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Review Article

Exploring the potential of essential oils as larvicides in the control of *Aedes* species: An overview

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Abstract
Aedes mosquitoes are key vectors of several fatal diseases, including dengue fever, chikungunya, Zika, and yellow fever, which pose serious global health hazards. The control of *Aedes* populations has historically been centered on the use of synthetic chemical insecticides. However, the increasing use of such chemicals is driving insecticide resistance, environmental toxicity, and adverse effects on non-target species. Thus, there is now immense enthusiasm to develop more environmentally friendly alternatives for larvicides. Plant essential oils have attracted many researchers as sources of new bio-larvicides due to their natural origin, biodegradability, and varied bioactive constituents. The active substances found in these oils are believed to be monoterpenes, sesquiterpenes, and phenolics, which, in turn, are reported to prove a significant toxic effect to the mosquito larvae as well. The present systematic review aimed to compile and synthesize recent studies (2012-2024) on essential oils from various plant species with larvicidal activity against *Aedes*. In this review, different plant families, extraction methods, chemical compositions, and reported LC_{50} values for activity are examined. Essential oils are seen as a promising and sustainable alternative for mosquito vector control. The use of essential oils should be promoted for integrated vector management, which could reduce reliance on synthetic insecticides and support safe mosquito control strategies. There is a need for more studies on formulations such as nanoemulsions, microencapsulation, and polymer-based delivery systems to enhance the stability, persistence, and field efficacy of essential oils.

Keywords: *Aedes*, Alternative, Biodegradable, Fatal diseases, Insecticides, Synthetic, Vector

INTRODUCTION

The mosquito family (Diptera: Culicidae) comprises many species that transmit viruses, bacteria, and parasites responsible for mosquito-transmitted diseases, which present a major challenge to public health globally (WHO, 2017; WHO, 2024). Family *Culicidae* consists of 3578 species, out of which 88 have been identified as vectors of around 78 human diseases, while 243 are recognized as potential disease carriers (AL-Eitan *et al.*,2024). Vector-borne diseases contribute to 17% of communicable diseases across the globe with annual

death tolls ranging from 500,000 to 1,000,000. Since the complex environmental determinants in the tropical and subtropical regions favour vector proliferation, therefore, over 80% of total population resides in regions that are vulnerable for at least one vector-borne disease, and more than half are exposed to two or more (Filho *et al*.,2025; WHO,2017; WHO, 2024). Among the mosquito family, *Anopheles, Aedes, Culex*, and *Mansonia* species are the major parasite vectors responsible for the emergence and re-emergence of diseases like Malaria, Dengue, Japanese Encephalitis, and Lymphatic Filariasis, mainly caused by arboviruses from the genera *Alphavirus, Flavivirus,* and *Orthobunyavirus*. (Table 1) (Braack *et al*.,2018; WHO,2017; WHO, 2024).

The impact of vector-borne diseases predominantly affects countries with low economies and limited resources for mitigation and management. Communities in sub-Saharan Africa, America, and South Asia are vulnerable to multiple significant (Malaria, Dengue, Japanese Encephalitis, Lymphatic Filariasis, Chagas diseases, and yellow fever) diseases (Golding *et al*.,2015). The unmanageable global distribution of these diseases underscores the critical need for control strategies. The traditional method mostly relies on chemical insecticides, primarily organophosphates, organochlorines, carbamates, and pyrethroids. This method initially shows effective and quick results, but prolonged and extensive use leads to mosquito resistance, invasion into the surrounding ecosystem, and destructive impacts on nontarget organisms and bioaccumulation. Synthetic pesticides have a list of negative impacts on the environment (Gan *et al*., 2021). Among other preventive methods to overcome these negative impacts, plant-based bioinsecticides emerge as the best alternative. Bioinsecticides mainly involve the use of secondary metabolites such as phytochemicals. The vast variety of phytochemicals in plant extract presents great potential as a sustainable control over mosquito vectors. Essentially, the base of the sender of these essential oils (Govindarajan *et al*.,2015; Chand, 2024)). Natural larvicides based on essential oils have a shorter half -life span, are target-specific, have stronger efficacy, are eco-friendly, readily available, and have great allelochemical variety making them a feasible and sustainable preference (Govindarajan and Benelli, 2016; (Nazmin *et al*., 2025; Kaushik *et al*., 2023). Several studies report that plant phytochemicals and essential oils exhibit larvicidal effects. However, the larvicidal efficacy varies with chemical concentrations, larval stages, and exposure time. The present study aimed to put forward an overview of the possible larvicidal action of essential oils against Aedes spp. mosquitoes that are vectors of various vector-borne diseases worldwide.

Methodology

This study conducted a systematic literature review using online sources, including national and international databases such as Google Scholar, PubMed, and Scopus. The search consists of keywords: “*Aedes*”, “Essential Oil”, and “Larvicide”. The search criteria were set to focus on articles published between 2012 and 2024 that examined the larvicidal potential of essential oils against *Aedes* species. E-books, conference abstracts, thesis, and the topics not related to essential oils impact on *Aedes spp*. were excluded from the study. Initially, 130 articles were selected but only 71 contained the relevant content.

Table 1. Overview of mosquito-borne diseases and their causative agents

Vector	Diseases	Causative agent	Genus of Causative agent
Anopheles	Malaria	*Plasmodium* species	*Plasmodium*
Aedes	Dengue	Dengue virus	*Flavivirus*
Aedes	Zika	Zika virus	*Flavivirus*
Aedes	Chikungunya	Chikungunya virus	*Alphavirus*
Aedes	Yellow fever	Yellow fever virus	*Flavivirus*
Culex	Japanese encephalitis	Japanese encephalitis virus	*Flavivirus*
Culex	West-Nile fever	West Nile fever virus	*Flavivirus*
Culex, Aedes	Lymphatic Filariasis	Wuchereria bancrofti	*Wuchereria*
Culex	Rift Valley fever	Rift Valley fever virus	*Phlebovirus*
Mansonia	Brugian filariasis	Brugia malayi	*Brugia*
Aedes	Ross River fever	Ross River virus	*Alphavirus*
Aedes, Culex	La Crosse encephalitis	La Crosse virus	*Orthobunyavirus*
Aedes, Culex	Oropouche fever	*Oropouche virus*	*Orthobunyavirus*

Source: World Health Organization (WHO) fact sheets on vector-borne diseases (2024, 2017)

Data extraction protocol

From each eligible study, information was systematically collated on LC_{50} values, associated measures of variability (95% confidence intervals or standard errors), the plant part utilized, and the *Aedes* species tested. Where multiple LC_{50} estimates were reported for the same essential oil–mosquito combination, the arithmetic mean was adopted as the representative value, with ranges or discrepancies documented to preserve accuracy although most studies provided a single specific LC_{50} value. Missing methodological details were denoted as "Not Reported (NR)" to ensure transparency and reproducibility. For chemical characterization, principal constituents were defined as compounds contributing the highest peak area percentage (PA%) to the total essential oil composition; in cases of multiple dominant compounds, all were included.

Larvicidal efficacy of essential oils

Laboratory evidence

Essential oils have demonstrated strong larvicidal efficacy against mosquito larvae, with their effectiveness depending on both the type of oil and its chemical composition. Table 2 highlights the larvicidal activity of various essential oils, presenting data such as LC_{50}, Part Used, Principal Constituents, Yield Percentage of EO and PA%. By comparing these parameters, the it provides a clear overview of which essential oils, based on their composition and yield, exhibit the highest potential for effective larval control.

This review evaluated contemporary studies on essential oils (EOs) as potential larvicides, with particular attention to their chemical composition and biological effectiveness. For inclusion, plant species or their oils were required to meet two key conditions: they had to produce significant larval mortality in standardized bioassays (WHO, 1996; 2005) with LC_{50} values not exceeding 100 ppm, and their chemical constituents needed to be clearly characterized. Altogether, 81 plant species representing 20 botanical families met these criteria and were compiled from the available literature. The majority of these species were concentrated within five families—Piperaceae, Lauraceae, Cupressaceae, Rutaceae, Asteraceae, and Myrtaceae. Considering LC_{50} < 100 ppm as the threshold for efficacy, several highly active oils were obtained from aromatic plants cultivated on a commercial scale under established agronomic practices, including *Piper*, *Coriandrum*, *Mentha*, *Thymus*, and *Eucalyptus* species. These taxa represent promising sources of bioactive compounds for the development of botanical larvicides. Nonetheless, only seven plants—such as *Chenopodium ambrosioides*, *P. cambodianum*, *P. cannium*, and *P. mutabile*—can be regarded as exceptionally potent, as their oils exhibited LC□□ values below 10 ppm. Essential oils from various plant families, as shown in the Table 2, exhibit a wide range of larvicidal activity against Aedes mosquitoes, primarily due to differences in their chemical composition. The most potent oils generally come from *Piperaceae* (such as *Piper cannium*, LC□□: 1.37 ppm), *Amaranthaceae* (*Chenopodium ambrosioides*, 9.1 ppm), and *Apiaceae (Trachyspermum ammi*, 16.1 ppm), all of which are rich in monoterpenes such as linalool, para-cymene, and thymol although differences in experimental conditions among studies limit direct comparisons of potency. Other families, such as Euphorbiaceae and Poaceae, also include highly active species, but many, such as *Asteraceae, Myrtaceae*, and *Lauraceae*, show moderate and variable potency depending on the dominant compounds present. In contrast, families such as Apocynaceae and Solanaceae generally have much higher LC_{50} values (lower potency), often due to differences in their chemical profiles. This pattern underscores that the strongest larvicidal effects are found in oils rich in certain monoterpenes, while families with other dominant compounds tend to be less effective overall.

Mechanisms of action as larvicides against *Aedes* mosquitoes

The larvicidal activity of essential oils against *Aedes* mosquitoes is closely linked to the diverse chemical nature of their principal constituents and the multiple mechanisms of action. Monoterpenes such as linalool from *Ocimum basilicum* (Lamiaceae) primarily exert toxicity by inhibiting acetylcholinesterase (AChE), disrupting neural transmission, and causing paralysis (Seo *et al*., 2015; Dris *et al*., 2017; Li *et al*., 2023, de Sousa *et al*., 2024). Similarly, monoterpene aldehydes like citral (neral and geranial), which are predominant in *Cymbopogon flexuosus* (Poaceae), impair mitochondrial respiration and enhance oxidative stress, thereby disrupting energy metabolism (Tripathi *et al*., 2009; Adhikary *et al*. 2024;Silva *et al*., 2024). Other monoterpenes, including limonene, α-pinene, and β-pinene, also inhibit AChE activity, leading to synaptic dysfunction and larval mortality (Regnault-Roger *et al*., 2012; Jamal and Mondal, 2024). Compounds such as sabinene and citronellal alter membrane permeability and ion transport, leading to neuromuscular disruption (Giatropoulos *et al*., 2018; Chand, 2024). Phenolic monoterpenes like thymol and carvacrol, abundant in *Thymus vulgaris* (Lamiaceae), destabilize lipid membranes and interact with gamma-aminobutyric acid (GABA)-gated chloride channels and octopaminergic receptors, resulting in neuronal hyperexcitation and paralysis (Priestley *et al*., 2003; Enan *et al*., 2001; Nazmin *et al*., 2025). The triterpenoid azadirachtin, derived from *Azadirachta indica* (Meliaceae), acts as an insect growth regulator by disrupting hormone-mediated molting and metamorphosis, ultimately reducing larval survival (Isman, 2006). Sesquiterpenes

Table 2. Larvicidal efficacy of plant-derived essential oils against *Aedes* mosquitoes: botanical sources, chemical constituents, and bioactivity metrics; *PA= Peak area percentage, *NR= Not reported

Family/ Species	Part Used	Principal Constituents	Yield % of EO	*Aedes* Species	PA%	LC_{50} Value	Variability (95% confidence intervals)	Exposure Time	Extraction Method	References
Chenopodium ambrosioides	Aerial part	*Para cymene*	0.09	Amaranthaceae *Aedes aegypti*	-	9.1 ppm	7.8-10.7	24 hrs	Hydro-steam distillation	Massebo *et al*., 2009;
Conyza sumatrensis	Leaf	cis-Lachnophyllumester	0.21	Asteraceae *Aedes aegypti*	-	21.7 µg/ml	(20.16–23.36)	24 hrs	Hydrodistillation	Hoi *et. al.,* 2017 Azeem *et al*., 2019
Erigeron canadensis	Leaves, stems	Limonene	0.22	*Aedes aegypti*	-	35.7 mg/L	23.92–59.97	24 hrs	Steam distillation	Azeem *et al*., 2019; Abbas *et al*., 2023
Parthenium hysterophorus	Leaf	GermacreneD	0.03	*Aedes aegypti*	-	432.28 mg/L	299.62–614.58	24 hrs	NA	Kumar *et al*., 2012
Tagetes minuta	Aerial part	Dihydrotagetone	0.54	*Aedes aegypti*		52.3 ppm	NA	24 hrs	Hydrodistillation	Azeem *et al*., 2019; Ruiz *et al*., 2011
T*agetes lucida*	Leaf	Methyl chavicol	0.4	*Aedes aegypti*		66.27 ppm	(63.7–68.7)	24 hrs	Hydrodistillation and Microwave assisted hydrodistillation	Vera *et al*., 2014
Blumea lacera	Aerial part	(E)-β-Caryophyllene	1.10	*Aedes aegypti,* *Aedes albopictus*	23.8	64.7 µg/ml	(59.8–70.1)	24 hrs	Hydrodistillation	Hoi *et al*., 2022
						116.7 µg/ml	(110.3–123.7)	24 hrs		
Blumea sinuta	Aerial part	Thymohydroquinone dimethyl ether	0.16	*Aedes aegypti,* *Aedes albopictus*	29.4	23.4 µg/ml	(21.2–25.8)	24 hrs		Hoi *et al*., 2022
						29.1µgµg/ml	(24.7–33.4)	24 hrs		

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Emilia sonchifolia	Aerial part	1-undecene	0.50	*Aedes aegypti,*	41.9	30.1 µg/ml	27.9–32.9)	24 hrs	Hoi *et al*., 2022
				Aedes albopictus		29.6 µg/ml	(27.4–32.0)	24 hrs	
Suphaeranthus africanus	Aerial part	1-decen-3-ol	0.25	*Aedes aegypti,*	36.9	50.7 µg/ml	(44.7–50.5)	24 hrs	Hoi *et al*., 2022
				Aedes albopictus		36.9 µg/ml	(34.3–39.6)	24 hrs	
Heracleum Sprengelianum	Leaf	Lavandulyl acetate	1.36	*Aedes albopictus*	-	37.5 µg/ml	(34.2–40.6)	24 hrs	Govindarajan & Benelli,2016
Trachyspermum ammi	Dry fruit	Thymol	2.41	*Aedes aegypti*	93.58	39.48 mgL−1	(38.21–40.57)	24 hrs	Pandiyan *et al*., 2019
Apium graveolens	Seed	Limonene	1.40	*Aedes aegypti*	NA	16.10 ppm	NA	24 hrs	Nouioura *et al*.,2024; Ver *et al*.,2014
Trachyspermum ammi	Seed	Thymol	1.20	*Aedes aegypti*	64.58	19 ppm	(15.7;22.5)	24 hrs	Sanei *et al*., 2024; Singh *et al*., 2017
Coriandrum sativum	Seed	Linalool	1.87	*Aedes aegypti*	53.79	20.57 ppm	(18.80;22.61)	24 hrs	Nagella *et al*., 2012; Mandal *et al*., 2015
				Annonaceae					
Cananga odorata	Leaf	Benzyl acetate	0.4	*Aedes aegypti*	18.2	52.96 ppm	(49.91–55.79)	24 hrs	Hydrodistillation	Vera *et al*.,2014
				Apocynaceae					
Cascabela thevetia	Seed	Benzene, 1,3 dimethyl, o-xylene, p-xylene	0.1	*Aedes aegypti*	10.14	95.19 ppm	(10.66-175.66)	24 hrs	Soxhlet solvent extraction using petroleum ether	Borah, 2012; Oyekunle, 2017

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Catharanthus roseus	Leaf	Linolenic acid	0.64	*Aedes aegypti*		86.913 ppm	(75.720–102.674)	24 hrs	Hexane extract	Sharma *et al.*, 2016; Lawal *et al.*, 2015
				Amaranthaceae						
Achyranthes aspera	Leaf	9-Octadecenamide, (Z)		*Aedes aegypti*		82.555 ppm	(73.554–91.860)	24 hrs	Hexane extract	Sharma *et al.*, 2016
				Cupresaceae						
Cupressus arizonica	Leaf	α-Pinene	0.2	*Aedes albopictus*	17.1	64.8 mg/L	(62.9–66.6)	24 hrs		Giatropoulos *et al.*, 2013
Cupressus benthamii	Leaf	Umbellulone	0.4	*Aedes albopictus*	15.9	54.6 mg/L	(52.2–57.0)	24 hrs	Hydrodistillation	Giatropoulos *et al.*, 2013
Cupressus macrocarpa	Leaf	Sabinene	0.3	*Aedes albopictus*	54.4	54.7 mg/L	(58.9–65.0)	24 hrs		Giatropoulos *et al.*, 2013
Cupressus sempervirens	Leaf	α-Pinene	0.2	*Aedes albopictus*	27.9	47.9 mg/L	(46.0–49.7)	24 hrs		Giatropoulos *et al.*, 2013
Cupressus torulosa	Leaf	α-Pinene	0.3	*Aedes albopictus*	18.5	57.1 mg/L	(54.1–59.9)	24 hrs		Giatropoulos *et al.*, 2013
Chamaecyparis lawsoniana	Leaf	Limonene	0.3	*Aedes albopictus*	31.3	37.5 mg/L	(36.5–38.7)	24 hrs		Giatropoulos *et al.*, 2013
Juniperus phoenicea	Leaf	α-Pinene	0.2	*Aedes albopictus*	31.3	55.5 mg/L	(53.0–58.0)	24 hrs	Hydrodistillation	Giatropoulos *et al.*, 2013
Tetraclinis articulata	Leaf	α-Pinene	0.02	*Aedes albopictus*	26.4	70.6 mg/L	(67.4–73.8)	24 hrs		Giatropoulos *et al.*, 2013
				Euphorbiaceae						
Ricinus communis	Seed	1,7–dimethyl hypoxanthine	0.2	*Aedes aegypti*	21.96	80.83 ppm	(28.61-122.52)	24 hrs	Soxhlet solvent extraction using petroleum ether	Sogan *et al.*,2018; Borah *et al*., 2012

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Croton blanchetianus	Leaf	eucalyptol	0.05	*Aedes aegypti* Fabaceae	18.17	64.88 µg/ml	(± 1.78)	17 hrs	Hydrodistillation	Lopes et. al., 2025
Pongamia pinnata	Seed	Oleic acid	0.5	*Aedes aegypti*	21.7	18.35 ppm	(12.17-70.61)	24 hrs	Soxhlet solvent extraction using petroleum ether	Borah, 2012; Rathod *et al*., 2017
Cassia occidentalis	Leaf	Cyperene	0.02	*Aedes aegypti*	10.8	117.45 ppm	104.353–138.047	24 hrs	Hexane extract	Sharma *et al*., 2016; Essien *et al*., 2018
Azadirachta indica	Seed	1,1'-Biphenyl, 2,2',5,5'-tetramethyl-	0.2	Meliaseae *Aedes aegypti*	9.08	23.64 ppm	(36.22-119.42)	24 hrs	Soxhlet solvent extraction using petroleum ether	Borah, 2012; Ahmed *et al*., 2023
Eucalyptus citriodora	Leaf	Citronellal	0.7	Myrtaceae *Aedes aegypti*	92.1	71.22 ppm	(63.91–81.62)	24 hrs		Vera *et al*.,2014
Syzygium aromaticum	Flower Bud	Eugenol	11.11	*Aedes aegypti*	56.32	66.90 mgL^{-1}	(62.41−71.87)	24 hrs	Hydrodistillation	Pandiyan *et al*.,2019
Eucalyptus staigeriana	Leaf	*Limonene*	0.3	*Aedes aegypti*	41.67	47.04 ppm	(43.92-50.12)	24 hrs	Steam distillation	Cruz *et al*., 2024
E. Caryophyllus	Bud	Eugenol	0.41	*Aedes aegypti*	87.67	92.67 ppm	(96.58-104.78)	24 hrs	Steam distillation	Cruz *et al*., 2024
Psidium guajava L.	Leaf	*(E)-Caryophyllene*	0.3	*Aedes aegypti*	19.4	63.35µg/ml	(49.51–81.13)	24 hrs		Mendes *et al*., 2017
E. tereticornis	Leaf	β-Phellandrene	0.59	*Aedes aegypti*	22.64	22.14 ppm	(19.98–23.93)	24 hrs	Hydrodistillation	Lucia *et al*., 2008
E. camaldulensis	Leaf	1,8-Cineole	0.38	*Aedes aegypti*	19.13	26.24 ppm	(24.93–28.58)	24 hrs	Hydrodistillation Hydrodistillation	Lucia *et al*., 2008
E. saligna	Leaf	β-Phellandrene	0.36	*Aedes aegypti*	34.02	22.16 ppm	(19.87–24.08)	24 hrs	Hydrodistillation Hydrodistillation	Lucia *et al*., 2008
E. gunnii	Leaf	β-Phellandrene	0.21	*Aedes aegypti*	17.95	21.13 ppm	(18.70–23.00)	24 hrs		Lucia *et al*., 2008
E. dunnii	Leaf	β-Phellandrene	0.62	*Aedes aegypti*	48.08	25.23 ppm	(23.15–27.15)	24 hrs		Lucia *et al*., 2008

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				Lamiaceae						
Mentha spicata	Leaf	Carvone	0.65	*Aedes aegypti*	48.60	56.08 ppm	(31.64–7.87)	24 hrs	Hydrodistillation	Govindaranjan *et al.*,2012
Plectranthus barbatus	Leaf	Eugenol	1.48	*Aedes albnopictus*		87.25µg/ml	(77.81–95.70)	24 hrs	Hydrodistillation	Govindaranjan *et al.*,2015
Mentha arvensis	Leaf	Menthone	0.67	*Aedes aegypti*	51.53	52.82 ppm	(48.11- 57.12)	24 hrs		Cruz *et al.*,2024; Manh *et al*., 2020
Vitex nagudo	Leaf	Caryophyllene	0.5	*Aedes aegypti*	27.98	50.86 ppm	±0.4	24 hrs	Steam distillation	Chandrasekaran *et al*., 2019; Hung *et al*., 2020
Vitex trifolia	Leaf	Eucalyptol	0.4	*Aedes aegypti*	16.38	57.77 ppm	±0.9	24 hrs		Chandrasekaran *et al*., 2019; Mottaghipisheh *et al*., 2024;
Origanum vulgare L.	Aerial part	Terpinen-4-ol	0.2	*Aedes aegypti*	40.0	13.3µg/ml	(11.9 14.9)	24 hrs	Hydrodistillation	de Oliveira *et al*., 2021
Thymus vulgaris L.	Aerial part	Thymol	0.4	*Aedes aegypti*	17.4	12.8µg/ml	(11.7 13.9)	24 hrs		de Oliveira *et al*., 2021
				Lauraceae			(20.92–27.45)			
Cinnamomum ovatum	Leaf	Eugenol	0.60	*Aedes aegypti,*	70.5	24.12 µg/ml		24 hrs		Dai *et al*., 2020
				Aedes albopictus		61.45 µg/ml	(55.66–68.20)		Hydrodistillation	
Cinnamomum tonkinense	Leaf	Linalool	0.33	*Aedes aegypti,*	32.2	17.44 µg/ml	(15.53–19.58)	24 hrs		Dai *et al*., 2020
				Aedes albopictus		42.89 µg/ml	(39.73–46.59)			

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Cinnamomum damhaensis	Leaf	Linalool	0.30	*Aedes aegypti*, *Aedes albopictus*	44.8	21.43 µg/ml 43.91 µg/ml	(18.66–24.15) (41.25–46.46)	24 hrs	Dai *et al*., 2020
Cinnamomum longipetiolatum	Leaf	Linalool	1.35	*Aedes aegypti*, *Aedes albopictus*	70.2	64.20 µg/ml 23.41 µg/ml	(55.67–73.61) (18.02–23.28)	24 hrs	Hydrodistillation	Dai *et al*., 2020
Cinnamomum polyadelphum	Leaf	Camphor	1.20	*Aedes aegypti*, *Aedes albopictus*	32.2	20.66 µg/ml	(21.37–25.78)	24 hrs		Dai *et al*., 2020
				Poaceae						
Cymbopogon flexuosus	Leaf	Geranial	0.4	*Aedes aegypti*	37.5	17.16 ppm	(13.78-21.37)	24 hrs	Hydrodistillation	Vera *et al.*,2014 Bhatt B. J. 2013
Cymbopogon citratus	Leaf	Neral	0.5	*Aedes aegypti*	29.5	123.30 ppm	(114.17-138.60)	24 hrs		Vera *et al.*,2014
				Piperaceae						
Piper nigrum	Seed	Thymol	0.39	*Aedes aegypti*	20.77	34.97 ppm	NA	24 hrs	Soxhlet solvent extraction using methanol	Lija- Escalinne *et al.*,2015
P. arboricola	Leaf	Limonene	0.32	*Aedes aegypti*	23.2	26.85 µg/ml	(24.55–29.52	24 hrs		Houng *et al*., 2019
P. bavinum	Leaf	Bicyclogermacrene	0.34	*Aedes aegypti*	8.9	15.5 µg/ml	(12.46–18.32)	24 hrs		Houng *et al*., 2019
P. cambodianum	Leaf	β- *Caryophyllene*	0.34	*Aedes aegypti*	19.1	8.86 µg/ml	(7.012–10.650)	24 hrs	Hydrodistillation	Houng *et al*., 2019
P. cannium	Leaf	linalool	0.10	*Aedes aegypti*	10.1	1.37 µg/ml	(1.252–1.513)	24 hrs		Houng *et al*., 2019
P. longum	Leaf	β- pinene	0.15	*Aedes aegypti*	10.6	5.34 µg/ml	(4.950–5.757)	24 hrs		Houng *et al*., 2019

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Table 2. Contd…….

P. mekongense	Leaf	Maaliol	0.32	*Aedes aegypti*	13.8	40.16 µg/ml	(37.09–42.88)	24 hrs		Houng *et al.*, 2019
P. montium	Leaf	β- bisabolene	0.10	*Aedes aegypti*	22.1	1.96 µg/ml	(1.778–2.169)	24 hrs		Houng *et al.*, 2019
P. mutabile	Leaf	β- *Caryophyllene*	0.38	*Aedes aegypti*	16.6	1.85 µg/ml	(1.715–1.997)	24 hrs		Houng *et al.*, 2019
P.politifolium	Leaf	Asaricin	0.37	*Aedes aegypti*	18.7	11.3 µg/ml	(7.905–9.811)	24 hrs	Hydrodistillation	Houng *et al.*, 2019
P. rubrum	Leaf	β- *Caryophyllene*	0.41	*Aedes aegypti*	22.9	24.98 µg/ml	(22.74–27.48)	24 hrs		Houng *et al.*, 2019
P. sarmentosum	Leaf	β- bisabolene	0.29	*Aedes aegypti*	40.3	22.80 µg/ml	(17.73–27.91)	24 hrs		Houng *et al.*, 2019
P. umbellatum	Leaf	β- *Caryophyllene*	0.025	*Aedes aegypti*	44.8	7.0 µg/ml	(6.659–8.469)	24 hrs		Houng *et al.*, 2019
				Ranunculaxeae						
Nigella sativa	Seed	Thymol	0.03	*Aedes aegypti*	19.13	53.9 ppm	(25.9- 79.2)	24 hrs	Hydrodistillation	Raj *et al.* 2015
				Rutaceae						
Swinglea glutinosa	Leaf	B-Pinenepiperitenone	0.2	*Aedes aegypti*	49.6	65.71 ppm	(61.64-70.76)	24 hrs		Vera *et al.*,2014
Citrus sinensis	Leaf	Limonene	0.2	*Aedes aegypti*	71.3	20.61 ppm	(16.49-23.82)	24 hrs		Vera *et al.*,2014
Ruta chalepensis L (wild)	Aerial part	2-Nonanone	0.2	*Aedes albopic-tus*	37.1	35.66 ppm	(26.92–49.97)	24 hrs	Hydrodistillation	Conti *et al.*, 2013
Ruta chalepensis L (cultivated)	Aerial part	2-Undecanone	0.4	*Aedes albopic-tus*	39.3	33.18 ppm	(23.45-41.56)	24 hrs		Conti *et al.*, 2013
Citrus aurantium	Leaf	Diethyl o- phthalate	0.4	*Aedes albopic-tus*	37.32	91.7 ppm	(83.5-93.8)	24 hrs		Jian *et al.*, 2022
Citrus paradisi	Leaf	Limonene	0.2	*Aedes albopic-tus*	60.51	100.9 ppm	(91.2-110.6)	24 hrs		Mendes *et al.*, 2017
				Schisandraceae						
Illicium verum	Dry fruit	Trans-anethole	3.51	*Aedes aegypti*	53.05	41.30 mgL^{-1}	(39.57–42.87)	24 hrs	Hydrodistillation	Pandiyan *et al.*, 2019
				Solanaceae						
Datura stramonium	Seed	Atropine	0.2	*Aedes aegypti*		88.69 ppm	(32.08-134.14)	24 hrs	Soxhlet solvent extraction using petroleum ether	Borah *et al.*, 2012
				Verbanaceae						
Lippia origanoides	Leaf	Carvacrol	1.4	*Aedes aegypti*	32.3	53.37 ppm	(50.60-56.60)	24 hrs		Vera *et al.*,2014
Lippia alba	Leaf	Carvone	0.6	*Aedes aegypti*	38.3	44.26 ppm	(41.56-47.01)	24 hrs	Hydrodistillation	Vera *et al.*,2014
Lantana camara	Leaf	Aromandandrene	0.3	*Aedes aegypti*	12.09	118.49 ppm	NA	24 hrs		Sharma *et al.*, 2016; Sonter *et al.*,2024

such as β-caryophyllene, germacrene D, and α-humulene, found in *Cinnamomum camphora* (Lauraceae), contribute to larvicidal effects by inducing oxidative stress, destabilizing cellular membranes, and potentially disrupting endocrine functions (Sundararajan *et al*., 2018; Xu *et al*., 2020). Aromatic ethers such as estragole and trans-anethole affect neurotransmitter pathways and ion channels, whereas long-chain alkenes and alcohols such as 1-undecene and 1-decen-3-ol impair cellular integrity by disrupting membrane lipid composition and respiratory enzyme function (Soonwera *et al*., 2022). This multi-target mode of action, involving different chemical classes and plant families, reduces the risk of resistance development in Aedes mosquitoes, highlighting essential oils as promising, eco-friendly, and potent larvicidal compounds.

DISCUSSION

This systematic review demonstrates the strong larvicidal potential of plant-derived essential oils against *Aedes* spp., with efficacy largely driven by their chemical composition rather than plant taxonomy alone. Essential oils exhibiting the lowest LC_{50} values, as shown in Table 2, consistently contained high proportions of neuroactive monoterpenes and phenolic compounds. Thymol-rich oils from *Trachyspermum ammi* (LC_{50}:16.1 ppm) and *Thymus vulgaris* (LC_{50}:12.8 µg/ml) displayed markedly high toxicity (Priestley *et al*., 2003; Enan *et al*., 2001), while linalool-rich oils from *Coriandrum sativum (*LC_{50}:20.57 ppm), and *Piper caninum (*LC_{50}:1.37µg/ml) demonstrated similarly strong effects (Seo *et al*., 2015; Dris *et al*., 2017). Likewise, eugenol-rich *Cinnamomum oyatum* (LC_{50}: 24.12µg/ml) and *Syzygium aromaticum* (LC_{50}: 66.9 mg/L) showed strong larvicidal action, corresponding to the neurotoxic and mitochondrial disruption properties of eugenol (Regnault-Roger *et al*., 2012). These correlations reinforce the notion that specific compounds, such as thymol, linalool, para-cymene, β-caryophyllene, and eugenol, are key drivers of larvicidal efficacy. A mechanistic interpretation of the LC_{50} patterns further supports this relationship. Thymol destabilizes larval cell membranes and interacts with GABA-gated chloride channels, consistent with the low LC_{50} values observed for *T. vulgaris* (Priestley *et al*., 2003). Linalool and α-pinene primarily exert toxicity via inhibition of acetylcholinesterase (AChE), leading to failure of neural transmission, as evidenced by their strong LC_{50} values in *P. caninum* (Seo *et al*., 2015; Dris *et al*., 2017). Sesquiterpenes such as β-caryophyllene and germacrene D contribute additional larvicidal activity by generating oxidative damage and destabilizing cellular membranes of *piper combodianum* (LC_{50}: 8.86 µg/ml) (Sundararajan *et al*., 2018; Xu *et al*., 2020). Collectively, these findings confirm that larvicidal potency reflects the molecular actions of dominant constituents rather than the plant family. Despite these clear mechanistic trends, the larvicidal efficacy of essential oils is not universal, because multiple contextual factors influence their phytochemical composition. Extraction techniques (e.g., steam distillation, hydrodistillation, solvent extraction) alter both yield and the relative abundance of bioactive constituents; for example, thermolabile compounds are better preserved under steam distillation than hydrodistillation (Tripathi *et al*., 2009). Geographical origin, climate, soil type, cultivation practices, and harvest season also influence phytochemical diversity and yield percentage (Sundararajan *et al*., 2018). Similarly, differences in larval instar stage, exposure duration, temperature, and humidity influence LC□□ estimates, and many studies do not report confidence intervals or standard errors, limiting statistical comparability. Thus, while LC_{50} rankings provide valuable insight into relative potency particularly for oils rich in thymol, linalool, and eugenol, they should be interpreted comparatively rather than as absolute measures of efficacy.

Limitation and future prospectives

Despite the promising larvicidal activity of essential oils demonstrated in laboratory assays, several limitations constrain their direct application in vector control programs. Essential oils are volatile compounds that undergo rapid degradation under sunlight, heat, and humidity, which reduces their persistence in natural environments (Isman, 2006; Regnault-Roger *et al*., 2012). Methodological variability, including differences in extraction techniques, larval stages tested, exposure times, and reporting units, further complicates direct comparisons across studies. Seasonal and geographical variation also influence yield and chemical composition, as demonstrated by Castelo, Del Menezzi, and Resck (2012), thereby affecting reproducibility and generalizability. Moreover, limited data exist on the ecological safety of essential oils, particularly their potential impacts on non-target organisms such as aquatic invertebrates and pollinators (Pavela, 2016; Soonwera and Phasomkusolsil, 2022).

Future research should therefore prioritize the development of standardized bioassay protocols to improve comparability across studies. Advances in formulation technology, including nanoemulsions, encapsulation, and synergistic blends, are needed to enhance stability, persistence, and targeted delivery of essential oils in field conditions (Pavela, 2016; Soonwera and Phasomkusolsil, 2022). Long-term field trials under diverse ecological settings are essential to validate laboratory findings and assess environmental safety. Ecological risk assessments must be integrated into future studies to ensure minimal impact on non-target organisms. Collectively, these efforts will help establish essential oils

as sustainable, eco-friendly components of integrated vector management strategies.

Conclusion

The larvicidal efficacy of essential oils' chemical constituents is hence closely related to the presence and concentrations of their major active components. These components influence the oil's biological activity and determine whether it can be characterized as a potential larvicidal agent. Based on the articles evaluated in this study, the various essential oils from different species promise potent applications as environmentally friendly means of controlling mosquito-transmitted diseases. Compounds like eugenol, limonene, thymol, pinene, and linalool, commonly found in various aromatic and medicinal plants, displayed strong larvicidal activity and could serve as an ecological and cost-effective non-synthetic alternative to chemical insecticides. Unfortunately, this field of research has many constraints that must be resolved before it can be applied routinely. The major issues include the need for a complete assessment of the toxicity of non-target organisms, potential long-lasting environmental impacts, and mostly incomplete or changing characterization of the essential oils' chemical composition. A deeper understanding of these aspects is thus critical to ensuring that essential oils from plants are used safely, efficiently, and appropriately in mosquito control programs.

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Conflict of interest

The authors declare that they have no conflict of interest.

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