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Essential oils as green pesticides: An overview

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ABSTRACT

Essential oils (EOs) obtained from different parts of plants consist of diverse chemical constituents. Most of the essential oils are rich in monoterpenes, sesquiterpenes and phenylpropenes. The diversity of chemical constituents imparts several biological activities such as insecticidal, repellent, attractant, antifeedant, oviposition deterrent, disruption in growth regulation, fungicidal and antiviral to these essential oils. Traditionally, EOs are being utilised for management of insect pests both in field crops and storage. Mostly these essential oils are found to affect insects by inhibiting several enzymes such as acetylcholine esterages, Glutathion S-transferages and also octopaminergic nervous system. They do not show toxicity against the mammals and fishes, due to absence of target site in these organisms. A few essential oils are exempted from pesticide registration and are being used as seasoning agents in food and beverage products. Moreover, these EOs can be a potential “green pesticide” against agricultural pests and support to the organic food production. The main purpose of this review is to emphasize on biological activities of EOs. This comprehensive and critical review will be helpful for chemists to develop more candidates based on these moieties and also for plant protectionists to identify promising EOs as per the need.

Keywords: Antifeedant, Antifungal activities, Essential oil, Growth Regulatory, Insecticidal, Oviposition deterrent, Repellent

Essential oils (EOs) are secondary metabolites synthesized by plants and play very important roles in plant defense and signalling processes. Synthetic pesticides are being widely used for management of pests to avoid losses both in field and post-harvest storage. The excess and unscientific uses of pesticides have raised the concern among producers and consumers about their residue and health effects over the last few years. The world-wide annual consumption of pesticides is around 3 million tonnes whereas annual cost is approximately $100 billion. Pesticide residues are the traces of chemical compounds that remain on or in the crop, water, soil and air and get into the environment as a result of application or by accident and can be found in the air, water and soil. To overcome the hazards associated with persistent pesticides and residues, there is need of a novel, highly selective and easily degradable chemicals. The identifying and exploring nature-origine pest control agents could become a possible substitute for the synthetic chemical pesticides and could help in decreasing the harmful impact of synthetic chemicals on nature and mankind. These nature origine biopesticicides could be crude extracts or essential oils obtained from any plant part and are called green pesticides. The term green pesticide includes all natural materials that can reduce the pest population (Mossa 2016). These are derived from organic sources which are considered environmentally friendly and cause less harm to human, animal health and to habitats and the ecosystem (Nollet and Rathore 2019). The green pesticides include involvement of green chemistry during their synthesis process and use of noble and advanced crop protection tools with new orientation of functional mechanism and refer to all kinds of control materials which originated naturally and beneficially minimize the pest population and eventually enhance quality and productivity. They are eco-friendly than synthetic product (Koul 2008, Mishra *et al.* 2020, Abdelatti and Hartbauer 2020). EOs are originated from the plants and they are volatile in nature with a pleasant aromatic feature and are known to produce a characteristic fragrance and a unique kind of plant scent. These are secondary metabolites of plant.The presence of EOs is varied from leaves to roots of the plant and it can be found in bark, stems, flowers, fruits and seed. The quantity of essential oil is varied from 0.01–10% but

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mostly it is available around 1–2%, in most of the plants. Chemically, a 10-carbon compound called monoterpene and 15 carbon compounds called sesquiterpenes and other higher terpenes are responsible for essence in the EOs but the major contributor are monoterpenes and sesquiterpenes whereas higher terpenes are available as minor constituents only (Chizzola 2013). EOs as green pesticides should focus on the development of formulations which could be successfully applied for management of pests.

Essential oils known as green pesticides

Originally the “Green concept” means the exclusion of pesticidal use and alternatives that are available. In this concept, EOs are a valuable input due to their volatility and limited persistence under field conditions.The majority of these are extracted through steam distillation of aromatic plants. Most of the EOs are produced commercially from the members of mint family. The EOs are a complex mixture of monoterpenes, sesquiterpenes, and related oxygenated terpenoids (Fig 1). Menthol is a major constituent of various mint species, 1,8-cineole from eucalyptus oils, thymol from thyme, eugenol from clove oil, and linalool from many plant species (Isman 2000). EOs act as octopamine neuromodulator which leads to their quick action on some pests whereas some are also reported as GABA-gated chloride channels inhibitors (Kostyukovsky *et al.* 2002, Priestley *et al.* 2003).

There are certain reports where EOs are observed as moderate toxic to mammals but, with the few exceptions, these are generally non-toxic to mammals, birds, and fish. As a result, they are specified under the category of "green pesticides". EOs have a short shelf life in the field due to their volatile nature. Therefore, predators and parasitoids are safe from residual contact as poisoning often happens in case of conventional insecticides (Kordali *et al.* 2005).

Pesticidal properties

The plants of families such as Myrtaceae, Lamiaceae, Asteraceae, Apiaceae and Rutaceae are highly targeted for anti-insect activities against insect orders, viz. Lepidoptera, Coleoptera, Diptera, Isoptera and Hemiptera. EOs have been explored for repellent, fumigant, larvicidal and adulticidal activities for insect control. Plant genus, *Artemisia* is

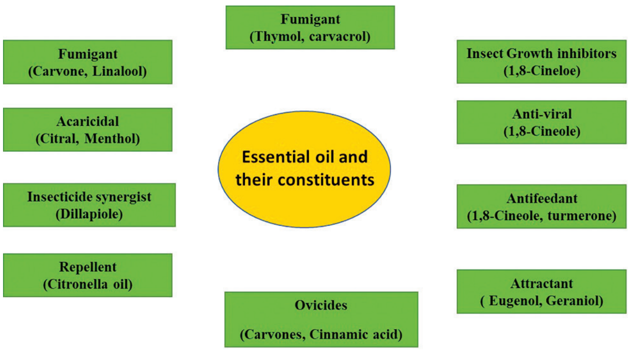

Fig 1 Biological activities of essential oils (EOs) and their derivatives

reported for repellent activity against coleopteran insects (Tripathi *et al.* 2000, Kordali *et al.* 2006, Negahban *et al.* 2007). Certain chemical compounds found in Bay leaves (*Laurus nobilis*) also possess repellent properties against cockroaches (Verma and Meloan 1981). The contact toxicity of oil-in-water formulations of different essential oils (pine oil, lemongrass oil, geranium oil, eucalyptus oil, palmarosa oil and citral) against polyphagus pest whitefly, *B. tabaci* have been reported (Nebapure *et al.* 2022). Palmarosa oil was found to possess highest contact toxicity with LC_{50} and LC_{90} values of 0.241 and 0.658% respectively at 24 h and 0.142 and 0.398% at 48 h after exposure. It was also recorded that geranium oil showed high phytotoxicity at 0.125% concentration in brinjal, *Solanum melongena* (var. MEBH-10) leaves, whereas, the eucalyptus and pine oils were not phytotoxic. Huixing *et al.* (1998) screened 25 plant essential oils against *C. maculatus*. They found that preventing penetration,weight loss and insect reduction after 45 day of the mung been storage were 100%, <0.13% and 99% respectively for *M. paniculata*, *Cinnamomum cassia*, *Pelargonium graveolens*, *Cinnamonum burmannii*, *Carum carvi*, *Foeniculum vulgare*, *Zanthoxylum bungeanum* and after 115 day of the storage the preventing penetration ,weight loss and insect reduction were 100%, 0.87% and 94.92% respectively for *Ocimum basilicum* and *Chenopodium ambrosiokeds* essential oils.

The presence of linalool in grape fruit repels *Anastrepha suspense* female from oviposition in immature grape fruit. Similarly, Limonene present in *Citrus aurantium* is toxic to coleopteran weevil, *Callosobruchus phasecoli* (Jacobson 1982). The EOs of *Cinnamomum camphora*, *C. cassia* and *C. zeylanicum* have repellent action against mosquitoes (Kim *et al.* 2003, Prajapati *et al.* 2005). Chaiyasit *et al.* (2006) determined toxic effect of essential oil of *Curcuma zedoaria* to control mosquito. The chemical compound ocimene is repellent to the leaf cutter ant (Harborne 1987). Carvone present in Apiaceae family plant attracts aphid while linalool acts as repellent (Chapman *et al.* 1981, Harborne 1987). Many monoterpenes and methyl esters are evaluated as repellent and have attractant properties against bark beetle, *Denroctonus* species (Seigler 1983). Presence of a monoterpene in the wood of Western red cedar (*Thuja plicata*) is toxic to larvae of the old house borer (*Hylotrupes bajulus*) (Alfaro *et al.* 1981).

Composition of essential oil and efficacy

EOs are complex mixtures of terpenes (pinene, limonene, p-cymene etc.) and terpenoids such as acyclic monoterpene alcohols (linalool, geraniol), monocyclic alcohols (menthol, terpineol, 4-carvomenthenol etc), monocyclic ketones (pulegone, menthone, carvone), monocyclic oxides (1,8-cineole), aliphatic aldehydes (citral, citronellal), aromatic phenols (thymol, eugenol), bicyclic alcohol (verbenol), bicyclic monoterpenes ketones (thujone), acids (citronellic and cinnamic acid, and esters (linalyl acetate). The condensation of isopentenyl pyrophosphate units results into the formation of major constituents of EOs,

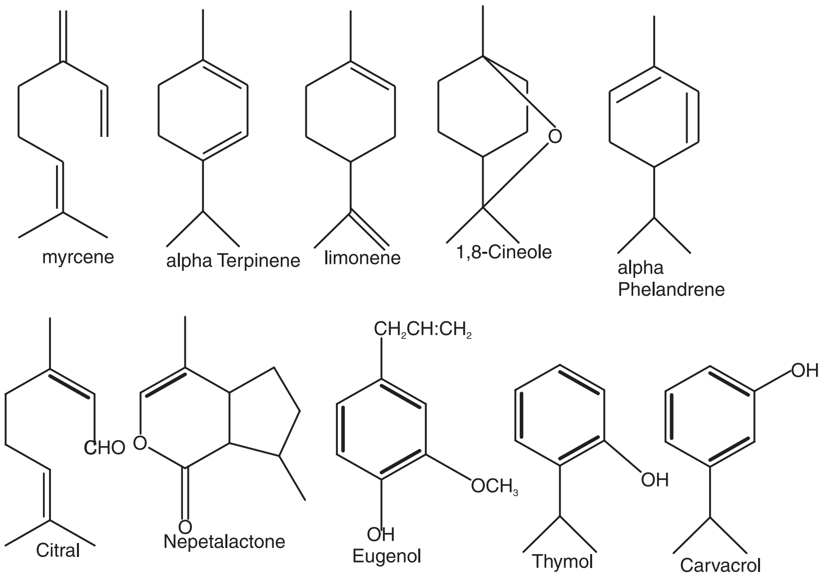

Fig 2 Chemical structures of few terpenoids of EOs.

mono and sesquiterpenoids.Whereas, diterpenes cannot be extracted through steam distillation therefore, diterpenes are not the component of EOs. Fig 2 depicts some of the chemical structures of essential oil constituents that have potential biological activity.

The essential oil constituents present in insecticides and growth inhibitor are lipophilic and act as toxic, antifeedant and deterrents to a number of insects. Various monoterpenoids have been reported to have pesticidal properties against many insect pests (Chintalchere *et al.* 2020). The eugenol was found most effective termiticide against *Coptotermes formosanus* (subterranean termite). It also works as a fumigant with antifeedant in nature. Eugenol is effective against several pests like asian armyworm, granary weevil, common house fly, and corn root worm etc. (LD_{50} = 2.5–157.6 µg/insect) (Lee *et al.* 2001). It is also effective against *Periplanata americana* (Bhatnagar *et al.*1993). Citralis, an acyclic monoterpenoid is found approximately 60–80% in lemon grass. It occurs in the form of mixture of Z (cis) and E.

Mode of action of essential oils

Mode of action in insect: Many molecular investigations have reported that EOs derived from plants act as pesticides and insect repellents. Mostly EOs inhibit the acetylcholinesterase (AChE) and octopamine pathways (Pezzementi *et al.* 2006, Kim *et al.* 2016). Among the various mechanisms AChE inhibition is most common because AChE is major enzyme in nervous system of insects and also plays important role in neuronal communication (Gnagey *et al.* 1987, Marcel *et al.* 1998). AChE inhibition can generate neurotransmitter toxic effects by membrane disruption at post-synaptic junction resulting in nerve current interference (Marrs and Maynard 2013). Likewise, octopamine is also one of the important hormones in insect nervous system (Evans 1980). Inhibition of octopamine causes physiological activity in insect (Evans 1981, Orchard *et al.* 1982). EOs can also inhibit GABA receptors which affect binding of GABARs (GABA receptors) in insects (Sigel and Steinmann 2012). Eugenol, sabinene, 1, 2-dimethoxy-4-(2-methoxyethenyl) benzene, beta-asarone and methyl eugenol rich essential oil derived from *Atalantia monophylla* found reducing protein, esterase, acetylcholine esterase and glutathione s-transferase significantly in pulse beetle *C. maculatus* and rice weevil *Sitophilus oryzae.* Similarly, *Acalypha wilkesiana* leave oil was also found to possess inhibitory effect on SOD, CAT, GPx, AChE, Car EST and GST, antioxidants, neurotransmitters, and enzymes. Studies have shown that enzyme activity has increased at lower dosages of oil extracts (0.2 and 0.4 ml) and has decreased dramatically at higher doses of oil (0.6, 0.8, and 1.0 ml).

Mode of action in fungi: EOs inhibit the growth of fungus in a variety of ways. Disruption of cell wall biosynthesis by preventing the development chitin and glucans. Inhibition of ergosterol by various EOs causes osmotic, metabolic and structural instability in fungus (Kerekes *et al.* 2013). Many of EOs can harm the ATPases activity of fungus by interfering with main functional enzymes associated with mitochondria. The decrease in activity of mitochondrial enzymes, viz. lactate dehydrogenase, succinate dehydrogenase and malate dehydrogenase result in a reduction in mitochondrial content. EOs can also reduce quorum-sensing (QS) activity in fungi by inhibiting cell-to-cell communication including N-acyl homoserine lactones (AHLs), glucan, and tryptophol (Rasmussen *et al.* 2005, Williams 2007).

Fumigants

Due to the low molecular weight and high volatile nature, monoterpenes are suitable for insect fumigants. Linalool, pulegone and limonene are identified to be potential fumigants for management of stored grain pests like rice weevil. Linalool (*Mentha citrate*) exhibited remarkable fumigant toxicity against rice weevils (Singh *et al.* 2008). The fumigant activity of l-carvone is 24 times greater than its contact toxicity to grain borer (Tripathi *et al.* 2003).

Tripathi *et al.* (2001) reported that the carvacrol, carvones, carveol, cinnamaldehyde, citral, citronellal, cinnamic acid fenchone, geraniol, linalool, menthol, menthone, pulegone, terpineol, thymol, thujone, verbenol and verbenone exhibit their fumigant property against *Musca domestica* and *T. castaneum*. The fumigation toxicity of 12 synthetic allelochemicals was tested against adult pulse beetles, *C. maculatus,* and *C. chinensis.* Acetophenone and cis-jasmone were shown to be the most efficient fumigants against adult beetles of *C. maculatus* and *C. chinensis* (LC_{50}=0.23-0.33 µl/250 ml air). Among all the compounds examined, cis-jasmone was shown to be the most effective oviposition inhibiting volatile (Nebapure and Chitra 2019).

GC-MS profiling of *Murraya paniculata* leaf essential oil revealed Aromadendrene (23.9%), Germacrene-D (23.3%), β- caryophyllene (17.2%) and Humulene (4.28%) as major constituents. This essential oil possessed fumigant toxicity against egg, larval and adult stages of almond moth *Cadra cautella* after 48 and 72 h of the exposure period (Nazari *et al.* 2022)

Li *et al.* (2010) evaluated the essential oil of *M. exotica* against *Sitophilus zeamais* and *T. castaneum.* They found that essential oil of the plant has fumigant toxicity against *S. zeamais* and *T. castaneum* adults with LC_{50} values of 8.29 and 6.84 mg/l, respectively. Al-Sarar *et al.* (2014) reported the fumigant toxicity of essential oils extracted from *Mentha longifolia* and *Lavandula dentate* against *C. maculatus* with the LC_{50} values 4.43 and 7.92 µl/l and anti-acetylcholin esterase activity with LC_{50} values of 1.01 and 9.74 µl/ml. The contact and fumigant behavior of *Cinnamomum zeylanicum* essential oil and its two constituents, cinnamaldehyde and linalool, against two stored pests, *C. maculatus* and *S. Oryzae* was studied by Brari and Thakur (2015). Ajayi *et al.* (2014) have examined the fumigant toxicity of eight essential oil components, viz. 1-8-cineole, carvacrol, eugenol, menthone, linalool, S-limonene, β-pinene, and α-pinene to pulse beetle, *Callosobruchus maculatus* at 0.25–60 µl/l of air. 1-8-Cineole, carvacrol, and eugenol induced maximum adult mortality at a dosage of 10 µl/l of air after 24 h exposure. 1-8-Cineole and carvacrol were found to be most toxic at 24 h, respectively with LC_{50} values of 0.24 and 0.6 µl/l air. β-Pinene and α-pinene were the least toxic at 24 h, respectively, with LC_{50} values of 31 and 31.4 µl/l. The experiments also showed that vapour pressure was negatively associated with the toxicity. Similarly, Wahba *et al.* (2018) investigated the fumigant and admixing toxicity of four monoterpenoid compounds namely eugenol, isoeugenol, carvacrol and thymol against the *C. maculatus.* Fumigant toxicity of eugenol and carvacrol presented the highest toxic effect with LC_{50} values of 34.58 and 37.34 mg/l air, respectively after 72 h exposure time, while thymol achieved moderate toxicity with LC_{50} values of 45.32 mg/l air. For the second method, admixing with cowpea seeds test, thymol and carvacrol achieved the highest toxicity values with LC_{50} of 0.46 and 0.53 mg/g seeds after one week of exposure time, followed by eugenol (1.75 mg/g). The data indicated that isoeugenol was the lowest effective compound. Also, thymol detected the highest efficacy when it was admixed with seeds than fumigant. In contrast, eugenol achieved the high activity as fumigant rather than admixing method.

Antifeedants

Antifeedant are compounds that cause deterrent to insect from feeding once they come in contact. The α-terpineol, citronellal and thymolare act as effective antifeedants against *Spodoptera litura* (Tak and Isman 2017). Essential oil from *E. camaldulensis* was found as bio-efficient for management of larvae of *Spodoptera litura*. Linalool (*L. scandans)* and 1,8-cineole (*E. camaldulensis)* species have been identified as most effective ingredients. Linalool was effective with LD_{50} of 85.5 µg/larva whereas 1,8-cineole was found effective with LD_{50} of 126.6 µg/larva. When applied in 1:1 ratio, 1,8-cineole synergized the impact of linalool at an application rate of 18 µg/larva. Linalool with 1,8-cineole also showed synergistic effects.The antifeedant test of 1,8- cineole was conducted against *T. castaneum* (Tripathi *et al.* 2001). Carvone and dihydrocarvone monoterpene constituents of *Curcuma longa* showed the antifeedant activities against grain borer, red flour beetle and rice weevil (Tripathi *et al.* 2003). *Curcuma longa* and *Zingiber officinale* oils reported effective insect antifeedant and IGRs (Agarwal *et al.* 2000, Chowdhury *et al.* 2000, Agarwal and Walia 2003).The antifeedant and insect growth regulator (IGR) activities of a chloroform extract of Glory lily (*Gloriosa superba*) seed extract were found to be the most effective against *Spodoptera litura* (Nebapure *et al.* 2015). Another study found that extract from lily tubers was effective as an antifeedant against fall armyworm, *Spodoptera litura* (Nebapure *et al.* 2016). The potential of *Murraya paniculata* leaf extracts against leaf-eating caterpillars and almond moth was investigated. Hexane extract had the most antifeedant action against *S. litura,* while methanol extract had the highest antifeedant activity against almond moth (Nazari *et al.* 2021).

Repellents

Repellent nature of EOs of eucalyptus, geranium, lemon, and lavender has been reported against castor bean tick (Jaenson *et al.* 2006). In addition to this, plants (basil, cinnamon, geranium, lavender, pine, cedar, pennyroyal, rosemary, citronella, thyme, peppermint and verbena) showed repellent activity. Most of these EOs showed repellencies for short time (less than 2 h). The mosquito repellent activity against *Culex* species of many monoterpenes constituted EOs is well known. The mosquito *A. aegypti* was used to test several essential oils for their *in vitro* repellent capabilities. The EOs of *Cymbopogon nardus*, *Syzygium aromaticum*, *Zanthoxylum limonella* and *Pogostemon cablin* were identified as most efficient amongst all with their repellency lasting up to two hours (Choi *et al.* 2002).

Oviposition inhibitors and ovicidal action

Majoram and 1,8-cineole application at a concentration of 1% lead to 30–50% downfall in oviposition rate (Djebir *et al.* 2019). Garlic oil was identified to be an impactful deterrent for oviposition of *P. xylostella* (Govindaraddi 2005) and it has been studied that application of bael (*Aegle marmelos)* essential oil at the concentration of 250 mg oil per 50 eggs decreases the hatching of *Spilosoma oblique* eggs upto 99.5% (Tripathi *et al.* 2003). Surface treatment of the EOs of L-carvone at the rate of 7.22 mg/cm^2 lead to a total suppression of hatching of *T. castaneum* eggs. Various terpenoids such as carvacrol, carvones, cinnamic acid, cinnamaldehyde, citral, carveol, citronellal, fenchone, geraniol, linalool, menthol, thymol, verbenol and other have been evaluated as ovicidal against *M. domestica* eggs (Tripathi *et al.* 2003). The contact toxicity and ovipositional deterrent activity of lemongrass and citral against *Bemisia tabaci* (Whitefly) have been reported. After 48 h, mortality from lemongrass oil and citral was 35.2–90.12% and 28.58–82.2%, respectively, compared to control. Citral has been identified as a bioactive molecule, responsible for the mortality and ovipositional deterrent activity of the oil against *B. tabaci* (Mondal *et al.* 2021a). The potential of *Eucalytpus globulus* leaf extracts against *B. tabaci* was investigated. Essential oil was discovered to be extremely harmful to whiteflies. *E. globulus* oil contains the bioactive compound 1,8-cineole, which has insecticidal and oviposition preventive properties (Mondal *et al.* 2021b).

Attractants

Many EOs have been extracted and tested as attractants against the different types of insect pests. Amongst which, eugenol and geraniol are proved to be good attractants. These can be used as baits in traps to attract the Japanese beetle, whereas methyl-eugenol is used to attract the oriental fruit fly (Vargas *et al.* 2000). Some other compounds like cinnamyl alcohol, cinnamaldehyde, geranylacetone and α-terpineol were tested as attractant against the maize rootworm beetles (Hammack 1996). Lemongrass essential oil contains several geraniol and terpenes found effective against various sucking pest such as thrips, and mealybugs etc. The use of lemongrass oil on yellow and blue traps can attract pests. The compositions of cis-jasmone have been found as effective attractant to adult lepidoptera.

Antifungal agents

Few EOs were analyzed for their antifungal activity against *Fusarium moniliformi* and *F. oxysporum* (Bowers and Locke 2000), *Botrytis cinerea* (Wilson *et al.* 1997), *Aspergillus niger* (Paster *et al.* 1995), *R. solani, F. solani, Bipolaris oryzae*, and *Pythium ultimum* (Daferera *et al.* 2000). In comparison to insects, more stable results were found in various fungal species. Amongst all the evaluated EOs, the carvacrol and thymol were identified as highly efficient to majority of the fungal pathogens. The exact mechanism of action of these compounds towards fungi isn't really specified but it might be attributed to their basic capability to breakdown or damage the cohesion of cellular membranes (Isman and Machial 2006).

Antiviral agents

The volatile oils and pure extracts from the plants were discovered to help the host in combating with virus infections. The tobacco mosaic virus (TMV) infection on tobacco (*Nicotiana glutinosa)* were significantly reduced by application of the EOs of *Melaleuca alternifolia* (Bishop 1995). Similarly, EOs from *Carum copticum*, *Ageratum conyzoides*, *Peperomia pellucida*, *Ocimum sanctum* and *Callistemon lanceolatus* were found effective against cowpea mosaic virus (CMV) and mung bean mosaic virus (MBMV). According to Ray *et al.* (2000), the application of 3000 ppm concentration of *Ocimum sanctum* essential oil resulted in a greater suppression of infection of different viruses such as MBMV (90%) and CMV (89.6%).

Phytotoxicity and safety of EOs

Natural products safety is also important than synthetic molecules of pesticides. Therefore, phytotoxicity of EOs need serious concern while formulating products for agricultural and landscape use (Lindberg *et al.* 2000) because usually natural products used for insect pests management are not always subject to testing. Repellents may have an progressively important role in eradicating insects from institutions, clinics and cooking areas. Most of the commercial EOs are counted in the GRAS list fully permitted by FDA and EPA in USA for food and beverage consumption (EPA 1993). Nevertheless, this does not safeguard that the preparation or product will work successfully as formulated by a specific producer. The least important of these ranges from quite minor misunderstandings in providing misinformation to consumers. For example, oil of eucalyptus promoted for use against mosquitoes can serve as an attractant for another blood feeding pest (Braverman and Mullens1999). Plants produce an extensive variety of insect toxins which may be hazardous to mammals as well as insects (D'Mello 1997). For example, oil of *Melaleuca alternifolia* has been utilized in Australia as traditional mixture for insect bites (Budhiraja *et al.* 1999). The common problematic response of tea tree oil is contact dermatitis and reported more than 30 human cases (Hausen *et al.* 1999). Thujonein Eos of *Artemisia absinthium* is strong neurotoxin affecting the GABA system (Hold *et al.* 2000). Likewise *Mentha pulegium* oil contains pulegone which is oxidized by cytochrome P-450 system into methofuran (Nelson *et al.* 1992) and such metabolites attach to proteins and result in severe poisoning, convulsions, and loss of organ function (Burkhard *et al.* 1999). In dogs and cats, melaleuca oil toxicosis has been linked to depression, trembling muscles, weakness and loss of coordination (Villar *et al.* 1994). D-limonene which is a component of a number of EOs namely, grapefruit, mandarian, orange, lemon has been reported to cause dermatitis (Nilsson *et al.* 1999). Therefore, commercialization of the essential oil-based pesticides should undergo rigorous registration process.

Commercialization of essential oil-based pesticides

There are few of the products available as commercial formulation. Mycotech Corporation produces Cinnamite™ (cinnamaldehyde 30% EC), is an insecticide cum fungicide for horticultural and glasshouse crops and Valero™ is an acaricide/fungicide used in citrus, nut, grape, and berry crops. Ecosmart technologies produce dust and aerosol formulations comprising proprietary mixtures of EOs molecules, including eugenol and 2-phenethyl propionate to control household pests. D-limonene formulation and citronellal is utilized against mosquito as repellents. Commercial products, viz. Buzz Away® (oils of lemongrass, citronella, eucalyptus and cedarwood), Green Ban® (oils of cajuput, safrole free sassafrass, citronella, etc.) and

Sin-So-Soft® (various oils and stearates) are formulated time to time (Chou *et al.* 1997). Commercial products for agriculture are used in certain European countries like BIOXEDA (clove based fungicide/bactericide), BIOX-M (*Mentha spicata* based growth regulator) and LIMOCIDE-OROCIDE-PREV-AM and ESSEN'CIEL (Sweet orange based insecticide) (Raveau *et al.* 2020).

Though, the EOs commercial product is an important area of concern and it may be influenced by various factors, viz. physical, chemical and biological properties of the substances as well as mode of applications. Hence, it is important to develop and commercialize essential oil-based pesticides while taking all the utmost care.

Advantages and disadvantages

EOs are comparatively non-toxic to mammals, fish and low toxic to non-target organism than commercial synthetic pesticides. These compounds have less residual activity and very low chance of insect resistance development. These compounds are eco-friendly and can be compatible with Integrated Pest Management as green or safer pesticides. Some of the limitations include, EOs have less efficacy and regulatory approval takes more time. They require (>1% a.i.) more dose, repeat and frequent application. They have high cost for extraction and less quantity is obtained from the plant materials. A large amount of production is required to make its commercial application.

Conclusion

EOs are known for broad spectrum and diverse activities towards insect pest and act as repellents, insecticides, antifeedants and deterrents to oviposition, attractants, growth regulators, antiviral and antifungal. In toxicological tests, they are comparatively non-hazardous to fishes and mammals. EOs as "green/safer pesticides" can indeed be beneficial in management of pests in agriculture, especially in organic farming. Pesticides derived from EOs have been proven to be successful against a wide variety of storage pests, household pests, agricultural pests. These pesticides could be used as fumigants, oviposition deterrent and/or insect repellent, in granular formulations or direct contact sprays. Resistance emergence is a biggest concern of most chemical pesticides, however resistance to essential oil-based pesticides is expected to evolve quite slowly. In the developing nations which have abundant native plants biodiversity, these pesticides could potentially have the strongest influence on the Integrated Pest Management (IPM) strategies.

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