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ROLE OF AROMATIC PLANT EXTRACTS IN ECO-FRIENDLY PEST MANAGEMENT: SOURCES, MODES OF ACTION, FORMULATIONS, AND ADOPTION CONSTRAINTS (NARRATIVE REVIEW)

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Abstract

Eco-friendly pest management is increasingly important due to pesticide resistance, residue concerns, and non-target impacts on beneficial organisms.(1) Aromatic plant extracts—especially essential oils (EOs) and solvent extracts rich in terpenoids and phenylpropanoids—offer broad bioactivity against insect pests, plant pathogens, and in some contexts storage pests, often through multi-target mechanisms (e.g., neurophysiological disruption, membrane damage, repellency and feeding deterrence)(2). Such multi-site activity can reduce the likelihood of rapid resistance evolution compared with single-site chemistries (3), but field performance is frequently limited by volatility, oxidation and photodegradation (4). This review synthesizes evidence on (i) major aromatic sources and representative active constituents, (ii) mechanisms of action relevant to insects and plant pathogens, (iii) application pathways in integrated pest management (IPM) for field and stored-product systems, (iv) formulation advances (nanoemulsions, microencapsulation, inclusion complexes) to improve stability and controlled release, and (v) practical constraints including standardization, phytotoxicity, non-target risk assessment, and regulatory dossier requirements. Overall, aromatic plant extracts are promising tools for greener crop protection, but reliable scaling

requires stronger links between chemical fingerprints and efficacy benchmarks, improved formulations validated in field trials, and clearer regulatory pathways for botanicals.

Keywords: aromatic plants; essential oils; botanical pesticides; biopesticides; integrated pest management; terpenoids; phenylpropanoids; nanoemulsions; microencapsulation

1. Introduction

The extensive use of synthetic pesticides has contributed to resistance development, environmental contamination, and human exposure concerns [5]. Botanical pesticides are therefore increasingly explored as reduced-risk alternatives because plant secondary metabolites evolved as natural defense compounds against herbivores and pathogens [6]. Conventional pesticides have supported yield gains, yet repeated use has contributed to resistance in pest populations, environmental contamination, and concerns about human exposure via residues. Botanical pesticides are widely studied as "reduced-risk" tools because many plant secondary metabolites evolved as defenses against herbivores and pathogens, and some botanicals can fit organic and IPM programs when used appropriately.

Aromatic plants represent a key group within botanicals due to their EO constituents such as thymol, carvacrol, eugenol, linalool, and 1,8-cineole, which exhibit insecticidal, pesticidal, repellent, antifeedant, and antimicrobial properties [7, 14-18].

Importantly, EO activity often involves multiple targets (e.g., GABA-gated chloride channels, octopaminergic signaling, and acetylcholinesterase inhibition), which helps explain broad-spectrum effects and can slow resistance development when botanicals are rotated thoughtfully within IPM. Multi-target activity involving GABA receptors, acetylcholinesterase inhibition, and octopaminergic signaling contributes to broad-spectrum efficacy and resistance mitigation when used within IPM programs [8].

Despite strong laboratory efficacy, commercialization and consistent field performance remain challenging. Variability in EO composition (chemotype, geography, harvest time and extraction method), rapid loss in field conditions (evaporation/UV/oxidation), and regulatory requirements for specification and safety data can limit adoption.

2. Materials and Methods (Narrative Literature Review)

This paper uses a narrative review approach to synthesize research on aromatic plant extracts for pest management across field crops and stored-product systems. A narrative review was selected because the literature includes diverse plant species, chemotypes, extraction methods, formulations (crude EOs, solvent extracts, nano-systems), target pests (insects, mites, fungi, bacteria), bioassay designs, and endpoints that complicate quantitative meta-analysis.(9)

2.1 Search strategy and selection

Search terms included: “aromatic plant extracts,” “essential oils,” “botanical pesticides,” “bioinsecticide,” “biofungicide,” “stored-product pests,” “fumigant,” “nanoemulsion,” “microencapsulation,” “cyclodextrin,” and “IPM.” Priority was given to high-quality reviews and regulatory guidance documents that synthesize broad evidence on efficacy, mechanisms and constraints, supplemented by representative experimental and formulation papers where needed to illustrate specific mechanisms or delivery advances. Key anchor sources included authoritative entomology reviews on botanicals and essential oils, recent cross-disciplinary reviews on EO biopesticides, stored-product pest reviews, and guidance on botanical dossiers from international regulatory bodies. (10)

2.2 Data extraction and synthesis

For each eligible source, information was extracted on: (i) plant species and extract types, (ii) dominant chemical constituents and chemotypes, (iii) target pest/pathogen groups and application modes, (iv) modes of action and mechanistic evidence, (v) formulation strategies and stability/persistence outcomes, and (vi) constraints (standardization, phytotoxicity, non-target concerns, and regulatory requirements). Findings were synthesized thematically.

3. Aromatic Plant Extracts: Types and Bioactive Chemistry

3.1 Essential oils (EOs)

EOs are volatile, lipophilic mixtures typically dominated by monoterpenes (e.g., thymol, carvacrol, linalool), sesquiterpenes, and phenylpropanoids (e.g., eugenol). Bioactivity often reflects both major constituents and synergistic/antagonistic interactions among minor constituents. Consequently, two EOs from the same species can differ substantially depending on chemotype, growth conditions, season, and extraction method. (11)

3.2 Solvent extracts and hydrosols

Beyond EOs, aromatic plants can be extracted with ethanol, methanol, hexane, or water to obtain less-volatile fractions enriched in phenolics, flavonoids, tannins, and other metabolites. These extracts may provide longer residual action than EOs in some contexts, but they can also increase variability and phytotoxicity risks depending on solvent type, concentration, and crop sensitivity. Broader botanical pesticide reviews treat crude extracts as important for farmer-level use and as starting points for standardization and product development. (12)

4. Studied Aromatic Plants with Pesticidal Potential

Table 1 lists frequently studied aromatic plants with pesticidal potential, representative dominant compounds, and typical target groups. The table is compiled from major reviews on EOs/plant extracts for insect control, EO biopesticides, and stored-product pest management.

Table 1. Aromatic plants reported to show pesticidal potential (representative examples)

Plant (Family)	Common name / part used	Representative dominant constituents (examples)	Typical reported targets / uses	Key supporting sources
Ocimum basilicum (Lamiaceae)	Basil (leaves/EO)	linalool, estragole (chemotype-dependent)	repellency/insecticidal; antimicrobial	Gupta et al., 2023 (19)
Ocimum tenuiflorum (syn.	Tulsi (leaves/EO)	eugenol and related	antifungal; insecticidal potential	Gupta et al., 2023

O. sanctum) (Lamiaceae)		phenylpropanoids (variable)		
Thymus vulgaris (Lamiaceae)	Thyme (aerial parts/EO)	thymol, carvacrol	insecticidal/repellent; neuroactive modes	Regnault-Roger et al., 2012
Origanum vulgare (Lamiaceae)	Oregano (aerial parts/EO)	carvacrol, thymol	insecticidal/repellent; antimicrobial	Regnault-Roger et al., 2012
Rosmarinus officinalis (Lamiaceae)	Rosemary (aerial parts/EO)	1,8-cineole, camphor (variable)	insecticidal/repellent; antimicrobial	Gupta et al., 2023
Mentha spp. (Lamiaceae)	Mint (leaves/EO)	menthol, menthone (species-dependent)	insecticidal/repellent; stored-product use	Gupta et al., 2023; Nikolaou et al., 2021(20)

Cymbopogon citratus (Poaceae)	Lemongrass (leaves/EO)	citral (geranial/neral)	insecticidal/repellent; antimicrobial	Gupta et al., 2023
Cymbopogon nardus (Poaceae)	Citronella (leaves/EO)	citronellal/citronellol/geraniol	repellent; insecticidal	Regnault-Roger et al., 2012
Syzygium aromaticum (Myrtaceae)	Clove (buds/EO)	eugenol	fumigant/contact toxicity; repellency	Regnault-Roger et al., 2012; Rajendran & Sriranjini, 2008
Cinnamomum verum (Lauraceae)	Cinnamon (bark/EO)	cinnamaldehyde, eugenol (variable)	insecticidal; antimicrobial; storage protection	Gupta et al., 2023; Nikolaou et al., 2021
Eucalyptus spp. (Myrtaceae)	Eucalyptus (leaves/EO)	1,8-cineole (species-dependent)	insecticidal/repellent; antimicrobial	Regnault-Roger et al., 2012; Gupta et al., 2023

Foeniculum vulgare (Apiaceae)	Fennel (seeds/EO)	anethole (often), others	insecticidal/repellent	Gupta et al., 2023
Coriandrum sativum (Apiaceae)	Coriander (seeds/EO)	linalool (often)	insecticidal/repellent	Gupta et al., 2023
Citrus spp. (Rutaceae)	Citrus peel oils	limonene (often)	repellency/insecticidal; stored-product relevance	Nikolaou et al., 2021

5. Modes of Action Relevant to Pest Management

A key advantage of aromatic extracts is their multi-target activity, which supports both direct control and resistance management when deployed strategically.

5.1 Neurophysiological disruption in insects

EO constituents can interfere with insect neural signaling through multiple pathways. Major entomology reviews describe neurotoxic effects linked to GABA-gated chloride channels, octopaminergic signaling, and inhibition of acetylcholinesterase (AChE), leading to knockdown, paralysis, or altered behavior such as repellency and feeding suppression.

5.2 Respiratory, cuticular penetration, and membrane disruption

Because EOs are volatile and lipophilic, they can penetrate the insect cuticle and may act as fumigants—particularly relevant in closed or semi-closed stored-product environments. In microbes, EO components frequently disrupt cell membranes, increase permeability, and impair energy metabolism, supporting their reported antibacterial and antifungal activities in crop protection contexts.

5.3 Growth regulation and behavioral modification

Beyond acute toxicity, aromatic extracts can reduce oviposition, deter feeding, or impair larval development and adult emergence. Reviews summarize these effects as important for IPM because they can reduce population growth even when immediate mortality is incomplete, especially when combined with other control tactics.

6. Applications in Eco-friendly Pest Management

6.1 Field crop protection (insects and plant pathogens)

EOs and aromatic extracts can be applied as contact sprays, repellents, and antimicrobial treatments. Recent syntheses emphasize their role as bioinsecticides and biofungicides while noting that efficacy depends strongly on dose, formulation, and environmental conditions (temperature, UV exposure, rainfall).

6.2 Stored-product protection

Stored commodities are attacked by many beetles and moths, and EO volatility can be beneficial for fumigant action. Reviews on stored-product pest management highlight plant products and EOs as candidates for contact and fumigant control, supporting reduced-residue protection in storage systems when safety and efficacy are validated.

6.3 Role in integrated pest management (IPM)

Aromatic extracts generally perform best when integrated with monitoring, thresholds, sanitation, resistant varieties, and biological control. Botanical insecticide reviews argue that botanicals are most defensible as part of diversified programs—used in rotation or targeted application windows—rather than as one-for-one replacements for conventional pesticides.

7. Formulation and Delivery: Why It Matters

7.1 Core problem: volatility and degradation

A consistent limitation of EOs is rapid loss by evaporation and degradation (oxidation/photolysis), which reduces residual activity in field conditions and can demand frequent re-application. These constraints are repeatedly highlighted in broad reviews of botanicals and EO-based insect control.

7.2 Microencapsulation and controlled release

Microencapsulation is widely used to protect EOs, reduce volatility, and enable controlled release. A dedicated review of EO microencapsulation summarizes techniques and materials used to stabilize EOs and improve their practical use.

7.3 Nanoemulsions and biopolymer carriers

Nanoemulsions can improve dispersion in water, enhance adhesion and bioavailability, and slow release. Recent studies and reviews describe chitosan-based systems and related biopolymer carriers as promising for controlled release and improved antimicrobial performance, illustrating the broader direction of "delivery-enabled" botanical pesticides.

7.4 Inclusion complexes (e.g., cyclodextrins)

Inclusion complexes (commonly cyclodextrins) can reduce volatility, protect sensitive constituents, and improve handling. Regulatory and applied research discussions often cite such stabilization approaches as key for translating lab efficacy into more consistent field outcomes.

8. Benefits and Constraints

8.1 Key benefits

1. **Reduced persistence/residue potential (context-dependent):** Many EO constituents degrade relatively quickly compared with persistent conventional pesticides, which can support reduced-residue goals when efficacy is sufficient.
2. **Multiple mechanisms of action:** Multi-target effects can support resistance management within IPM rotations.
3. **Compatibility with IPM:** Botanicals can complement cultural and biological control when application timing and selectivity are considered.

8.2 Main constraints

1. **Variability and standardization:** EO composition varies with chemotype, season, geography and extraction parameters, complicating product specification and repeatable efficacy.

2. **Short residual activity:** Volatility and environmental degradation reduce field persistence without stabilization strategies.
3. **Phytotoxicity risk:** Higher doses and some solvent systems can damage sensitive crops; formulation and dose optimization are needed for crop-specific safety.
4. **Regulatory and data requirements:** Botanicals still require dossiers with identity/specification and safety data. International guidance documents outline how botanical active substances are evaluated and what data packages are expected.

9. Regulatory and Safety Considerations

Regulatory frameworks differ by jurisdiction, but international guidance recognizes that botanicals require clear characterization of composition, specifications, and risk assessment approaches. The OECD has published a guidance document specifically addressing botanical active substances used in plant protection products, including how to apply data requirements and dossier expectations.

In the European context, guidance documents discuss options for addressing data requirements in botanical dossiers, acknowledging practical issues such as complex mixtures and challenges in radiolabeling.

For public-health vector control, the World Health Organization has guidance that includes botanical and microbial pesticide registration considerations for vector control products.

10. Future Scope and Research Gaps

1. **Quality control that predicts efficacy:** Stronger links between GC-MS chemical fingerprints and bioactivity benchmarks to reduce batch variability and support labeling/specifications.

2. **Formulation R&D validated in real conditions:** More field-scale and storage-scale trials comparing crude EOs vs stabilized systems (microencapsulation/nanoemulsions) under UV, heat, and rain exposure.
3. **Economics and implementation:** Cost-per-hectare, application frequency, compatibility with existing spray programs, and farmer adoption studies.
4. **Non-target and ecosystem studies:** Pollinator and natural enemy impacts under realistic exposure scenarios to strengthen IPM recommendations and registration packages.
5. **Regulatory harmonization for low-risk botanicals:** Clearer, more predictable pathways to reduce commercialization bottlenecks while maintaining safety standards.

11. Conclusion

Aromatic plant extracts—particularly essential oils—represent a practical, eco-friendly direction for pest management due to broad bioactivity, multi-target mechanisms, and compatibility with IPM goals. Evidence synthesized in major entomology and plant-science reviews supports strong potential across insect pests, plant pathogens, and stored-product protection, especially when botanicals are used strategically rather than as direct one-to-one replacements for conventional pesticides. However, large-scale adoption depends on solving recurring barriers: chemical variability, limited persistence, phytotoxicity management, and regulatory/standardization requirements. Advances in microencapsulation and nano-delivery systems, combined with chemical-efficacy quality control and robust field validation, are the most actionable pathways to improve reliability and support commercialization of aromatic plant-based biopesticides.

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