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Botanical insecticide as simple extractives for pest control

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Abstract: One of the most important global problems is protecting crops from insects. For the control of insects, synthetic chemicals are continuously used, and their toxicity endangers health of farm operators, animals and food consumers. The negative effects on human health led to a resurgence of interest in botanical insecticides due to their minimal costs and ecological side effects. In this, we review the use of plant compounds (essential oils, flavonoids, alkaloids, glycosides, esters and fatty acids) having anti-insect effects and their importance as an alternative to the chemical compounds used in the elimination of insects in different ways, namely repellents, feeding deterrents/antifeedants, toxicants, growth retardants, chemosterilants, and attractants. Botanical insecticides affect only target insects, not destroy beneficial natural enemies and provide residue-free food and safe environment. We, therefore, recommend using botanical insecticides as an integrated insect management program which can greatly reduce the use of synthetic insecticides.

Subjects: Botany; Plant & Animal Ecology; Entomology

Keywords: natural products; insecticides; active constituents; crop protection; insect

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PUBLIC INTEREST STATEMENT

Provision of food has always been a challenge facing mankind. A major cornerstone in this challenge is the competition from insects. Insect pests inflict damage to humans, farm animals and crops. They are responsible for destroying one fifth of the world's total crop production annually. Considerable losses of agricultural products add a serious burden to people's daily life. There is an urgent need to move toward natural products as insecticides because it reduces negative impacts to human health and the environment, and we recommend the botanical insecticides to reduce the insect population and increase food production. Therefore, this study is useful for farmers, producers and exporters of crops and recommends the use of botanical insecticides as an alternative to chemicals or synthetic insecticides to eliminate insects and maintain crops and meet the risks of food shortages as well as the preservation of the environment and human and animal health.

1. Introduction

Insects are the most diverse species of animals living on earth and can be found in all habitats. Less than 0.5% of the total number of the known insect species are considered pests, and only a few of these can be a serious menace to people. Insects inflict damage to humans, farm animals and crops. Some insects can constitute a major threat to entire countries or a group of nations. One prominent example is the tsetse fly that puts about 100 million people and 60 million head of cattle at risk in sub-Saharan Africa due to the transmission of trypanosomiasis (ICIPE, 1997; Imms, 1964).

Provision of food has always been a challenge facing mankind. A major cornerstone in this challenge is the competition from insects. Herbivorous insects are said to be responsible for destroying one-fifth of the world's total crop production annually. Particularly in the tropics and sub-tropics, where the climate provides a highly favorable environment for a wide range of insects. In the developing countries, the problem of competition from insects is further complicated with a rapid annual increase in the human population. Taking into consideration sudden problems caused by drought in places such as Africa, considerable losses of agricultural products add a serious burden to people's daily life. The introduction of alien insects into new habitats due to the global increase of trade and transport causes another dilemma. Insects inflict their damage on stored products mainly by direct feeding. Some species feed on the endosperm causing loss of weight and quality, while other species feed on the germ, resulting in poor seed germination and less viability. Thus, due to damage done by insects, grains lose value for marketing, consumption or planting. In addition to direct consumption of the product, insect pests contaminate their feeding media through excretion, molting, dead bodies and their own existence in the product, which is not commercially desirable. Damage done by insects encourages infection with bacterial and fungal diseases through transmission of their spores (Malek & Parveen, 1989; Santos, Maia, & Cruz, 1990).

In this review, we will focus on biological control of insects in crop production using botanical products. We provide an overview of botanical insecticides from the chemical point of view and classify their effects on insects.

2. Types of botanical insecticides

2.1. Essential oils

Plant secondary natural products are natural chemicals extracted from plants and used as an excellent alternative to synthetic or chemical pesticides (Regnault-Roger & Philogène, 2008; Sithisut, Fields, & Chandrapathya, 2011). In addition insecticide resistance to synthetic pesticides, which led to a significant losses of food arising from failure of chemicals in pest and annually caused economic losses of several billion dollars worldwide (Elzen & Hardee, 2003; Pereira, Sanaveerappanavar, & Murthy, 2006; Shelton, Zhao, & Roush, 2002), Furthermore, United States Food and Drug Administration (FDA) recognized botanical pesticides (essential oils) as safe than synthetic pesticides which caused increase in risk of ozone depletion, neurotoxic, carcinogenic, teratogenic and mutagenic effects in non-targets and cross- and multi-resistance in insects (Regnault-Roger, Vincent, & Arnason, 2012).

Essential oils extracted from aromatic plants have increased considerably as insecticides owing to their popularity with organic growers and environmentally conscious consumers. They have repellent, insecticidal, antifeedants, growth inhibitors, oviposition inhibitors, ovicides, and growth-reducing effects on a variety of insects (Don-Perdo, 1996; Elzen & Hardee, 2003; Koshier & Sedy, 2001; Lu, 1995; Pereira et al., 2006; Regnault-Roger et al., 2012; Shelton et al., 2002; Sithisut et al., 2011; Tripathi, Prajapati, Khanuja, & Kumar, 2003). Essential oils possess interesting larvicidal effects on *Limantria dispar* (Lepi-doptera: Lymantridae, gypsy moth) larvae (Moretti, Sanna-Passino, Demontis, & Bazzoni, 2000), insecticidal activity, repellent properties against ants, cockroach, bedbugs, head lices flied and moth and toxic to termites. *Mentha piperita* oil repels ants, flies, lice, moths' and is effective against *Callosobruchus maculatus* and *Tribolium castanum* (Kordali, Cakir, Mavi, Kilic, & Yildirim, 2005). *Trachyspermum* sp. oil has larvicidal against *Aedes aegypti* and southern house mosquito, *Culex quinquefasciatus* (Tripathi et al., 2000). Nepetalactone, the active constituent in catnip (*Nepeta cateria*) essential oil is highly effective for repelling mosquitoes, bees and other flying insects. It repels mosquitoes more than DEET. It is particularly effective against *A. aegypti* mosquito, a vector for yellow fever virus. Oils of *Zingiber officinale* rhizomes and *Piper cubebaberries* were exhibited insecticidal and antifeeding activities against *Tribolium castaneum* and *Sitophilus oryzae* (Chaubey, 2012a, 2012b). Tagetes species oil possesses as anti-insect activity on *Ceratitis capitata* and *Triatoma infestans* (López et al., 2011). *Melaleuca alternifolia* essential oil possesses the fumigant toxicity against *Sitophilus zeamais* (Min et al., 2016). Rosemary, oregano, yarrow, eucalyptus and mint oils used as the safe compounds for surface treating or fumigation in cockroach control. Oregano oil used as a potential repellent against *Supella longipalpa* (Sharififard, Safdari, Siahpoush, Hamid, & Kassiri, 2016). Kanat, Hakk, and Alma (2003) found that essential oils of many plants have insecticidal effects against the larvae of pine processionary moth, *Thaumetopoea pityocampa*. Also, *Laurus nobilis* essential oil was toxic activities against *Rhyzopertha dominica* and *T. castaneum* (Ben Jemba, Tersim, Toudert, & Khouja, 2012). *Lavandula hybrida*, *Rosmarinus officinalis,* and *Eucalyptus globulus* oils were insecticidal on *Acanthoscelides obtectus* adults (Papachristos, Karamanoli, Stamopoulos, & Menkissoglu-Spiroudi, 2004). Moreover, essential oil of *Tagetes minuta* has toxicity against *Cochliomyia macellaria* (Diptera: Calliphoridae) and as acaricidal, repellent (Chaaban, de Souza, Martins, Bertoldi, & Molento, 2017). Eugenol which the principle compound of the essential oils from basil oil have a strong repellent effect on mosquitoes and linalool also in basil oil has toxic effect to the *Bruchid zabrotes* sub *fasciatus* and other storage pests (Chogo & Crank, 1981; Weaver, Dunkel, Ntezurubanza, Jackson, & Stock, 1991). Essential oil of *Zingiber zerumbet* has repellant against *Lasioderma serricorne* (Wu et al., 2017). *Juniperus procera* essential oil was exhibited significant repellent against the malarial vector *Anopheles arabiensis* (Karunamoorthi, Girmay, & Hayleeyesus, 2014). Terpinen-4-ol; 1,8-cineol; verbenone and camphorin Eucalyptus oil were active against *A. obtectus* adults (Tholl, 2006), antifeedant against biting insects, insecticidal agents and prevent mosquito bite (Bakkali, Averbeck, Averbeck, & Idaomar, 2008; Batish, Singh, Kohli, & Kaur, 2008; Fradin & Day, 2002; Isman & Machial, 2006). Lucia et al. (2007) reported that essential oil from *Eucalyptus globules* is toxic to *A. aegypti* larvae. Seyoum, Killeen, Kabiru, Knols, and Hassanali (2003) reported that burning of leaves of *Eucalyptus citriodora* used as protection against mosquitoes in Africa. Also, CDC (Center for Disease Control and Prevention, USA) recommended the use of lemon eucalyptus oil (with p-menthane-3,8-diol, PMD, as active ingredient) for protection against West Nile virus that causes neurological disease or even death and is spread by mosquitoes (CDC, 2005).

Toloza et al. (2006) concluded the fumigant toxicity/repellent activity of essential oil from *Eucalyptus cinerea*, *Eucalyptus viminalis,* and *Eucalyptus saligna*, against permethrin-resistant humanhead lice. The pesticidal and antifeedant activities of eucalyptus oils has been due to 1,8-cineole, citronellal, citronellol, citronellyl acetate, p-cymene, eucamalol, limonene, linalool, α-pinene, Υ-terpinene, α-terpineol, alloocimene, and aromadendrene components (Batish, Singh, Setia, Kaur, & Kohli, 2006; Cimanga et al., 2002; Li, Madden, & Potts, 1996; Liu, Chen, Wang, Xie, & Xu, 2008; Watanabe et al., 1993). Eucalyptus oils rich in cineole have affective against varroa mite, *Varroa jacobsoni*-an important parasite of honey bee (Calderone & Spivak, 1995), *Tetranychus urticae, Phytoseiulus persimilis* and *Dermatophagoides pteronyssinus* (Choi, Lee, Park, & Ahn, 2004; El-Zemity, Hussien, Saher, & Ahmed, 2006). Eucalyptus essential oil significantly reduced the number of tick bites in humans and concluded that it could be used to reduce tick-borne infections (Chagas et al., 2002; Gardulf, Wohlfart, & Gustafson, 2004). Pujiarti and Fentiyanti (2017) reported that *Eucalyptus deglupta* essential oils have repellent activity against *C. quinquefasciatus* mosquito. Eugenol, isoeugenol, methyleugenol, methyl isoeugenol, coumarin, coniferyl aldehyde, diniconazole, ethyl cinnamate, and rosmarinic acid against red palm weevil posses as antifeedant activity against adults of red palm weevil (*Rhynchophorus ferrugineus*) (AlJabr, Hussain, Rizwan-ul-Haq, & Al-Ayedh, 2017; Aref, Valizadegan, & Farashiani, 2015; Shukla, Vidyasgar, Aldosari, & Abdel-Azim, 2012).

2.2. Alkaloid

Alkaloids are the most important group of natural substances playing an important role in insecticidal (Balandrin, Klocke, Wurtele, & Bollinger, 1985; Rattan, 2010). Wachira et al. (2014) concluded that pyridine alkaloids extracted from *Ricinus communis* against the malaria vector *Anopheles gambiae*. Furocoumarin and quinolone alkaloids extracted from *Ruta chalepensis* leaves showed larvicidal and antifeedant activities against the larvae *Spodoptera littoralis* (Emam, Swelam, & Megally, 2009). Acheuk and Doumandji-Mitiche (2013) found that alkaloids extract of *Pergularia tomentosa* caused antifeeding and larvicidal effects. Lee (2000) concluded that pipernonaline and piperidine alkaloids have mosquito larvicidal activity. Alkaloids from *Arachis hypogaea* extract have larvicidal activity against chikungunya and malarial vectors (Velu et al., 2015).

2.3. Flavonoids

Flavonoids could be useful in a pest-management strategy. Flavonoids play an important role in the protection of plants against plant feeding insects' and herbivores (Acheuk & Doumandji-Mitiche, 2013). Both flavonoids and isoflavonoids protect the plant against insect pests by influencing their behavior, growth, and development (Simmonds, 2003; Simmonds & Stevenson, 2001). Rutin and quercetin-3-glucoside in *Pinus banksiana* inhibit the development and increase the mortality of *L. dispar* (Gould & Lister, 2006). Quercetin and rutin glycosides in peanuts caused increased mortality of the tobacco armyworm (*Spodoptera litura*) (Mallikarjuna, Kranthi, Jadhav, Kranthi, & Chandra, 2004). In rice, three flavone glucosides inhibit digestion in insects and function as deterrent agents in *Nilaparvata lugens* and herbivores (Acheuk & Doumandji-Mitiche, 2013). Diwan and Saxena (2010) found that flavinoid glycosides isolated from *Tephrosia purpuria* showed insecticidal property on *C. maculatus* grubs. Isoflavonoids and proanthocyanidins are other classes of flavonoids responsible for plant protection against insects. Forexample, naringenin procyanidin inhibits the development of *Aphis craccivora* andherbivores (Acheuk & Doumandji-Mitiche, 2013). Kumar, Bhadauria, and Mishra (2015) concluded that quercetin/azadirachtin insecticide can be a safe and efficient insecticide which improved the activity of *Euphaedra orientalis* and is non toxic to it, and also is environmentally less harmful as it is easily biodegradable. Goławska, Sprawka, Łukasik, and Goławski (2014) found that two polyphenolic flavonoids (flavanone naringenin and flavonol quercetin) used as insecticides of the pea aphid, *Acyrthosiphon pisum* (Hemiptera: Aphididae). Santos et al. (2016) conclude that *Tagetes erecta* and *Tagetes patula* have phytotoxic compounds (flavonoids) that can promote and expand its use as a natural insecticide. Golawska, Kapusta, Łukasik, and Wojcicka (2008) suggests that quercetin, kaempferol + RCO-, kaempferol, tricin, apigenin + RCO-, and apigenin are good for control of the insect pests.

Goławska and Łukasik (2012) showed the effects of isoflavone genistein and flavone luteolin on the feeding behavior of the pea aphid. Flavonoid glycosides in alfalfa affect feeding behavior of pea aphid (Goławska, Łukasik, Goławski, Kapusta, & Janda, 2010; Goławska, Łukasik, Kapusta, & Janda, 2012). Morimoto, Kumeda, and Komai (2000) showed that flavonoids can act as feeding deterrents. Flavonoids from *A. hypogaea* extract have larvicidal activity against chikungunya and malarial vectors (Velu et al., 2015).

2.4. Glycosides

Cyanogenic glucosides presented in plant species and considered to have an important role in plant defense against herbivores (Zagrobelny et al., 2004). Al-Rajhy, Alahmed, Hussein, and Kheir (2003) concluded that the cardiac glycoside, digitoxin, from *Digitalis purpurea*, a cardiac glycosidal (cardenolide) extract from *Calotropis procera*, azadirachtin and neem oil from *Azadirachta indica* posses against larvae and adult stages of the camel tick, *Hyalomma dromedarii*. Also, Kubo and Kim (1989) found that flavan glycosides, Viscutin-1, -2 and -3, which exhibit insect growth inhibitory activity against the cotton pest insect; *Pectinophora gossypiella*. However, iridoid glycosides posses as insect antifeeding on gypsy moths (*L. dispar*, Lymantriidae) and buckeyes (*Junonia coenia*, Nymphalidae) (Bowers & Puttick, 1989). Also, cyanogenic glycosides are known as plant defense chemicals and found in cassava, bamboo, flax, and other plants. They are effective against stored-product insects as fumigants. Due to their insecticidal activity to insects, cyanohydrins can be used as an alternative fumigant and also as soil fumigants (Park & Coats, 2002). Dave and Lediwane (2012) found that anthraquinones isolated from *Cassia* species posses as antimalarial and insecticidal activity. Glycosides from *A. hypogaea* extract have larvicidal activity against chikungunya and malarial vectors (Velu et al., 2015). Juvenogens have a potential application in insect pest control (Wimmer et al., 2007).

2.5. Esters and fatty acids

Allyl cinnamate caused rapid toxic effects in *S. littoralis* larvae at low concentrations potential for use in pest control (Giner, Avilla, Balcells, Caccia, & Smagghe, 2012). Schmidt, Tomasi, Pasqualini, and Ioriatti (2008) demonstrated that ethyl (*E*,*Z*)-2,4-decadienoate (pear ester) have insecticide against *Cydia pomonella*.

Fatty acids methyl esters were isolated from *Solanum lycocarpum* have larvicidal activity against the vector *C. quinquefasciatus* (Silva, Ribeiro Neto, Alves, & Li, 2015). Mullens, Reifenrath, and Butler (2009) showed that saturated fatty acids (particularly C8, C9 and C10) used as repellents or antifeedants against houseflies, horn flies and stable flies. Samuel, Oliver, Wood, Coetzee, and Brooke (2015) concluded that fatty acids mixture (C8910) has toxicity and repellence against insecticide susceptible and resistant strains of the major malaria vector *Anopheles funestus*. Yousef, EL-Lakwah, and EL Sayed (2013) reported that toxicity and reduction in larval body weight of linoleic acid against the larvae of *S. littoralis*.

3. Insecticide effects on insects

Botanical insecticides affect various insects in different ways depending on the physiological characteristics of the insect species as well as the type of the insecticidal plant. The components of various botanical insecticidal can be classified into six groups namely; repellents, feeding deterrents/antifeedants, toxicants, growth retardants, chemosterilants, and attractants (Rajashekar, Bakthavatsalam, & Shivanandappa, 2012).

3.1. Repellents

A botanical pesticide have a repellent property, where keeps away the insect pest, and protect the crops (Isman, 2006) with minimal impact on the ecosystem, as they drive away the insect pest from the treated materials by stimulating olfactory or other receptors (Talukder, 2006; Talukder, Islam, Hossain, Rahman, & Alam, 2004). Botanical pesticides are considered safe in pest control because they have low or none pesticide residue making them safe to the people, environment and ecosystem (Talukder et al., 2004). Ghavami, Poorrastgoo, Taghiloo, and Mohammadi (2017) found that essential oils of *Ziziphora tenuiore*, *Myrtus communis*, *Achillea wilhelmsii* and *M. piperita* have repellent activities against human fleas. Rahdari and Hamzei (2017) demonstrated the efficacy of *M. piperita*, *R. officinalis,* and *Coriandrum sativum* oils for applying in organic food protection due to repellent activity of essential oils on *Tribolium confusum*. Zhang et al. (2017) reported the repellent activities of six *Zanthoxylum* species including *Z. armatum*, *Z. dimorphophyllum*, *Z. dimorphophyllum* var. *spinifolium*, *Z. piasezkii*, *Z. stenophyllum,* and *Z. dissitum* essential oils against two storage pests including *T. castaneum* and *L. serricorne* adults and the essential oils of these six *Zanthoxylum* species essential oils possessed significant repellent activities against *T. castaneum* and *L. serricorne* adults. The different repellent activities on two insects might be attributed to the different anti-insect mechanism and different non persistent volatility of essential oil sample. Kimutai et al. (2017) demonstrated that the essential oils of *Cymbopogon citratus* and *T. minuta* on the sandfly, *Phlebotomus* duboscqi. However, the effectiveness of the repellents depends on multiple factors including the type of repellents (active ingredients), formulation, mode of application, environmental factors (temperature, humidity, and wind), the attractiveness of individual people to insects, loss due to removal by perspiration and abrasion, the sensitivity of the insects to repellents, and the biting density. In addition, *Origanum onites* essential oil had repellent activity against *Amblyomma americanum* (L.) and *A. aegypti* (L.). Carvacrol and thymol were strongly repellent to *A. aegypti* and *A. americanum*. Thus, carvacrol-rich *O. onites* essential oil, carvacrol, and possibly thymol appear to have potential for use to protect humans and domestic animals against mosquitoes and ticks.

Various natural fatty acids have insecticidal properties, some involving action on acetylcholinesterase and octopaminergic receptors (Perumalsamy, Jang, Kim, Kadarkarai, & Ahn, 2015). A saturated fatty acid mixture composed of octanoic acid (also called caprylic acid, nonaoic acid and decanoic acid (also called capric acid), collectively called "C8910 acids" (C8, C9, and C10 mixture), repelled horn flies. C8910 acids deterred horn flies from feeding by > 85% and the pest was also strongly repelled (Zhu, Brewer, Boxler, Friesen, & Taylor, 2015). Feeding deterrence caused by C8910 acids and > 50% antifeedancy was observed (Zhu et al., 2015). The naturally occurring oleic and linoleic acids, and methyl oleate synergized the repellency of DEET and the monoterpenoids cuminyl alcohol, cuminaldehyde, and a-phellandrene (Hieu, Choi, Kim, Wang, & Ahn, 2015; Showler, 2017).

3.2. Feeding deterrents/antifeedants

Botanical pesticides that inhibit feeding or disrupt insect feeding by rendering the treated materials unattractive or unpalatable (Rajashekar et al., 2012; Talukder, 2006). The insects remain on the treated material indefinitely and eventually starve to death. Liao et al. (2017) demonstrated that oil of *M. alternifolia* and their chemical constituents possessed obvious antifeedant activities against *Helicoverpa armigera* Hubner. The phytoconstituents found in the leaf extract of *Khaya senegalensis* include tannins, saponins, flavonoids, steroids, and alkaloids may have been responsible for the mortality of *Dinoderus porcellus* (Loko et al., 2017). Chaudhary et al. (2017) and Ghoneim and Hamadah (2017) pointed that azadirachtin which is prominent constituent of neem established as a pivotal insecticidal ingredient. It acts as an antifeedant, repellent, and repugnant agent and induces sterility in insects by preventing oviposition and interrupting sperm production in males. The same result obtained by Abdullah et al. (2017) who found that, 1,8-cineol found in Galangal essential oil exhibited antifeedant activity, repellent activity, and toxicity effect toward the termites. Jose and Sujatha (2017) revealed that terpenoids, coumarin and phenols, present in the methanol extracts of *Gliricidium sepium* exhibited significant antifeedant activity. This indicated that the active compounds present in the plant inhibit the larval feeding behavior while others disrupt hormonal balance or make the food unpalatable. These active substances may directly act on the chemosensilla of the larvae resulting in feeding deterrence.

3.3. Toxicity

Some botanical pesticides are toxic cause death to stored product insects (Padin, Fuse, Urrutia, & DalBello, 2013). Rotenone is considered as a toxic compound since it is a mitochondrial poison which blocks the electron transport chain and prevents energy production (Hollingworth, Ahammadsahib, Gadelhak, & McLaughlin, 1994). As an insecticide, it is a stomach poison because it must be ingested to be effective (Isman, 2006). Essential oil of *Lavandula angustifolia* exhibited good fumigant and contact toxicity against granary weevil adults. In addition, a strong repellent activity is able to disrupt granary weevil orientation to an attractive host substrate (Germinara et al., 2017). Trivedi, Nayak, and Kumar (2017) demonstrated fumigant toxicity against the stored grain pest *Callosobruchus chinensis*. The essential oils of cinnamon, clove, rosemary, bergamot, and Japanese mint showed potential to be developed as possible natural fumigants or repellents for control of the pulse beetle. Lucia, Toloza, Guzmán, Ortega, and Rubio (2017) found that the mortality of adults and eggs for head lice associated with the use of (geraniol, citronellol, 1,8-cineole, linalool, α-terpineol, nonyl alcohol, thymol, menthol, carvacrol, and eugenol) essential oils. Bouguerra, Djebbar, and Soltani (2017) showed that *Thymus vulgaris* essential oil exhibited significant activity and could be considered as potent natural larvicidal agent against *Culex pipiens*. Zhao, Liu, Liu, and Liu (2017) indicated that the essential oil of *Echinops grijsii* roots and the isolated thiophenes have an excellent potential for use in the control of *Aedes albopictus*, *Anopheles sinensis,* and *C. pipiens* pallens larvae and could be used in the search for new, safer and more effective natural compounds as larvicides. Wu et al. (2017) observed the toxicity and repellent activities of the rhizomes of *Z. zerumbet* (L.) Smith (Zingiberaceae) essential oil contains the component α-caryophyllene against cigarette beetles (*L. serricorne*). Alkan, Gokce, and Kara (2017) indicate that *Heracleum platytaenium* and *Humulus lupulus* extracts have great potentials as insecticides in the management of larvae of *Leptinotarsa decemlineata.* Papanastasiou et al. (2017) showed the toxicity of limonene, linalool and α-pinene on adult Mediterranean fruit flies. Qari, Nilly, Abdel-Fattah, and Shehawy (2017) showed DNA damage due to alterations in enzymatic system (acetylcholinesterase, acid phosphatase, alkaline phosphatase, lactate dehydrogenase and phenol oxidase), total protein and DNA concentration after treatment with essential oils of *Citrus aurantium*, *Eruca sativa*, *Z. officinale* and *Origanum majorana* against *R. dominica*. Park, Jeon, Lee, Chung, and Lee (2017) demonstrated that *T. vulgaris* oil had the highest insecticidal toxicity followed by *R. graveolens*, *C. aurantium*, *L. petersonii,* and *A. millefolium* oils. The insecticidal toxicity of *T. vulgaris* oil against *P. shantungensis* nymphs was about 1.3-fold more than that against *P. shantungensis* adults. Differences in the insecticidal toxicities of plant-derived oils may be explained on the basis of species-specific responses to plant species, phytochemicals, and the weight and size of *P. shantungensis* adults and nymphs.

3.4. Growth retardants and development inhibitors
Botanical pesticides showed deleterious effects on the growth and development of insects, reducing the weight of larva, pupa and adult stages and lengthening the development stages (Talukder, 2006). Plant derivatives also reduce the survival rates of larvae and pupae as well as adult emergence (Koul, Waliai, & Dhaliwal, 2008). It has been reported that both azadirachtin and neem seed oil increased aphid nymphal mortality significantly at 80 and 77%, respectively, and at the same time increasing development time of those surviving to adulthood (Kraiss & Cullen, 2008). Many botanical pesticides have been reported to have a pronounced effect on the developmental period, growth, and adult emergence (Shaalan, Canyon, Younes, Abdel-Wahab, & Mansour, 2005).

3.5. Sterility/reproduction inhibitors
Sterility can be induced by sterile insect technique (SIT) or a chemosterilant, a chemical compound that interferes with the reproductive potential of sexually reproducing organism (Morrison et al., 2010). Chemosterilants are used to control economically destructive or disease-causing pests (usually insects) by causing temporary or permanent sterility of one or both of the sexes or preventing maturation of the young to a sexually functional adult stage (Navarro-Llopis, Vacas, Sanchis, Primo, & Alfaro, 2011; Wilke et al., 2009). It has been reported that plant parts, oil, extracts, and powder mixed with grain reduced insect oviposition, egg hatchability, postembryonic, and progeny development (Asawalam & Adesiyan, 2001; Shaalan et al., 2005). Hexane extracts of *Andrographis lineat*, *A. paniculata,* and *T. erecta* showed 100% ovicidal activity against *Anopheles subpictus* (Elango et al., 2009). Some botanical insecticides are used as chemosterilants, for example, at the physiological level azadirachtin blocks the synthesis and release of molting hormones from the prothoracic gland, leading to incomplete ecdysis in immature insects and in adult insects it leads to sterility (Isman, 2006).

Garlic essential oil and its constituents, diallyl sulfide and diallyl disulfide have been highly toxic to *S. zeamais* and *T. castaneum* (Ho, Koh, Ma, Huang, & Sim, 1996; Huang, Lam, & Ho, 2000) at different developmental stages. Plata-Rueda et al. (2017) showed that *Tenebrio molitor was* more susceptible in the pupal stage followed by larvae and adults exposed to diallyl sulfide and diallyl disulfide. One possible explanation for the developmental stages difference is that efficacy may be affected by the penetration of the garlic compounds into the body and the ability of the insect to metabolize these compounds. When insects exposed to the garlic essential oil displayed altered locomotion activity, and muscle contractions and paralysis were observed. Paralysis and muscle contractions can be explained by the toxic effect in the nervous system. The toxicity of essential oils in insects indicates neurotoxic action with hyperactivity, hyperextension of the legs and abdomen and rapid knockdown effect or immobilization (Prowse, Galloway, & Foggo, 2006; Zhao et al., 2013). Acetylcholinesterase is an enzyme that has been shown to be inhibited by garlic compounds and can act only or in synergism as diallyl disulfide, diallyl trisulfide, and allicin (Bhatnagar-Thomas & Pal, 1974; Singh & Singh, 1996). Diallyl sulfide in garlic compounds have toxic effect in *T. molitor* and may cause inhibition by cross-linking with essential thiol compounds in enzyme structures, altering the functional shape of the protein and denaturalization (Halliwell & Gutteridge, 1999). Also, diallyl disulfide as main volatile compound in garlic essential oil has repellent properties to *S. zeamais* and *T. castaneum* (Huang et al., 2000). Diallyl disulfide, and diallyl sulfide have high activities of behavioral deterrence against *T. molitor*, as evaluated by the behavioral responses of larvae and adults to different odor sources and the number of insects repelled, indicating their potential to the pest control in stored products. As well as garlic essential oil compromised the respiration rate of *T. molitor*. Thus, low respiration rate is an indicator of physiological stress, and essential oils can compromise insect respiration by impairing muscle activity, leading to paralysis (Correa, Faroni, Haddi, Oliveira, & Pereira, 2015; de Araújo et al., 2017; Guedes, Oliveira, Guedes, Ribeiro, & Serrão, 2006).

Dehghani-Samani, Madreseh-Ghahfarokhi, Dehghani-Samani, and Pirali-Kheirabadi (2015) showed that essential oil of *E. globulus* had repellent activity against *Dermanyssus gallinae* due to the essential oil components such as 1, 8-cineole, citronellal, citronellol, citronellyl acetate, p-cymene, eucamalol, limonene, linalool, α-pinene, g-terpinene, α-terpineol, alloocimene, and aromadendrene. Among the various components of eucalyptus oil, 1, 8-cineole is the most important one which is largely responsible for a variety of its pesticidal properties and insecticide effects. Jayakumar, Arivoli, Raveen, and Tennyson (2017) recorded the repellent activity of camphor, citronella, eucalyptus, lemon and wintergreen oil essential oils against stored product pests; the adult rice weevil *S. oryzae* Linnaeus 1763 (Coleoptera: Curculionidae) due to essential oils components repellent nor attractant activity. The protection of stored products and the phytochemical constituents from essential oils can work synergistically, improving their effectiveness.

Ho, Ma, Goh, and Sim (1995) concluding that adult mortality might be attributed to the contact toxicity or to the abrasive effect on the pest cuticle (Mathur, Shankar, & Ram, 1985), which might also interfere with the respiratory mechanism of insect (Agarwal, Lal, & Gupta, 1988; Kim, Roh, Kim, Lee, & Ahn, 2003; Schoonhoven, 1978). Fumigation studies showed that the essential oils had a “knock down effect” on the test insect. Essential oils act by inhibiting insect acetylcholinesterase (AChE) and thus, ultimately blocking the nerve functions. Also, Obeng-Ofori and Amitaye (2005) who observed signs of immobilization with flexed legs and clinging to the grain outstretched meta thoracic wings from the elytra and paralysis of the dead or dying insects. The enzyme AChE is also the target site of inhibition by organophosphates and carbamate insecticides (Matsumura, 1985). The observed rapid action of essential oils could be attributed to their property of acting in the vapor phase, hence gaining entry into the insect’s internal systems with ease through the spiracles; whereas, in topical application procedures, the insect is protected by its exoskeleton against external influences.

Essential oils possess acute contact and fumigant toxicity to insects (Abdelgaleil, Mohamed, Badawy, & El-arami, 2009), repellent activity (Nerio, Olivero-Verbel, & Stashenko, 2009), antifeedant activity (Huang et al., 2000), as well as development and growth inhibitory activity (Waliwitiya, Kennedy, & Lowenberger, 2008). Repellent activity has been linked to the presence of essential oils that cause death of insects by inhibiting AChE activity in the nervous system (Houghton, Ren, & Howes, 2006). Essential oils being more useful as insect fumigants (Regnault-Roger & Hamraoui, 1993; Weaver et al., 1991) and have strong toxicity to insects due to high volatility and lipophilic properties can penetrate into insects rapidly and interfere in physiological functions (Lee et al., 2002; Negahban, Moharramipour, & Sefidkon, 2007). Due to their high volatility, they have fumigant and gaseous action on stored product insects. Carvacrol component has broad insecticidal and acaricidal activity against agricultural, stored product, medical pests and acts as a fumigant being highly toxic to adults of *S. oryzae* (Ahn, Lee, Lee, & Kim, 1998). Besides, menthol, methonene, limonene, β-pipene, α-pipene, pulegone, linalool and linalyl acetate exhibited fumigant toxicity in *S. oryzae* and inhibited AChE activity (Koul et al., 2008; Lee, Choi, Lee, & Park, 2001; Lee, Lee et al., 2001; Singh, Siddiqui, & Sharma, 1989). Caryophyllene, a volatile compound, was reported to be a strong fumigant and toxic to *S. zeamais* (Chu, Liu, Jiang, & Liu, 2010).

The insecticidal activity varies with plant-derived material, insect species, and exposure time. The presence of volatile compounds having strong odor would have blocked the tracheal respiration of the insects leading to their death. Similar observation was made by Liu and Ho (1999) against *S. zeamais* and *T. castaneum*. Brown (1951) however, pointed out that the amount of fumigant absorbed depends on whether the insect’s initial contact with the fumigant resulted in supplication or stimulation of the tracheal opening. Moreover, the ability of the insect to exclude vapor from its cuticle and prevent dehydration of body fluid plays a vital role in susceptibility or tolerance to fumigants of various life stages of insects particularly beetles and weevils infesting stored products (El-Nahal, Schmidt, & Risha, 1989). 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 where essential oils can be inhaled, ingested or skin absorbed by insects (Regnault-Roger, 1997).

The presence of volatile compounds is responsible for strong odor that could block the tracheal respiration of the insects leading to their death (Pugazhvendan, Ross, & Elumalai, 2012). The mode of action of oils was partially attributed to interference in normal respiration, resulting in suffocation (Schoonhoven, 1978). Most insects breathe through the trachea which usually leads to the opening of the spiracle.

These spiracles might have been blocked thereby leading to suffocation (Adedire, Obembe, Akinkurolere, & Oduleye, 2011; Ileke & Olotuah, 2012) Essential oils are presumed to interfere with basic metabolic, biochemical, physiological, and behavioral functions of insects (Mann & Kaufman, 2012). Essential oils block the spiracles, resulting in blockage of respiratory siphons (asphyxiation) and death (Kaufmann & Briegel, 2004; Rotimi, Chris, Olusola, Joshua, & Josiah, 2011). Further, Rattan (2010) reviewed the mechanism of action of essential oils on the body of insects and documented several physiological disruptions, such as inhibition of AChE, disruption of the molecular events of morphogenesis, and alteration in the behavior and memory of cholinergic system. Of these, the most important activity is the inhibition of AChE activity as it is a key enzyme responsible for terminating the nerve impulse transmission through synaptic pathway. Plant oils affect AChE and have an action on the nervous system (Mikhaiel, 2011). Recent research has demonstrated the interference of Monoterpenes with AChE activity in insects (Chaubey, 2012a, 2012b). Essential oils are lipophilic in nature and can be inhaled or ingested. The rapid action against insect pests is indicative of a neurotoxic mode of action and interference with the neuromodulator octopamine (Enan, 2005) or GABA-gated chloride channels (Priestley, Burgess, & Williamson, 2006).

Several essential oil components act on the octopaminergic system of insects. Octopamine is a neurotransmitter, neurohormone, and circulating neurohormone-neuromodulator, and its disruption results in total breakdown of the nervous system (Hollingworth, Johnstone, & Wright, 1984). Thus, the octopaminergic system of insects represents a target for insect control. Low molecular weight terpenoids are too lipophilic to be soluble in the hemolymph after crossing the cuticle, and the proposed route of entry is tracheae (Veal, 1996) and may also bind to target sites on receptors that modulate nervous activity (Hollingworth et al., 1984) and interrupt normal neurotransmission leading to paralysis and death.

3.6. Attractants

Botanicals chemicals that cause insects to make oriented movements toward their source are called insect attractants. They influence both gustatory (taste) and olfactory (smell) receptor or sensilla. Iso-thiocyantes from seeds of *Crucifera*, sugar and molasses and terpenes from bark in with pheromones are natural attractants for various insects of Cruciferaea and bark beetles. In onion propylmercapton from *Umbelliferae* and phenylacetaldehyde from flowers of *Araujia serisofera* are attracted carrot fly (*Psila rosae*) and Lepidoptera, respectively. Insect attractants can be used in three ways for the control of insects. In sampling or monitoring insect populations to assess the extent of infestation and decides the measure of control to be adapted in lusting insect to insecticide-coated traps or poison baits and in distracting insects from normal mating, aggregation feeding or ovipostion. They do not kill the insects therefore, do not disturb ecosystem. They can be used to misguide the insects to wrong oviposition sites whereby their number will go down by starvation or by producing unfertilized eggs. They cannot be relied as sole control measure used only in integrated control program (Arora, Singh, & Dhawan, 2012).

4. Conclusion

Botanical insecticides are natural chemicals extracted from plants with insecticidal properties and used as an excellent alternative to synthetic or chemical pesticides for crop protection to avoid negative or side effects of synthetic insecticides. Botanical pesticides (essential oils, flavonoids, alkaloids, glycosides, esters and fatty acids) have various chemical properties and modes of action and affect on insects in different ways namely; repellents, feeding deterrents/antifeedants, toxicants, growth retardants, chemosterilants, and attractants. So it is preferable to use the botanical insecticides instead of synthetic insecticide and these botanical insecticides are recognized by organic crop producers in industrialized countries. So, we recommended using botanical insecticidal and being promoted and research is being conducted to find new sources of botanical insecticides.

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