Education. Zurbaran, Badajoz, Spain: Formatex Research Center; 2013. pp. 1364-1374

[70] Nel A, Xia T, Madler L, Li N. Toxic potential of materials at the nanolevel. Science. 2006;**311**(5761):622-627

[71] Nayak AP, Tiyaboonchai W, Patankar S, Madhusudhana B, Souto EB. Curcuminoids-loaded lipid nanoparticles: Novel approach towards malaria treatment. Colloids and Surfaces B: Biointerfaces. 2010;**81**: 263-273

[72] Kaur IP, Bhandari R, Bhandari S, Kakkar V. Potential of solid lipid nanoparticles in brain targeting. Journal of Controlled Release. 2008; **127**:97-109

[73] Solomon B, Sahle FF, Gebre-Mariam T, Asres K, Neubert RHH. Microencapsulation of citronella oil for mosquito-repellent application: Formulation and in vitro permeation studies. European Journal of Pharmaceutics and Biopharmaceutics. 2012;**80**:61-66

[74] Anjali CH, Sudheer Khan S, Margulis-Goshen K, Magdassi S, Mukherjee A, Chandrasekaran N. Formulation of water-dispersible nanopermethrin for larvicidal applications. Ecotoxicology and Environmental Safety. 2010;**73**: 1932-1936

[75] Khot L, Sankaran S, Maja J, Ehsani R, Schuster E. Applications of nanomaterials in agricultural production and crop protection: A review. Crop Protection. 2012;**35**:64-70

[76] Devi N, Maji TK. Study of complex coacervation of gelatin A with sodium carboxymethyl cellulose: Microencapsulation of neem (*Azadirachta indica* A. Juss.) seed oil (NSO). International Journal of Polymeric Materials and Polymeric Biomaterials. 2011;**60**(13):1091-1105

[77] Asnawi S, Abd Aziz A, Abd Aziz R, Khamis AK. Formulation of geranium oil loaded solid lipid nanoparticles for mosquito repellent application. Journal of Chemical and Natural Resources Engineering. 2008;**2**:90-99

[78] Yang FL, Li SG, Zhu F, Lei CL. Structural characterization of nanoparticles loaded with garlic essential oil and their insecticidal activity against *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Journal of Agricultural and Food Chemistry. 2009;**57**:10156-10162

[79] Nuchuchua O, Sakulku U, Uawongyart N, Puttipipatkhachorn S, Soottitantawat A, Ruktanonchai1 U. In vitro characterization and mosquito (*Aedes aegypti*) repellent activity of essential-oils-loaded nanoemulsions. AAPS PharmSciTech. 2009;**10**(4): 1234-1242

[80] Jerobin J, Sureshkumar RS, Anjali CH, Mukherjee A, Chandrasekaran N. Biodegradable polymer based encapsulation of neem oil nanoemulsion for controlled release of Aza-A. Carbohydrate Polymers. 2012;**90**(4): 1750-1756

[81] Ibrahim SS. Applications of some biotechnological methods for controlling the most important pests of potatoes [thesis]. Fac. Sci, Al-Azhar University, Egypt. 2017

[82] Campolo O, Cherif A, Ricupero M, Siscaro G, Grissa-Lebdi K, Russo A, et al. Citrus peel essential oil nanoformulations to control the tomato borer, *Tuta absoluta*: Chemical properties and biological activity. Scientific Reports. 2017;**7**:13036. DOI: 10.1038/s41598-017-13413-0

[83] Khoobdel M, ahsaei SA, farzaneh M. Insecticidal activity of polycaprolactone nanocapsules loaded with *Rosmarinus officinalis* essential oil in *Tribolium castaneum* (Herbst). Entomological Research. 2017;**47**:175-184

[84] Louni M, Shakarami J, Negahban M. Insecticidal efficacy of nanoemulsion containing *Mentha longifolia* essential oil against *Ephestia kuehniella* (Lepidoptera: Pyralidae). Journal of Crop Protection. 2018;**7**(2):171-182

[85] Alexandratos N, Bruinsma J. World Agriculture Towards 2030/2050: The 2012 Revision. ESA Working Paper; Rome: FAO; 2012