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The Potential of Essential Oils From Medicinal Plants as "New Age Pesticides" in Agriculture

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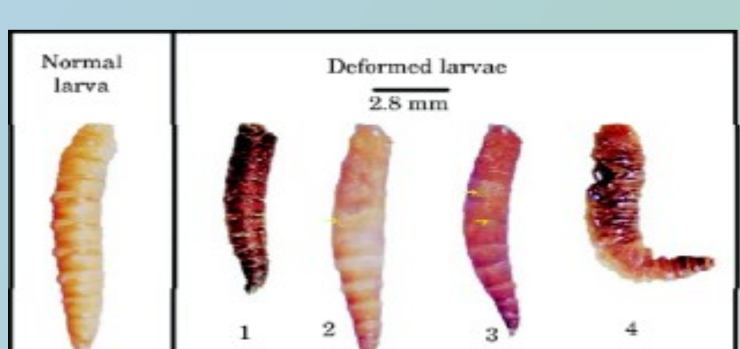
Abstract

Aromatic plants naturally produce essential oils (EOs) as secondary metabolites in the secretory glands of specific plant organs. These oils provide both direct and indirect defenses against herbivores and pathogenic microorganisms. EOs are composed of complex mixtures of terpenes, terpenoids, and phenylpropanoids as their primary components. Known for their antioxidant, antimicrobial, and anti-inflammatory properties, EOs derived from medicinal plants have broad applications in cosmetics, the food industry, and traditional medicine. By the end of the twentieth century, the antimicrobial properties of EOs had attracted significant scientific interest, highlighting their potential as alternatives to synthetic pesticides in agriculture. Among the most studied and widely used EOs for their bioactive effects on plant pathogens, pests, and weeds are those derived from citronella, lavender, rosemary, lemongrass, thyme, peppermint, cinnamon, clove, eucalyptus, sage, tea tree, oregano, and citrus. Although the literature contains extensive data on the effectiveness of EOs against plant pathogens, pests, and weeds, their practical application in agriculture remains surprisingly limited. The main limitations for their commercial use in agriculture include manufacturing constraints, their lipophilic and highly volatile nature, production costs, and variability in their composition. Emerging innovations, such as nanoencapsulation, offer promising solutions to overcome some of these challenges. This review compiles and discusses the latest scientific literature on the biological activities of EOs from medicinal plants against plant pathogens, pests, and weeds, their chemical composition, and modes of action. Additionally, the review explains both the benefits and limitations of using EOs as alternatives to synthetic pesticides, as well as the regulatory and approval processes involved.

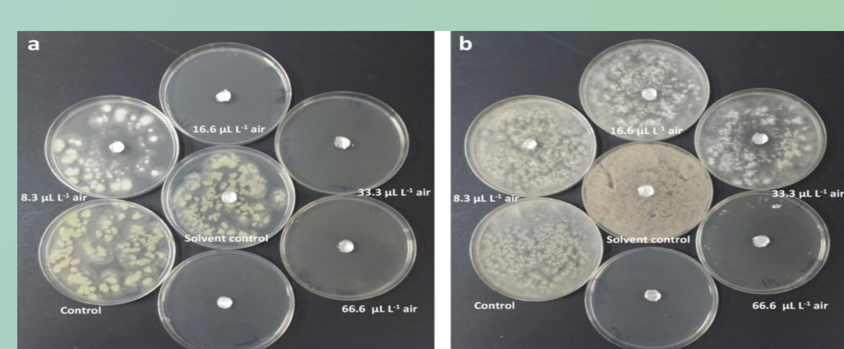
Keywords: biopesticides, terpens, terpenoides, phenylpropanoids, mode of action, regulations, agriculture

Introduction

According to the European Pharmacopoeia, essential oils (EOs) are complex mixtures of volatile, aromatic, lipophilic compounds obtained from plant material through methods such as steam or water distillation, dry distillation, or mechanical processes without the application of heat. These compounds are predominantly localized in the leaves and flowers of higher plants and are primarily biosynthesized via enzymatic mevalonate (MVA) and methylerythritol phosphate (MEP) pathways. The commercialization of EO-based biopesticides began in the 1990s with the introduction of EcoSMART, a formulation containing oils such as peppermint, clove, rosemary, and thyme, demonstrating efficacy against a range of phytopathogens and insect pests. Recent bibliometric analysis indicates that over 60% of related studies are published within the last four years, which reflects a growing scientific interest of EOs as biopesticides. The majority of these studies focus on insecticidal activity against *Lepidoptera* and emphasize oils such as lemongrass, citronella, clove, and eucalyptus. Additional investigations have identified EOs with insecticidal, herbicidal, acaricidal, nematocidal, antibacterial, and antifungal activities. However, only a limited number have been approved as commercial biopesticides, un-



Morphological abnormalities in larvae after treatment with EO (Khater, 2013)



Antifungal activity of *Calamintha nepeta* EO against *Penicillium digitatum* (a) and *Botrytis cinerea* (b) (Ambrocio et al., 2019)

Antimicrobial activity

EOs exhibit both single and multi-target bioactivity against microorganisms, with their efficacy largely attributed to their chemical composition. While major EO compounds are often studied, bioactivity is typically enhanced by the unique chemical profiles of EOs, which depend on the plant species, plant part, and extraction method. EO's lipophilic nature allows them to penetrate microorganism cell walls, increasing permeability, and contributing to higher bioactivity, especially against gram-positive bacteria with an outer peptidoglycan layer. For example, *Psoralea glandulosa* EO was found effective against *Clavibacter michiganensis*, a seed-borne pathogen. Terpene alcohols with varying carbon chain lengths, such as **farnesol** and **nerolidol**, have shown strong antibacterial properties. Monoterpenes, commonly found in thyme and oregano EOs, are particularly effective against plant pathogens acting by disrupting cell membranes and interfering with metabolic processes. **Thymol**, for instance, inhibits *Botrytis cinerea*, *Fusarium oxysporum*, and *Alternaria alternata*, while **carvacrol** targets *Rhizoctonia solani*. Other monoterpenes like **linalool** and **menthol** demonstrate efficacy against root rot pathogens and postharvest molds. Additionally, compounds like **eucalyptol** (1,8-cineole) from *Eucalyptus globulus* show effectiveness against *Verticillium dahliae* and *Xanthomonas* spp. Terpenes such as **α-pinene** and **β-pinene,** found in conifer oils, also display strong antimicrobial activity against

Some EOs based commercial biopesticidies for plant protection

EO source	Commercial name	Producer	Effective against
Allium sativum	GC-3	JH Biotech, Inc., California	Powdery Mildew
Clove oil *Garlic oil*	GC-Mite	JH Biotech, Inc., California	various mites and insects
Clove oil	BIOXEDA, Matratec, WeedZap	Xeda International Brandt, JH Biotech, Inc.	Fungicide, bioherbicide
Thyme oil	Tymox	Laboratoire M2	powdery mildew, gray mold and fire blight
Rosmarinus officinalis	EcoTrol Plus (10%) Hexacide (5%) Sporan (17.6%)	EcoSMART Technologies Inc.	Mites, aphids, beetles, thrips, whiteflies, caterpillars, mealybugs
Orange oil	GreenMatch	Pomerix	Aphids, whiteflies, soft-bodied insects
Neem essential oil combined with Beauveria bassiana (a fungal biopesticide	Naturalis-L	Agrigrem Ltd.	Whiteflies, aphids, and thrips
Beauveria bassiana and rosemary EO	BotaniGard MAXX	Certis Biologicals	aphids, thrips, and spider mites
Rosemary, geraniol and peppermint EOs	Ecotec	Brandt Consolidated, Inc.	Mites, thrips, and aphids

Chemical composition of EOs

Essential oils (EOs) are complex mixtures of volatile organic compounds (VOCs), lacking fatty substances typically found in oils. Their chemical composition is influenced by factors such as plant physiology, climate, soil conditions, plant health, harvest timing, and extraction methods. The development of chromatographic and spectroscopic techniques has advanced the identification of EO constituents, with terpenes, terpenoids, and phenylpropanoids being the most abundant and bioactive compounds. Terpene synthesis occurs in plastids via the 2C-methyl-D-erythritol-4-phosphate (MEP) pathway, with isopentenyl diphosphate and dimethylallyl diphosphate as precursors.

EO compoundivi	Chemical class	Source/Essential Oil	Effectiveness
Azadirachtin	Tetranortriterpenoid	Neem	Broad-spectrum insecticidal and antifungal; disrupts feeding, molting, reproduction
Citronellal	Monoterpenoid aldehyde	Citronella, geranium, lemongrass	Repellent/insecticidal (mosquitoes, aphids, mealybugs, thrips); nematicidal and fungicidal activity
Geraniol	Monoterpenoid alcohol	Citronella, geranium, lemongrass	
Carvacrol	Monoterpenoid phenol	Oregano, thyme	Potent antifungal, anti-*Rhizoctonia activity, insect/acarid toxicity;*
Camphor	Monoterpenoid ketone	Eucalyptus, rosemary	Antifungal, insecticidal, acaricidal; inhibits nematode egg hatching
1,8-Cineole (Eucalyptol)	Monoterpenoid ether	Eucalyptus, rosemary	
Eugenol	Phenylpropanoid	Clove, cinnamon	Antifungal (e.g. *Colletotrichum, Fusarium), insecticidal, acaricidal*
Trans- Anethole	Phenylpropanoid	Fennel, anise, star anise	Insecticidal and nematicidal activity
Linalool	Monoterpenoid alcohol	Lavender, basil, coriander	insecticidal/fumigant (stored-grain pests, thrips)
Thymol	Monoterpenoid phenol	Thyme, oregano, savory	Strong antifungal (*Fusarium, Verticillium, Phytophthora) and miticidal activity*

Limitations and challenges

Despite increasing evidence of the pesticidal and repellent efficacy of essential oils (EOs), commercial products remain scarce due to several challenges. Key limitations include the availability of adequate plant biomass, variability in EO chemical composition, difficulties in formulation standardization, and regulatory barriers. While some EOs are produced at scale for aromatherapy or food applications, those from rare or difficult-to-cultivate species face supply constraints, limiting their commercial viability. Chemical variability within species necessitates strict quality control and standardization to maintain consistent bioactivity.

Pros and Coins	
Availability of adequate plant biomass	Valuable in integrated pest management
Composition can vary between batches or brands	Valuable in organic agriculture
Lower Efficacy than synthetic pesticides	Low mammalian toxicity
Frequent reapplication	Target-Specific
Often more expensive	Low environmental persistence

Conclusions

Essential oils (EOs) have demonstrated efficacy against a range of plant pests and diseases, including fungi, insects, and nematodes. Their synergistic effects lower the risk of resistance development, positioning them as promising biopesticides. However, challenges such as biomass availability, chemical instability, formulation difficulties, and potential phytotoxicity hinder their widespread use. Addressing these issues could be facilitated through plant domestication and cultivation, which may improve chemical stability (chemotype consistency) and biomass production. Advanced formulations could also mitigate volatility and enhance chemical stability, optimizing EOs for practical use. Recent studies have also explored the indirect effects of EOs, such as priming, which enhances plant defense mechanisms. Research on EO-induced priming, particularly in response to fungal pathogens, has shown promising results. Notably, seed coating with EOs has demonstrated priming effects in *Solanum lycopersicum* seedlings against *Fusarium oxysporum*, triggering metabolic and epigenetic changes with minimal EO usage and long-lasting effects. These findings underscore the potential of EOs in biopesticide development, but further research is necessary to elucidate the influence of EO composition on

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