

PLANT VOLATILE OILS AND COMPOUNDS AS ECOFRIENDLY MOSQUITO CONTROL PRODUCTS: REVIEW ON RECENT DEVELOPMENTS

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ABSTRACT: Mosquitoes occupy the first place among the most dangerous insects in the world, because they kill more than five lakhs people every year around the world by transmitting lethal pathogens. People use many methods and devices to combat the mosquito problem. Chemical pesticides are commonly used to control mosquitoes and their bites around the world. Since the last two decades public has started to avoid the use of synthetic chemicals for mosquito management due to their harmful effects on environment and human health. Pesticide resistance in mosquitoes is a major side effect of synthetic chemical applications. Volatile oils or essential oils obtained from green plants are considered as reliable alternatives for mosquito management. Several hundred volatile oils and volatile compounds have been tested against eggs, larva, pupa and adults of various vector mosquito species. Oils, extracts and powders of leaf, flowers and bark of many aromatic plants are being used as mosquito repellents in many countries for many centuries. Scientific validation of biological activities of several botanicals has been intensified in the last three decades and several herbal mosquito control products have been commercialized. The aim of the present review article is to provide up-to-date information on biological activities of plant volatile oils and volatile compounds against vector mosquitoes and to highlight the promising volatile compounds for the development of new herbal mosquito control products.

Keywords: volatile oils, 1,8- cineole, thymol, larvicides, repellents, mosquitoes.

INTRODUCTION

Mosquitoes are major public health pests throughout the world. They are distributed all over the world, except Antarctica. World mosquito fauna comprises 3541 species grouped under 112 genera (Tyagi et al., 2015); more than a hundred species of mosquitoes are capable of transmitting various diseases to humans and other vertebrates. Female mosquitoes transmit many pathogenic organisms and cause diseases such as malaria, West Nile virus (WN), dengue, filariasis, yellow fever, Japanese encephalitis and Chikungunya among humans. Mosquito bites also cause considerable pain and loss of sleep; weight loss and decreased milk production in farm animals have been reported due to mosquito bites (Nour et al., 2009).

At present several synthetic insecticides and growth regulators namely methoprene, pyriproxyfen and diflubenzuron and microbial products from *Bacillus thuringiensis israelensis* and *B. sphaericus* are used in mosquito control programmes (Shalan et al., 2005; Ben-Dov, 2014; Lacey et al., 2015). Pyrethroids and malathion are recommended as adulticides and temephos (an organophosphate insecticide better known as Abate[®]), petroleum oils, S-methoprene (Insect growth regulator), *Bacillus thuringiensis israelensis* and *B. sphaericus* are recommended as mosquito larvicides (Brattsten et al., 2009). Vector mosquitoes have developed resistance against many synthetic pesticides due to injudicious use of pesticides and in fact this is the major reason for the resurgence of many mosquito-borne diseases (Becker et al., 2003). Since 1947 more than 100 mosquito species have been reported as resistant to one or more insecticides (Hemingway and Ranson, 2000; Hemingway et al., 2002).

Prevention of mosquito bite is the most common approach among the public. Personal protection by means of avoidance techniques such as using physical and chemical barriers, treatment of fabric with toxicants and the use of topical (skin) repellents is the commonly advocated approach for preventing mosquito bite (Barnard and Xue, 2004).

Plant products are considered as ecofriendly insecticides and are potential alternatives to synthetic insecticides. Pyrethrum, derris, quassia, nicotine, hellebore, anabasine, azadirachtin, d-limonene camphor and turpentine were widely used as alternate insecticides in developed countries before the introduction of synthetic organic insecticides (Wood, 2003). Plant essential oils are ecofriendly 'green pesticides' and safe to mammals and environment (Mossa, 2016). Essential oils are complex mixtures of compounds mainly of monoterpenes and sesquiterpenes. Several scientific studies have disclosed the efficacy of plant volatile oils and volatile compounds in pest and vector management (Mondal and Khalequzzaman, 2006; Paulraj and Ignacimuthu, 2007; Pavunraj et al., 2007; Sivanandhan et al., 2021). Many volatile oils have larvicidal, pupicidal and oviposition deterrent effects against vector mosquitoes (Chantawee and Soonwera, 2018)

The present review article highlights the promising volatile oils and plant volatile compounds which show significant larvicidal and repellent activities against common vector mosquitoes.

LARVICIDAL ACTIVITY OF VOLATILE OILS AND VOLATILE PLANT COMPOUNDS

Mosquito control programmes are largely targeting the larval stage in their breeding sites with larvicides (El Hag et al., 1999 & 2001). Larviciding is a successful method of reducing mosquito population in their breeding places before they emerge into adults (Tiwarly et al., 2007). Application of synthetic larvicides in aquatic ecosystems may cause harmful effects on human beings and many other non-target organisms. In search of alternative pesticides many investigators have explored the beneficial role of plant extracts, plant compounds, actinomycetes sea weeds and mushroom extracts against mosquito larvae (Campbell and Sullivan, 1993; Thangam and Kathiresan, 1994; Pandey et al., 2007; Nazar et al., 2009; Ganesan et al., 2018; Darvin et al., 2019; Sivanandhan et al., 2019; Monisha et al. 2020). Many essential oils showed good larvicidal activities against mosquito species and are reported as environmentally safe insecticides (Corbet et al., 1995; Pitasawat et al., 2007). Some effective essential oils as larvicides against different mosquito species are given in Table 1.

Table 1. Some effective volatile oils and their major components reported for mosquito larvicidal activity

Essential oil source	Target species	Effective concentration or LC ₅₀	Major components in the oil	Reference
<i>Boswellia serrata</i>	<i>Culex pipiens</i>	83.36 ppm	NS	Khater and Shalaby (2007)
<i>Brassica compestris</i>		71.37 ppm		
<i>Calocedrus formosana</i> Florin Bark	<i>Aedes aegypti</i>	51.8 mg/ml	NS	Cheng et al. (2003)
<i>C. formosana</i> Florin leaf		56.3 mg/ml		
<i>Carum ptroselinum</i>	<i>Cx. pipiens</i>	152.94 ppm	NS	Khater and Shalaby (2007)
<i>Chenopodium ambrosioides</i> (aerial parts)	<i>Anopheles arabiensis</i>	17.5 ppm		Massebo et al. (2009)
	<i>A. aegypti</i>	9.1 ppm		
<i>Cinnamomum camphora</i> leaves	<i>Anopheles stephensi</i>	LC50 = 0.026% LC95 = 0.128% at 24 h	Eucalyptol (53.49%) B-terpinene (17.44%) α -terpineol (9.45%)	Xu et al. (2020)

<i>Citrus aurantium</i> subsp. <i>Bergamia</i> fruit rind (cold pressed)		58.73 mg/L (48 h)	Linalyl acetate	
<i>C. aurantium</i> subsp. <i>Bergamia</i> fruit rind (hydrodistillation)	<i>Cx. pipiens</i>	106.6 mg/L (48 h)	Linalool and Limonene	Eleni et al. (2009)
<i>C. aurantium</i> subsp. <i>Bergamia</i> Leaves		68.53 mg/L (48 h)	Linalyl acetate and Limonene	
<i>Corymbia citrodora</i> leaves	<i>An. arabiensis</i>	40.3 ppm		Massebo et al. (2009)
	<i>Ae. aegypti</i>	38.7 ppm		
<i>Cryptomeria japonica</i>		48.1 mg/ml	NS	Cheng et al. (2003)
<i>C. japonica</i> leaf	<i>Ae. aegypti</i>	37.6 mg/ml	NS	
<i>Curcuma aromatica</i>	<i>Ae. aegypti</i>	36.3 ppm		Choochote et al. (2005)
<i>Cymbopogon citrates</i> Stapf.	<i>Ae. aegypti</i>	69 ppm (24 h)	geranial (60.3%) and neral (39.7%).	Cavalcanti et al. (2004)
<i>C. nardus</i> (L.) Rendle (2 nd Fraction)	<i>Cx. quinquefasciatus</i>	1.7 mg/l (1.4 mg/l after 3 months of storage at 29°C)	Myrcene	Ranaweera and Dayananda (1996)
<i>Cymbopogon winterianus</i> (Citronella oil)	<i>Ae. aegypti</i>	LC50= 111.84 µg mL ⁻¹	NS	Cansian et al. (2021)
<i>Cyperus esculentus</i>	<i>Cx. pipiens</i>	47.17 ppm	NS	Khater and Shalaby (2007)
<i>Dendropanax morbifera</i> flowers	<i>Ae. aegypti</i>	62.32 ppm	γ-elemene (18.59%), tetramethyltricyclohydrocarbon (10.82%), β-selinene (10.41%), α-zingibirene (10.52%), 2-isopropyl-5-methylbicyclodecen (4.2%), β-cubebene (4.19), and 2,6-bis(1,1-Dimethylethyl)-4-phenol (4.01%).	Chung et al. (2009)
<i>Eruca sativa</i>	<i>Cx. pipiens</i>	86.06 ppm	NS	Khater and Shalaby (2007)
<i>Eucalyptus montana</i> leaves	<i>An. arabiensis</i>	68.3 ppm		Massebo et al. (2009)
	<i>Ae. aegypti</i>	52.9 ppm		
<i>Ipomoea cairica</i> Linn.	<i>Cx. tritaeniorhynchus</i>	14.8 ppm		Thomas et al. (2004)
	<i>Ae. aegypti</i>	22.3 ppm	-	
	<i>An. stephensi</i>	14.9 ppm		
	<i>Cx. quinquefasciatus</i>	58.9 ppm		
<i>Lavandula angustifolia</i>	<i>Cx. pipiens</i>	LC50 = 140µg/ml	Linalool (32.23%)	El-Akhal et al. (2021)
		LC=90=450µg/ml	Linalyl acetate (14.23%)	
<i>Lavandula dentata</i>		LC50=2670 µg/ml	1,8-Cineole (49.82%)	
		LC90=7400 µg/ml	Camphor (6.31%)	
<i>Lippia adoensis</i> leaves	<i>An. arabiensis</i>	56.4 ppm		Massebo et al. (2009)
	<i>A. aegypti</i>	47.1 ppm		
<i>L. sidoides</i>	<i>Ae. aegypti</i>		Thymol	Carvalho et al. (2003)
<i>L. sidoides</i>	<i>Ae. aegypti</i>	63 ppm (24 h)	Thymol (80.8%); p-Cymene (8.6%); Trans-Caryophyllene (5.1%)	Cavalcanti et al. (2004)
<i>Mentha spicata</i> leaves	<i>An. arabiensis</i>	85.9 ppm		Massebo et al. (2009)
	<i>Ae. aegypti</i>	67.8 ppm	NS	
<i>Nigella sativa</i> leaves	<i>An. arabiensis</i>	23.4 ppm		NS
	<i>Ae. aegypti</i>	32.1 ppm		

<i>Ocimum americanum</i> L.	<i>Ae. aegypti</i>	67 ppm (24 h)	E-Methyl-Cinnamate (70.9%); Z-Methyl-Cinnamate (8.8); Trans-Bergamotene (6.8%); Trans-Caryophyllene (4.6%)	Cavalcanti et al. (2004)
<i>O. basilicum</i> L (four accessions)	<i>Anopheles</i> sp.	190 µL/L to 300 µL/L	eugenol, geraniol and linalool	Nour et al. (2009)
<i>O. gratissimum</i> L.	<i>Ae. aegypti</i>	60 ppm (24 h)	Eugenol (43.7%); 1,8-cineole (32.7%); Z-Ocimene (6.2%); Trans-Caryophyllene (4.1%)	Cavalcanti et al. (2004)
<i>O. lamiifolium</i> leaves	<i>An. arabiensis</i>	20.9 ppm		Massebo et al. (2009)
	<i>Ae. aegypti</i>	8.6 ppm		
<i>O. suave</i> leaves	<i>An. arabiensis</i>	53.5 ppm		Massebo et al. (2009)
	<i>Ae. aegypti</i>	29.8 ppm		
<i>Pinus longifolia</i> (pine oil)	<i>An. stephensi</i>	112.6 ppm	K-terpineole (12.89%); Isoeugenol (4.93%); Eugenol (3.14%); Caryophyllene (2.94%)	Ansari et al. (2005)
	<i>Ae. aegypti</i>	82.1 ppm		
	<i>Cx. quinquefasciatus</i>	85.7 ppm		
<i>P. gaudichaudianum</i>		121 µg/ml	Viridiflorol (27.5%), Aromadendrene (15.55%), β-Selinene (10.5%), Ishwarane (10%)	Morais et al. (2007)
<i>P. hostmanianum</i>	<i>Ae. aegypti</i>	54 µg/ml	Asaricin (27.37%), Myristicin (20.26%), Dillapiol (7.66%), Germacrene D (6.82%), Piperitone (5.58%)	
<i>P. humaytanum</i>		156 µg/ml	Caryophyllene oxide (16.63%), β-Selinene (15.77%), Spathulenol (6.33%), b-Oplophenone (6.02%), Sesquicineole (5.03%)	
<i>Piper marginatum</i> Jacq. (leaves)		23.8 ppm	(Z)-Asarone (30.4%), Patchouli alcohol (16%), Elemol (9.7%), Bicyclogermacrene (9.4%), (E)-Caryophyllene (7.5%), (E)-Asarone (6.4%)	Autran et al. (2009)
<i>P. marginatum</i> (stem)	<i>Ae. aegypti</i>	19.9 ppm	(E)-Asarone (32.6%), Patchouli alcohol (25.7%), (Z)-Asarone (8.5%), Elemicin (6.9%), (E)-Caryophyllene (6.8%), Seychellene (5.8%), (E)-Methyl isoeugenol (3.6%)	
<i>P. marginatum</i> (inflorescence)		19.9 ppm	Patchouli alcohol (23.4%), (E)-Asarone (22.1%), (E)-Caryophyllene (13.1%), α-Acoradiene (9.7%), α-Copaene (9.4%), (Z)-Asarone (4.5%), δ-Elemene (3.1%)	
<i>P. nigrum</i> seeds	<i>An. arabiensis</i>	33.5 ppm		Massebo et al. (2009)
	<i>Ae. aegypti</i>	9.1 ppm	NS	
<i>P. permucronatum</i>	<i>Ae. aegypti</i>	36 µg/ml	Dillapiol (54.7%), Myristicin (25.61%), Elemicin (9.92%), Asaricin (8.55%)	Morais et al. (2007)

<i>Satureja montana</i> (stems, leaves and flowers)		37.7 mg/L	Carvacrol (55.42%), γ -terpinene (13.24%), <i>p</i> -cymene (9.45%)	
<i>S. thymbra</i> (stems and leaves)		44.5 mg/L	Thymol (42.15%), γ -terpinene (20.12%), <i>p</i> -cymene (10.39%)	
<i>S. thymbra</i> (stems, leaves and flowers)		64.4 mg/L	Carvacrol (30.39%), Thymol (24.32%), γ -terpinene (14.64%), <i>p</i> -cymene (9.19%)	
	<i>Cx. pipiens</i> biotype <i>molestus</i>			Michaelakis et al. (2007)
<i>S. spinosa</i> (stems and leaves)		56.1 mg/L	Carvacrol (47.12%), Thymol (12.39%), γ -terpinene (6.49%), <i>p</i> -cymene (5.48%), β -caryophyllene (4.98%), thymol, methyl ether (4.05%)	
<i>S. parnassica</i> ssp. <i>parnassica</i> (stems and leaves)		52.1 mg/L	Thymol (44.39%), γ -terpinene (12.32%), <i>p</i> -cymene (8.35%), Carvacrol (6.36%), β -caryophyllene (4.42%)	
<i>Schinus molle</i> leaves	<i>An. arabiensis</i>	21.0 ppm	NS	
	<i>Ae. aegypti</i>	9.6 ppm		
<i>S. molle</i> seeds	<i>An. arabiensis</i>	26.5 ppm	NS	Massebo et al. (2009)
	<i>Ae. aegypti</i>	14.5 ppm		
<i>Thymus vulgaris</i> leaves	<i>An. arabiensis</i>	33.7 ppm	NS	
	<i>Ae. aegypti</i>	17.3 ppm		
<i>Thymus vulgaris</i>	<i>Aedes aegypti</i>	---	Thymol	Maia et al. (2019)
<i>Trigonella foenumgrecurum</i>	<i>Cx. pipiens</i>	32.42 ppm	NS	Khater and Shalaby (2007)
<i>Zanthoxylum armatum</i> DC seeds	<i>Cx. quinquefasciatus</i>	49 ppm	Linalool, Limonene, E-methyl cinnamate	Tiwary et al. (2007)
	<i>Ae. aegypti</i>	54 ppm		
	<i>An. stephensi</i>	58 ppm		
<i>Zingiber cassumunar</i>	<i>Ae. albopictus</i>	LC ₅₀ =44.9 μ g/L in 24 h	(-) terpinen-4-ol (1) (isolated by bioassay-guided isolation)	Li et al. (2021)
<i>Ziziphora clinopodioides</i> Lam.	<i>An. stephensi</i>	14.9 (μ g/ml)	Pulegone, Piperitone, Menth-2-en-1-ol and carvacrol	Mohammadreza (2008)
	<i>Cx. pipiens</i>	16.5 (μ g/ml)		

NS- Not Studied

Larvicidal activity of essential oils of nine Brazilian plants was studied against *Aedes aegypti*. *Ocimum americanum* and *O. gratissimum* oils recorded 100 per cent mortality at 100 ppm concentration and their effect was comparable to *Lippia sidoides* and *Cymbopogon citrates* (Cavalcanti et al., 2004). Plant volatile oils contain a range of bioactive compounds. Identification and confirmation of larvicidal components present in the active essential oils by separation techniques such as TLC and GC-MS is an essential part of work in the bioassay experiments. Nour et al. (2009) have documented the larvicidal activity of essential oils obtained from four Sudanese accessions of Basil (*Ocimum basilicum*) against *Anopheles* larvae. They found that accession no. 16 (introduced from UA Emirates) and 17 (introduced from Germany) were more effective with LC₅₀ of 190 and 200 μ L L⁻¹ respectively. They reported that eugenol, geraniol and linalool were the major volatile components in the basil essential oils and these compounds caused 100 per

cent larval mortality within half an hour of exposure. Essential oil of *Tridax procumbens* leaves showed larvicidal activity against *Aedes aegypti* at LC_{50} concentration of $79.0 \mu\text{g mL}^{-1}$ and $69.15 \mu\text{g mL}^{-1}$ in 24 and 48 h, respectively. Thymol (48.22%), γ -Terpinene (15.93%), *o*-Cymene (10.27%) and Carvacrol methyl ether (7.7%) were detected as major compounds in *T. procumbens* essential oil by GC-MS analysis method (Brandão et al., 2021). Essential oils of 28 plant species were tested individually against *Cx. quinquefasciatus* larvae and adults and binary combinations of effective oils were again tested. Combination of *Allium sativum* (bulbs) and *Citrus paradisi* (leaves) oils at 1:1 volume ratio recorded the highest larvicidal activity and GC-MS analysis revealed the presence of diallyl disulfide, linalool, citronellal and caryophyllene oxide as major constituents (Mahanta and Khanikor, 2021).

It is generally concluded that the major component present in the volatile oil may be the actual cause of larval death. To confirm this, the individual compound of interest should be tested for its activity. Some studies have indicated that the volatile compounds thymol and carvacrol were responsible for larvicidal activity against mosquito larvae. Carvalho et al. (2003) studied the larvicidal activity of essential oil of *Lippia sidoides* and its major components thymol and carvacrol against *Ae. aegypti*. They reported that the pure essential oil and dilution of oil at 1: 2 ratio recorded 100 per cent larval mortality within 5 minutes and thymol recorded 100 per cent larval mortality at 0.04% within 30 min. Dilutions of oil at 1: 5 and 1: 10 ratios caused 100 per cent larval mortality within 20 minutes and after 24 h respectively. Carvacrol did not cause any larval mortality at 0.04% concentration. Cavalcanti et al. (2004) have also reported the larvicidal activity of *L. sidoides* oil against *Ae. aegypti*. Their study clearly indicated that 63 ppm of *L. sidoides* oil killed 50 per cent larvae in 24 h and they reported that the oil contained thymol (80.8%) as the major component. Besides *L. sidoides* oil Cavalcanti et al. (2004) screened eight more essential oils from Brazilian plants against *Ae. Aegypti* larvae. They found that the essential oils of *Ocimum americanum*, *O. gratissimum* and *C. citratus* were as potent as *L. sidoides* and caused 100 per cent mortality at a concentration of 100 ppm. Michaelakis et al. (2007) analysed the essential oils of *Satureja montana* and *S. thymbra*, which showed high toxicity against the larvae of *Culex pipiens* biotype *molestus* and found that carvacrol or thymol were the major components. According to them the larvicidal activity was a result of the synergistic effect of the phenolic compounds with other components that were present in the oils tested. In a study essential oils were extracted from leaves of 10 *Piper* spp. and larvicidal activity was studied against strains of Pyrethroid resistant and susceptible *Ae. Aegypti*. Among the ten species, five species viz., *Piper aduncum*, *P. marginatum*, *P. gaudichaudianum*, *P. crassinervium*, and *P. arboretum* were found to be active since they recorded larvicidal activity between 90–100% at 100 ppm concentration. The active compounds in the oils namely (*E*)-Anethole, β -Asarone, γ -Terpinene, *p*-Cymene, Limonene, α -Pinene, β -Pinene and Dillapiole showed larvicidal activity between 90-100% at 100 ppm (Filho et al., 2021). Knio et al. (2008) studied the larvicidal activity of essential oils extracted from commonly used medical and culinary herbs in Lebanon against the fourth instar larvae of seaside mosquito *Ochlerotatus caspius*. They found that thyme inflorescence extract was the most potent larvicide followed by parsley seed oil, aniseed oil and coriander fruit oil. Based on GC-MS analysis they reported that thymol, sabinene, carvacrol, anethole and linalool were the major components of parsley seeds and leaves, alpine thyme inflorescences, aniseeds and coriander fruits respectively. These studies support the fact that thymol in volatile oils is a toxicant against mosquito larvae. (Cavalcanti et al., 2004; Cheng et al., 2004; Choochote et al., 2005; Knio et al., 2008; Maia et al., 2019)

Tiwary et al. (2007) studied the larvicidal activity of volatile oils obtained from the seeds of *Zanthoxylum armatum* against *Cx. quinquefasciatus*, *Ae. aegypti* and *An. stephensi*. They analysed the volatile oils by GC-MS and found that linalool (57%) and limonene (19.8%) were the major components. Linalool was reported as mosquito repellent by Omolo et al. (2004) and Traboulsi et al. (2005). At the same time

Traboulsi et al. (2002) and Cheng et al. (2004) discovered that linalool at higher doses caused larval mortality. The study by Chantraine et al. (1998) indicated that linalool did not cause larval mortality in *Ae. aegypti* at doses ranging between 10 and 100 ppm.

Kelm and Nair (1998) isolated two compounds from hexane extract of *Ocimum sanctum* leaves and stem and screened them against *Ae. aegyptii* larvae. They claimed that eugenol and (*E*)-6-hydroxy-4,6-dimethyl-3-heptene-2-one exerted larvicidal activity at 200 and 6.25 $\mu\text{g mL}^{-1}$ concentrations respectively in 24 h.

Several investigators have reported that 1,8-cineole is mainly responsible for pesticidal properties against many insects (Duke, 2004). Lucia et al. (2007) studied the larvicidal activity of *Eucalyptus grandis* and pine resin essential oils (turpentine) and their major components namely α - and β -pinene and 1,8-cineole against third and fourth instar *Ae. aegypti* larvae. They recorded that turpentine oil was more active (LC_{50} of 14.7 ppm) than the essential oil of *E. grandis* (LC_{50} : 32.4 ppm), which contained 1,8-cineole. Klocke et al. (1987) found that 1,8-cineole, present in the volatile oil of *H. fitchii*, did not exhibit any significant mosquito larvicidal activity. But the oil acted as a moderate feeding repellent and highly effective ovipositional repellent against adult *Aedes aegypti*.

Chung et al. (2009) have reported that the essential oil obtained from *Dendropanax morbifera* flowers had a significant toxic effect against early fourth instar larvae of *Ae. aegypti* with an LC_{50} and LC_{90} of 62.32 and 131.21 ppm respectively and the oil contained 27 compounds; the major components were γ -elemene (18.59%), tetramethyl tricyclohydrocarbon (10.82%), β -selinene (10.41%), α -zingibirene (10.52%), 2-isopropyl-5-methylbicyclodecen (4.2%), β -cubebene (4.19%) and 2,6-bis (1,1-Dimethylethyl)-4-phenol (4.01%). The pure compound that was isolated from the essential oils gave higher larvicidal activity than crude essential oils. Tripathi et al. (2004) have reported that the compound piperitenone oxide that was isolated from oil of *Mentha spicata* variety *viridis* recorded higher larvicidal activity (LD_{50} =61.64 $\mu\text{g/ml}$) than the crude essential oil (LD_{50} =82.95 $\mu\text{g/ml}$) against *An. stephensi*.

Cheng et al. (2009) evaluated the larvicidal activity of leaf essential oils of six chemotypes of cinnamon (*Cinnamomum osmophloeum*) against *Ae. albopictus*, *Armigeres subalbatus* and *Cx. quinquefasciatus*. In their study the leaf essential oils of cinnamaldehyde type (LC_{50} =40.8 $\mu\text{g/ml}$; LC_{90} = 81.7 $\mu\text{g/ml}$) and cinnamaldehyde/cinnamyl acetate type (LC_{50} =46.5 $\mu\text{g/ml}$; LC_{90} = 83.3 $\mu\text{g/ml}$) recorded the maximum inhibitory effect against *Ae. albopictus* larvae. They also reported that the effective constituents in leaf essential oils were *trans*-cinnamaldehyde and benzaldehyde and the LC_{50} values of these constituents against *A. albopictus* larvae were below 50 $\mu\text{g/ml}$.

The larvicidal activity of essential oils varies between different mosquito species. Pitasawat et al. (2007) have reported that among the aromatic oils obtained from five different plant species, *Carum carvi*, *Apium graveolens*, *Foeniculum vulgare*, *Zanthoxylum limonella* and *Curcuma zedoaria*, *Z. limonella* oil was the most effective against *A. aegypti* with LC_{50} and LC_{95} values of 24.61 and 55.81 ppm, respectively and *C. zedoaria* oil was the most effective against *A. dirus* larvae (LC_{50} and LC_{95} values: 29.69 and 40.23 ppm, respectively). Eleven essential oils out of 12 obtained from plants namely *Chenopodium ambrosioides* (aerial parts), *Ocimum lamiifolium* (leaves), *O. suave* (leaves), *Schinus molle* (leaves and seeds), *Piper nigrum* (seeds), *Corymbia citriodora* (leaves), *Eucalyptus globules* (leaves), *Lippia adoensis* (leaves), *Mentha spicata* (leaves) and *Thymus vulgaris* (leaves) were evaluated. They showed higher larval toxicity in *Ae. Aegypti* than *An. arabiensis* after 24 h exposure and oil obtained from *Nigella sativa* (leaves) recorded higher toxicity against *An. arabiensis* (Massebo et al., 2009). In a review Shaalan et al. (2005) had stated that mosquito larvae of different species displayed different susceptibilities to the same phytochemical and *Aedes* larvae, in general, were robust and less susceptible to insecticides and botanicals than *Culex* larvae.

IMPROVING THE LARVICIDAL ACTIVITY OF VOLATILE OILS

Studies on the improvement of the larvicidal activity of volatile oils have been done by some investigators. Corbet et al. (1995) have studied the usefulness of some surfactants to increase the larvicidal activity of essential oils. In their study they used 1% insoluble surfactant (Arosurf MSF) and 1% detergent with eucalyptus and turpentine oils separately. They reported that refined turpentine at a dose of 2 μl per tub ($=0.13 \mu\text{l cm}^{-2}$) acted faster due to the addition of surfactants (turpentine: Arosurf: detergent 100:1:1 by volume) causing higher mortality in fourth instar *Cx. pipiens* form *molestus* at 24 and 48 h after treatment, than familiar surface-active larvicide Arosurf alone.

REPELLENT PROPERTY OF VOLATILE OILS

The relationship between man and blood sucking insects is very old and man has learnt adequate techniques to avoid the mosquito biting. Keeping away the adult mosquitoes from human habitats and preventing mosquito bites are vital tactics in personal protection from mosquito borne diseases. Repellents are the prime products used for the protection from mosquito bites. Due to the enormous developments in science and technology new insect repellents are being discovered. Synthetic repellents are the most commonly used materials against mosquitoes. DEET (N, N-diethyl-3-methylbenzamide) is the most commonly used synthetic mosquito repellent. Insect repellent property of DEET was first discovered in 1953 and the first DEET product was introduced in 1956 (Peterson and Coats, 2001). It is an effective insect repellent against a broad spectrum of insects including mosquitoes.

Injudicious use of synthetic skin repellents which contain DEET may affect human health (Qui et al., 1998; Eden et al., 2020). Some investigators have pointed out the allergic reactions and human toxicity of DEET (Robbins and Cherniack, 1986; Edwards and Johnson, 1987; Qui et al., 1998). Peterson and Coats (2001) have noted that encephalopathy in children, urticaria syndrome, anaphylaxis, hypotension and decreased heart rate are some toxic effects associated with DEET. Trigg (1996), Walker et al. (1996), Debboun et al. (2000), Peterson and Coats (2001), Fradin and Day (2002) and Badolo et al. (2004) have pointed out that DEET has the ability to act as a good solvent for plastics and other synthetic materials and search for alternative repellents including natural products are essential. Since DEET is a chemical, a concentration of less than 10 per cent is recommended for children.

The novel repellents are mainly based on human safety. Electronic mosquito repellent is said to be environmentally friendly. But these electronic devices have been shown to have no effect as a mosquito repellent (Andrade and Bueno, 2001). In many countries aromatic plants are playing important role in mosquito management since ancient times. Very early report on mosquito repellent properties of essential oils was made by Penfold and Morrison (1952). They have reported the repellent and insecticidal activities of forty Australian essential oils against vector insects including mosquitoes. They reported that the essential oils obtained from *Dacrydium franklini*, *Backhousia myrtifolia*, *Mela-leuca bracteata* and *Zieria smithii* were the most effective.

In African countries *Hyptis suaveolens*, *Ocimum* spp. and *Daniellia oliveri* are used as traditional repellents against mosquitoes (Curtis et al., 1991). Aromatic plants contain volatile oils and volatile compounds which are responsible for their mosquito repellent property. In table 2 the mean protection time or repellency time of some essential oils against different mosquito species is given. The essential oil of *Ocimum suave* contained eugenol and six terpenoid substances and was an effective mosquito repellent (Chogo and Crank, 1981). Literature on the repellent activity of volatile oils against different mosquito species is plenty (Yang and Ma, 2005; Gillij et al., 2008). Repellency of volatile oils extracted from six plant species

namely *Croton pseudopulchellus*, *Mkilua fragrans*, *Endostemon tereticaulis*, *Ocimum forskolei*, *O. fischeri* and *Plectranthus longipes* was evaluated against *An. gambiae sensu strict* (Odalo et al., 2005). Citronella and pennyroyal essential oils have been used as repellents against insects since ancient times (Jantan and Zaki, 1999).

Table 2. Repellent activity of some essential oils against vector mosquitoes

Volatile oil source	Target mosquito	Repellency/ Protection time	Effective concentration	Reference
<i>Acantholippia seriphoides</i>		70 min	50 %	
<i>Aloysia citriodora</i>	<i>Aedes aegypti</i>	90 min	12.5 %	Gillij et al. (2008)
<i>Baccharis spartioides</i>		90 min	12.5%	
<i>Cinnamomum mollisimum</i>	<i>Ae. aegypti</i>	100%	0.0379 mg cm ²	Jantan and Zaki (1999)
Citronella + vanillin	<i>Ae. aegypti</i> , <i>Anopheles dirus</i> , <i>Culex quinquefasciatus</i>	100% (6 h),	0.1 ml of 25% oil in 5% vanillin per 3x10 cm skin in the arm	Tawatsin et al. (2001)
<i>Citrus limon</i> Burm	<i>An. stephensi</i>		1%	Oshaghi et al. (2003)
<i>C. citronella</i> (lemon grass oil)	<i>An. culicifacies</i>	100 %	Pure oil (1 ml)	Ansari et al. (2005)
	<i>Cx. quinquefasciatus</i>	98.5%		
<i>Cymbopogan martinii martinii</i> Stapf var <i>sofia</i>	<i>An. sundaicus</i>	8 hrs (98.7%) (in indoor) and 6 hrs (96.52%) (in outdoor)	Pure oil (1ml)	Das and Ansari (2003)
<i>Cymbopogan nardus</i>	<i>Ae. aegypti</i>	72.2%	0.0047 mg cm ²	Jantan and Zaki (1999)
<i>Eucalyptus saligna</i>	<i>Ae. aegypti</i>	90 min	50 %	Gillij et al. (2008)
<i>Litsea elliptica</i>	<i>Ae. aegypti</i>	100%	0.0379 mg cm ²	Jantan and Zaki (1999)
<i>Melissa officinalis</i> L.	<i>An. stephensi</i>		1%	Oshaghi et al. (2003)
<i>Minthostachys mollis</i>	<i>Ae. aegypti</i>	60 min	50 %	Gillij et al. (2008)
<i>Nepeta parnassica</i> (vegetative stage)	<i>Cx. pipiens</i>	88.5 %	10 mg	Gkinis et al. (2003)
Pinus longifolia	<i>An. culicifacies</i>	100 %	Pure oil (1 ml)	Ansari et al. (2005)
	<i>Cx. quinquefasciatus</i>	97.4 %		
Piper aduncum	<i>Ae. aegypti</i>			Misni et al. (2008)
<i>Pogostemon cablin</i>	<i>Ae. aegypti</i>	71.4%	0.0047 mg cm ²	Jantan and Zaki (1999)
<i>Rosmarinus officinalis</i>	<i>Ae. aegypti</i>	90 min	50%	Gillij et al. (2008)
<i>Tagetes minuta</i>		90 min	25 %	
<i>Zanthoxylum piperitum</i> + 5% vanillin	<i>Ae. aegypti</i> (In laboratory study)	2.5 h*	0.1 ml of oil in 3x10 cm skin area	Kamsuk et al. (2006)
	<i>Ae. gardnerii</i> , <i>An. barbirostris</i> , <i>Armigeres subalbatus</i> , <i>Cx. tritaeniorhynchus</i> , <i>Cx. gelidus</i> , <i>Cx. vishnui</i> and <i>Mansonia uniformis</i>	100% (for 120 min) (in field condition)		

*Median complete protection time

The mosquito repellent property of volatile oils is measured in terms of total protection time. *Piper aduncum* essential oil gave 95.2% protection against *Ae. albopictus* bites under laboratory conditions (Misni et al., 2009); the protection was reduced to 83.3% after 4 h, 64.5% after 6 h, and 51.6% after 8 h postapplication. Deet is used as standard reference in the repellent bioassay studies which involves plant volatile oils or volatile compounds. Oshaghi et al. (2003) compared the effectiveness of lemon and melissa

oils with Deet and reported that lemon (92.70%) and melissa (92.67%) oils gave less protection than Deet (97%) against *An. stephansi* in guinea-pigs; however these differences were not significant. Tawatsin et al. (2001) extracted volatile oils from four plant species namely turmeric (*Curcuma longa*), kaffir lime (*Citrus hystrix*), citronella grass (*Cymbopogon winterianus*) and hairy basil (*Ocimum americanum*) by steam distillation method and evaluated the repellent activity against three mosquito vectors *Ae. aegypti*, *A. dirus* and *Cx. quinquefasciatus*. They found that the volatile oils from turmeric, citronella grass and hairy basil significantly gave maximum protection from three mosquito species and the repellency was increased for up to eight hours when 5% vanillin was added with the oils. They also reported that the standard repellent DEET gave protection for at least eight hours against only two mosquito species *Ae. aegypti* and *Cx. quinquefasciatus* but DEET with 5% vanillin gave protection against all the three mosquito species for at least eight hours.

Das and Ansari (2003) have reported that 1 ml of the essential oil of *Cymbopogon martinii martinii* var *sofia* oil when applied on the body parts gave 8 (98.7%) and 6 h (96.52%) of protection in indoor and outdoor respectively against *An. sondaicus* when tested for a period of 12 h. They reported that palmarosa oil contained geraniol (76.15%) as the major component.

Maguranyi et al. (2009) evaluated the repellency of essential oils from 11 Australian native plants against *Ae. aegypti*, *Cx. quinquefasciatus*, and *Cx. annulirostris* under laboratory conditions. Based on the preliminary results they selected the three most effective oils, mixed them and tested the repellency. *Prostanthera melissifolia* essential oil gave the longest protection time (110 min.) against *Cx. quinquefasciatus* and the repellency against *Ae. aegypti* was increased when the blend of *Leptospermum petersonii*, *Prostanthera melissifolia*, and *Melaleuca alternifolia* was tested at 5% v/v. They recommended the use of the blend of the above three oils as a short term repellent or under conditions of low mosquito abundance.

The effectiveness of mosquito repellents depends on many environmental factors. According to Barnard et al. (1998) the effect of repellents can vary greatly among mosquito species. A repellent will not protect all users equally and several factors such as species of the mosquito, density of organisms in the immediate surroundings, user's age, sex and biochemical attractiveness to the biting insect, ambient temperature, humidity and wind speed determine the effectiveness of a repellent (Golenda et al., 1999; Maibach et al., 1966; Muirhead-Thomson, 1951; Fradin, 2001; Fradin and Day, 2002). The essential oils obtained from different parts or during different stages of the same plant may have variations in their components, which is considered as a major cause for their differential activities. Gkins et al. (2003) isolated essential oils from the aerial parts of *Nepeta parnassica* at both vegetative and flowering stages and evaluated them against *Cx. pipiens molestus*. They recorded a significant repellent activity at 10 mg of oil obtained from the vegetative stage of *N. parnassica* when compared with the flowering stage, which was due to the quantitative variation in the components of both oils. The main metabolites of vegetative-stage oil were recorded as 4 α ,7 α ,7 β -nepetalactone (22.0%), 1,8-cineole (21.1%), α -pinene (9.5%) and 4 α ,7 β ,7 α -nepetalactone (7.9%).

ENHANCING THE REPELLENT ACTIVITY OF VOLATILE OILS

Most of the essential oils have a short protective duration against mosquitoes due to their high volatility (Kamsuk et al., 2006). This limitation can be overcome by making a formulation with some fixatives like liquid paraffin (Oyedele et al. 2002) vanillin (Tawatsin et al. 2001), salicylic acid (Blackwell et al., 2003), and mustard and coconut oils (Das et al. 2003). In a field study it was observed that the essential oil of *Zanthoxylum piperitum* fruits with 5% vanillin provided better protection against a wide range of mosquito populations than oil without vanillin; vanillin-oil combination was also found to be more effective.

tive than 25% DEET (Kamsuk et al., 2006). Choochote et al. (2007) have reported the repellent property of essential oils of fruits, rhizomes and seeds of ten plants namely *Amomum xanthioides*, *Curcuma zedoaria*, *Kaempferia galanga*, *Anethum graveolens*, *Apium graveolens*, *Carum carvi*, *Foeniculum vulgare*, *Piper longum*, *Zanthoxylum limonella* and *Zanthoxylum piperitum* against *Ae. aegypti*. The complete protection time of individual oils and mixtures of two effective oils with and without 10 per cent vanillin was studied. *Z. piperitum*, *A. graveolens* and *K. galangal* provided repellency against *A. aegypti* with median complete-protection times of 1, 0.5 and 0.25 h, respectively and the protection time of *Z. piperitum*, *Z. limonella*, *K. galangal* and *C. zedoaria* increased significantly when 10% vanillin was incorporated. The highest median complete protection time (2.5 h) was recorded by *Z. piperitum* oil +10% vanillin. The mixtures of oils were not found to be so effective. Volatile compounds citronellal, citronellol, and geranio were isolated from essential oil of *Cymbopogon winterianus* (Java citronella) and made into a air freshener gel for slow release of volatile compound. Geraniol and citronellol recorded 78 and 77% repellent activity, respectively and the activity was maintained up to 16.82 and 12.77 days for geraniol and citronellol, respectively in gel form (Eden et al., 2020).

CONCLUSIONS

Plant volatile oils and volatile compounds are promising mosquito control products. They are generally safe to human beings and other mammals. The mosquito control property of volatile oils is due to the presence of volatile compounds. From this review it is clear that some compounds like 1,8-cineole, linalool, limonene, eugenol and thymol have been frequently reported as effective larvicides and repellents against mosquitoes. Research on improving the efficacy of volatile oils is currently getting more importance. More research is needed for developing novel volatile oil formulations with controlled release technology and broad range activity against all vector mosquito species.

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REFERENCES

- Andrade, C.F.S. & Bueno, V.S. (2001). Evaluation of electronic mosquito-repelling devices using *Aedes albopictus* (Skuse) (Diptera: Culicidae). *Neotropical Entomology*, 30(3), 497-499.
- Ansari, Md., Mittal, P., Razdan, R. & Sreehari, U. (2005). Larvicidal and mosquito repellent activities of Pine (*Pinus longifolia* Family: Pinaceae) oil. *Journal of vector borne diseases*, 42, 95-99.
- Autran, E.S., Neves, I.A., da Silva, C.S.B., Santos, G.K.N., da Câmara, C.A.G. & Navarro, D.M.A.F. (2009). Chemical composition, oviposition deterrent and larvicidal activities against *Aedes aegypti* of essential oils from *Piper marginatum* Jacq. (Piperaceae). *Bioresource Technology*, 100, 2284-2288.
- Badolo, A., Ilboudo-Sanogo, E., Ou'edraogo, P.A. & Costantini, C. (2004). Evaluation of the sensitivity of *Aedes aegypti* and *Anopheles gambiae* complex mosquitoes to two insect repellents: DEET and KBR 3023. *Tropical Medicine & International Health*, 9, 330.
- Barnard, D.R. & Xue, R.D. (2004). Laboratory evaluation of mosquito repellents against *Aedes albopictus*, *Culex nigripalpus*, and *Ochlerotatus triseriatus* (Diptera: Culicidae). *Journal of Medical Entomology*, 41(4), 726-30.
- Barnard, D.R., Posey, K.H., Smith, D. & Schreck, C.E. (1998). Mosquito density, biting rate and cage size effects on repellent tests. *Medical and Veterinary Entomology*, 12(1), 39-45.
- Becker, N., Petric, D., Zgomba, M., Boase, C., Dahl, C., Lane, J. & Kaiser, A. (2003). *Mosquitoes and their control*. Kluwer Academic/Plenum Publishers: New York.
- Ben-Dov, E. (2014) *Bacillus thuringiensis* sub sp. *israelensis* and its dipteran-specific toxins. *Toxins*, 6, 1222-1243.
- Blackwell, A., Stuart, A.E. & Estambale, B.A. (2003). The repellent and antifeedant activity of *Myrica gale* oil against *Aedes aegypti* mosquitoes and its enhancement by the addition of salicylic acid. *The Journal of the Royal College of Physicians of Edinburgh*, 33, 209

- Brandão, B.L., Santos, L.L., Martins, R.L., Rodrigues, A.B.L., Rabelo, E.de.M., Galardo, A.K.R. et al. (2021). Larvicidal evaluation against *Aedes aegypti* and antioxidant and cytotoxic potential of the essential oil of *Tridax procumbens* L. leaves. The Scientific World Journal, Vol.2021, Article ID 2172919 (<https://doi.org/10.1155/2021/2172919>)
- Brattsten, L.B., Hamilton, G.C. & Sutherland, D.J. (2009). Insecticides recommended for mosquito control in New Jersey. In: *New Jersey Agricultural Experiment Station*, Publication No. P-08001-01-08.
- Campbell, R.L. & Sullivan, W.W. (1993). The relative toxicity of nicotine, anabasine, methyl anabasine and lupinine for culicine mosquito larvae. *Journal of Economic Entomology*, 26, 500–509.
- Cansian, R.L., Staudt, A., Bernardi, J.L., Puton, B.M.S., Oliveira, D., de Oliveira, J.V. et al. (2021). Toxicity and larvicidal activity on *Aedes aegypti* of citronella essential oil submitted to enzymatic esterification. *Brazilian Journal of Biology*, 83, e244647
- Carvalho, A.F.U., Melo, V.M.M. & Craveiro, A.A., Machado, M.I.L., Bantim, M.B., Rabelo, E.F. (2003). Larvicidal activity of the essential oil from *Lippia sidoides* Cham. against *Aedes aegypti* Linn. *Memórias do Instituto Oswaldo Cruz*, 98(4), 569-571
- Cavalcanti, E.S.B., de Moraes, S.M., Lima, M.A.A. & Santana, E.W.P. (2004). Larvicidal activity of essential oils from Brazilian plants against *Aedes aegypti* L. *Memorias do Instituto Oswaldo Cruz*, Rio de Janeiro, 99(5), 541-544.
- Chantawee, A. & Soonwera, M. (2018). Efficacies of four plant essential oils as larvicide, pupicide and oviposition deterrent agents against dengue fever mosquito, *Aedes aegypti* Linn. (Diptera: Culicidae). *Asian Pacific Journal of Tropical Biomedicine*, 8(4), 217-225
- Chantraine, J.M., Laurent, D., Ballivian, C., Saavedra, G., Ibanez, R. & Vilaseca, L.A. (1998). Insecticidal activity of essential oils on *Aedes aegypti* larvae. *Phytotherapy Research*, 12, 350–354.
- Cheng, S.S., Chang, H.T., Chang, S.T., Tsai, K.H. & Chen, W.J. (2003). Bioactivity of selected plant essential oils against the yellow fever mosquito *Aedes aegypti* larvae. *Bioresource Technology*, 89, 99–102
- Cheng, S.S., Liu, J.Y., Tsai, K.H., Chen, W.J. & Chang, S.T. (2004). Chemical composition and mosquito larvicidal activity of essential oils from leaves of different *Cinnamomum osmophloeum* provenances. *Journal of Agricultural and Food Chemistry*, 52, 4395–400
- Cheng, S.S., Liu, J.Y., Huang, C.G., Hsui, Y.R., Chen, W.J. & Chang, S.T. (2009). Insecticidal activities of leaf essential oils from *Cinnamomum osmophloeum* against three mosquito species. *Bioresource Technology*, 100(1), 457-464.
- Chogo, J.B. & Crank, G. (1981). Chemical composition and biological activity of the Tanzanian plant *Ocimum suave*. *Journal of Natural Products (Lloydia)*, 44, 308–311.
- Choochote, W., Chaityasit, D., Kanjanapothi, D., Rattanachanpichai, E., Jitpakdi, A., Tuetun, B. et al. (2005). Chemical composition and anti-mosquito potential of rhizome extract and volatile oil derived from *Curcuma aromatica* against *Aedes aegypti* (Diptera: Culicidae). *Journal of vector ecology*, 30(2), 302-309.
- Choochote, W., Chaitong, U., Kamsuk, K., Jitpakdi, A., Tippawangkosol, P., Tuetun, B. et al. (2007). Repellent activity of selected essential oils against *Aedes aegypti*. *Fitoterapia*, 78, 359-364
- Chung, I.M., Kim, M.Y., Park, S.D., Park, W.H. & Moon, H.I. (2009). *In Vitro* evaluation of the antiplasmodial activity of *Dendropanax moribifera* against chloroquine-sensitive strains of *Plasmodium falciparum*. *Phytotherapy Research*, 23(11), 1634-1637.
- Corbet, S.A., Danahar, G.W., King, V., Chalmers, C.L. & Tiley, C.F. (1995). Surfactant-enhanced essential oils as mosquito larvicides. *Entomologia Experimentalis et Applicata*, 75(3), 229-236
- Curtis, C.F., Lines, J.D., Baolin, Lu & Renz, A. (1991). Natural and synthetic repellents. In: Curtis, C.F. (Ed.), *Control of disease vectors in the community*. Wolfe, London, pp. 75–92.
- Darvin, S.S., Ganesan, P., Stalin, A., Rajan, S., Gabriel Paulraj, M., Balakrishna, K. et al. (2019). Effect of tiliamosine, a bis, benzyloquinoline alkaloid isolated from *Tiliacora acuminata* (Lam.) Hook. f. & Thom on the immature stages of filarial mosquito *Culex quinquefasciatus* Say (Diptera: Culicidae), *Experimental Parasitology*, 204, 107719 (<https://doi.org/10.1016/j.exppara.2019.107719>).
- Das, M.K. & Ansari, M.A. (2003). Evaluation of repellent action of *Cymbopogon martinii martinii* Stapf var *sofia* oil against *Anopheles sun-daicus* in tribal villages of Car Nicobar Island, Andaman & Nicobar Islands, India. *Journal of Vector Borne Diseases*, 40, 100–104
- Das, N.G., Baruah, I., Talukdar, P.K. & Das, S.C. (2003). Evaluation of botanicals as repellents against mosquitoes. *Journal of Vector Borne Diseases*, 40, 49–53
- Debboun, M., Strickman, D., Solberg, V.B., Wilkerson, R.C., McPherson, K.R., Golenda, C. et al. (2000). Field evaluation of DEET and piperidine repellent against *Aedes communis* (Diptera: Culicidae) and *Simulium venustum* (Diptera: Simuliidae) in the Adirondack mountains of New York. *Journal of Medical Entomology*, 37, 919–923.
- Duke, J.A. (2004). Dr. Duke's phytochemical and ethnobotanical databases. Available online at <http://www.ars-grin.gov/duke/> (accessed on 9 June, 2008).
- Eden, W.T., Alighiri, D., Supardi, K.I. & Cahyono, E. (2020). The mosquito repellent activity of the active component of air freshener gel from Java Citronella oil (*Cymbopogon winterianus*). *Journal of Parasitology Research*, vol. 2020, article ID 9053741, (<https://doi.org/10.1155/2020/9053741>)
- Edwards, D.L. & Johnson, C.E. (1987). Insect–repellent-induced toxic encephalopathy in a child. *Clinical Pharmacology*, 6, 496–498.
- El-Akhal, F., Ramzi, A., Farah, A., Zoubi, Y.E., Benboubker, M., Taghzouti, K. & Lalami, A. El. O. (2021). Chemical composition and larvicidal activity of *Lavandula angustifolia* subsp. *angustifolia* and *Lavandula dentata* spp. *dentata* essential oils against *Culex pipiens* larvae, vector of West Nile virus. *Psyche: A Journal of Entomology*, Vol. 2021, Article ID 8872139, 7 pages, <https://doi.org/10.1155/2021/8872139>
- Eleni, M., Antonios, M., George, K., Leandros, S.A. & Prokopios, M. (2009). High quality bergamot oil from Greece: Chemical analysis using chiral gas chromatography and larvicidal activity against the West Nile Virus vector. *Molecules*, 14, 839-849

- El Hag, E. A., El Nadi, A. H. & Zaitoon, A. A. (1999). Toxic and growth retarding effects of three plant extracts on *Culex pipiens* larvae (Diptera: Culicidae). *Phytotherapy Research*, 13, 388-392.
- El Hag, E.A., Abd-El Rahman, El-Nadi, H. & Zaitoon, A.A. (2001). Effects of methanolic extracts of neem seeds on egg hatchability and larval development of *Culex pipiens* mosquitoes. *Indian Veterinary Journal*, 78, 199-201.
- Filho, A.A.P., D'Ávila Pessoa, G.C., Yamaguchi, L.F., Stanton, M.A., Serravite, A.M., Pereira, R.H.M. et al. (2021). Larvicidal activity of essential oils from *Piper* species against strains of *Aedes aegypti* (Diptera: Culicidae) resistant to pyrethroids. *Frontiers in Plant Science*, 12: 685864. DOI: 10.3389/fpls.2021.685864
- Fradin, M.S. (2001). Insect repellents. In S.E. Wolverson (Ed.), *Comprehensive dermatologic drug therapy* (pp. 717-734). Philadelphia: W.B. Saunders.
- Fradin, M.S. & Day, J.F. (2002). Comparative efficacy of insect repellents against mosquito bites. *The New England Journal of Medicine*, 347(1), 13-18
- Ganesan, P., Stalin, A., Gabriel Paulraj, M., Balakrishna, K., Ignacimuthu, S. & Al-Dhabi, N.A. (2018). Biocontrol and non-target effect of fractions and compound isolated from *Streptomyces rimosus* on the immature stages of filarial vector *Culex quinquefasciatus* Say (Diptera: Culicidae) and the compound interaction with Acetylcholinesterase (AChE1). *Ecotoxicology and Environmental Safety*, 4, 161:120-128
- Gillij, Y.G., Raquel, G. & Julio, Z. (2008). Mosquito repellent activity of essential oils of aromatic plants growing in Argentina. *Bioresource technology*, 99(7), 2507-2515
- Gkinis, G., Tzakou, O., Iliopoulou, D. & Roussis, V. (2003). Chemical composition and biological activity of *Nepeta parnassica* oils and isolated Nepetalactones. *Zeitschrift für Naturforschung*, 58c, 681- 686
- Golenda, C.F., Solberg, V.B., Burge, R., Gambel, J.M. & Wirtz, R.A. (1999). Gender related efficacy difference to an extended duration formulation of topical N,N-diethyl-m-toluamide (DEET). *American Journal of Tropical Medicine and Hygiene*, 60, 654-657.
- Hemingway, J. & Ranson, H. (2000). Insecticide resistance in insect vectors of human disease. *Annual Review of Entomology*, 45, 371-391.
- Hemingway, J., Field, L. & Vontas, J. (2002). An overview of insecticide resistance. *Science*, 298, 96-97.
- Jantan, I. & Zaki, Z.M. (1999). Development of environment-friendly insect repellents from the leaf oils of selected Malaysian plants. *ASEAN Review of Biodiversity and Environmental Conservation*, VI, 1-7
- Kamsuk, K., Choochote, W., Chaithong, U., Jitpakdi, A., Tippawangkosol, P., Riyong, D. et al. (2006). Effectiveness of *Zanthoxylum piperitum*-derived essential oil as an alternative repellent under laboratory and field applications. *Parasitology Research*, 100(2), 339-45.
- Kelm, M.A. & Nair, M.G. (1998). Mosquitocidal compounds and a Triglyceride, 1,3-Dilinolenoyl-2-palmitin, from *Ocimum sanctum*. *Journal of Agricultural and Food Chemistry*, 46(8), 3092-3094
- Khater, H.F. & Shalaby, A.A.S. (2007). Potential of biologically active plant oils for controlling of *Culex pipiens* (Diptera:Culicidae). *Acta Scientiae Veterinariae*, 35(2), 153-160
- Klocke, J.A., Darlington, M.V. & Balandrin, M.F. (1987). 1,8-Cineole (Eucalyptol), a mosquito feeding and ovipositional repellent from volatile oil of *Hemizonia fitchii* (Asteraceae). *Journal of Chemical Ecology*, 13, 2131-2141
- Knio, K.M., Usta, J., Dagher, S., Zournajian, H. & Kreydiyyeh, S. (2008). Larvicidal activity of essential oils extracted from commonly used herbs in Lebanon against the seaside mosquito, *Ochlerotatus caspius*. *Bioresource Technology*, 99(4), 763-768
- Lacey, L.A., Grzywacz, D., Shapiro-Ilan, D.I., Frutos, R., Brownbridge, M. & Goettel, M.S. (2015). Insect pathogens as biological control agents: Back to the future. *Journal of Invertebrate Pathology*, 132, 1-41.
- Li, M.X., Ma, Y.P., Zhang, H.X., Sun, H.Z., Su, H.H., Pei, S.J. & Du, Z.Z. (2021). Repellent, larvicidal and adulticidal activities of essential oil from Dai medicinal plant *Zingiber cassumunar* against *Aedes albopictus*. *Plant Diversity*, 43, 317-323.
- Lucia, A., Audino, P.G., Seccacini, E., Licastro, S., Zerba, E. & Masuh, H. (2007). Larvicidal effect of *Eucalyptus grandis* essential oil and turpentine and their major components on *Aedes aegypti* larvae. *Journal of American Mosquito Control Association*, 23(3), 299-303.
- Maguranyi, S.K., Webb, C.E., Mansfield, S. & Russell, R.C. (2009). Are commercially available essential oils from Australian native plants repellent to mosquitoes? *Journal of American Mosquito Control Association*, 25(3), 292-300
- Mahanta, S. & Khanikor, B. 2021. Mosquitocidal activity of twenty-eight plant essential oils and their binary mixtures against *Culex quinquefasciatus*, (Diptera: Culicidae). *Heliyon*, 7(2), e06128 (<https://doi.org/10.1016/j.heliyon.2021.e06128>)
- Maia, J.D., Corte, R.L., Martinez, J., Ubbink, J. & Prata, A.S. (2019). Improved activity of thyme essential oil (*Thymus vulgaris*) against *Aedes aegypti* larvae using a biodegradable controlled release system. *Industrial Crops and Products*, 136, 110-120,
- Maibach, H.I., Skinner, W.A., Strauss, W.G. & Khan, A.A. (1966) Factors that attract and repel mosquitoes in human skin. *JAMA*, 196, 263-266.
- Massebo, F., Tadesse, M., Bekele, T., Balkew, M. & Michael, T.G. (2009). Evaluation on larvicidal effects of essential oils of some local plants against *Anopheles arabiensis* Patton and *Aedes aegypti* Linnaeus (Diptera, Culicidae) in Ethiopia. *African Journal of Biotechnology*, 8 (17), 4183-4188
- Michaelakis, A., Theotokatos, S.A., Koliopoulos, G. & Chorianopoulos, N.G. (2007). Essential oils of *Satureja* species: Insecticidal effect on *Culex pipiens* larvae (Diptera: Culicidae). *Molecules*, 12, 2567-2578
- Misni, N., Sulaiman, S. & Othman, H. (2008). The repellent activity of *Piper aduncum* Linn (Family: Piperaceae) essential oil against *Aedes aegypti* using human volunteers. *Journal of Tropical Medicine and Parasitology*, 31, 63-69
- Misni, N., Sulaiman, S., Othman, H., Omar, B., (2009). Repellency of essential oil of *Piper aduncum* against *Aedes albopictus* in the labora-

- tory). Journal of the American Mosquito Control Association, 25(4), 442-447
- Mohammadreza, V. 2008. Essential oil composition and biological activity of *Ziziphora clinopodioides* Lam. from Iran. American-Eurasian Journal of Sustainable Agriculture, 2(1), 69-71
- Mondal, M. & Khalequzzaman, M. (2006). Toxicity of essential oils against red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Journal of Bio Science, 14, 43-48
- Monisha, D., Sivasankar, V., Prabhakaran, M. & Gabriel Paulraj, M. (2020). Mosquito larvicidal activity of *Enhalus acoroides* (L.f) Royle and *Halophila ovalis* (R. Br) Hook. f. against the deadly vectors *Aedes aegypti* and *Culex quinquefasciatus*. South African Journal of Botany, 133(1), DOI:10.1016/j.sajb.2020.06.021.
- Morais, S.M., Facundo, V.A., Bertini, L.M., Cavalcanti, B.E.S., Francisco, J.A., Ferreira, S.A. et al. (2007). Chemical composition and larvicidal activity of essential oils from *Piper* species. Biochemical Systematics and Ecology, 35, 670-675.
- Mossa, A.T.H. (2016). Green pesticides: Essential oils as biopesticides in insect-pest management. Journal of Environmental Science and Technology, 9(5), 354-378.
- Muirhead-Thomson, R.C. (1951). The distribution of anopheline mosquito bites among different age groups: A new factor in malaria epidemiology. BMJ, 1, 1114-1117.
- Nazar, S., Ravikumar, S., Williams, G.P., Ali, M.S. & Suganthi, P. (2009). Screening of Indian coastal plant extracts for larvicidal activity of *Culex quinquefasciatus*. Indian Journal of Science and Technology, 2(3), 24-27
- Nour, A.H., Elhussein, S.A., Osman, N.A., Nour, A.H. & Yusoff, M.M. (2009). A Study of the essential oils of four Sudanese accessions of basil (*Ocimum basilicum* L.) against *Anopheles* mosquito larvae. American Journal of Applied Sciences, 6 (7), 1359-1363.
- Odalo, J.O., Omolo, M.O., Malebo, H., Angira, J., Njeru, P.M., Ndiege, I.O. et al. (2005). Repellency of essential oils of some plants from the Kenyan coast against *Anopheles gambiae*. Acta Tropica, 95, 210-218.
- Omolo, M.O., Okinyo, D., Ndiege, I.O., Lwande, W. & Hassanali, A. (2004). Repellency of essential oils of some Kenyan plants against *Anopheles gambiae*. Phytochemistry, 65, 2797-802
- Oshaghi, M.A., Ghalandari, R., Vatandoost, H., Shayeghi, M., Kamali-nejad, M., Khaledi, H.T. et al. (2003). Repellent effect of extracts and essential oils of *Citrus limon* (Rutaceae) and *Melissa officinalis* (Labiatae) against main malaria vector, *Anopheles stephensi* (Diptera: Culicidae). Iranian Journal of Public Health, 32(4), 47-52.
- Oyedele, A.O., Gbolade, A.A., Sosan, M.B., Adewoyin, F.B., Soyelu, O.L. & Orafidiya, O.O. (2002). Formulation of an effective mosquito-repellent topical product from Lemongrass oil. Phytomedicine, 9(3), 259-262
- Pandey, V., Agrawal, V., Raghavendra, K. & Dash, A.P. (2007). Strong larvicidal activity of three species of *Spilanthes* (Akarkara) against malaria (*Anopheles stephensi* Liston, *Anopheles culicifacies*, species C) and filarial vector (*Culex quinquefasciatus* Say). Parasitology Research, 102, 171-174.
- Paulraj, M.G. & Ignacimuthu, S. (2007). Effect of some volatile oils on life stages and orientation behavior of *Lasioderma serricorne* (Fab.) (Coleoptera: Anobiidae). In S. Ignacimuthu and S. Jayaraj (Eds.), Biotechnology and Insect Pest Management (pp. 171-176), Elite Publishing House Pvt. Ltd..
- Pavunraj, M., Paulraj, M.G. & Ignacimuthu, S. (2007). Effect of plant volatile oils in protecting stored peanuts against *Tribolium castaneum* (Herbst.) (Coleoptera: Tenebrionidae) infestation. Insect Environment, 13(1), 3-4.
- Penfold, A.R. & Morrison, F.R. (1952). Some Australian essential oils in insecticides and repellents. Soap, Perfumery Cosmetics, 52, 933-934.
- Peterson, C. & Coats, J. (2001). Insect repellents – past, present and future. Pesticide Outlook, 154-158.
- Pitasawat, B., Champakaew, D., Choochote, W., Jitpakdi, A., Chaithong, U., Kanjanapothi, D. et al. (2007). Aromatic plant-derived essential oil: An alternative larvicide for mosquito control. Fitoterapia, 78(3), 205-210
- Qui, H., Jun, H.W. & McCall, J.W. (1998). Pharmacokinetics, formulation, and safety of insect repellent *N,N*-diethyl-3- methylbenzamide (DEET): A review. Journal of American Mosquito Control Association, 14, 12-27.
- Ranaweera, S. S. & Dayananda, K.R. (1996). Mosquito-larvicidal activity of some Sri-Lankan plants Journal of the National Science Council of Sri Lanka, 24 (2), 63-69.
- Robbins, P.J. & Cherniack, M.G. (1986). Review of biodistribution and toxicology of the insect repellent *N,N*-diethyl-*m*-toluamide (DEET). Journal of Toxicology and Environmental Health, 18, 503-525.
- Shaalan, E.A.S., Canyon, D., Younes, M.W.F, Wahab, H.A. & Mansour, A.H. (2005). A review of botanical phytochemicals with mosquitocidal potential. Environment International, 31, 1149-1166.
- Sivanandhan, S., Ganesan, P., David, R.H.A., Gabriel Paulraj, M. & Ignacimuthu, S. (2019). Mosquitocidal activity of the pale brittle stem mushroom *Psathyrella candolleana* (Agaricales) against three vector mosquitoes. International Journal of Medicinal Mushrooms, 21(7), 725-734.
- Sivanandhan, S., Ganesan, P., Stalin, A., Gabriel Paulraj, M., Rajan, S., Balakrishna, K. et al. (2021). Mosquitocidal effect of monoterpene ester and its acetyl derivative from *Blumea mollis* (D. Don) Merr against *Culex quinquefasciatus* (Diptera: Culicidae) and their *in silico* studies. Experimental Parasitology, 223, 108076 (<https://doi.org/10.1016/j.exppara.2021.108076>).
- Tawatsin, A., Wratten, S.D., Scott, R.R., Thavara, U. & Techadamrongsin, Y. (2001). Repellency of volatile oils from plants against three mosquito vectors. Journal of vector ecology, 26(1), 76-82.
- Thangam, T.S. & Kathiresan, K. (1994) Studies on mosquito larvicidal activity of *Rhizophora apiculata*. International Journal of Pharmacognosy, 32(1), 33-36.

- Tiwary, M., Naik, S.N., Tewary, D.K., Mittal, P.K. & Yadav, S. (2007). Chemical composition and larvicidal activities of the essential oil of *Zanthoxylum armatum* DC (Rutaceae) against three mosquito vectors. *Journal of Vector Borne Diseases* 44, 198–204.
- Traboulsi, A.F., Taoubi, K., El-Haj, S., Bessiere, J.M. & Rammal, S. (2002). Insecticidal properties of essential plant oils against the mosquito *Culex pipiens molestus* (Diptera: Culicidae). *Pest Management Science*, 58, 491–5.
- Traboulsi, A. F., El-Haj, S., Tueni, M., Taoubi, K., Nader, N. A. & Mrad, A. (2005). Repellency and toxicity of aromatic plant extracts against the mosquito *Culex pipiens molestus* (Diptera: Culicidae). *Pest Management Science*, 61, 597-604.
- Trigg, J.K. (1996). Evaluation of *Eucalyptus*-based repellent against *Anopheles* spp. in Tanzania. *Journal of American Mosquito Control Association*, 12, 243–246.
- Tripathi, A.K., Prajapati, V., Ahmad, A., Aggarwal, K.K. & Khanuja, S.P.S. (2004). Piperitenone oxide as toxic, repellent, and reproduction retardant toward malarial vector *Anopheles stephensi* (Diptera: Anophelinae). *Journal of Medical Entomology*, 41(4), 691–698.
- Tyagi, B.K., Munirathinam, A. & Venkatesh, A. (2015). A catalogue of Indian mosquitoes. *International Journal of Mosquito Research*, 2(2), 50-97
- Walker, T.W., Robbert, L.L., Copeland, R.A., Githeko, A.K., Wirtz, R.A., Githure, J.I. et al. (1996). Field evaluation of arthropod repellents, DEET and a piperidine compound, A13- 37220, against *Anopheles funestus* and *Anopheles arabiensis* in West Kenya. *Journal of American Mosquito Control Association*, 12, 172–176.
- Wood, A. (2003). Compendium of pesticide common names: Insecticides. (<http://www.alanwood.net/pesticides/index.htm>).
- Xu, Y., Qin, J., Wang, P., Li, Q., Yu, S., Zhang, Y. & Wang, Y. (2020). Chemical composition and larvicidal activities of essential oil of *Cinnamomum camphora* (L.) leaf against *Anopheles stephensi*. *Journal of the Brazilian Society of Tropical Medicine*, Vol.:53:e20190211: doi: 10.1590/0037-8682-0211-2019

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