PLANT ESSENTIAL OILS TO THE RESCUE–AN EPIC BATTLE WITH BIOPESTICIDES FOR PEST CONTROL IN AGRICULTURE

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Abstract. Overuse of synthetic pesticides can harm the ecosystem, develop insect resistance, and endanger a variety of non-target species, such as humans, animals, and plants, if they are not applied based on the safety instructions. The agricultural and public health sectors have begun to advocate bio-insecticides as a substitute for synthetic insecticides. Plant-based biopesticides are becoming more and more popular due to their selective targeting, low environmental impact, biodegradability, and safety for non-target species. This article summarizes recent research examining the application of essential oils as biopesticides and discusses the challenges associated with their use. Prospects for bioinsecticides application in modern agriculture are available in low number of commercial biopesticides based on plant essential oils. They are effective against a wide range of insects due to their diverse mechanisms of action and points of action. Many problems, such as declining stability and efficacy of essential oils in different environmental settings, need to be managed before plant essential oils are extensively employed as commercial biopesticides. Plant-based alternatives are thus already beginning to replace xenobiotics; these bioproduct-based companies will broaden their product offerings and replace xenobiotic usage with plant-based biopesticides.
Keywords: *bioinsecticide, IPM, pesticides, plant extracts, sustainable agriculture*

Abbreviations: PEO, plant essential oil; VOCs, volatile organic compounds; NE-EOs, nanoencapsulated essential oils; PDI, polydispersity index; PEG, polyethylene glycol

Introduction

The world's food supply must expand 50% by 2050 to feed its growing population with the current condition of climate change and limited availability of cultivable land. Modern agricultural systems now require the use of pesticides to protect crops from diseases and pests (Rosegrant et al., 2024). Brazil used an estimated 719.51 thousand metric tons of pesticides in 2021 (*Fig. 1*), which is more than in any other country. Following that came the United States with 457.39 thousand tons consumed. Pesticide use worldwide in that year amounted to 3.53 million metric tons. Between 1990 and 2021, the number of pesticides used in agriculture increased globally by 96%. 1.7 million metric tons of herbicide were consumed worldwide in 2021, compared to less than a million metric tons of other pesticide categories. Pesticide use in agriculture is expected to rise over the next four years, from about 4.3 million metric tons (Mmt) in 2023 to a value of around 4.41 Mmt in 2027, on a global scale (Statista, 2023).

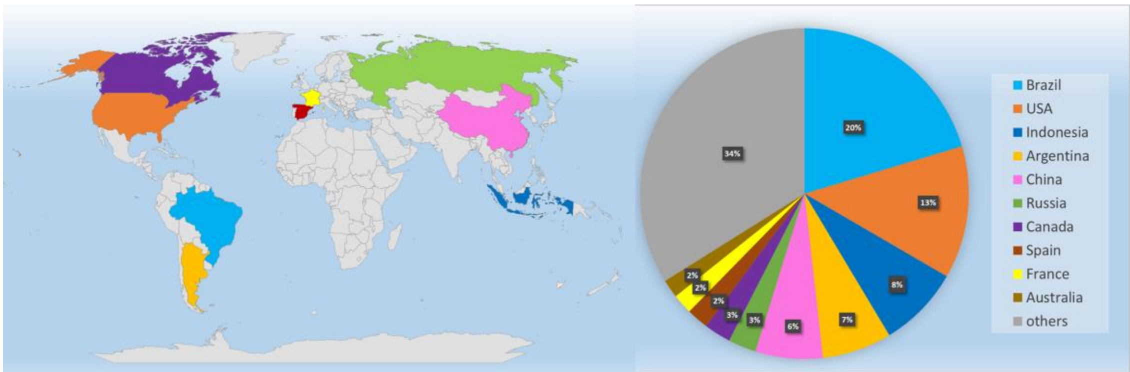

Figure 1. *Leading countries in pesticide consumption in 2021 (Statista, 2023)*

Extended use of synthetic pesticides has left residues affecting many environmental factors. Synthetic pesticides used frequently can damage the environment, lead to the emergence of pest resistance and pose risks to a number of nontarget species viz., people, animals and plants. There is a "widespread worldwide pesticide contamination risk," according to a study that was published in Nature GEO science and looked at over 100 agrochemicals used in 168 different countries (Raj et al., 2023). Therefore, a sustainable strategy requires the investigation of workable eco-friendly alternatives. As a result, bio-insecticides have been promoted as an alternative to synthetic insecticides in the agricultural and public health sectors (Mossa, 2016). Due to their target specificity, environmental friendliness, biodegradability, and safety for people and other living things, plant-based biopesticides are garnering a lot of attention in this area. Plant essential oils (PEOs) or their active components are among the important biopesticides that are being extensively researched for use against weeds, pests, and microbes (Gupta et al., 2023).

Many of the important natural components found in essential oils and plant extracts can be utilized safely in pest and disease control because of their tendency to degrade in nature (El Khetabi et al., 2022). Regardless of their benefits, barely 5% of the world's pesticides are biopesticides (Kumar et al., 2021; Rakshit et al., 2021). However, biopesticides are expanding quickly and are expected to surpass chemical pesticides in the near future with an average yearly growth rate of 9–20% (Lahlali et al., 2022). Byproducts of essential oil extraction that are used in the manufacture of nanopesticides can be good sources of reducing and stabilizing agents. A surprising lack of commercial biopesticides based on essential oil presents prospects for their use in contemporary agriculture (Pavela and Benelli, 2016). This article provides a summary of the most recent studies on the use of essential oil as biopesticides and also the difficulties in employing essential oils as biopesticides.

Materials and methods

This review extensively utilized updated scientific databases, including Science Direct, Elsevier, ANSInet, Web of Science, PubMed, Springer, Taylor & Francis, Wiley Online Library, and Google Scholar. Additionally, textbooks, local publications, statista

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and conference proceedings were consulted to supplement the data. Over 76 papers and studies were meticulously reviewed to gather comprehensive information on the application of essential oils as biopesticides in agriculture. The selection process involved screening based on predefined inclusion criteria related to essential oils, types of bioactive compounds, and their applications. EndNote software was utilized for efficient reference management, while figures were created using Microsoft PowerPoint and Microsoft Excel.

Plant essential oil

Theophrastus von Hohenheim, frequently referred as Paracelsus, a Swiss physician, first used the word “essential oil” in 1523, when he was attempting to separate the “Quinta essentia” of several herbal remedies. The term “essential oil” can also refer to volatile, etheric, or aetheroleum oils. They are developed in aromatic plants where mixtures of volatile substances, known as secondary metabolites, are created. In other words, essential oils are concentrated liquids that are hydrophobic or hydrophilic and include volatile molecules from plants that are aromatic or aliphatic. An aromatic, highly concentrated oil derived from plants that may be extracted using pressure, hydro diffusion, or steam distillation. Gas chromatography combined with mass spectrometry (GC-MS) is typically used to identify the constituents of an essential oil (Oladipupo et al., 2022).

The majority of essential oil extractions are carried out via distillation, solvent extraction or expression. The most used extraction method is distillation which uses water in either the liquid or steam phase or both. Steam or water distillation is used for removing them from the plant. The volatile components are drawn into the plant by water and then condense into a water - oil separation. Essential oils often have densities that are lower than that of water (Perricone et al., 2015).

The climate in which the plant is harvested as well as the validity of the extraction determine the composition of virgin oil (Price and Price, 2011). The establishment of a chemotype within one kind of plant can be influenced by various factors such as weather, animals, insects, coexisting vegetation, and geographic location. This can ultimately impact the substances that are extracted and identified in a plant’s essential oils. Their distinct physical, chemical, and biological characteristics are a result of the hundreds of diverse compounds that make them up. Furthermore, the extraction of aromatic plants with organic solvents may yield oleoresins; carbon dioxide may be used to make better extracts without the need for solvents (Mossa, 2016).

Chemical composition of essential oil

The volatile essential oil chemicals can be divided into four groups: Terpenes, Benzene derivatives, Hydrocarbons, and other unrelated compounds. Essential oils are categorized into Hemiterpenes (C5), Monoterpenes (C10), Sesquiterpenes (C15), Diterpenes (C20), triterpenes (C30) and tetraterpenes (C40) based on the amount of isoprene units in their chemical structures. Additionally, terpenoids or oxygenated terpenes have extra functional groups like ester, alcohol, and carboxylic acid, among others (Bakkali et al., 2008).

Acyclic alcohols like linalool, geraniol, and citronellol, Cyclic alcohols like menthol, isopulegol, and terpeniol, Bicyclic alcohols like borneol and Verbenol are among these chemical structures, Phenolic substances like thymol and carvacrol, Ketones, including

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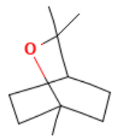
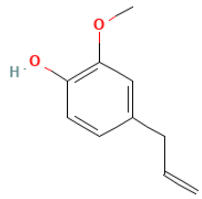
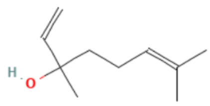
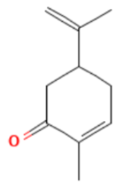
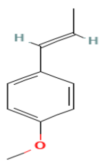
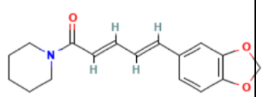
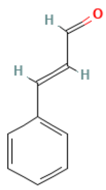
thujone, menthone, and carvone, Citronellal, citral, Acids like chrysanthemic acid are aldehydes and Oxides like cineole (Mossa, 2016; Tripathi and Vibha, 2009; Isman, 2016; Raghavan, 2006). Some of the major constituents of common essential oil-bearing crops is given in *Table 1*.

Table 1. *Common essential oil-bearing plants and their primary components*

Crops	Scientific name	Primary constituents	Molecular structure	Molecular formula
Indian bay leaves Cardamom Eucalyptus Rosemary Sage	*Cinnamomum tamala* *Elettaria cardamomum* *Eucalyptus globulus* *Rosmarinus officinalis* *Salvia officinalis*	1,8-cineole		$C_{10}H_{18}O$
Allspice Clove	*Pimenta dioica* *Syzygium aromaticum*	Eugenol		$C_{10}H_{12}O_2$
Coriander Sweet Basil	*Coriandrum sativum* *Ocimum basilicum*	Linalool		$C_{10}H_{18}O$
Caraway Dill leaf	*Carum carvi* *Anethum graveolens*	Carvone		$C_{10}H_{14}O$
Star anise Fennel	*Illicium verum* *Foeniculum vulgare*	Anethole		$C_{10}H_{12}O$
Black pepper	*Piper nigrum*	Piperine		$C_{17}H_{19}NO$
Cinnamon	*Cinnamomum verum*	Cinnamaldehyde		C_9H_8O

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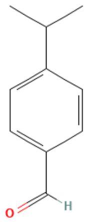
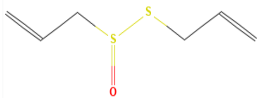
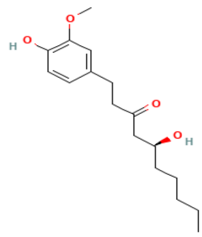
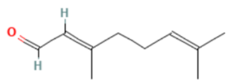
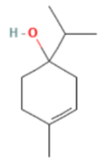
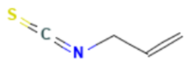
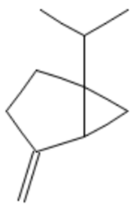
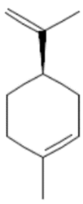
Cumin	*Cuminum cyminum*	Cuminaldehyde		$C_{10}H_{12}O$
Garlic	*Allium sativum*	Allicin		$C_6H_{10}OS_2$
Ginger	*Zingiber officinale*	Gingerol		$C_{17}H_{26}O_4$
Lemongrass	*Cymbopogon citratus*	Citral		$C_{10}H_{16}O$
Marjoram	*Origanum majorana*	Terpinen-4-ol		$C_{10}H_{18}O$
Mustard	*Brassica nigra*	Allyl isothiocyanate		C_4H_5NS
Nutmeg	*Myristica fragrans*	Sabinene		$C_{10}H_{16}$
Orange	*Citrus sinensis*	d-limonene		$C_{10}H_{16}$

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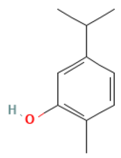
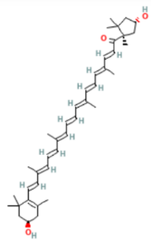
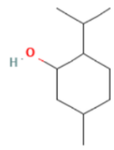
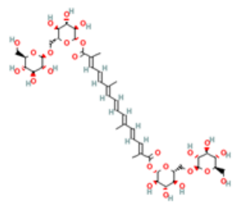
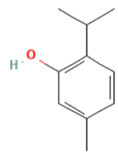
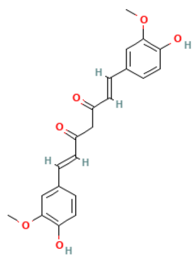
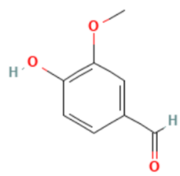
Oregano	*Origanum vulgare*	Carvacrol		$C_{10}H_{14}O$
Paprika	*Capsicum annuum* var. *Longum*	Capsanthin		$C_{40}H_{56}O_3$
Peppermint	*Mentha piperita*	Menthol		$C_{10}H_{20}O$
Saffron	*Crocus sativus*	Crocin		$C_{44}H_{64}O_{24}$
Thyme	*Thymus vulgaris*	Thymol		$C_{10}H_{14}O$
Turmeric	*Curcuma longa*	Cucurmin		$C_{21}H_{20}O_6$
Vanilla	*Vanilla planifolia*	Vanillin		$C_8H_8O_3$

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Benefits of essential oils

PEOs have historically been employed in the food and perfume industries. Scripts from a variety of historical periods, including India 5000 BC, Mesopotamia, and Greece 3000 BC, documented the extraction and use of essential oils (Dima and Dima, 2015).

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More than 3000 components have been identified in approximately 17,500 aromatic plant species that are grown worldwide (Maddocks-Jennings et al., 2005). The fragrance and flavor industries have traditionally used PEOs. Recently, the popularity of their usage in aromatherapy has increased markets for suppliers of essential oils. Although the traditional use of numerous plants and their preparations to ward off insects and other pests has been well-documented, there are very few commercially successful repellents, much less insecticides, based on PEOs before the late 1990s (Isman et al., 2011). Since its discovery, essential oils have been employed in cult rites, as culinary tastes and additions, as well as in pharmaceuticals, aphrodisiacs, cosmetics, and other products. Essential oils are currently drawing more attention for both research and various kinds of applications. Due to its numerous applications (*Fig. 2*) in food, medicine, cosmetics, fragrances, aromatherapy, and agriculture, essential oil demand is at an all-time high (Calo et al., 2015).

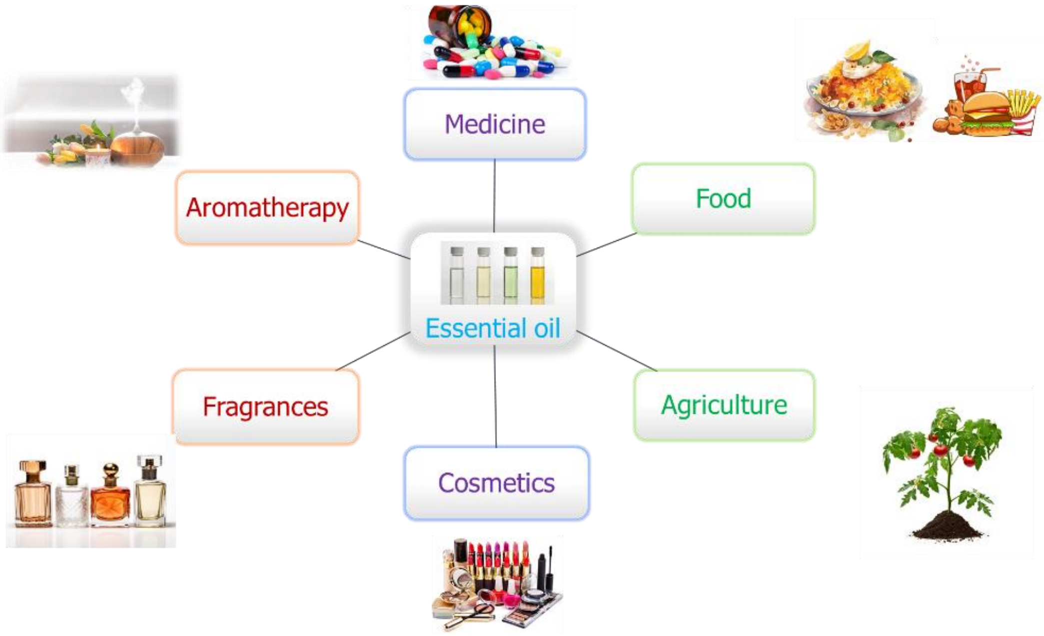

Figure 2. *Industrial applications of essential oils*

The widespread use of plant essential oils in medicines and foods generally suggests that they are not particularly hazardous to mammals. A majority of essential oils and their active ingredients have been shown to be safe for mammals. A few noteworthy exceptions were discovered, though (Isman et al., 2011). For instance, *Mentha pulegium*, pennyroyal oil is said to be poisonous to both people and animals (Miguel, 2010).

Biopesticides

The regulatory restrictions and increase in pest resistance, leads to the fall of synthetic pesticides. Bio-insecticides have emerged as a synthetic pesticide substitute in the agricultural and public health sectors (Khater, 2012). Due to their appeal among organic growers and consumers who care about the environment, essential oils are

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typically regarded as low risk insecticides that has witnessed a considerable increase in use over the past few years (Sharma et al., 2023).

All-natural substances like plant extracts, essential oils, etc. that can lower the insect population and boost food output are referred to as “green pesticides” (Mossa, 2016). Subsequently, there are a few characteristics of essential oils that make them useful for managing insects (Isman et al., 2011). Since they have a variety of modes of action and sites of action, they have broad activity against many insects. They are insecticidal, deterrent, fumigant, antifeedant, and attractive among other things. Essential oils and its components are non-toxic to mammals. They have a relatively short residual half-life on plants. The essential oils can be used as pesticides straight out of the bottle, as its “active ingredient” or as co-adjutants in other pesticide formulations (Mossa, 2016).

Because of their lipophilic chemical composition essential oils can penetrate insects and result in metabolic malfunction and mortality (Lee et al., 2004). Molecular weights, the point of entrance of the toxin and the mechanisms of action are the elements that influence the toxicity of an essential oil (Kim et al., 2010; Carrasco et al., 2016; Abou-Taleb et al., 2016). The effects of essential oils on ecosystems and human health appear to be less severe than those of synthetic plant protection products (PPP), which are classified under the US Food and Drug Administration’s Generally Recognized as Safe (GRAS) product categories (Koul et al., 2008). Programs for integrated pest management may include essential oils and plant extracts (Santana de Oliveira et al., 2021).

The effectiveness and usability of essential oils as environmental friendly and long-lasting biopesticides by demonstrating their herbicidal, insecticidal, acaricidal, nematicidal, and antibacterial activities (Assadpour et al., 2023). The pesticidal properties of some essential oil are given in *Table 2*.

Table 2. *Some essential oil-bearing plants with pesticidal properties*

Essential oil crop	Pest/micro-organism	Reference
Piper nigrum	*Blattella germanica*	(Peterson et al., 2002)
Carum copticum	*Sitophilus oryzae* *Tribolium castaneum*	(Sahaf et al., 2007)
Carum carvi	*Sitophilus oryzae*	(López et al., 2008)
Cinnamomum camphora	*Rhyzopertha dominica* *Cryptolestes pusillus*	(López et al., 2008)
Coriandrum sativum	*Sitophilus oryzae* *Rhyzopertha dominica* *Cryptolestes pusillus*	(López et al., 2008)
Artemisia sieberi	*Plutella xylostella*	(González et al., 2014)
Cymbopogon flexuosus, *Cymbopogon martini,* *Cymbopogon nardus*	*Acharia fusca* *Euprosterna elaeasa*	(Hernández-Lambraño et al., 2014)
Cinnamomum verum *Cupressus sempervirens* *Thymus vulgaris*	*Botrytis cinerea*	(Rguez et al., 2018)
Origanum vulgare	*Bjerkandera adusta*	(Kapustová et al., 2021)
Amphineuron opulentum, *Cassia alata* *Cassia tora,* *Murraya paniculata* *Tithonia diversifolia*	*Oligonychus coffeae*	(Deka et al., 2022)

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Insecticidal activity

Essential oils and plant extracts have been subjected to a number of bioassays to show promise for controlling certain important insect and mite populations. The essential oils derived from *Artemisia* species show insecticidal effect against some insects, such as coleopteran beetles. They operate as an insect repellant and have vapor toxicity (Kordali et al., 2006). Research evidences revealed that, piperitone has insecticidal effects on *Callosobruchus maculatus* and trans-ethyl cinnamate has antifeedant effects. But *Spodoptera littoralis* was resistant to both piperitone and trans-ethyl cinnamate, both of which were derived from *Artemisia judaica* essential oil (Abdelgaleil et al., 2008; Ketoh et al., 2006). The *Vinca rosea* and *Callistemon lanceolatus* essential oils and their combinations against *Helicoverpa armigera* showed the strongest antifeedant efficacy (Halder et al., 2012).

The Western red cedar, *Thuja plicata,* produces monoterpenes (e.g., β-thujaplicin) that have insecticidal activity against the larvae of the old-house borer, *Hylotrupes bjulus.* In contrast, *Reticulothermes flavipes* termites showed only weak insecticidal activity when exposed to α and β -thujaplicin (Mossa, 2016). The efficacy of black pepper, *Piper nigrum* extracts against green peach aphids *(Myzus persicae)* was found to be 80%, and the efficiency may be increased to 98.33% through its synergistic actions with other plant extracts (Ahmed et al., 2021). The use of *Thymus zygis, Thymus vulgaris,* and *Mentha suaveolens* essential oils were identified as potent ixodicidal and anti-feedant agents. Further these plants can be developed as biopesticides to successfully manage ticks and insect pests (Valcárcel et al., 2021).

Fungicides activity

Research on potential herbal remedies for plant diseases is widespread. For instance, the effects of *Thymus vulgaris* and *Cinnamomum verum* essential oil and *Cupressus sempervirens* essential oil on managing the grey mold in tomatoes caused by *Botrytis cinerea* are documented by (Perumal et al., 2016). The *Cupressus sempervirens* oil’s main ingredients, α-pinene, α-cedrol, and β-caryophyllene, had the highest levels of antifungal activity (Rguez et al., 2018; Ismail et al., 2013). In a petri plate assay, 38 PEOs significantly inhibited mycelial growth and spore germination in fungal pathogens of common pulses, including *Aphanomyces euteiches, Botrytis cinerea, Colletotrichum lentis* (Parikh et al., 2021).

Potentially hazardous oomycetes, such as *Phytophthora,* have been investigated for resistance to volatile organic compounds (VOCs) from soybean plants. *Phytophthora sojae,* the cause of soybean root rot, and *Phytophthora nicotianae* cause of black shank, were simultaneously injected with VOCs, which predominately contained 4-ethylphenol. VOCs inhibited the growth of infections by causing damage to their cell membrane. These VOCs are ideal for simultaneously controlling major soil borne diseases because they have strong antifungal activity against other soil-borne phytopathogenic fungi like *Rhizoctonia solani, Fusarium graminearum, Gaeumannomyces graminis var tritici,* and *Fusarium oxysporum* (Ge et al., 2021; Lahlali et al., 2022).

Nematicidal activity

Very few bioactivity evaluation bioassays using various essential oils and plant extracts have been conducted on regulating distinct nematode populations, in contrast to

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research on insects and mites. *Citrus sinensis*, *Cymbopogon nardus*, and *Melaleuca alternifolia* have been found to have nematicidal potential against the cotton root-knot worm, *Meloidogyne incognita* (Kundu et al., 2021). Garlic *(Allium sativum)* and cinnamon *(Cinnamon cassia)* essential oils had the most potent nematicidal activity against juvenile phase of *Meloidogyne incognita* (Jardim et al., 2020, 2018). Juvenile phase of the fake root-knot nematode, *Nacobbus aberrans* was effectively eliminated by *Pimpinella anisum* and *Origanum vulgare* essential oils (Sosa et al., 2020).

Herbicidal activity

In actuality, allelopathic interactions and allelochemicals control the weedicide properties of essential oils (Batish et al., 2006). PEOs of *Eucalyptus citriodora*, *Lavandula angustifolia* and *Pinus sylvestris* were found to be efficient at controlling weeds. Camphor, 1,8-cineole, and linalool were the main active compounds, which helps to eradicate the weeds (Ibáñez and Blázquez, 2019). The phytotoxic effect on the germination and growth of several weeds viz., *Sonchus arvensis*, *Lolium rigidum*, *Trifolium campestre and Phalaris canariensis* has been reported on aqueous PEOs of *Pinus radiata* and *Cupressus sempervirens* (Ismail et al., 2021).

Management of storage pests

The volatile oils are often employed in agriculture mostly in greenhouses and food storage as a fumigant against insects (Ebadollahi et al., 2010). The rapidly penetrating and non-toxic residues left behind by the treated items give essential oil a broad range of effectiveness against a variety of insects. The Indian meal moth, *Plodia interpunctella*, and the Mediterranean four moth, *Ephestia kuehniella* are significant stored-product insect pests that seriously harm processed foods including nuts and grains (Jesser et al., 2020). A range of cyclohexenone compound have toxicity (LC50) against *Plodia interpunctella* larvae and adults in a fumigant toxicity bioassay. Seudenone have an LC50 against *P. interpunctella* larvae and adults. These findings show that these essential oils are more harmful to *P. interpunctella* larvae than to adults (Park and Lee, 2018).

Management of urban insects

Urban insect is an invasive species that tends to spread and destroy the environment of urban human society, both financially and health-wise. The common bed bug, *Cimex lectularius* L., and the tropical bed bug, *Cimex hemipterus*, are two species that are significant ectoparasites of humans and occasionally other animals (Liu et al., 2014). In a treated surface bioassay, the essential oil from *Oreganum vulgare* leaf had an EC50 i.e., effective concentration necessary to generate 50% repellency against the common bed bug, *Cimex lectularius* after 24 h and 100% repellency after 3 h when 10% of the essential oil was utilized (Sharififard et al., 2018). *Piper nigrum* essential oil had 49 and 55% repellency after 12 h, against *Blattella germanica* nymphs and adults, respectively (Wagan et al., 2017). When Lamiaceae essential oils were employed, similar effects against *B. germanica* nymphs and adults were observed (Peterson et al., 2002).

The essential oil of vetiver oil, *Vitiveria zizanioides* and its components have shown a variety of mosquito-repelling properties. β-caryophyllene oxide, vetiver oil and their binary combinations were assessed their ability to repel four mosquito species. Regardless of the test settings or species, the compound combinations induced a

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substantially stronger reaction in the mosquitoes than single compounds. Combination of binary combinations + Vetiver oil (1:2) with *Anopheles minimus* and *Culex quinquefasciatus* produced the strongest synergistic effect (Nararak et al., 2022) International products like EcoSMART - ant and roach killer and mosquito repellent employs peppermint oil (1.5%), which is already used commercially. Additionally, it is one among the ingredients in topical insect and flea repellents.

Nano-insecticides

The latest trend in protecting essential oils from deterioration and lengthens their half-life of residue by lowering evaporation is nanoformulation. Due to the tiny particle size, these nano-formulations can increase essential oil's activity. It was soluble, mobile, and had a large surface area. They have little mammalian toxicity due to their solvent elimination. But for essential oils nano formulations, polymeric nanoparticles are the most promising and more repellent than essential oil (Negahban et al., 2014). For instance, at 1.9 ppm, Artemisia oil nanoencapsulation demonstrated more activity than oil. These nanocapsules had an anti- *Plutella xylostella* activity of 80 and 62% for pure oil, respectively (González et al., 2014; Kah et al., 2013).

When Nanoencapsulated essential oils (NE-EOs) were screened against a group of fungal strains, the results indicated a significant antifungal effect. At MIC (Minimum inhibitory concentrations) values ranging from 0.125 to 0.25 mg/mL, the results showed that NE-EOs reduced the development of the fungi under study. These concentrations were between two and four times lower than those seen in pure essential oils. *Aspergillus fumigatus, Cladosporium aggregatocicatricatum, Cladosporium herbarum* and *Pleurotus eryngii* were effectively inhibited from growing by NE-EOs at a MIC of 0.125 mg/ml. Furthermore, the fungus *Bjerkandera adusta* was inhibited by *Origanum vulgare* NCs at this dose (Kapustová et al., 2021). By using polyethylene glycol (PEG) nanoparticles containing essential oils and physicochemical characterization, (González et al., 2014) determined the fatal and sublethal activity of the particles against *Rhizopertha dominica* and *Tribolium castaneum.* After six months of storage, the 10% ratio EO-PEG nanoparticles' average diameter was found to be less than 235 nm (with a PDI-Polydispersity Index of less than 0.280) and their loading efficacy was found to be greater than 75%. Additionally, the number of essential oils in the particles fell by around 25%. The slow and continuous release of active terpenes from the essential oil nanoparticles appears to be the reason for the significant increase in residual contact toxicity. Furthermore, the nanoformulation changed the nutritional physiology of stored product pests and increased the essential oil contact toxicity.

Mode of action of plant essential oil

Essential oils have varying modes of action (*Fig. 3*) depending on the type of pest and weeds. Some of the mechanisms have been discussed below.

Insect: Insects have reportedly been known to inhale, consume or absorb essential oils through their skin. The bioinsecticidal activity of PEOs is aided by the inhibition of insect-specific receptors. Monoterpenes found in PEOs have the ability to inhibit AChE and cause neurotoxicity in organisms, especially arthropods. Monoterpenoids such as linalool impact the ion transport and AChE enzyme release via acting on the neural system of an insect (Re et al., 2000). PEOs have the ability to alter neuronal activity by

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binding to octopamine receptors, which can cause the insect nervous system to completely collapse (Tripathi et al., 2009).

Weeds: PEO's mode of action on weeds differs from plant to plant and is mostly influenced by the chemical makeup of the different PEOs or their constituents. For instance, monoterpenes may cause disruptions to the lipid organization, while phenylpropanoids may function via attaching to membrane receptors (Lins et al., 2019).

Fungal cells: Upon PEO entrance, the cell wall, plasma membrane, and crucial organelles are disrupted, leading to the release of intracellular components and the death of fungal cells (Khoury et al., 2019).

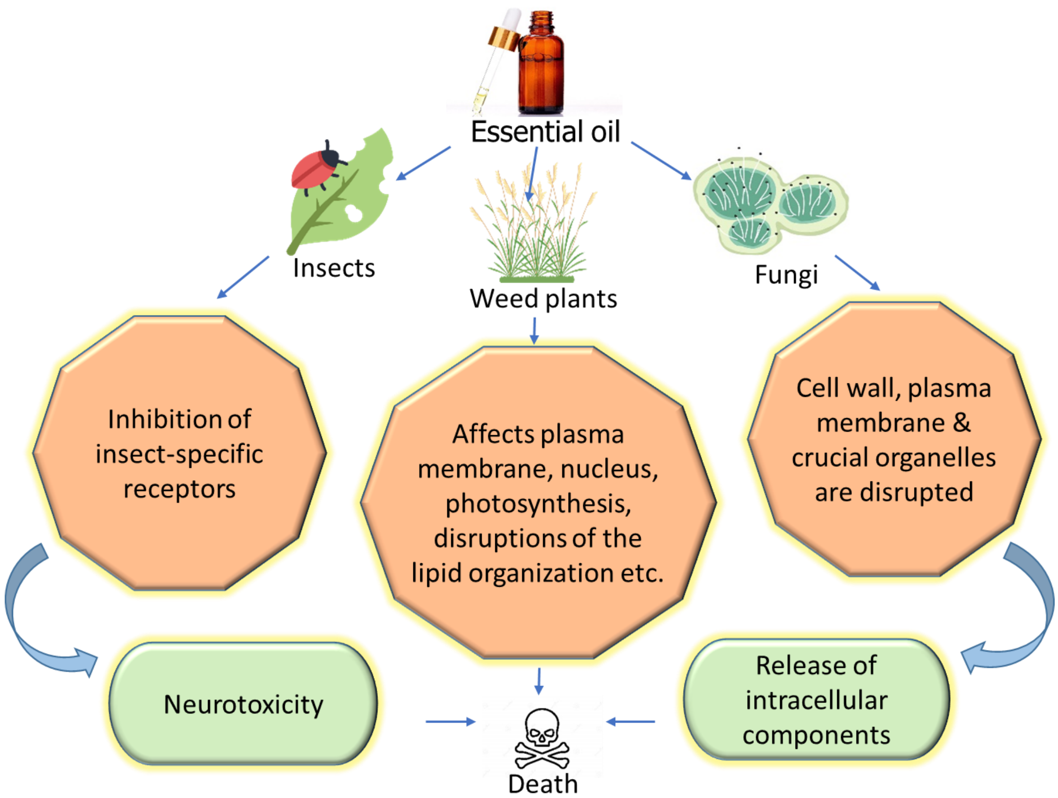

Figure 3. *Mode of action of essential oil against insects, weeds and fungi*

Commercialized essential oils

Some insecticides based on essential oils were introduced by EcoSMART technologies in the USA. In 1998, they employed essential oils made from thyme, rosemary, peppermint, cinnamon, and other plants. An aphidicide, miticide, and fungicide mixture was created by Mycotech Corporation. These compositions are built around cinnamon oil that contains 30% EC cinnamaldehyde. Insecticides EcoPCOR have been introduced thanks to EcoSMART technologies. Eugenol and 2-phenethyl propionate are the main active components. They were employed by pest control specialists as well as against flying and crawling insects. The active component in the EcoTrolTM formulation is rosemary oil. They were applied to horticultural crops as an insecticide and miticide. Insecticide made from garlic oil was also produced in the US. The active component in these formulations is mint oil (Khalfi et al., 2006; Isman et al., 2011). Biofungicide named BIOXEDA produced in Europe has Clove oil as one of its

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ingredients. Made of sweet orange oil, LIMOCIDE and OROCIDE function as both biofungicides and bioinsecticides. In the United States, there are commercial bioherbicides called Matratec, WeedZap, and GreenMatch EX that contain clove oil, 45% clove oil plus 45% cinnamon oil, and lemongrass oil, as one of the primary ingredients, respectively (Gupta et al., 2023).

In India, there are different products are available but remarkably one is AGRONEEM, which is a contemporary pesticide based on a herbal extract of neem seed kernels oil *(Azadirachta indica).* Its main active component is Azadirachtin which is an intricate Tetranortriterpenoid that exhibits a variety of effects on insects, thereby shielding plants from potential threats. India has authorized the use of eucalyptus leaf extract, which is high in 1,8-cineole, as an insecticide component (Isman, 2016). However, only very few biopesticide formulations based on essential oils have been used commercially to till date. Therefore, the transition to plant-based alternatives is already underway and these bio product-based industries will grow in the near future as the current human population becomes more aware of the dangers of utilizing various hazardous xenobiotics as pesticides that pose serious risks to the environment and human health (Singh and Pandey, 2018).

Constrains and challenges

Key benefits and drawbacks associated with the usage of essential oil-based biopesticides is strictly regulated. Essential oils and plant extracts, on the other hand, are biologically unstable since they are rapidly ruined by ambient pH, oxygen, light, and moderate temperatures. Aside from being highly volatile, essential oil have limited aqueous solubility (Pavela and Benelli, 2016). There is need for an enormous cultivable area, source plants, suitable climate and collection of plant material at the appropriate time to maintain the quality of the raw materials. The coexisting vegetation and the presence of animals and insects can indirectly and directly influence the chemotype of a medicinal plant species through competition for resources, allelopathy, pollination and seed dispersal dynamics, herbivory responses, symbiotic relationships, and microenvironmental effects. Understanding these ecological interactions is crucial for managing and conserving medicinal plant species and optimizing their cultivation for medicinal use. *Artemisia annua*, used for producing artemisinin (an antimalarial compound), responds to herbivory by increasing the production of artemisinin and other defensive chemicals. Herbivores like caterpillars can trigger these chemical defenses, potentially enhancing the medicinal properties of the plant. Ants create nests and pathways that can affect soil structure and nutrient cycling around medicinal plants (Steinberger et al., 2024).

The active compounds in plants vary chemically depending on where they are grown, are further limitations on product purity. Weather conditions can influence plant chemistry by directly affecting physiological processes like photosynthesis and respiration, altering the availability of water and nutrients, and inducing changes in response to light and atmospheric conditions. These factors collectively determine the chemical composition of plants, including their nutrient content and the concentrations of bioactive compounds important for defense, growth, and reproduction (Damalas and Koutroubas, 2020).

Further research on usage of essential oil will face several major constrains viz., the creation of effective stabilization processes (such as microencapsulation); the

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simplification of the intricate and expensive biopesticide authorization requirements; and the improvement of plant growing conditions and extraction procedures to produce essential oils with homogeneous chemical compositions. The market's clearance from several international regulatory organizations, along with economic factors, constitutes the last obstacle (Werrie et al., 2020). To overcome these obstacles (*Fig. 4*), efforts are being made. It is still difficult to use these invasive plant extracts as biopesticides in developing countries especially among resource-poor smallholder farmers and locals (Stevenson et al., 2017; Uyi et al., 2021).

Figure 4. *Constraints of essential oils as pesticides*

Conclusion

The high demand for PEOs and their bioactive components as biopesticides underscores their popularity in ecological agriculture. The essential oil's properties that made them suitable for insect management. Essential oils exhibit a wide range of insect-controlling properties such as insecticidal, fumigant, antifeedant, attraction, and repellency, targeting various insects selectively. Because of their natural volatility, essential oils serve as effective fumigants against agricultural and stored food pests. Furthermore, certain approved products have been employed in greenhouses, horticultural crops, and urban pest control to manage insect infestations. Previously essential oils are widely used as commercial biopesticides, a number of issues, including the decreased stability and effectiveness of essential oils under varying environmental conditions, must be resolved. Henceforth, essential oil nano-encapsulation is required to increase its stability, reduce side effects, lower the overall dosage and frequency of doses, boost repellent action, and provide sustained release. Hence, appropriate methodical and progressive strategy to use natural products against various agricultural pests is required now for a healthy, sustainable environment for the future generations.

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