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Mosquito Repellents of Natural Origins from Aromatic Plant-Derived Essential Oils: A Narrative Review

Eka Candra Lina[1], Muslim Bin Aqeel[2], Intan Haslina Ishak[3], Novri Nelly[4], Mohd Dasuki Sulain[5], Nurhidanatasha Abu Bakar[6]
[1]Department of Plant Protection, Faculty of Agriculture, Universitas Andalas, Limau Manis Padang, West Sumatera 25163, Indonesia. Lembaga Penelitian dan Pengabdian kepada Masyarakat, STP LPPM Building, Universitas Andalas, Limau Manis Padang, West Sumatera 25163, Indonesia
[2]School of Health Sciences, Health Campus, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan, Malaysia
[3]School of Biological Sciences, Universiti Sains Malaysia, 11800 Gelugor, Pulau Pinang, Malaysia
[4]Department of Plant Protection, Faculty of Agriculture, Universitas Andalas, Limau Manis Padang, West Sumatera 25163, Indonesia
[5]School of Health Sciences, Health Campus, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan, Malaysia.
[6]School of Health Sciences, Health Campus, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan, Malaysia.

Abstract: *Dengue, Zika, and chikungunya arboviral diseases pose serious threats to global public health, primarily transmitted by Aedes aegypti and Aedes albopictus. The conventional use of chemical insecticides to control these vectors is becoming increasingly ineffective due to rising insecticide resistance and environmental concerns. In response, essential oils (EOs) derived from aromatic plants have garnered growing interest as natural, eco-friendly alternatives, owing to their volatile bioactive compounds with broad-spectrum repellent and insecticidal properties. This review provides a critical overview of EO-based mosquito repellents, focusing on their botanical origins, chemical compositions, bioactivity profiles, and mechanisms of action. Notably, compounds such as monoterpenes (e.g., citronellal, thymol, and carvacrol) and sesquiterpenes (e.g., β-caryophyllene), particularly from plant families like Lamiaceae, Asteraceae, and Myrtaceae, have demonstrated significant repellent activity, sometimes comparable to synthetic agents like N,N-diethyl-meta-toluamide (DEET) under laboratory conditions. However, the high volatility of these compounds limits their long-term efficacy. To address this, advanced formulation technologies, including nanoemulsions, lipid-based carriers, polymeric microcapsules, and cyclodextrin complexes, have been developed to enhance EO stability and prolong their release profiles. Furthermore, emerging insights into their molecular mechanisms, such as inhibition of transient receptor potential ankyrin 1 (TRPA1), modulation of odorant-binding receptors, and disruption of olfactory signalling, shed new light on their repellent potential. Despite encouraging laboratory outcomes, further efforts in formulation standardisation, regulatory assessment, and field validation are essential to position EOs as viable, sustainable alternatives to synthetic repellents.*

Keywords: *Aromatic plant-based essential oils; Mosquito repellents; Bioinsecticides; Nanoformulations; Sustainable vector control*

1 INTRODUCTION AND BACKGROUND OF THE STUDY

1.1 Vector control using bioinsecticides

Bioinsecticides, also known as biopesticides derived from natural products such as bioactive plant compounds, pheromones, and microorganisms, represent a promising alternative to chemical insecticides. These agents offer targeted pest control with reduced environmental impact and lower toxicity to humans and non-target organisms. The United States Environmental Protection Agency (US EPA) classifies biopesticides into three main categories: plant-incorporated protectants (PIPs), microbial pesticides, and biochemical pesticides (United States Environmental Protection Agency, 2023).

PIPs are substances produced by genetically modified plants that express pesticidal properties inherited from other organisms. A common example is the incorporation of *Bacillus thuringiensis* (Bt) toxin genes into crops (Bt-PIPs), which enables plants to produce insecticidal proteins (Jurat-Fuentes & Crickmore, 2017; Kumar et al., 2008). Similarly, the integration of plant viral coat proteins (PVCP-PIPs) helps protect plants from viral infections (Gordon & Waterhouse, 2006). These PIPs provide effective pest resistance while minimizing harm to the environment and human health.

Microbial pesticides, on the other hand, utilise naturally occurring microorganisms, such as bacteria, fungi, or viruses as active agents. These microbes exert their effects through mechanisms like pathogenic infection, competitive inhibition, or the production of bioactive compounds such as mycotoxins or bacterial toxins (Arthurs & Dara, 2019; Montesinos, 2003). Their high specificity toward target pests and limited persistence in the environment make them suitable for sustainable pest management. Among microbial agents, various subspecies and strains of *Bacillus thuringiensis* are the most widely used, each tailored to control specific insect larvae by producing unique protein toxins (Raymond & Federici, 2017; Soberón et al., 2016).

Biochemical pesticides constitute the third category and consist of naturally occurring substances that affect insect behaviour or physiology through non-toxic modes of action. These include insect sex pheromones that interfere with mating patterns (Liang et al., 2020; Wang et al., 2019), as well as plant-derived compounds that function as attractants, deterrents, or repellents (Foster, 2008; Biasazin et al., 2014). Their mode of action makes them highly compatible with integrated vector management strategies, especially in environmentally sensitive areas.

1.2 Vector control using plant-based bioinsecticides

Plants naturally protect themselves from insect pests and pathogens by synthesising a diverse array of defensive phytochemicals, which function as repellents, feeding deterrents, toxins, and growth regulators (Bhambhani et al., 2021). Leveraging this innate defence system, various plant parts such as stems, leaves, bark, roots, fruits, peels, and seeds, as well as a synergistic combination of different plants, can be formulated into effective plant-based bioinsecticides. Once applied, these phytochemicals disrupt insect physiology through multiple modes of action by inhibiting AChE and GABA-gated chloride channels (Höld et al., 2000; Khorshid et al., 2015; Rajashekar et al., 2014), interfering with sodium-potassium ion exchange and nerve-cell membrane function (Isman, 2006), blocking calcium channels, and activating nicotinic acetylcholine and octopamine receptors (Green et al., 2013; Farooqui, 2012).

Among the most potent are secondary metabolites, such as essential oils, alkaloids, phenolics, terpenoids, and steroids, which have demonstrated pronounced mosquitocidal properties (Senthil-Nathan, 2022; Shaalan et al., 2005). These plant-derived compounds can exert ovicidal, larvicidal, adulticidal, and oviposition-deterrent effects by targeting the nervous, respiratory, and endocrine systems of mosquitoes (Senthil-Nathan, 2020). Their ovicidal and larvicidal actions are particularly valuable because they eliminate mosquitoes at immobile stages before they mature, helping to break transmission cycles early. In parallel, botanical repellents prevent adult female mosquitoes from biting humans, directly reducing disease transmission. Traditional use in regions like India and China has highlighted numerous plant products, especially essential oils, with strong repellent activity (Şengül Demirak & Canpolat, 2022; Tisgratog et al., 2016; Zhu et al., 2018).

2. Essential oil-containing mosquito repellents and their properties

Repellents containing essential oils (EOs) work by surrounding the users with volatile compounds that mosquitoes find unattractive at close range, even though the insects may still be drawn toward human odours from a distance. Their efficacy, however, is influenced by environmental factors such as temperature, humidity, and wind speed, as well as formulation characteristics that govern evaporation rate and skin penetration. For instance, alcohol-based formulations often penetrate the stratum corneum more deeply, accelerating evaporation and shortening protection time (Bissinger & Roe, 2010), while perspiration can further dilute the active compounds and diminish their repellent effect. Consequently, the choice of carrier and formulation technology is critical to prolonging the release and retention of these volatile bioactive compounds.

As compiled in Table 1, among the most potent EO-containing repellents are those from *Lamiaceae, Asteraceae, Myrtaceae, Fabaceae,* and *Apiaceae*, which are produced in the cytoplasm and plastids of plant cells (Nagegowda, 2010) and consist primarily of monoterpenes along with other hydrocarbons and phenylpropenes (Şengül Demirak & Canpolat, 2022; Silvério et al., 2020). Key monoterpenes, such as α-pinene, γ-pinene, p-cymene, limonene, terpinolene, eugenol, thymol, camphor, citronellol, and citronellal, have been repeatedly shown to repel a variety of mosquito species (Gillij et al., 2008; Pandey et al., 2009; Jaenson et al., 2006).

Extensive bioassays on *Thymus* spp. (*Lamiaceae*) demonstrate the high repellent potency of their EOs against *Culex* mosquitoes. In human forearm tests, compounds like carvacrol, p-cymene, linalool, α-terpinene, and thymol from *Thymus vulgaris* oil provided protection equal to or exceeding that of N,N-diethyl-m-methylbenzamide (DEET) in both duration and intensity (Park et al., 2005). Similar protective effects were observed in hairless mouse models (Choi et al., 2002). Additionally, *T. leucospermus* and *T. teucrioides* EOs, dominated by p-cymene, exhibited repellent activity against *Cx. pipiens* comparable to the synthetic repellent icaridin (Pitarokili et al., 2011). Field trials with carvacrol-rich EOs from *Satureja thymbra*, *Origanum onites*, and *Thymbra spicata* achieved zero mosquito landings against *Ae. albopictus* over five-minute exposures, matching DEET's performance (Evergetis et al., 2018).

Beyond *Lamiaceae*, *Nepeta cataria* (catnip) EO, rich in monoterpene lactone nepetalactone, has demonstrated remarkable broad-spectrum repellence, effectively deterring *Aedes*, *Anopheles*, and *Culex* mosquitoes, as well as biting flies like *Stomoxys calcitrans* and *Musca domestica* (Zhu et al., 2009; Reichert et al., 2019). Notably, nepetalactone was found to repel *Ae. aegypti* up to ten times more effectively than DEET under laboratory conditions (Reichert et al., 2019). These findings underscore the potential of EOs and careful formulation to rival synthetic repellents in both efficacy and environmental safety.

EOs from a wide range of aromatic plant families have demonstrated significant repellency against *Aedes* mosquitoes. For example, EOs extracted from *Asteraceae* species such as *Baccharis spartioides* (spartium), *Verbenaceae* plants like *Aloysia citriodora* (lemon beebrush), and *Lamiaceae* members including *Rosmarinus officinalis* (rosemary) were all tested against *Ae. aegypti*, with limonene and camphor emerging as the principal active compounds that maintained repellence even at low concentrations (12.5 %) (Gillij et al., 2008). Similarly, *Ae. albopictus*, *Anopheles dirus*, and *Culex quinquefasciatus* proved sensitive to EOs produced from Thai aromatic plants in the *Lamiaceae, Araliaceae,* and *Piperaceae* families (Tawatsin et al., 2006). In these studies, oils from *Eleutherococcus trifoliatus* (climbing ginseng), *Schefflera leucantha* (hanuman prasankai), *Piper nigrum* (black pepper), and *Vitex trifolia* (simpleleaf chastetree) provided up to eight hours of protection, comparable to DEET and IR3535 against *Ae. albopictus*. Moreover, EOs from widely used *Myrtaceae, Zingiberaceae, Rutaceae, Meliaceae, Magnoliaceae,* and *Lauraceae* plants, including *Melaleuca cajuputi* (cajuput), *Curcuma longa* (turmeric), *Alpinia galanga* (galangal), *Zingiber officinale* (ginger), and *Murraya paniculata* (orange jasmine), as well as *Psidium guajava* (guava), *Myristica fragrans* (nutmeg), *Aglaia odorata* (Chinese perfume tree), *Manglietia garrettii* (magnolia), and *Litsea cubeba* (mountain pepper), delivered eight-hour repellence against *An. dirus* (Tawatsin et al., 2006).

Beyond monoterpenes, several sesquiterpenes and other classes of phytochemicals contribute to these EOs' efficacy. Compounds like guaiol, α-bisabolol, and α-cadinol (from *Zingiber nimmonii*), germacrene D (from *Murraya paniculata*), and nootkatone and β-caryophyllene (from *Lantana montevidensis* and *Zingiber nimmonii*) have all been identified, with β-caryophyllene showing especially strong activity against *Aedes* mosquitoes (Gillij et al., 2008). Additionally, the diterpene alcohol phytol (from *Murraya paniculata*) and the aromatic phenol coumarin have been linked to potent biting-deterrent effects against *Ae. aegypti* (Cantrell et al., 2016), underscoring the diverse chemical arsenal plants deploy for mosquito repellence.

Table 1: Repellent efficacy of plant-derived EOs against mosquito species

Name of the plant and families	**Name of the compounds**	**Insects**	**References**
Family *Lamiaceae*			
Thymus vulgaris	carvacrol, ρ-cymene, linalool, α-terpinene and thymol	*Cx. pipiens*	(Park et al. 2005) (Choi et al. 2002)
Thymus leucospermus	p-cymene, γ-terpinene, thymol and borneol	*Cx. pipiens*	(Pitarokili et al. 2011)

Thymus teucrioides	p-cymene, γ-terpinene, thymol, borneol and α-pinene	*Cx. pipiens*	(Pitarokili et al. 2011)
Satureja pilosa	Thymol, carvacrol, p-cymene	*Ae. aegypti*	(Semerdjieva et al., 2020)
Satureja thymbra	α-phellandrene γ-terpinene, sabinene, β-pinene, δ-3-carene, eucalyptol, D-fenchone, 2-nonanone, 2-undecanone, estragole, carvacrol, p-cymene, and methyl eugenol	*Ae. albopictus*	(Evergetis et al. 2018)
Origanum onites	α-phellandrene γ-terpinene, sabinene, β-pinene, δ-3-carene, eucalyptol, D-fenchone, 2-nonanone, 2-undecanone, estragole, carvacrol, p-cymene, and methyl eugenol.	*Ae. albopictus*	(Evergetis et al. 2018)
Thymbra spicata	α-phellandrene γ-terpinene, sabinene, β-pinene, δ-3-carene, eucalyptol, D-fenchone, 2-nonanone, 2-undecanone, estragole, carvacrol, p-cymene, and methyl eugenol.	*Ae. albopictus*	(Evergetis et al. 2018)
Nepeta cataria	nepetalactone, Alstonine	*Ae. aegypti* *An. gambiae* *Cx. quinquefasciatus*	(Reichert et al., 2019)
Rosmarinus officinalis	limonene and camphor	*Ae. aegypti*	(Gillij et al., 2008)
Vitex trifolia	α-pinene, α-thujene, cis-ocimene, β-pinene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Lavandula dentata	Camphor, fenchone, exo-fenchol, B-pinene, furanoid, limonene, camphene, a-pinene	*Ae. albopictus*	(Bedini et al., 2018)
Mentha piperita	limonene, pulegone, 1,8-cineole, piperitone, caryophyllene, α- and ß-pinenes,	*Ae. aegypti*	(Kumar et al., 2018)
Baccharis spartioides	limonene and camphor	*Ae. aegypti*	(Gillij et al., 2008)

Artemisia verlotiorum	Chrysanthenone, B-caryphyllene, y-muurolene, 1,8-cineole, a-pinene, myrcene	*Ae. albopictus*	(Bedini et al., 2018)
Rhanterium epapposum	Camphene, myrcene, limonene, a-pinene, sabinene, B-pinene	*Ae. aegypti*	(Demirci et al., 2017)
Carpesium abrotanoides	Caryophyllene, trans-nerolidol	*Ae. aegypti*	(Haris et al., 2022)
Eupatorium capillifolium	methyl thymol, 2,5-dimethoxy-p-cymene, myrcene	*Ae. aegypti*	(Tabanca et al., 2010)
Tagetes patula	caryophyllene oxide, p-caryophyllene, spathulenol	*Ae. aegypti*	(Ali et al., 2016)
Anthemis melampodina	α-pinene, β-eudesmol	*Ae. aegypti*	(Yusufoglu et al., 2018)
Anthemis scrobicularis	β-eudesmol	*Ae. aegypti*	(Yusufoglu et al., 2018)
Aloysia citriodora	limonene and camphor	*Ae. aegypti*	(Gillij et al., 2008)
Lantana montevidensis	p-elemene, β-caryophyllene, germacrene	*Ae. aegypti*	(Blythe et al., 2016)
Lippia pedunculosa	piperitenone oxide, (R)-limonene	*Ae. aegypti*	(Nascimento et al., 2017)
Lippia javanica	α-pinene, 1,3-5 cycloheptatriene, β phellandrene, (+)-2-carene, 3-carene, eucalyptol and caryophyllene oxide	*Ae. aegypti*	(Lukwa et al., 2009)
Family *Araliaceae*			
Eleutherococcus trifoliatus	2-pinen-10-ol, 1,2-epoxy-p-menth-8-ene, 2-pinen-10-ol, verbenol, (±)-2(10)-pinen-3-one, eucalyptol	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Schefflera leucantha	Verbenol, (±)- 2(10)-pinen-3-one, eucalyptol	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Piper nigrum	Caryophyllene, caryophyllene oxide, a-caryophyllene, copaene, isocaryophyllene, linalool, limonene, B-pinene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Syzygium aromaticum or *Eugenia caryophyllata*	Eugenol, terpene-4-ol	*Ae. albopictus*	(Bairagi et al., 2022)

Eucalyptus globulus	Eucalyptol, carene, camphene, γ-terpinene, α-terpineol	*Ae. albopictus* *An. stephensi* *Ae. aegypti*	(Hazarika et al., 2022)
Eucalyptus niten	1,8-cineole, p-cymene, β-triketones, alkyl esters	*Ae. aegypti* *Ae. albopictus*	(Alvarez Costa et al., 2017)
Melaleuca cajuputi	p-cymene, γ-terpinene, α-terpineol, Beta Caryophyllene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Psidium guajava	β-Caryophyllene oxide, β-Pinene, α-Humulene, Limonene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Myristica fragrans	Linalool, Sabinene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Family *Poaceae*			
Cymbopogon nardus	Geraniol, citronellal, geranial, limonene, linalool, citronellol	*Ae. albopictus* *Ae. aegypti*	(Hazarika et al., 2022)
Cymbopogon citratus	Geranial, eucalyptol, isoneral, camphene, linalool	*Ae. albopictus*	(Hazarika et al., 2022)
Curcuma longa	Terpinolene, p-cymene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Alpinia galanga	1,8-Cineole, β-Pinene, α-Terpineol, Terpinen-4-ol	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Zingiber officinale	β-Sesquiphellandrene, zingiberene, citral	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Zingiber nimmonii	myrcene, β-caryophyllene, α-humulene, and α-cadinol	*An. stephensi* *Ae. aegypti* *Cx. quinquefasciatus*	(Govindarajan et al., 2016)
Curcuma aromatica	xanthorrhizol, 1H-3a, 7-methanoazulene, curcumene	*Ae. aegypti*	(Choochote et al., 2005)
Family *Rutaceae*			

Murraya paniculata	Caryophyllene, a-caryophyllene, germacrene B, a-cardinol, caryophyllene oxide, phytol, nerolidol	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Ruta chalepensis	2-undecanone, 2-nonanone, 2-nonyl acetate	*Ae. aegypti* *An. quadrimaculatus*	(Ali et al., 2016)
Citrus sinensis	Limonene, β-pinene	*Ae. albopictus*	(Giatropoulos et al., 2012)
Citrus limon	Limonene, β-pinene	*Ae. albopictus*	(Giatropoulos et al., 2012)
Citrus paradise	Limonene, β-pinene	*Ae. albopictus*	(Giatropoulos et al., 2012)
Aglaia odorata	a-cadinol, spathulenol, caryophyllene, ylangene, thunbergol, cardinol	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Manglietia garrettii	Nerolidol, caryophyllene, a-caryophyllene, a-caryophyllene, globulol, cadinol, a-cardinol, B-pinene,	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Magnolia grandiflora	1-decanol, 1-octanol	*Ae. aegypti*	(Ali et al., 2020)
Family *Lauraceae*			
Litsea cubeba	Citronellal, linalool, limonene, eucalyptol, B-pinene, isopulegol, a-pinene	*Ae. aegypti* *Ae. albopictus* *An. dirus* *Cx. quinquefasciatus*	(Tawatsin et al., 2006)
Umbellularia californica	thymol, umbellulone, 1,8-cineole, α-terpineol	*Ae. aegypti*	(Tabanca et al., 2013)
Cinnamomum cassia	Cinnamaldehyde, benzaldehyde, cinnamyl alcohol	*Ae. aegypti*	(Aungtikun & Soonwera, 2021)

3. Modes of action of essential oil-containing repellents

Most mosquito repellents currently on the market contain synthetic compounds such as DEET, IR3535, and picaridin, as well as phytochemicals derived from EOs. However, the precise modes of action and the molecular targets involved in repellent activity remain unclear due to limited information on the proteins and molecules involved in this process. Although some studies have provided insights into the characteristics of insect olfactory systems, the understanding of how repellents exert their effects at the molecular level is still incomplete and warrants further investigation (Park et al., 2005). The following sections are the postulated mechanisms of action of EO-containing repellents against the mosquito.

3.1 Activation of transient receptor potential ankyrin 1

A growing body of research has revealed that mosquito repellents, especially those that contain EOs, act through multiple mechanisms targeting the insect's sensory systems. One such mechanism involves the activation of transient receptor potential ankyrin 1 (TRPA1) channel, which are ligand- and temperaturegated ion channels capable of detecting noxious heat and chemical irritants in the environment. These TRPA1 channels are evolutionarily conserved across vertebrates and invertebrates, although their sensitivity thresholds and chemical responses can vary significantly between species (Park & Piermarini, 2025) (Laursen et al., 2023). In *Ae. aegypti*, TRPA1 functions as a nociceptive sensor that is activated by environmental irritants such as citronellal and catnip oil, two known components of EO-containing repellents. Upon activation, these TRPA1 agonists trigger avoidance behaviour, contributing to the repellent effect. The mode of action is electrophysiological: TRPA1 agonists stimulate the ion channels involved in environmental sensing and host-seeking, effectively disrupting mosquito orientation toward potential hosts. However, pre-activation of TRPA1 by elevated temperatures above 32°C has been shown to desensitise the receptor to subsequent chemical agonists, thereby reducing repellent efficacy. Notably, this thermally induced reduction in responsiveness was not observed in non-TRPA1-targeting repellents like DEET, indicating a unique temperature-sensitive pathway associated with TRPA1-mediated repellence (Park & Piermarini, 2025).

3.2 Odorant receptor modulation

In addition to TRPA1 activation, another key mechanism by which repellents function is through interference with odorant receptor (OR) pathways. Mosquitoes detect human hosts by sensing volatile compounds emitted from the skin and breath, such as lactic acid, ammonia, and carbon dioxide. These odorants are first bound and transported by odorant-binding proteins (OdBPs) located in the sensillar lymph of antennal sensilla to the ORs. Certain volatile botanical compounds, such as geranyl acetate, nerolidol, α-bisabolol, thymol acetate, and p-cymen-8-yl, can bind competitively to OdBPs, preventing the natural host-emitted odorants from reaching the receptors (Portilla-Pulido et al., 2020) (da Costa et al., 2019). This competitive inhibition disrupts the normal host-seeking behaviour and reduces the probability of mosquito bites.

3.3 Disruption of the olfactory signal

Further reinforcing the repellence effect, EO components also interfere with olfactory signalling at the level of the olfactory receptor neurons (ORNs). Mosquitoes rely heavily on their antennae and maxillary palps, both covered with sensilla containing ORNs and support cells, for detecting host cues. These neurons are responsible for translating chemical signals into electrical impulses that drive behaviour. Repellents act through several pathways to disrupt this signal processing. Four general mechanisms have been identified: (1) activation of olfactory receptors tuned to aversive compounds, (2) stimulation of pheromone receptors that induce avoidance, (3) inhibition of ORs that respond to attractive cues, and (4) prolonged activation of attractive odorant receptors that leads to desensitization (Shanbhag et al., 1999) (Clark & Ray, 2016). Together, these modes of action, including TRPA1 activation, OR modulation, and disruption of olfactory signalling, form a multifaceted defensive strategy by which EO–based repellents impair mosquito host-seeking behaviour. Continued research into these molecular mechanisms is essential to optimise botanical repellents for both efficacy and environmental safety.

4. Advances in nano-formulated essential oil-containing repellents

EOs derived from plants are attractive active ingredients for mosquito repellents due to their natural origin and broad-spectrum activity. However, their practical application is limited by their high volatility and rapid degradation, resulting in short-lived protection. To overcome these limitations, recent advances in nano and micro formulation technologies, such as nanoemulsions, lipid-based nanoparticles, liposomes, and polymeric capsules, have been developed to enhance the stability, control the release, and improve the skin compatibility of EO-based repellents (Kechagia et al., 2024). These modern encapsulation strategies serve multiple functions, such as reducing evaporation, protecting volatile constituents from degradation, and prolonging repellent efficacy. The following sections outline key formulation technologies and highlight their reported advantages in enhancing the protective performance of EOs (Nwagwu et al., 2024).

4.1 Nanoemulsion and microemulsion

Nanoemulsion and microemulsion are oil-in-water dispersions with droplet sizes typically ranging from 10 to 200 nm. These formulations significantly increase the surface area and solubility of hydrophobic EO components, which enhance chemical stability and enable sustained release. Their fine droplet dispersion, often achieved using surfactants, reduces the volatility of EO-based repellents. For instance, *RSC Nanoscale Advances* reported that EO nanoemulsions exhibit improved water solubility, tunable loading capacities, and greater chemical stability [80]. A practical example includes the eucalyptus oil nanoemulsion and microemulsion, which demonstrated extended protection times of up to 170 minutes depending on concentration, which was comparable to DEET and significantly better than pure eucalyptus oil (Nwagwu et al., 2024). Similar enhancements were observed with the peppermint oil nanoemulsions, which provided prolonged repellence at reduced dosages. Thus, nanoemulsions not only preserve volatile EO compounds but also facilitate controlled release, thereby extending their repellent effects against mosquitoes (Adem et al., 2024).

4.2 Lipid-based nanocarriers

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) are lipid-based delivery systems designed to encapsulate hydrophobic EO molecules within a biocompatible lipid matrix. These nanocarriers limit volatilisation by physically entrapping the EO and releasing it gradually as the lipid matrix degrades or diffuses. According to *RSC Nanoscale Advances*, these systems effectively control the rate of EO evaporation, supporting sustained repellence (Nwagwu et al., 2024). For example, SLN-encapsulation of *Zataria multiflora* EO (particle size ~134 nm) tripled the protection time, from approximately 30 minutes with unformulated oil to 93 minutes with SLN formulation. Similar results were observed with neem oil nanoparticles, which showed improved repellent performance compared to raw pure oil.

NLCs, which combine both solid and liquid lipids, offer enhanced encapsulation and flexibility in delivery. In a Greek field study, an NLC formulation combining multiple EOs achieved a median complete protection time (CPT) of ~45 minutes, intensely longer than the 3 minutes achieved with a conventional emulsion. The effectiveness of NLCs in preserving volatile EO components and enhancing repellent efficacy by an order of magnitude demonstrates their significant potential (Kechagia et al., 2024). Furthermore, their physical stability is notable: an *MDPI Applied Sciences* study found NLCs retained droplet size and zeta potential for over 90 days at room temperature, confirming their long-term formulation stability (Kechagia et al., 2024).

4.3 Polymeric nanoparticles and capsules

Polymeric delivery systems, including nanocapsules, microspheres, micelles, and hydrogels, are constructed from biocompatible polymers such as gelatin, chitosan, alginate, cellulose, and poly (lactic-co-glycolic acid) (PLGA). In these systems, EO-containing repellents are either embedded within a polymeric matrix or encapsulated in core–shell structures, allowing for controlled and prolonged release. *Nanoscale Advances* highlights that such polymers slow diffusion, block ultraviolet (UV) and oxidative degradation, and enhance the retention of volatile actives. For example, microcapsules co-encapsulating plant EOs and DEET within a cellulose-based matrix maintained 100% repellence against *Cx. quinquefasciatus* for up to 4 hours, outperforming unencapsulated citronella formulations (Nwagwu et al., 2024).

4.4 Cyclodextrins and other carriers

Cyclodextrins (CDs) are cyclic oligosaccharides that form host–guest inclusion complexes with EO molecules, shielding them from environmental degradation. By encapsulating the EO within the CD cavity, these carriers improve chemical stability, reduce oxidation, and support a slower, more controlled release. *RSC Reviews* describes how β-cyclodextrin-citronella complexes released citronella at a slower rate than standard formulations, thereby prolonging repellent activity. CDs have also been successfully applied with synthetic repellents: one CD–DEET formulation showed a slower release profile and reduced skin absorption compared to ethanol-based DEET products, indicating not only prolonged protection but also enhanced safety (Nwagwu et al., 2024).

5. CONCLUSION AND FUTURE RESEARCH DIRECTION

Ongoing mosquito-borne diseases such as dengue, Zika, and chikungunya continue to pose serious global public health challenges, primarily transmitted by *Ae. aegypti* and *Ae. albopictus*. The growing resistance of these vectors to conventional synthetic insecticides, along with concerns over environmental and human health impacts, underscores the urgent need for sustainable alternatives. In this context, EOs derived from aromatic plants have garnered considerable interest due to their rich composition of volatile phytochemicals, particularly monoterpenes and sesquiterpenes, that exhibit notable repellent and insecticidal properties. Notably, plant families such as *Lamiaceae, Asteraceae,* and *Myrtaceae*, and compounds like citronellal, thymol, carvacrol, and β-caryophyllene, have demonstrated repellent efficacy comparable to DEET in short-term applications. However, a major limitation lies in the high volatility of EOs, which leads to rapid evaporation and reduced duration of protection. To overcome these shortcomings, recent advances in formulation technologies, such as nanoemulsions, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), polymeric microcapsules, and cyclodextrin complexes, have shown promise in enhancing EO stability, controlled release, and skin compatibility. Furthermore, mechanistic studies reveal that EO-based repellents act through multiple biological pathways, including activation of the TRPA1 receptor, modulation of odorant-binding proteins (OdBPs), and disruption of odorant receptor (OR) signalling. While these findings highlight the multifaceted repellent potential of EOs, current formulations still fall short of matching synthetic compounds in terms of long-term performance, formulation stability, and regulatory approval. This narrative review has consolidated findings from both experimental and field studies to highlight key plant families and their bioactive constituents with potent short-term repellent effects against *Aedes* and other mosquito species. Despite their potential, the volatility and formulation challenges of EOs remain critical obstacles to their widespread application. Looking ahead, future research should prioritise the development of improved EO-based delivery systems for sustained efficacy, identification of novel phytochemicals from underexplored aromatic plants, and deeper mechanistic understanding using molecular and electrophysiological tools. Additionally, standardised field testing across varied environmental conditions, comprehensive toxicological profiling, and cost-effectiveness assessments are essential to validate their practical viability. With continued interdisciplinary research and innovation, EO-based repellents hold significant promise as an effective and eco-friendly component of integrated mosquito vector management strategies.

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