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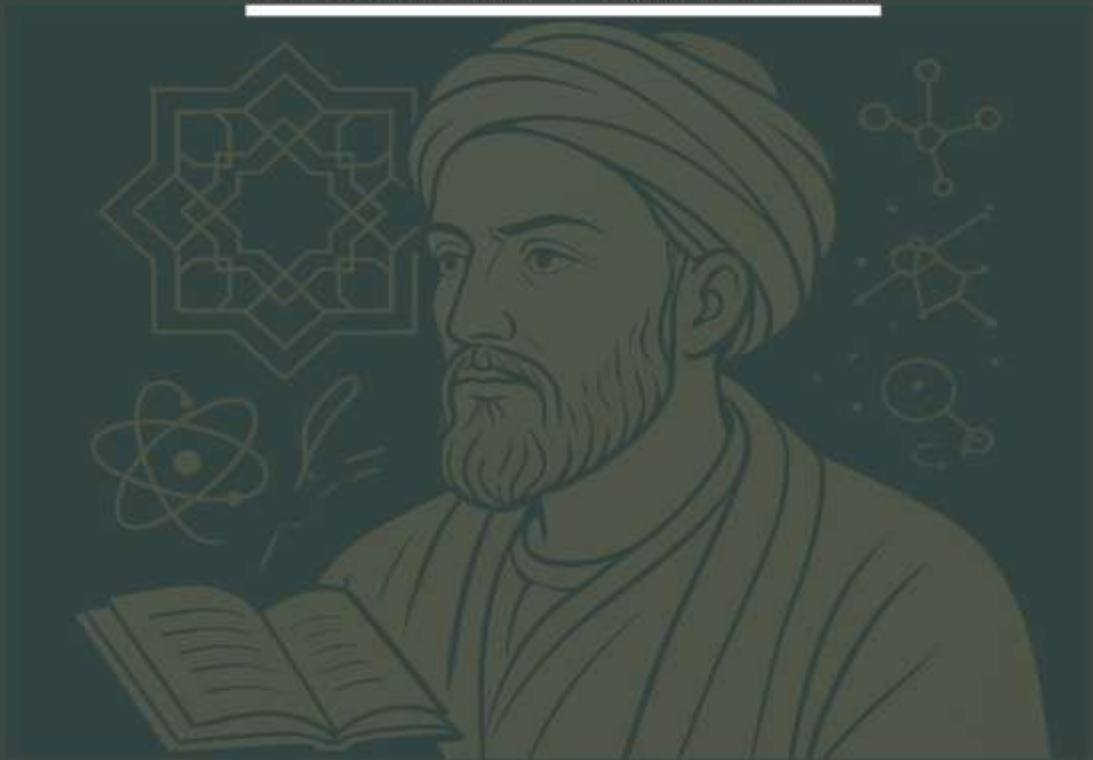

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PLANT DERİVED ESSENTİAL OİLS AS ECO-FRIENDLY ALTERNATIVES OF SYNTHETİC PESTİCİDES

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Abstract

Essential oils are natural, aromatic compounds extracted from plants, known for their complex chemistry and powerful biological activity. Over the past few decades, they've emerged as promising candidates for eco-friendly pest control substances in agriculture. With proven effectiveness against a wide range of pests, including fungi, bacteria, insects, nematodes, and mites, essential oils offer a natural alternative to synthetic pesticides. Their strength lies in their diverse chemical makeup, particularly terpenes and related compounds, which can disrupt cell membranes and vital processes in plant pathogens. However, despite encouraging research, only a few EO-based products have reached the market. Challenges such as inconsistent chemical profiles, limited biomass availability, formulation issues, and regulatory barriers continue to hinder their wider use. Still, there is growing interest in overcoming these obstacles through cultivation strategies, improved extraction methods, and advanced formulations that enhance stability and efficacy. Recent studies also show that EOs can act as elicitors, enhancing the natural defenses in plants. The paper 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, secondary metabolites, aromatic compounds, terpenes, phenylpropanoids.

1. 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 (Siqueira et al., 2022). 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 (Sharma et al., 2023). The majority of these studies focus on insecticidal activity against *Lepidoptera* and emphasize oils such as lemongrass, citronella, clove, and eucalyptus (Ramasamy and Subramanian, 2022). Additional investigations have identified EOs with insecticidal, herbicidal, acaricidal, nematocidal, antibacterial, and antifungal activities (Naz et al., 2021). However, only a limited number have been approved as commercial biopesticides, underscoring the need for further research into their mechanisms of action, regulatory compliance, and integration into pest management systems.

2. 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 (Bakkali et al., 2008). 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 (Lee and Lee, 2018) (Table 1). Terpene synthesis occurs in plastids via the 2C-methyl-D-erythritol-4-phosphate (MEP) pathway, with isopentenyl diphosphate and dimethylallyl diphosphate as precursors (Rodriguez and Dyer, 2019).

Table 1. Some EOs compounds and their effectiveness

compound	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*

3. 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 (Bakkali et al., 2008). 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 (Zuzarte and Pimenta, 2013). For example, *Psoralea glandulosa* EO was found effective against *Clavibacter michiganensis*, a seed-borne pathogen (Singh and Kapoor, 2017). Terpene alcohols with varying carbon chain lengths, such as farnesol and nerolidol, have shown strong antibacterial properties (Costa et al., 2021). 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* (Koul and Walia, 2020) while carvacrol targets *Rhizoctonia solani* (Gheorghe and Stănescu, 2020). Other monoterpenes like linalool and menthol demonstrate efficacy against root rot pathogens and postharvest molds (Dziri and Chouchen, 2021). Additionally, compounds like eucalyptol (1,8-cineole) from Eucalyptus globulus show effectiveness against *Verticillium dahliae* and *Xanthomonas* spp. (Morteza-Semnani and Fathi, 2007). Terpenes such as α-pinene and β-pinene, found in conifer oils, also display strong antimicrobial activity against fungi like *Fusarium* spp. and *Botrytis cinerea* (Carmona and Vila, 2019). This growing body of research highlights the potential of EOs as eco-friendly biopesticides in agriculture (Table 2).

Table 2. 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	Botani Gard MAXX	Certis Biologicals	aphids, thrips, and spider mites
Rosemary, geraniol and peppermint EOs	Ecotec	Brandt Consolidated, Inc.	Mites, thrips, and aphids

4. LIMITATIONS AND CHALLENGES

One of the main advantages of essential oils is their natural origin, which makes them biodegradable and generally safer for the environment than synthetic pesticides. They tend to have low toxicity to humans, animals, and beneficial insects such as bees, making them an appealing choice for integrated pest management (Aydin and Duman, 2017). Moreover, essential oils can act against a broad spectrum of pests and pathogens. For instance, neem oil is widely used to deter insect pests, while tea tree and thyme oils are known for their antifungal effects (Koul and Walia, 2018). Their use also contributes to reducing chemical residues in food and soil, promoting healthier ecosystems. However, essential oils also have several limitations. Their efficacy is often lower and less consistent than that of conventional pesticides, as their volatile nature causes them to degrade quickly when exposed to sunlight or high temperatures. This short persistence means they need to be applied more frequently, which can increase labor and costs. Additionally, the production of essential oils can be expensive, and large-scale application may not be economically viable for all farmers. Another drawback is the potential for phytotoxic effects, as high concentrations or improper application can harm plant tissues (Calvo and Jaramillo, 2019). Overall, while essential oils represent a promising and environmentally friendly alternative for plant protection, their practical use still faces challenges related to stability, cost, and standardization that need to be addressed before they can fully replace synthetic pesticides.

5. CONCLUSION

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 plant responses to biotic stress. This knowledge will be critical for optimizing EO applications and maximizing their effectiveness in agriculture.

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