



Nanoencapsulated EO-based drug delivery for pest control: from chemistry to formulation design

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Abstract

Rising resistance, regulatory pressure, and ecological costs of synthetic pesticides have accelerated interest in essential oil (EO) based biopesticides. Yet translation is constrained by EO volatility, low water miscibility, photo-oxidation, and rapid dissipation. This review consolidates advances in EO chemistry and nanoformulation to articulate newer drug design thereby linking molecular composition to delivery performance and agronomics. We summarize representative bioactives (e.g., thymol, carvacrol, eugenol, cinnamaldehyde, citral, menthol, and 1,8-cineole) and emphasize mechanistic pathways underlying insecticidal and antimicrobial action, including membrane perturbation, neuromodulation (acetylcholinesterase and octopaminergic signaling), respiratory/metabolic disruption, and repellency etc. We then compared various nanoencapsulation platforms, nanoemulsions, biopolymer and polymeric nanocapsules, lipid carriers (solid lipid nanoparticles and nanostructured lipid carriers), cyclodextrin complexes, and emerging metal–organic framework (MOF) systems as a common framework. By mapping formulation choices, performance trade-offs and reporting gaps are identified that hinder cross-study comparability. Further, commercial EO product blends including thyme–oregano, clove–cinnamon, citral-rich lemongrass formulations are discussed along with practical barriers to adoption, including shelf-life qualification, scalable manufacturing. Particular attention is given to environmental fate, residue dynamics, and compatibility with integrated pest management. Finally, we outline research priorities for standardized characterization, realistic exposure testing and field-validated efficacy to accelerate EO-based nanopesticides in sustainable pest management.

Keywords Pest control; terpenoids · Nanopesticide · Metal-Organic Frameworks · Scale up

Introduction

Plant essential oils (EOs) have attracted researchers' attention as promising alternatives in pest management. This is in fact because of growing concerns about the safety profiles

of chemical pesticides, especially following the introduction of synthetic compounds in the early 20th century (Green et al. 2020). These plants contain volatile oils that are stored in specialized glands called glandular trichomes (Zhang et al. 2025). These EOs are largely composed of composite mixtures of several phytoconstituents, including terpenoids, phenolics, and alkaloids (Boukhatem and Setzer 2020), which are reported to exhibit potent insecticidal, antifungal, and repellent properties (Aimad et al. 2022). The bioactive molecules act through diverse mechanisms, including neurotoxicity, disruption of metabolic pathways, and interference with reproductive, developmental growth stages in insects. (Boukhatem and Setzer 2020; Bedini et al. 2024). The importance of employing aromatic plants rich in EOs stems from their biodegradability, low toxicity to non-target organisms, and reduced risk of resistance development compared to those of synthetic pesticides (Marcelino et al. 2023). Even in several traditional medicinal systems, EOs including lavender (*Lavandula* spp.), clove (*Syzygium*

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aromaticum), Eucalyptus (*Eucalyptus globulus*), peppermint (*Mentha piperita*), and citronella (*Cymbopogon spp.*) have been traditionally employed in pest control practices across diverse cultures (Sgorbini et al. 2015; Mussalama et al. 2023; Singh and Paul 2024).

Nevertheless, the practical field implications of EOs face challenges pertaining to their physicochemical properties and ground performance (Raveau et al. 2020). Exceedingly volatile nature, vulnerability to environmental degradation however can decrease the persistence and effectiveness of EOs (Ebadollahi et al. 2022; Assadpour et al. 2023). Besides, conventional extraction and delivery methods can lead to inconsistent efficacy and pose difficulties in large-scale implementation (Moccia et al. 2023). These limitations highlight the need for innovative strategies to enhance the stability, bioavailability and targeted delivery of aromatic plant-derived bioactive compounds. In this context, integrating advanced technologies such as nanotechnology and real-time monitoring offers promising opportunities to address existing limitations.

Nanotechnology enables EOs to be formulated into nano-emulsions, nanocapsules, and other nanocarriers that protect active compounds from degradation, enable controlled release, and enhance penetration into target pest organisms. Nano-pesticides represent a transformative development in agrochemical technology, in which active ingredients, including EOs, are engineered at the nanoscale to enhance target specificity (Singh et al. 2021). Formulation design of nano-pesticides is thus an interdisciplinary convergence of nanotechnology, surface chemistry, and formulation science. Critical Quality Attributes (CQAs), including encapsulation efficiency, particle-size homogeneity, zeta potential, and active ingredient release kinetics, must be precisely modulated during formulation design of nano-pesticides (Danaei et al. 2018).

This broadly examines current technological developments that improve EOs application as nano-pesticides and real-time monitoring technologies inside the framework of pest management. This integrative approach has the potential to enhance the efficacy, sustainability, and scalability of pest management strategies. Therefore, this review aims to elucidate the current status and challenges of EOs in pest control, including their use with nanotechnology and sensor-based and AI-driven monitoring systems.

Essential oils in pest management

Essential oils obtained from aromatic plants contain volatile bioactives with broad relevance to pest and pathogen management (Hatt et al. 2019). The aromatic plants produce numerous secondary metabolites with multiple anti-pesticide

and pest-repellent properties, for instance, limonene, thymol, citral, and eugenol (Kumar et al. 2022). Investigations have increasingly focused on a detailed understanding of the chemistry, biological activities, and formulation design of these compounds. Below is a detailed overview of EOs and their pesticidal capabilities (Table 1; Fig. 1).

Bioactive compounds from EOs and their mode of action

EOs extracted from aromatic plants comprise several bioactive compounds, including terpenes, terpenoids, phenylpropanoids, aldehydes, ketones, and phenolics, and each exhibits distinct mechanisms targeting pests (Chaudhari et al. 2021a; Dassanayake et al. 2021). Terpenoids are among the most abundant and diverse compounds in EOs, known for their strong fumigant and neurotoxic effects against insects (Chaudhari et al. 2021b). Compounds such as limonene (from citrus oils), α -pinene (from pine oils), carvone (from caraway), and 1,8-cineole (from eucalyptus) primarily target the octopaminergic system in insects, which is analogous to the adrenergic system in vertebrates (Jankowska et al. 2017). This leads to hyperexcitation, paralysis, and eventually death (Liu et al. 2022). Additionally, their high volatility can block tracheal gas exchange, leading to suffocation in soft-bodied pests (Ramulu 2020). Terpenoids also disrupt insect membranes due to their lipophilicity, leading to ionic imbalance and cellular collapse (Yap et al. 2021). Their ability to mask plant odors or mimic alarm pheromones enhances their repellent and antifeedant properties (Qasim et al. 2024). These compounds have demonstrated effectiveness against mosquitoes, aphids, beetles, and various agricultural caterpillars (Adedayo et al. 2025).

Phenolic compounds, pesticidal/repellent properties, for example, linalool, a terpenoid found in lavender, exerts neurotoxic effects specifically against aphids by disrupting their nervous systems and reducing feeding activity (García et al. 2024; Xue et al. 2024). Phenylpropanoids such as eugenol, a compound from clove, primarily function as repellents against mosquitoes by disrupting their olfactory receptors, thereby preventing host detection and feeding (Shoushan 2012) (Table 1; Fig. 1). The diverse modes of action exhibited by these compounds not only ensure broad-spectrum pest control but also help mitigate resistance development among pest populations, making EOs valuable components of sustainable pest management strategies (Dassanayake et al. 2021). (Fig. 1).

Aldehydes, including citral, citronellal, and cinnamaldehyde, are highly reactive compounds that exert their bioactivity by covalently binding to amino and thiol groups in insect proteins and enzymes (Ganjewala et al. 2012). This inhibits key metabolic enzymes involved in energy

Table 1 Major bioactive compound classes in EOs their mechanisms of action and supporting evidence for pest management applications

Compound Class	Key Examples	Mechanisms of Action	Target Pests	References
Terpenoids	Limonene, α -Pinene, Carvone, 1,8-Cineole	- Octopamine receptor disruption- Respiratory inhibition (fumigant)- Membrane disruption- Repellency and feeding deterrence	Mosquitoes, aphids, beetles, caterpillars	(Boncan et al. 2020)
Phenolics	Thymol, Carvacrol, Eugenol	- Membrane disruption- Enzyme/protein denaturation- Oxidative stress induction- Neurotoxicity and growth inhibition	Termites, mosquitoes, stored-product pests, beetles	(Azab 2018; Sankara et al. 2020)
Phenylpropanoids	Cinnamaldehyde, Anethole, Estragole	- Acetylcholinesterase inhibition- Octopaminergic disruption- Antifeedant and repellent effects- Growth and reproductive interference	Cockroaches, mosquitoes, mites, grain pests	(Ramamrosan et al. 2022)
Alcohols	Linalool, Geraniol, Menthol	- Neurotoxicity via ion channel interference- Cuticle penetration and desiccation- Oviposition deterrent- Membrane destabilization	Whiteflies, aphids, mosquitoes, storage pests	(Sims and O'Brien 2011; Benelli and Pavela 2018)
Aldehydes	Citral, Citronellal, Cinnamaldehyde	- Covalent binding to enzymes- Octopamine and cholinergic system interference- Repellency and contact toxicity- Respiratory disruption	Mosquitoes, cockroaches, termites, ticks	(Yang et al. 2014)
Ketones	Camphor, Menthone, Thujone	- GABA receptor antagonism- Neural overexcitation and paralysis- Fumigant and ovicidal effects- Respiratory inhibition	Fleas, mosquitoes, caterpillars, stored pests	(Ramadan et al. 2020; Saroj et al. 2020)
Esters	Linalyl acetate, Methyl salicylate, Geranyl acetate	- Acetylcholine modulation- Pheromone mimicry or interference- Knockdown effects- Cuticle penetration and behavioral disruption	Ants, mosquitoes, moths, beetles	(Zhang et al. 2013; Faly et al. 2024)

production and detoxification pathways. Aldehydes also disrupt the octopamine signaling system, impairing movement and behavior (Aljaafari et al. 2022). Citronellal and citral, for example, are effective repellents and are widely used in mosquito deterrent formulations (Iovinella et al. 2022). Similarly Cinnamaldehyde demonstrates strong contact toxicity against cockroaches and termites, while also acting as an antifeedant by altering taste receptor responses in various insect pests (Oladipupo 2022; Dzięgielewska et al. 2023).

Esters, such as linalyl acetate, geranyl acetate, and methyl salicylate, contribute to the insecticidal and repellent activities of EOs through multiple pathways (Zhang et al. 2023b). These compounds disrupt acetylcholine signaling, a critical neurotransmitter system in insects, leading to impaired muscle coordination and paralysis (Jankowska et al. 2017). Esters also destabilize insect cell membranes and may mimic pheromonal signals, thereby confusing social insect behavior, such as trail-following in ants (Yew and Chung 2015). Furthermore, their volatile nature enhances fumigant action, while their hydrophilic products, alcohols

and acids, often exhibit additional insecticidal properties. Esters are notably effective against mosquitoes, moths, beetles, and ants (Walia et al. 2014) (Fig. 2).

Currently available EOs-based products for pest control

The market offers several EOs-based products derived from aromatic plants for pest control in agricultural and domestic settings. These formulations, including emulsions, sprays, and granular products, primarily utilize extracts from neem, citronella, peppermint, clove, and other aromatic species (Benelli et al. 2018b; Campolo et al. 2018). Such products leverage the natural pesticidal, repellent, and antimicrobial properties of EOs to effectively control insect pests, fungi, and bacteria (Table 2). Their adoption is especially beneficial in organic farming and post-harvest storage, helping to prevent spoilage and minimize chemical residues in food products (Chaudhari et al. 2021a). Despite their natural origin, these products require careful formulation to maintain efficacy and stability, often incorporating additives and

Fig. 1 Structure of major compounds and their classes within EOs

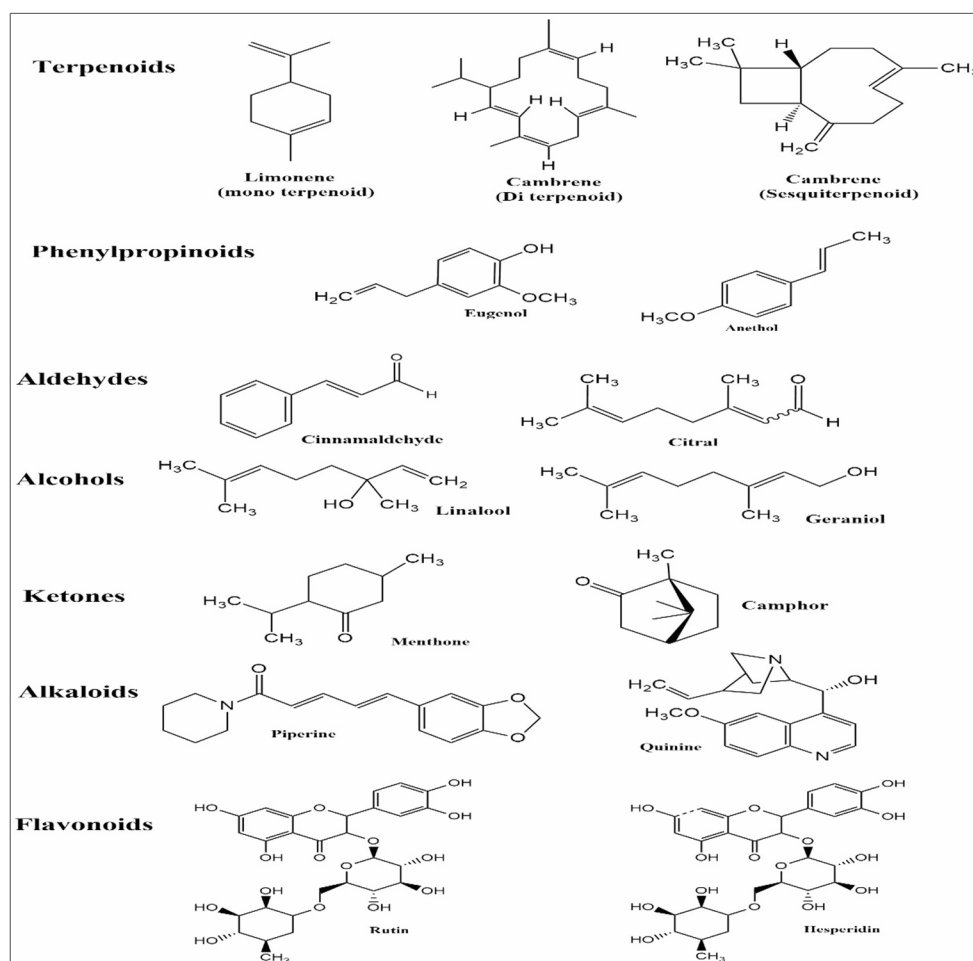


Fig. 2 Schematic presentation of major compound classes and their mechanisms

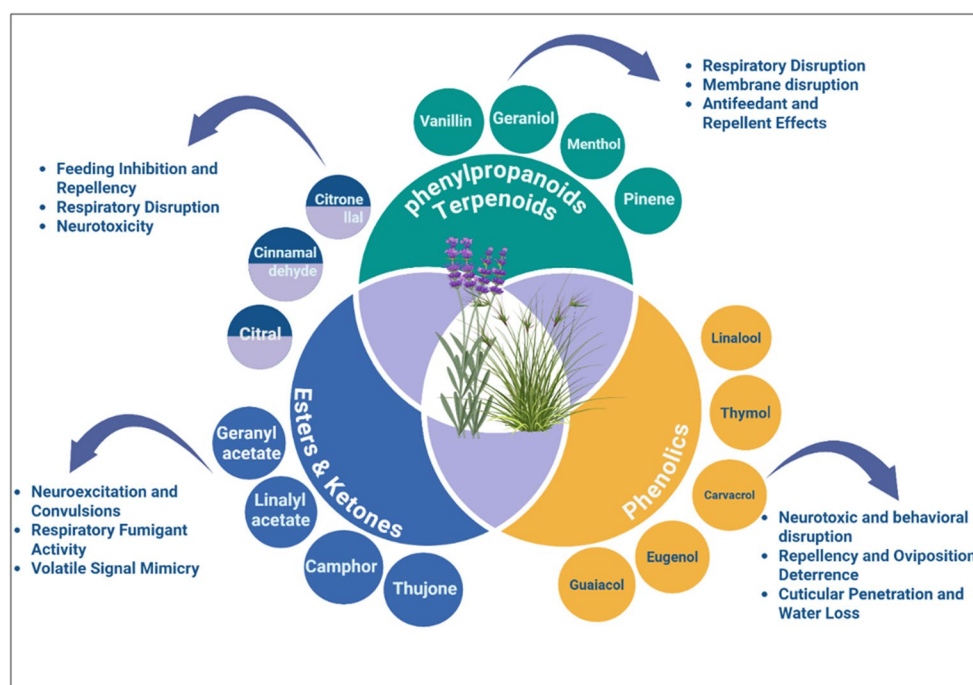


Table 2 Major bioactive compounds in aromatic plants and their target pests with available commercial products

Formulation Type	Plant Source	Target Pests	Major Component	Commercial Product Examples	Reference
Emulsions	Neem	Aphids, whiteflies, thrips, mealybugs, caterpillars	Azadirachtin	Eco-Neem	(Singh and Prithiviraj 1997; Khan et al. 2012)
Emulsions	Citronella	Mosquitoes, flies, ants	Citronellal	Mosquito Guard®	(Revay et al. 2013)
Emulsions	Eucalyptus	Houseflies, mosquitoes	Eucalyptol (1,8-Cineole)	Citriodiol®	(Gardulf et al. 2004)
Emulsions	Lemongrass	Mosquitoes, ants, weevils	Citral	Wondercide®	(Machtinger and Li 2017)
Sprays	Clove	Mites, aphids, ants	Eugenol	BIOXEDA®	(Cáceres et al. 2020; Álvarez et al. 2024)
Sprays	Peppermint	Mosquitoes, fleas, moths	Menthol	KeyPlex Ecotrol®	(Moore et al. 2006)
Nano-formulations	Neem oil	Whiteflies, aphids, mosquitoes	Azadirachtin	Literature*	(Abubakar et al. 2023)
Nano-formulations	Citronella oil	Mosquitoes, houseflies	Citronellal	Literature*	(Higuchi et al. 2023)
Nano-formulations	Clove oil	Mites, fungal pests, storage insects	Eugenol	Literature*	

* literature details available in citations

surfactants to enhance solubility and persistence under field conditions (Dassanayake et al. 2021). However, the relatively high cost of EOss, variability in product quality, and regulatory challenges continue to limit their widespread use compared to those of synthetic pesticides (Benelli et al. 2018a).

Limitations and challenges of conventional application of plant EOs

While EOs show significant promise for pest control, their conventional application faces several critical limitations (Ebadollahi et al. 2022). A primary challenge is their high volatility, which leads to rapid evaporation and degradation upon exposure to environmental factors such as sunlight, heat, and oxygen (Lucia and Guzmán 2020; Chaudhari et al. 2021a). This volatility reduces their residual activity, leading to shorter protection periods and necessitating frequent reapplications that increase labor and costs (Turek and Stintzing 2013). Additionally, limited EOs availability owing to extraction yield constraints and seasonal variability—poses supply challenges and elevates market prices (Widiaswanti et al. 2019). Although EOs exhibit strong pest-control potency, precise dosing is essential to prevent phytotoxicity and minimize adverse effects on beneficial organisms (Werrie et al. 2020). Challenges related to the instability and high potency of EOs hinder their field effectiveness and complicate formulation development, frequently leading to inconsistent pest control outcomes (Yamine et al. 2023) (Fig. 3).

Current status of aromatic plants-based pest control

Currently, aromatic plant-based pest control represents a growing niche within sustainable agriculture; however, it remains underutilized compared to that of synthetic chemicals (Greff et al. 2023). Ongoing research has focused on

advancing formulation technologies—such as nanoencapsulation and microemulsions—to enhance the stability and delivery of EOs (Barradas and De Holanda E Silva, 2021; Weisany et al. 2022). Selective breeding and biotechnological interventions aim to enhance the yield and consistency of bioactive compound production in aromatic plants (Moharramipour and Negahban 2014). Field studies show the feasibility of integrating EOs-based products into pest management strategies, yielding positive outcomes in pest suppression and crop productivity (Weisany et al. 2022; Gupta et al. 2023; Zhou et al. 2024). Nevertheless, challenges, including high costs, regulatory barriers, and variable efficacy under field conditions, continue to limit the large-scale adoption of these technologies (Stathakis et al. 2023) [Table 2].

Nanotechnology in pest management

Nanotechnology includes the application of materials at the scale of 1–100 nm, has completely revolutionized numerous fields, including agriculture (Mukhopadhyay 2014). At this nanoscale, materials exhibit unique physical, chemical, and biological properties that differ significantly from those of their bulk counterparts (Prasad et al. 2017). In agricultural pest management, nanotechnology offers opportunities to address key limitations of conventional pesticides by using EO-based nano-/pesticides, which often exhibit poor stability, high volatility, and low bioavailability (Gupta et al. 2021; Jafir et al. 2023).

Nanoformulations of EOs and extracts

As previously discussed, nanoformulations constitute a significant technological advancement for stabilizing and delivering EOs derived from aromatic plants. Several nanoformulations, including nano-emulsions, nano-capsules,

Fig. 3 Summary of interconnected challenges associated with the conventional use of aromatic plant-based pest control products



Solid lipid nanoparticles (SLNs), and Nano-gels, are of key interest with reference to EOs encapsulation. The nanoemulsions are extensively studied systems consisting of nanosized oil droplets (typically 20–200 nm) dispersed in aqueous media (Lucia and Guzmán 2020). Their small droplet size offers a large surface area and kinetic stability, enhancing the dispersion of hydrophobic EOs in water-based formulations (Pavoni et al. 2020). This enhanced dispersion enables uniform application, enhances bioavailability and extends residual effectiveness against pests. Nanoemulsions also permit lower application rate and reduce toxicity to non-target organisms than those of conventional emulsions (Ali et al. 2022).

Nanocapsules differ from nanoemulsions by encapsulating the EOs within a polymeric or lipidic-based shell (Gupta and Variyar 2016). This encapsulation protects sensitive bioactive compounds from environmental stressors such as ultraviolet light, oxygen, and temperature fluctuations, significantly enhancing their shelf-life and field persistence (Zabot et al. 2022). The controlled release mechanism reduces the frequency of drug applications and minimizes the risk of phytotoxicity and environmental pollution (Tao et al. 2023). Common materials for nanocapsule synthesis include biodegradable polymers such as chitosan and alginate, as well as lipid matrices such as triglycerides or waxes, all recognized for their environmental compatibility (Dos Santos et al. 2016).

The SLNs combine the benefits of lipid-based carriers with the physical stability needed for agricultural

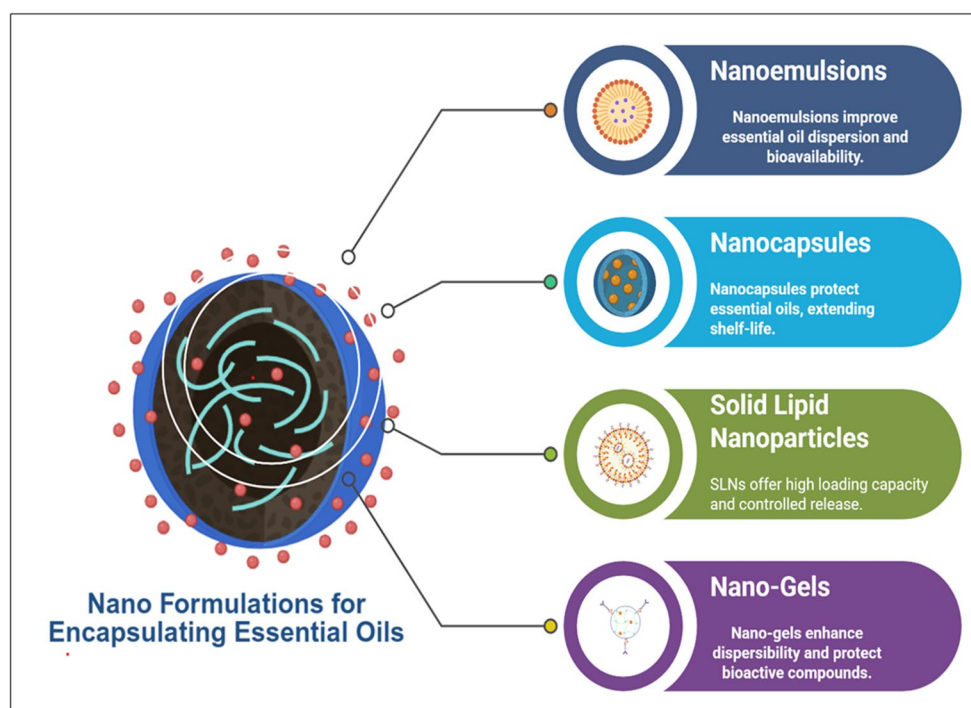
formulations. Composed of lipids that are solid at ambient temperature, SLNs offer high loading capacity for EOs while protecting them from volatilization and degradation (De Oliveira et al. 2015; Duong et al. 2020). The solid matrix enables prolonged controlled release and enhances penetration into pest tissues or plant surfaces. Their biodegradability and low toxicity make SLNs especially suitable for sustainable pest control (Bence et al. 2024).

Similarly, Nanogel formulations have emerged as advanced delivery systems for EOs, addressing critical challenges such as volatility, poor water solubility, and instability under environmental conditions (Alam et al. 2022). By encapsulating EOs within nano-sized hydrophilic polymeric networks, nano-gels enhance their aqueous dispersibility (Sindhu et al. 2022), protect bioactive compounds from degradation, and enable controlled and sustained release, thereby improving their efficacy and shelf life (Cao et al. 2023) (Fig. 4).

Nano pesticides

The formulations of pesticides exhibiting nanoscale dimensions (<400 nm) are considered as nanopesticides (Palermo et al. 2021). Nano-pesticides represent an innovative approach to agricultural pest management that combines nanotechnology with traditional pesticide principles. Their advancement is driven by the need to overcome the limitations of traditional pesticides, such as environmental toxicity, inefficiency, and limited persistence (Sharma et al.

Fig. 4 Various nano formulation systems are used for the encapsulation of EOs-based products



2022). These advanced formulations leverage nanoparticles (NPs) to improve pesticide efficacy, reduce environmental impact, and encourage controlled release. This includes enhanced solubility, increased bioavailability and greater stability in diverse environmental conditions. Nano-pesticides thus offer the potential for a more sustainable, targeted, and efficient solution to pest management (Kumar et al. 2025). Additionally, nano-pesticides are designed to reduce the development of pest resistance (Ali et al. 2023). By targeting biological pathways at the molecular level, they pose greater challenges for pests to develop resistance than traditional chemical pesticides.

Formulation methods of nano-pesticides

The formulation of nano-pesticides involves developing nanoscale carriers capable of encapsulating or loading pesticide molecules. Commonly used methods for formulating nano-pesticides comprise nanoprecipitation, solvent evaporation, and emulsion-based techniques (Paradva and Kalla 2023).

Nanoprecipitation is widely used for its simplicity and ability to produce nanoparticles with high drug-loading capacity. This method comprises dissolving the pesticide in a solvent, followed by rapid mixing with a non-solvent to promote nanoparticle precipitation (Zaibudeen 2025). Emulsion-based methods are widely used to fabricate nanopesticides. Polymeric nanocapsules are commonly prepared by emulsification–solvent evaporation: the active ingredient and a wall-forming polymer are

dissolved in a volatile organic solvent, emulsified into an aqueous stabilizer phase, and the solvent is removed, leaving polymer shells that entrap the active ingredient (Russell and Bruns 2023). Nanoemulsions and micro-emulsions are related emulsion platforms in which the active is typically solubilized in the dispersed (often oil) phase or at the oil–water interface and stabilized by surfactants/co-surfactants; limited partitioning into the aqueous phase may occur depending on polarity (Elsharkawy et al. 2022). This method thus provides improved stability and bioavailability compared to control. Furthermore, methods like lipid-based nanoparticles (liposomes and solid lipid nanoparticles), polymeric nanoparticles, and inorganic nanoparticles (e.g. silica, gold, and silver) are employed in nano-pesticide formulations (Chaugule and Shelar 2025). Each of these materials has diverse properties that can be tailored to enhance pesticide performance, including improving cellular uptake, stabilizing the pesticide, or providing controlled release.

Mechanisms of action of nano-pesticides

Nano-pesticides act through multiple mechanisms that are enhanced by their nanoscale formulation properties. One of the most essential mechanisms is enhanced penetration (Li et al. 2023). Their nanoscale size enables these particles to easily traverse protective barriers such as insect cuticles, fungal cell walls, or plant epidermis, allowing direct and efficient delivery of bioactive compounds to target tissues within pests (Kent et al. 2024).

This increased uptake enhances the potency and speed of action compared to that of bulk drug, which often suffers from limited solubility or poor adherence to pest surfaces (Mrwad et al. 2024). Another key mechanism is the controlled or sustained release of active ingredients enabled by nano-formulation structures such as nano-capsules and SLNs. Instead of releasing the entire payload at once, these systems gradually dispense bioactives over extended periods (Najafi-Taher et al. 2021). This prolonged release maintains effective concentrations of pest deterrents or toxins, reducing the need for frequent reapplications and decreasing the overall chemical load in the environment (Mo et al. 2022). Additionally, controlled release mitigates sudden high doses that can lead to phytotoxicity or disrupt beneficial insect populations (Salman et al. 2021).

Targeted delivery further distinguishes nanopesticides from conventional formulations. By incorporating surface modifications or ligand attachments, nanoparticles can be engineered to recognize and bind specific receptors or tissues in pest organisms. This selectivity enhances efficacy while minimizing harm to non-target species and the surrounding ecosystem (Zhang et al. 2023a). The high surface-area-to-volume ratio of nanoparticles intensifies their interaction with pests, potentially inducing synergistic toxic effects (Xu et al. 2022) (Fig. 5).

Case studies of EO-based nanopesticides

Case study 1 Essential Oil-Based Nano-Biopesticides against *Tribolium confusum*

This case study investigates the formulation of essential oils (EOs) into nano-emulsions as a potential solution for controlling *Tribolium confusum*, a common pest of stored products. Here eight commercially available EOs including anise (*Pimpinella anisum*), artemisia (*Artemisia vulgaris*), fennel (*Foeniculum vulgare*), garlic (*Allium sativum*), lavender (*Lavandula angustifolia*), mint (*Mentha piperita*), rosemary (*Rosmarinus officinalis*), and sage (*Salvia officinalis*) were formulated into nano-emulsions, and their bioactivity, including repellency and acute toxicity against *T. confusum*, was analysed. The physical characteristics of the nano-emulsions exhibited optimal droplet sizes ranging from 95.01 to 144.30 nm and polydispersity indices (PDIs) between 0.146 and 0.248, indicating stable, well-dispersed nano-formulations. All formulations exhibited repellency in area-preference assays. Repellency was quantified using RC_{50} (the concentration required to elicit 50% repellency under the test conditions), and the anise EO nanoemulsion showed the strongest repellency (RC_{50} = 0.033 mg). Acute toxicity trials discovered that most essential oil-based nano-emulsions caused immediate toxicity, and the garlic EO nano-emulsion resulted in the

maximum mortality of *T. confusum* adults (LC_{50} = 0.486 mg/L of air). These outcomes indicated garlic EO's potent toxicity and repellent properties. It was thus concluded that EO-based nano-emulsions present great promise as eco-friendly, sustainable alternatives for controlling post-harvest pests (Palermo et al. 2021).

Case Study 2 Assessment of nanoemulsified Citronella Essential Oil against *Cochliomyia hominivorax* Myiasis.

Cochliomyia hominivorax, myiasis in both animals and humans in the Americas. In this case study, the efficacy of a topical commercial formulation called Nano Citronella Plus® (15% (w/v) nanoemulsified citronella EO, vanillin, caprylic/capric triglyceride, polysorbate 80, sorbitan oleate, tocopheryl acetate, sodium benzoate, and water) was evaluated. The formulation is an oil-in-water nanoemulsion produced by high-pressure homogenization method. The nanoemulsion contains citronella essential oil. The formulation exhibited 100% lethality against eggs and first- and second-stage larvae of *C. hominivorax*. Third-stage larvae had a mortality rate of 69.33%, and the formulation also inhibited oviposition by female flies, preventing further egg laying. It was finally concluded that Nano Citronella Plus® verified potential as a herbal alternative for controlling and treating myiasis caused by *C. hominivorax*. The authors also concluded that formulation could serve as an eco-friendly alternative to conventional chemical treatments (Bricarello et al. 2021).

Case Study 3 *Allium sativum* essential oil-based nano-emulsion against *Planococcus citri* and its predator *Cryptolaemus montrouzieri*.

To address the challenges of volatility, poor water solubility, and instability, the authors in this case study formulated a stable, concentrated garlic EO-based nanoemulsion (15% EO) using high-pressure microfluidization. The formulated nano-emulsion was characterized chemically and physically, with the active compounds primarily consisting of sulfur derivatives (diallyl disulfide). The nano-emulsion remained stable for up to 1 year, with a droplet size of 221.4 nm. In biological experimentation, the nano-emulsion confirmed effective toxicity against the *Planococcus citri*, with lethal concentrations (LC_{90}) of 0.967% for direct exposure and 1.088% for indirect exposure after 48 h. Notably, it exhibited no harmful effects on the predator *Cryptolaemus montrouzieri*, indicating its selectivity and safety. Thus Garlic EO nanoemulsions are a promising alternative to synthetic insecticides, combining high stability with selective pest control and minimal predator impact (Modafferi et al. 2024).

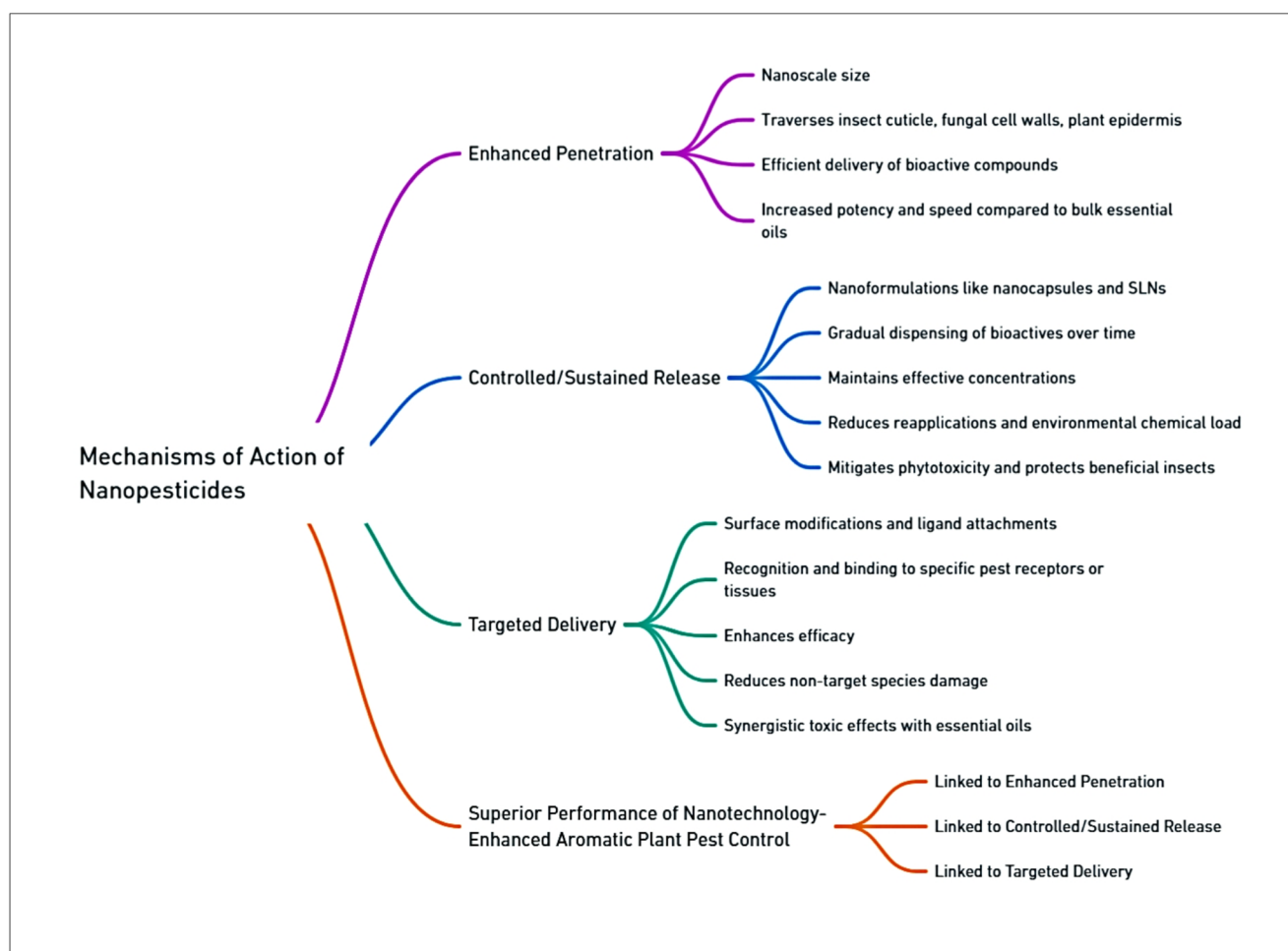


Fig. 5 Mind map illustrating mechanisms of actions of nano-pesticides linking enhanced penetration, slow release, and targeted delivery as key contributors for using aromatic plant-based pest control

Case study 4 Evaluation of fennel, mint, and Sweet orange EO-based nano-emulsions against *Rhyzopertha dominica*

This study established stable nano-emulsions from fennel, mint, and sweet orange essential oils (EOs) and determined their repellent efficacy against *Rhyzopertha dominica* (Giunti et al. 2021). The nanoemulsions had droplet sizes below 200 nm, and all formulations were highly effective at repelling the pest. Nevertheless, fennel-based emulsions exhibited lower repellency than mint and sweet orange oils. The study also investigated habituation, in which the pest's response to repeated exposure to the repellent decreased over time. Habituation was observed with mint- and sweet orange-based formulations, with slightly reduced pest response being frequency-dependent. More importantly, the pests regained full responsiveness within 24h of exposure, suggesting that the reduction in effectiveness was due to genuine learning rather than sensory or motor fatigue. These findings highlight the potential for habituation to reduce the effectiveness of EO-based biopesticides and emphasize the

need for this factor to be considered in pest management strategies. As summarized in Table 3, EO nanoemulsion case studies provide quantitative links between formulation CQAs (e.g., droplet size/PDI, stability) and efficacy end-points (e.g., repellency indices, LC_{50}/LC_{90}) across stored-product pests and myiasis control. This table also highlights key translational constraints such as stage-dependent susceptibility, habituation under repeated exposure, sensitivity to deployment conditions, and remaining non-target/regulatory requirements.

Real-time implications and field applications

Formulation scale-up and cost analysis

The EO-based nanoformulations offer an important alternative to traditional insecticide control methods. The transition from laboratory-scale synthesis to industrial-scale production requires careful optimization of formulation

Table 3 Evidence of EO nanoemulsions across pest systems (condensed; standardized abbreviations)

Pest system/ target	EO/key actives	Formulation type (process)	Baseline comparator	Main outcome	Key endpoints	Main constraints/notes	Ref
Stored-product beetle <i>T.</i> <i>confusum</i>	8 EOs (anise, artemisia, fennel, garlic, lavender, mint, rosemary, sage)	O/W NEs	Untreated/ bulk EO (implicit)	Repel- lency + acute toxicity	Size 95–144 nm; PDI 0.146–0.248; RC_{50} 0.033 mg (anise); LC_{50} 0.486 mg/L air (garlic)	Performance depends on application form (aerosol/gel) and stor- age conditions	(Palermo et al. 2021)
Myiasis fly <i>C.</i> <i>hominivorax</i>	Citronella EO (commercial blend)	Commer- cial O/W NE (HPH)	Conven- tional chemical control (as alternative)	Ovicidal/lar- vicidal + ovi- position inhibition	100% (eggs, L1–L2); 69.33% (L3); ovipo- sition inhibited	Reduced efficacy in L3; topical safety/reg- ulatory considerations	(Bricarello et al. 2021)
Citrus mealy- bug <i>P. citri</i> (+predator <i>C.</i> <i>montrouzieri</i>)	Garlic EO; sulfur derivatives (e.g., diallyl disulfide)	NE (HPM; 15% EO)	Synthetic insecticides/ bulk EO (implicit)	Effec- tive + predator- safe	Stable 1 year; size 221.4 nm; LC_{90} 0.967% (direct), 1.088% (indirect), 48 h	Requires broader non- target testing + field validation; route- dependent dosing	(Modafferi et al. 2024)
Stored-product pest <i>R.</i> <i>dominica</i>	Fennel, mint, sweet orange EOs	EO NEs	Untreated (repellency baseline)	Repellency; habituation	Size < 200 nm; repel- lency high; response recovered ≤ 24 h	Habituation may reduce repeated-use efficacy; IPM rotation/ timing advised	(Giunti et al. 2021)

O/W=oil-in-water, NE=nanoemulsion, PDI=polydispersity index, RC_{50} = repellent concentration, LC_{50}/LC_{90} = lethal concentration, L1–L3=larval stages 1–3

procedures. These methods need to be modified to meet Good Manufacturing Practice (GMP) and regulatory safety guidelines. Moreover, process variables including mixing speed, temperature control, and solvent recovery efficiency significantly impact production yield and stability (Sammassagi et al. 2025).

Green, solvent-free nanosynthesis approaches are increasingly favored due to their reduced environmental impact and economic viability. Use of biopolymers such as chitosan, starch, zein derivatives are employed as biodegradable nanocarriers, which lowers both production cost and environmental persistence (Kućuk et al. 2023). Equipment scalability is another critical factor, where lab-scale homogenizers must be replaced by high-pressure or ultrasonic systems capable of continuous processing (Rai et al. 2026). Moreover, process reproducibility and quality assurance remain central to successful upscaling. Lastly, cost-effectiveness remains a determining factor in the practical adoption of nano-PEO insecticides for agricultural use. Although initial formulation costs are higher due to materials and equipment, long-term benefits include reduced pesticide dosage and prolonged activity.

Shelf-life and storage conditions

The stability and shelf-life of nano-insecticide formulations are key parameters influencing field applicability and commercial success. Encapsulation of EOs within nanocarriers effectively mitigates degradative processes by shielding the active compounds from external environmental factors (Li

et al. 2025). Moreover, nanocarriers enhance thermal and photo-stability, enabling storage under a broader range of ambient conditions (Ferreira et al. 2022).

The physicochemical stability of nanoformulations depends on their zeta potential, particle size, and encapsulation efficiency (Shah et al. 2014). Studies report that lipid-based nano-emulsions exhibit extended shelf lives under optimal conditions (Dhaval et al. 2022). However, polymeric nanoparticles like chitosan or PLGA may require refrigeration to prevent hydrolysis or microbial growth, especially in aqueous suspensions (Jain et al. 2010). Desiccation and lyophilization are additional strategies to improve storage durability of sensitive formulations. Incorporating natural antioxidants within the formulation can further delay oxidation and extend shelf-life (Petcu et al. 2023). Ultimately, maintaining product integrity during storage improves user confidence and ensures consistent insecticidal efficacy across multiple application cycles.

Performance in greenhouse and field trials

Experimental investigation largely supports the efficacy of EO based nano-emulsions against common agricultural pests under greenhouse or field-like conditions (Menossi et al. 2021). For example, a recent study used nano-emulsions of EOs derived from certain plant oils to control pests such as aphids (*Aphis gossypii*), leaf-feeding caterpillars (*Spodoptera littoralis*), and mites (*Tetranychus urticae*). The nanoemulsions exhibited good stability (as verified by drop-let-size and TEM measurements) and led to a substantial

pest mortality and decreased feeding damage as compared to untreated controls (Abd-Elnabi et al. 2025).

Moreover, beyond their direct insecticidal effects, some EO-nanoformulations can also stimulate plant defense responses. For instance, a recent investigation reported overexpression of plant defense-related genes (e.g., salicylic acid and jasmonic acid pathway genes) in treated plants. It was evident that this nano-EO application may support plant innate immunity, together with causing pest mortality (Joshi 2025). This dual mode pest suppression and enhanced plant defense makes EO-nanoformulations a valuable tool in sustainable crop protection frameworks. Nevertheless, the practical “Field” application needs a careful optimization of formulation parameters, application methods, and dose.

Post-harvest storage of crops is disparagingly threatened by various storage pests and conventional chemical fumigants and insecticides. This is due to enhanced toxicity, presence of chemical residues, pest resistance, and environmental hazards (Damalas and Eleftherohorinos 2011).

Commercial EO-based pest control products

Currently, several commercially available EO-based products use publicly accessible primary sources (manufacturer labels/technical sheets and, where available, regulatory listings) and record only label-disclosed EO actives and use claims (Table 4).

Limitations

Despite rapid growth, the literature has several recurrent limitations. First, comparator baselines are inconsistent (bulk EO vs. coarse emulsions vs. commercial products), making effect sizes difficult to interpret across studies (Bom et al. 2020). Second, formulation reporting is often incomplete

key CQAs (PDI, zeta potential, encapsulation efficiency, release profiles) are missing in many datasets—hindering reproducibility (Panwar et al. 2026). Third, efficacy evidence is predominantly laboratory-based, with relatively few semi-field or field trials that incorporate realistic UV/temperature/rainfall conditions and agronomic endpoints. Fourth, non-target and environmental fate assessments remain uneven, particularly for repeated applications and aquatic exposure scenarios (Soni et al. 2026). Finally, EO compositional variability (chemotype, extraction method, storage) is not always controlled, which can confound comparisons and slow regulatory translation (Barra 2009).

Recent breakthroughs and emerging trends in nano-insecticides

A major advance involves using Metal–Organic Frameworks (MOFs) as carriers for agrochemicals. MOFs are highly porous materials built from metal nodes and organic linkers (Basak et al. 2024b). In agriculture, MOF nanoparticles have shown efficient loading and controlled release of insecticides (Zong et al. 2022). Their porous structures enable high active-ingredient payload while protecting them from premature degradation (Basak et al. 2024a). Several examples have been reported in literature based on successful pesticide delivery using this recent trend (Chen et al. 2023; Ma et al. 2023; Wang et al. 2023).

The MOF+dsRNA delivery study introduces a new paradigm, joining both nanotechnology with gene-silencing (biopesticide) mechanisms. This supports your idea of “next-gen nano-pesticides” beyond EO or synthetic chemicals. Metal–Organic Frameworks (MOFs) have recently gained attention as advanced dsRNA carriers due to their high porosity, tunable structure, and exceptional adsorption

Table 4 EO-based products/blends with declared composition, targets, and approval context

Product name	Region/market	EO components/declared actives	Target pests/use claims	Application method	Approval/registration context
eco-neem®	AU/NZ	Neem extract (Azadirachtin A & B)	Chewing/sucking insects (e.g., aphids, whiteflies, caterpillars)	Foliar spray	“Registered organic insecticide” (as marketed)
Mosquito Guard®	US	Citronella oil (repellent)	Mosquito repellent	Topical/clothing (label)	EPA product label (PDF)
Citriodiol®	US	PMD/Oil of Lemon Eucalyptus category	Arthropod repellency	Repellent formulations	EPA-listed skin-applied repellent ingredients
Wondercide®	US	Plant/EO actives (product line; minimum-risk)	Household/pet pests (product-specific)	Ready-to-use spray	FIFRA 25(b) minimum-risk (company states)
EcoTrol® PLUS	US	Rosemary oil 10%, peppermint oil 2%, geraniol 5%	Contact insecticide/miticide (label)	Spray/surface (label)	Label indicates 25(b) exemption; SDS discloses actives
Bioxeda (Xeda International)	France/EU	Composition not consistently disclosed in public listing	Post-harvest plant protection (authorization scope)	Post-harvest treatment	Authorized in France (ANSES E-Phy); also listed by CABI portal

capacity (Soriano-Giles et al. 2023). A breakthrough study demonstrated that Zn-based ZIF-8 MOFs coated with polydopamine (PDA) could significantly enhance RNAi efficiency in *Spodoptera frugiperda*, a major agricultural pest. The MOF-PDA nanocarriers proficiently encapsulated dsRNA and protected it from enzymatic degradation in the insect gut (Maraveas et al. 2024).

Another emerging strategy is the co-delivery of multiple agents in a single nanosystem. Recent studies propose combining botanical compounds (e.g., essential oils) with synthetic insecticides or synergists within a single nanocarrier (Carvalho et al. 2021). These dual-action nanoformulations exhibit synergistic effects, often achieving higher efficacy at lower doses (Li et al. 2023 a), as seen with EOs. One specific example involving prothioconazole (PRO) and pyrimethanil (PYR) formulation in core-shell structured nanoparticles against *Botrytis cinerea* and *Fusarium graminearum*. It was evident that RO-PYR NPs suggestively improved photostability and foliage adhesion of PRO) and PYR and reduced their volatility and leaching potential (Wang et al. 2023).

Recent breakthroughs and emerging trends in nano-insecticides Stimuli-responsive nano release systems represent a third trend and such systems activate drug release under specific environmental or biological conditions (pH, moisture, temperature, pest enzyme presence) (Sethuraman et al. 2021). This approach improves timing and targeting, minimizing waste and non-target exposure (Yu et al. 2024). The development of “green” nano-insecticides reduce environmental risks while maintaining efficacy. The zein/polymer nanocarrier system is another interesting development for future work that offers sustainable, scalable nanocarriers. Zein is a prolamin protein derived from maize and is biocompatible, biodegradable, and considered low-toxicity and environmentally friendly. Several investigations have successfully employed Zein in nanocarrier systems. For instance, Boncan et al. (2020) encapsulated these volatile essential-oil compounds carvone and limonene into Zein nanoparticles (Table 5).

Conclusion

This review synthesizes current evidence on essential oil (EO)-based nanoformulations for insect pest management in agricultural systems and highlights the formulation principles that govern their performance. EOs from aromatic plants contain diverse bioactive constituents, particularly terpenoids and phenolic compounds. These contribute to significant insecticidal and repellent activity through membrane disruption, neurophysiological interference, and behavioral deterrence. However, the practical use of free EOs remains limited due to high volatility, physicochemical

Table 5 Recent trends and key findings in nano-pesticides research

Year	Key Techniques	Essential Oil(s) Used	Reference
2023	Nanoformulations	various	(Gupta et al. 2023)
2023	RAFT	Plant oils (general)	(Adeyemi et al. 2023; Pirithiraj et al. 2025)
2023	Nanoemulsions	Honeysuckle and Patchouli	(Hikal et al. 2023)
2023	Ultrasonication;	Geranium, Peppermint	(Jesser et al. 2023)
2024	Stimuli responsive	Tea Tree	(Hao et al. 2024)
2024	Nano-encapsulated	<i>Mentha pulegium</i>	(Sharifiyan et al. 2024)
2025	MOF-nanocarriers	Various	(Angeli GK et al. 2025)
2024	Zein polymer	<i>Ocimum basilicum</i> extract	(Amado et al. 2024)
2025	Stimulus responsive	<i>Litsea cubeba</i>	(Ding et al. 2024)
2025	Nanoemulsions	<i>Pelargonium graveolens</i>	(Ibrahim et al. 2025)
2025	Biopolymer nanocarriers	Lemongrass, Clove	(Luneja and Mkindi 2025)
2025	MOF + dsRNA delivery,	Not specified	(Wang et al. 2025)
2025	Smart release	Various	(Anjana et al. 2024)

instability and loss under field conditions. Nanoformulation strategies including nanoemulsions, nanocapsules, and SLNPs have emerged as effective approaches to mitigate these limitations. The case studies reviewed further support this trend, while also showing that performance is context-dependent and influenced by formulation quality, pest biology, and deployment conditions. A major contribution of this review is the comparative integration of EO chemistry, formulation design and translational constraints. In particular, emerging platforms such as biopolymeric nanocarriers and metal–organic framework (MOF)-based systems represent important advances for tunable delivery and next-generation nanopesticide design. Nevertheless, commercial translation still requires progress in scalable manufacturing, standardized characterization and efficacy reporting, regulatory alignment, cost-effectiveness, and long-term ecological risk assessment.

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