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Essential Oils from Plants: A Review on Eco-Friendly Mosquito Repellents

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Abstract- Essential oils from medicinal plants are widely used all over the world as insect repellents as they are highly safe and beneficial to environment with least ill-effects on animal and public health. Electronic databases including Science direct, PubMed, Scopus, Cochrane library and Scifinder were searched for papers on essential oils from plants with mosquito repellent efficacy. Ethnobotany, phytochemistry and repellent efficacy of plant essential oils were also discussed in this review. This review discusses in detail the mosquito-repellent plant essential oils which would be helpful in effective formulation of different essential oils for efficient control of mosquitoes, thus vector-borne diseases and for pharmacological studies, i.e., drug designing. This review would assist in finding studies on different mosquito-repellent plant essential oils at one stop, since it summarizes a large number of reports on essential oils.

***Keywords**:* Essential oil, mosquito repellent, *Aedes*, *Culex*, *Anopheles*, vector control

I. INTRODUCTION

Mosquitoes are a group of insects which do not cause diseases but act as vectors i.e. transmit a number of pathogens from infected ones to another, causing infectious diseases in human and animal populations. In 1996, WHO declared mosquitoes as Public Enemy Number one [1]. Insect-borne diseases particularly from mosquitoes have a great impact on public health, labour output and economic loss mainly in temperate regions [2] Totally 3500 mosquito species have been recorded all over the world. Among them, more than 100 species of mosquito are acting as vectors for many diseases [3, 4]. Mosqutioes transmit all the mosquito-borne diseases through biting their hosts. Mosquito bites cause allergic reactions including local skin irritation and systemic response, such as urticaria and angioedema. Because of environmental alteration and increasing globalization, the population of temperate regions which is easily infected with parasitic diseases has an increased risk of vulnerability to insect-borne illnesses [5,6]. *Anopheles, Culex* and *Aedes* species are the major vectors, which transmit most-prominent mosquito-borne diseases such as Japanese encephalitis, lymphatic filariasis, dengue, malaria, dengue haemorrhagic fever, yellow fever, Zika, West Nile fever, and chikungunya [7, 8].

The review article provides a detailed data on the efficient, plant based mosquito-repellnt essential oils, their names, parts used, percentage of efficacy against different mosquito species at specific concentrations, components of plant essential oils, etc. The review article discusses at a greator length details related to essential oil as repellents, components of essential oil, methodology of repellent assays, synthetic repellents and their adverse effects, experimental procedure for field condition, molecular aspects and future prospects and directions.

Aedes-*Aedes* is the vector for dengue and is widely distributed in tropical and subtropical areas, where it causes serious havoc in the human population. In 1970, the number of dengue-infected cases slightly increased to a higher level. More than 30% of the world population was affected and more than 50% was estimated to be at a risk of dengue transmission [9]. Dengue fever is endemic to the Southeast Asia, India, Bangladesh and Pakistan [10]. In 2005, a serious outbreak of chikungunya virus infection occurred in southwest Indian Ocean coastal region, and as a result more than 1.5 million patients were infected by chikungunya virus in India [11].

Culex- *Culex* is one of the main dreadful pantropical insect urban vectors in tropical and subtropical regions, which is responsible for transmitting a nematode worm *Wuchereria bancrofti* that causes *lymphatic filariasis* [12]. *Culex* is the most abundant house mosquito in towns and cities of temperate areas that spreads *lymphatic filariasis* in millions of people all over the world. 856 million people in 52 countries worldwide were threatened by lymphatic filariasis (http://www.who.int/mediacentre/factsheets/fs102/en/). 128 million people over 78 countries were infected with lymphatic filariasis, 25 million people around the world were infected with microfilaria, and 19 million people around the world were infected with filarial disease symptoms [13, 14]. *Japanese encephalitis virus* (JEV) is transmitted by *Culex* mosquitos. JEV is in the family of Flaviviridae and is the primary pathogen of viral encephalitis in Asia. Its infection rate varies according to the population and age with the death rates of 0.3–60%. Rare outbreaks of JEV in the territories of the US have occurred. In the previous years, JEV was effectively controlled primarily by vaccination. The countries mostly affected are China, Korea, Japan, Taiwan and Thailand. However, some other countries including Vietnam, Cambodia, Myanmar, India, Nepal and Malaysia still have periodic epidemics.

The adult *Culex* spp. are nocturnal mosquito, with highest activities after 1 h of darkness. They are mainly exophilic and regularly stay in indoors after feeding on blood. *Cx. tritaeniorhynchus* acts as a vector of filariasis [15,16]. It's biting causes sensitive reactions including skin irritation and universal reactions, like urticarial and angioedema. Temperate zones are more susceptible to parasitic diseases, and the risk of contracting insect-borne illnesses has increased due to environmental alteration and increasing globalization [5,6]

Anopheles- *Anopheles* is the primary vector of malaria. Totally 400 species of *Anopheline* have been identified, among which over 70 species are reported as actual vectors of human diseases. *Anopheles stephensi* is responsible for transmission of malaria in urban regions. Currently about 40% of the world population is endemic to malaria manifestation with about 300–500 million clinical cases of malaria and a death rate of 1.1–2.7 million. Malaria is still one of the most important communicable diseases in the world. Of the world population, 85.7% is exposed to the risk of malaria. 300 deaths were reported in malaria-attributable mortality as per reports [17,18,19,20]. No effective vaccine is available for malaria control, so the only efficient approach to control the incidence of this disease is to eradicate *Anopheles* mosquito vectors [21].

Life cycle of mosquitoes

The mosquito life cycle comprises two main stages: aquatic and terrestrial. Aquatic stage includes egg, larvae and pupae; terrestrial stage includes the adult. The entire life cycle, from an egg to an adult, takes approximately 8–10 days. Usually mosquitoes lay eggs in raft or single which may vary according to different mosquito species. Generally, a single female lays 200–300 eggs at a time. Mostly eggs are laid in the standing water, water with regular flood and dirty water. Most of the eggs hatch within 24–48 h into larvae that feed on microscopic organisms such as planktons and organic matter in the water. Young larvae undergo four instar stages, and at each of these stages they shed their skins and finally develop into pupae (http://www.mosquitoworld.net/about-mosquitoes/life-cycle/).

Mosquitos take 4–5 days to develop from larvae into pupae. Pupae are also called as tumblers which are comma shaped, enclosed in cocoons and they do not feed. In 2–4 days, the adult mosquitos emerge out from pupae (http://www.mosquitoworld.net/about-mosquitoes/life-cycle/) which rest on the water and wait to get their bodies dry out. Males take two complete days to develop their reproductive organs, and then seek out a female for mating by the sound of her wing beats. Usually males live upto 3–5 days by feeding on fruit and plant nectar. After mating, females continue laying eggs after every blood meal. Normal female mosquito can live up to 2 months under the best climatic condition (https://www.cdc.gov/dengue/resources/factSheets/MosquitoLifecycleFINAL.pdf).

Mosquito control by using synthetic insecticides

Currently, mosquito-borne diseases are a major threat all over the world, and the synthetic insecticides are playing a major role in controlling mosquito populations. Mosquito control plays a major role in controlling the mosquito-borne diseases. Mosquito control mainly relies on the synthetic insecticides, such as pyrethroids, organophosphates, organochlorines and carbamates. Temephos is one of the most commonly used synthetic insecticide, which is used against the larval stages of mosquitoes [22]. For efficiency, large quantities of these synthetic insecticides are applied in the field, which results in ecological problem, such as damage to the beneficial organisms and resistance development in insects against these chemical insecticides [23,24,25,26,27,28]. Therefore, insecticides from plant sources are efficient alternatives to such synthetic insecticides. Azadirachtin, a limonoid which acts as an insect feeding deterrent, mosquito larvicide, repellent and growth regulator is one example [29,30,31,32,33].

Mosquito repellents- Repelling mosquitoes from their biting is one of the measures to control the transmission of the infectious diseases that are transmitted through the biting of infected mosquitoes. Repellents are substances which act locally or from a distance, in deterring an insect from flying to, landing on or biting human or animal skin [34,35]. As an approach to prevent mosquito bites for individual protection, the using of repellents is generally accepted as it plays an important role in preventing insect-borne diseases by reducing man–mosquito contact. Prevention of mosquito bites is possible through the application of repellents or physical barriers such as bed nets. Protection of humans and animals from biting of mosquitoes has been already accepted as part of an overall integrated insect-borne disease control program [36,37,38,34,35,39]. A variety of substances, including smoke, plant extracts, oils, tars and mud have been used over the centuries to repel mosquitoes [40].

Synthetic Repellents and Their Adverse Effects

Synthetic repellents are efficient in protecting people from blood-feeding insects such as ticks, mites and other arthropods thereby reducing transmission of arthropod-borne diseases. N,N-Diethyl-3-methylbenzamide (DEET) is one of the most well-known synthetic insect repellents and has been used as a repellent against mosquito for more than half a century [40.35,41]. Several studies have been documented on long-lasting protection of DEET against a wide variety of insect vectors. Currently, DEET is the most successful and accessible synthetic repellent in various commercial formulations such as solutions, lotions, gels, creams, aerosols, sticks and impregnated towelettes[42,43,44,45,46]. Furthermore, picaridin (2-(2-hydroxyethyl)-1-piperidinecarboxylic acid 1-methylpropyl ester) is shown to be effective at providing protection against biting mosquitoes [47,48]. Synthetic chemicals such as diethyl toluamide, dimethyl phthalate, chlorpyrifos, dichlorvos, cypermethrin and ethohexadiol are also used as repellents against mosquito biting [49,50]. The efficacy of protection by using synthetic repellents relies on the preparation of formulation, application pattern, species and feeding behavior of the insects [47].

DEET is commonly safe for topical use if applied as recommended; however, some studies report adverse effects or toxicity to man, unsafe for children since it possibly causes encephalopathy and affects immune systems, when used incorrectly or in the extended term [47, ,34,35,51,46]. The environment and people’s health are vulnerable to DEET and its related compounds [52]. DEET is not readily degradable by hydrolysis at environmental pHs and thus a ubiquitous pollutant of aquatic ecosystems. DEET has adverse effects such as irritation in skin and mucous membranes, serious neurologic effects, and is toxic to central nervous system of different age groups, specifically unsafe for children [43,44,45,46]. Undesirable features of DEET are unpleasant odor, uncomfortable oily or sticky feeling, and danger to plastics and synthetic rubber [53,52,47,2]. To avoid these inconveniences, repellents derived from plant sources are promising — which are effective, safe to users and inexpensive — to replace DEET [54].

Essential oil as repellents

Repelling mosquitoes from biting by using natural materials is advantageous since they do not harm the human and other beneficial organisms. On the contrary, synthetic repellents are reported to be harmful, since they cause several side effects to humans and beneficial organisms. Essential oils from aromatic plants are reported as potential repellents against mosquito vectors. Generally essential oils are used in manufacturing fragrances, and as flavoring agents for foods and beverages. Plant volatiles act as multiple and novel target sites to reduce the insecticide resistance of mosquitoes and also act as fumigants, contact insecticides, repellents, and antifeedants. They can adversely affect the growth rate and reproduction behaviour of mosquitoes, and have a longer duration of repellence than the synthetic chemicals.

Volatile oils extracted from plants and their major components like monoterpenes and sesquiterpenes are alternative sources for controlling mosquitoes at their immature stages and giving protection from biting of adult mosquitoes. Plant volatile oils, commonly used as fragrances and flavoring agents for foods and beverages, were recommended as an alternative source constituting numerous bioactive phytochemicals that could be potentially used for insect control [55]. Essential oils from plants act on multiple and novel target sites to reduce the development of resistance in mosquitoes. Because these oils are eluted from natural source, they are quite safe and beneficial to environment with least impact on animal and public health. Essential oils are applied to humans in a similar way to other conservative insecticides and they tend to be selective and have a little or no harmful effects [56,57,30,58,59,60].

Collection of Essential oil from Plants

The plant parts are crushed to release the volatiles. The solid-phase micro-extraction is used to extract volatile oils from the plants. Both dried and fresh plant parts underwent steam distillation by using Clevenger apparatus and then get placed in an extraction column connected to a round-bottomed distillation flask containing distilled water with approximately five times as much water and 10 glass beads. The flask is heated to about 100°C and allowed to boil until distillation is completed. The liquid-formed oil is collected with the help of a separating funnel. The collected mixture (distilled water and oil) is allowed to settle for 1 day. Separate layers of water and essential oil are formed and the water (lower) layer is slowly drawn out and removed to get the essential oil. The isolated oil is dried over anhydrous sodium sulfate and then collected and kept in an amber-colored bottle at 4°C until it is tested for mosquito repellency. This process is repeated until at least 20 ml of oil has been recovered. For repellency estimation, each oil and DEET are prepared in two formulations: 25% (v/v) in absolute ethanol with and without 5% vanillin [61,62,63,64,65,66,67,68].

Repellent Assay Method

Repellent efficiency of essential oil and its formulation added with 5% vanillin is evaluated against different mosquito species by using the human bait method, a previously recommended method [69,70,71,72,73]. For repellent assays, mosquito colonies are reared under laboratory condition. The adult mosquito is maintained at 25±2°C and 80±10% relative humidity (RH) under a photoperiod of 14:10 h (light/dark) by using slightly modified procedures described by Limsuwan et al. (1987). Mostly 5- to 7-days-old females are starved out and used for experimental studies. DEET (25% solution in ethanol with and without vanillin) is used to compare the repellency of essential oil isolated from plants. For repellency, experiments are carried out in 10 m×10 m ×3 m room at 27–35°C and 60–80% RH — day biting mosquito experiment in daytime; night-biting mosquito experiment in night time. *Aedes aegypti* is tested from 08:00 to 16:00 h, while *An. stephensi* and *Culex quinquefasciatus* are tested between 16:00 and 24:00 h [74].

Totally 200–300 non-blood-starved female mosquitoes are selected at random and placed in an experimental cage (30 cm ×30 cm ×30 cm) and left to acclimatize for 1 h. Human volunteers wear a plastic glove with a 3 cm ×10 cm window on the ventral part of the forearm, after cleaning with distilled water. Treated area of the skin is exposed to the mosquitoes. The essential oils are applied at 1.0, 2.5 and 5.0 mg/cm^2 separately in the exposed 30 cm^2 marked area of a forearm [75]. The right forearm of each volunteer is allowed to dry for 1 min at room temperature. For control, the left forearm is treated with an equivalent volume of 5% vanillin in ethanol solution. The left arm is put into the cage and kept for 3 min; at least two mosquitoes must land on the test area. The arm is shaken off before the mosquito imbibes any blood and withdrawn from the cage.
Consequently, the right arm is introduced into the cage for the same period and the number of mosquitoes landing on and attempting to feed is noted down. If no mosquito bite is evident during the 3-min exposure, the arm is withdrawn from the cage. The control and test arms are interchanged regularly. Arm exposure is continued at 15 min intervals. Tests for the determination of duration of protection are conducted according to the previously described methods [76,77,78]. Each sample is tested five times with different volunteers. One volunteer is used for one sample per day. Each person is assigned randomly and the volunteers are blinded to the repellent applied. No information is provided to the volunteers on the likely duration of action of each repellent [79,66,80,2]. Percentage and average protection time are calculated according to standard procedures described by Ansari and Razdan [81].

$$\%\text{Repellency} = \frac{\text{Ta} - \text{Tb}}{\text{Ta}} \times 100\%$$

where Ta is the number of mosquitoes in the control group and Tb is the number of mosquitoes in the treated group.

Kunming Mice Used for Repellent Experiment

Kunming mice are placed in the container supinely with their abdomens cleaned and depilated. Hairless area of the mice is 2 cm × 2 cm and for 2 min the mouse is put into a mosquito cage 0 cm ×30 cm ×30 cm containing 200–300 non-fed females. It is observed whether the number of mosquitoes that bite the mouse is more than 20. Essential oils are tested at different concentrations 1–15%. Prepared oil is (5 $\mu l/cm^2$) smeared on the exposed part of the mouse abdomen and allowed to dry. Mouse is put in the mosquito cage for 2 min and removed, and this is repeated at an interval of 1 h for 7 h. Finally the total number of blood-fed females is noted down. Triplicate is used for each sample. The percentage of repellency is calculated using the following formula [82].

Percentage of protection (100%) = [(Control – Treated) /Control] ×100

For control, ethanol is smeared on the abdomen and the number of bites are compared with that of treated mouse. The data are analyzed using repeated measures of analysis of variance (ANOVA) and completed by Statistical Analysis Systems (Version 8.2).

Experimental Procedure for Field Condition

For the next stage of field repellent experiment, the formulation is tested against mosquitoes. Different volunteers with one control for each concentration are used in the tests. In every experiment, 2 ml aliquots of repellent materials are applied evenly between the knee and ankle of all volunteer's leg and tested. The experiment is conducted in triplicate on each subject during the study. For reference control, 5% vanillin in ethanol solution is applied in a similar manner. Volunteer's untreated areas are protected from mosquito bites by wearing head-net, gloves, socks, jacket, and long trousers folded up to the knee. Avoid applying any other cosmetic materials. The volunteers are made to sit in a row, at least 20 m apart from each other. Test and control subjects sitting 5 m apart from each other are exposed with both legs for 120 min with an observation of mosquito bite for every10-min period so that 12 biting collections are made on each volunteer. The mosquitoes are collected before imbibing any blood and stored in plastic cups, which are changed at every collecting site and stored in a moisture box until the processing of specimens. For every 10-min period the volunteers are moved to a new site. The collected mosquitoes are identified with stereomicroscope by using the taxonomic keys described by Tanaka [83] and Rattanarithikul and Panthusiri [84]. Percentage of repellency is calculated using exposure period and biting rate of the mosquitoes compared with the control. The volunteers' positions are changed at night to avoid the bias from any variations in host-seeking ability of mosquitoes.

Repellency Test in Large Room

The repellency tests are conducted in a 6 m × 6 m × 3 m room. The room has fluorescent lamps, door and six glass-windows that are always closed during the tests. 10 min before, 200–300 non-blood-fed females are released into the room. Three different volunteers are used for both control and tests. 3 ml of oil is applied on the area of the assessment — volunteer's leg, from knee to ankle; one leg is used for test and the other serves as control, and the covering surface area is about 782–826 cm^2. After application, volunteers go inside the room and sit on the chairs in a triangle position with 1.5 m space from each other. For repellency evaluation, the landed mosquitoes are collected. In each repellent test of 6 h, volunteers are allowed every 10 min for every half-an-hour interval and mosquito bites are observed. The position of volunteers is changed to allow for any variation. At each break, all mosquitoes are collected and released back into the room to maintain their number. Different days and time are used to test different mosquito species. Every test is carried out for 6 h and the timing of the test depends on the target mosquitoes: 10:00–16:00 h for *Ae. aegypti* and 18:00–24:00 h for *Anopheles* and *Culex* [85].

II. ESSENTIAL OIL AS MOSQUITO REPELLENTS

Plant essential oils are reported to be lipophilic in nature and they interfere with metabolic, biochemical, physiological, morphological and behavioral functions of insects [202]. Essential oils showing repellent properties and containing toxic effects against mosquitoes act as fumigants, contact insecticides, repellents and antifeedants or they can adversely affect the growth rate and reproduction, and have longer duration of repellence than synthetic chemicals on behavior of insect pests [86,63,87,88,89,90,91,92,93,94,60,95,96,97,98,99].

Synergistic effect between different components of the volatile oils may result in a higher bioactivity and increased repellent response. Components in combination present good repellency compared with when it is a single compound. Therefore, the essential oil containing specific main compounds may be an indication of its prospective use but does not warrant on proof of activity. Composition of essential oil may vary significantly among different aromatic plant species and between the same varieties from different ecological areas [100,101].

Volatile oils extracted from *Juniperus* and *Cupressus* genera of the family Cupressaceae were reported for their repellent activities against mosquitoes *Culex pipiens*, *Cx. quinquefasciatus*, *Ae. aegypti*, and *An. stephensi* [102,103,104,86,105,106,107,108,109]. Some repellent formulations such as citronella, camphor, tar, pennyroyal and castor oils provided a long-lasting protection from insect bites [110,111]. Some of the essential oils from Australian plants *Dacrydium franklinii* Hook f., *Backhousia myrtifolia* Hook. & Harv., *Melaleuca bracteate* F. Muell., and *Zieria smithii* Jacks. presented repellent activity against mosquitoes and other insects. [112] Barnard found thyme (*Thymus vulgaris* L.) and clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry) oils applied at different concentrations (5%, 10%, 25%, 50%, 75%, and 100%) effectively repelled against two mosquito species — *Ae. aegypti* and *Anopheles albimanus*.

Penfold and Morrison [113] prepared a mixture of essential oils from *Litsea elliptica* Blume, *Cinnamomum mollissimum* Hook.f., *Cymbopogon nardus* (L.) Rendle and *Pogostemon cablin* (Blanco) Benth. and tested its repellent efficacy against *Ae. aegypti*. They prepared a cream containing 15% leaf oil of *L. elliptica* Blume, *C. mollissimum* Hook.f., and *C. nardus* (L.) Rendle in the ratio of 1:1:1 that repelled mosquito at 96.6% during the experiment. Peppermint oil from *Mentha piperita* L. presented a strong repellent activity against *Anopheles annularis*, *Anopheles culicifacies*, and *Cx. quinquefasciatus* at 100%, 92.3% and 84.5%, respectively [114]. Volatile oils from turmeric (*Curcuma longa* L.), hairy basil (*Ocimum basilicum* L.) and citronella (*Cymbopogon citratus* (DC.) Stapf) acted as contemporary repellents against both day- and night-biting mosquitoes [85] At a maximum of 8 h, 100% repellency against mosquitoes was observed for the essential oils of litsea (*Litsea cubeba* (Lour.) Pers.), cajeput (*Melaleuca leucadendra* (L.) L.), niaouli (*Melaleuca quinquenervia* (Cav.) S.T.Blake), violet (*Viola odorata* L.) and catnip (*Nepeta cataria* L.) [86]. Sissoo oil from *Dalbergia sissoo* Roxb. (F. Leguminosae) showed 91.6% repellency against *An. stephensi*, *Ae. aegypti* and *Cx. quinquefasciatus* [114].

15 essential oils from plants were tested for their repellency against mosquitoes. Among them, thyme (*T. vulgaris* L.) and clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry) oil exhibited most strong repellency against tested mosquitoes and these were potent alternatives to DEET [102, 81,115]. The protection time was increased significantly by the addition of 10% vanillin with *Zanthoxylum piperitum* Benn. oil ($P<0.05$) [85,116,117,]. More than 400 species of aromatic plant species in Lamiaceae family have traditionally been used in developing countries for their insecticidal and repellent properties against several insect species [118,119,120,121,122,123]. In western Kenya, growing of *Hyptis suaveolens* (L.) Poit. plants, or placing of branches or whole plants in houses was one of the most effective methods to repel malaria vector *Anopheles gambiae*. This plant significantly repelled mosquitoes indoors at night [124,125,126].

Volatiles from *Cupressus funebris* Endl., *Juniperus communis* L. and *Juniperus chinensis* L. constantly repelled female *Ae. aegypti* mosquitoes from biting, at different concentrations [107,127]. Amer and Mehlhorn [105] isolated essential oils from *Juniperus virginiana* L. and *J. communis* L. and prepared a formulation in a 20% solution against *Ae. aegypti*, *An. stephensi* and *Cx. quinquefasciatus*, which provided 100% skin protection against *Cx. quinquefasciatus* but weaker repellency in *Ae. Aegypti* and *An. stephensi*. Moderate repellent activities were observed in essential oil of *Tagetes minuta* L. for tested mosquito [128].

Essential oil from *Eucalyptus* species was reported to be potential as mosquito repellents [124,129]. Essential oils from *Litsea elliptica* Blume, *C. mollissimum* Hook.f., *Cymbopogon nardus* (L.) Rendle, and *P. cablin* (Blanco) Benth. Were tested as they presented repellency against mosquito species [130]. Tawastin [131] isolated essential oil of 18 plants from 11 families and prepared a 10% solution in ethanol. The results showed that it repelled night-biting mosquitoes *An. dirus*, *Cx. quinquefasciatus* and *Ae. albopictus* (repellency 4.5–8 h). 100% repellent activity was reported from essential oil of *Zingiber officinale* Roscoe against *Cx. quinquefasciatus* at 120 min [132]. Essential oil of clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry), peppermint (*M. piperita* L.), citronella (*C. citratus* (DC.) Stapf), turmeric (*C. longa*), hairy basil (*O. basilicum* L.), eucalyptus (*Eucalyptus* spp.), lavender (*Lavandula officinalis* Chaix) and catmint (*N. cataria* L.) were found to be effective repellents against mosquitoes [102,85,133,104,134]. Longer protection was observed from essential oil of *Eucalyptus citriodora* Hook. against *Cx. quinquefasciatus* than *Ae. aegypti* [105]. Tawatsin et al., (2001) [85] reported that volatiles from *Ocimum americanum* L. and *Cymbopogon winterianus* Jowitt ex. Bor. exhibited 2.6-fold longer protection against *Cx. quinquefasciatus* than *Ae. aegypti* [48,134].

Promising repellent activity was observed in the essential oils collected from *Eucalyptus maculate* Hook. Citriodon [135] *Cymbopogon* spp. [81], *Pelargonium citrosum* [115], *M. piperita* L. [114], *Ocimum* spp. [74], *Zanthoxylum limonella* (Dennst.) Alston [136], *Conyza newii* Oliv. & Hiern, *Plectranthus marrubioides* Hochst. ex Benth., *Tetradenia riparia* (Hochst.) Codd, *Tarchonanthus camphoratus* L., *Lippia javanica* (Burm.f.) Spreng., *Lippia ukambensis* Vatke [90], *Ocimum* spp. [137,85,], *Cymbopogon* spp. [138,81], *Eucalyptus maculata* var. *citriodora [135]*, *Artemisia vulgaris* L. [13], 9*Lantana camara* L. [140,141,], *M. piperita* L. [114], *Vitex rotundifolia* L.F. *[142]*, *Curcuma* spp. [143], *C. newii* Oliv. & Hiern, *P. marrubioides* Hochst. ex Benth., *T. riparia* (Hochst.) Codd, *T. camphoratus* L., *L. javanica* (Burm.f.) Spreng, *Tagetes* spp. [144], *Ocimum* spp. [145], *[90]* against vector mosquitoes.

O. americanum L., *L. camara* L. and *L. ukambensis* Vatke were shown to emit sufficient quantities of volatiles to provide significant repellency against *An. gambiae* under semi-field conditions [124,146]. Volatile oils extracted from turmeric (*C. longa* L.), kaffir lime (*Citrus hystrix* DC), citronella grass (*C. winterianus* Jowitt ex Bor) and hairy basil (*O. americanum* L.) showed strong repellency against three mosquito vectors *Ae. aegypti*, *An. dirus* and *Cx. quinquefasciatus* [74]. Essential oil of *C. citratus* (DC.) Stapf (72 min), *Cymbopogon nardus* (L.) Rendle (60 min), *Syzygium aromaticum* (L.) Merr. & L.M.Perry (54 min), *O. basilicum* L. (30 min), *Chromolaena odorata* (L.) R.M.King & H.Rob. (8.4 min), *Camellia sinensis* (L.) Kuntze and *E. citriodora* Hook. (3 min) exhibited repellency against *Ae. aegypti*. *Thymus serpyllum* L. essential oil presented repellency against mosquito species: 56.7% efficacy to *Ae. aegypti*, 33.3% to *An. stephensi* and 100% to *Cx. quinquefasciatus* within 8 h [105]. *T. vulgaris* L. had good repellent activity statistically equal to DEET against *Aedes albopictus* and *Cx. pipiens pallens* only for the first 2 h and 1 h, respectively [147,148].

Protection against mosquito bites has been reported from the plant genus *Cymbopogon* spp. [81], *Pelargonium citrosum* [115], *L. camara* L. *[140]*, *Tagetes* spp. [144] (Perich et al., 1995) and *Ocimum* spp. [145]. The essential oil of *T. minuta* L. and *Vitex negundo* L. provided a repellency of 90% for 2 h and that of *V. negundo* L. provided 1–3 h protection against tested mosquitoes [149,150] (Tyagi et al., 1994; Hebbalkar et al., 1992). Volatile oil obtained from hairy basil *Ocimum* spp. exhibited repellency against *Ae. aegypti* for only 15 min but that of *Ocimum gratissimum* L., *O. basilicum* L., *Ocimum basillicum* L. fa. *Citratum* and *Ocimum tenuiflorum* L. exhibited for 135, 75, 75 and 105 min, respectively [137]. Essential oils of *Foeniculum vulgare* Mill., *Laurus nobilis* L., *C. citratus* (DC.) Stapf and *Eucalyptus* spp. gave protection against mosquito attacks for more than 50 min at a concentration of 3%. Oils of *Cymbopogon excavates* (Hochst.) Stapf ex Burtt Davy, *Cymbopogon martinii martinii*, *Z. limonella* (Dennst.) Alston, *Syzygium aromaticum* (L.) Merr. & L.M.Perry, *Cymbopogon nardus* (L.) Rendle and *P. cablin* (Blanco) Benth. Provided better protection against *Ae. aegypti*, *Cx. quinquefasciatus* and *An. dirus* [151,152,43,153,136]. Repellent efficacy of essential oils from various plants has been summarized in Table 1 with reference to literature.

From, previous reports we conclude that essential oils are effectively repel the mosquitoes from biting. Certain reports strongly exhibit and suggest that essential oil gave 100% repellency against mosquitoes. In future these essential oil can be used to produce various effective products and formulations to control mosquito population therefore controlling vector borne diseases.

III. COMPONENTS OF ESSENTIAL OIL

Composition of the essential oil is variable depending on strain, chemotype, and geographic origin [154,155,156,157,]. Monoterpenes such as α-pinene, limonene, terpinolene, citronellol, citronellal, camphor and thymol, which are common constituents in volatile oils, are described in the literature as presenting mosquito repellent activity [158,59,159,160,161]. β- Caryophyllene is the most cited as a strong repellent from sesquiterpenes against *Ae. aegypti* [59,104,162].

Volatiles from *Z. piperitum* Benn. has limonene (37.99%), with minor amounts of sabinene (13.30%) and β-myrcene (7.17%) — constituting almost 59% [62]. *H. suaveolens* (L.) Poit. oil constitutes sabinene (21.9%), β-caryophyllene (16.1%), terpinolene (9.6%) and 4-terpineol (7.3%). Globally, 52 constituents were identified, accounting for 99.1% of the whole essential oil. Monoterpene hydrocarbons were the most represented volatiles (55.2%), followed by sesquiterpene hydrocarbons (24.1%) and oxygenated monoterpenes (10.5%). In addition, smaller amounts of oxygenated sesquiterpenes (7.2%) and diterpenes (1.9%) were detected. Non-terpene derivatives were present in very small amounts (0.2%) [67]. Oil of *Cupressus arizonica* Greene leaf was characterized by α-pinene (17.1%), followed by *trans*-muurola-3,5-diene (15.5%), umbellulone (8.0%) and limonene (7.4 %). *Cupressus benthamii* Endl. foliage oil includes umbellulone (15.9%), limonene (13.0%), δ-3-carene (9.5%), α-pinene (9.1%), abietatriene (26%) and *trans*- ance of α-pinene (54.1%). δ-3-Carene was the second major component (10.8%) while all the other constituents were presenting lower amounts (<5.5%). The leaf oil of *Cupressus torulosa* D. Don has wtotarol (19.3%) and *Cupressus macrocarpa* Hartw. has sabinene (21.8%), α-pinene (19.5%), terpinen-4-ol (18.9%) and γ-terpinene (7.9%). *Cupressus sempervirens* L. is characterized by the abundant presence of α-pinene (27.9%), δ-3-carene (21.4%) and cedrol (12%), as well as α-pinene (25.8%), sabinene (22.3%) and terpinen-4-ol (9.3%). Aerial parts of *Chamaecyparis lawsoniana* (A.Murray bis) Parl. were terpinen-4-ol (22.0%), sabinene (21.0%), camphor (7.8%) and citronellol (7.3%). *Tamarix articulate* Vahl. was mainly characterized by α-pinene (26.4%) and bornyl acetate (25.3%) followed by camphor (9.5%) and limonene (8.7%) [65,163,164,165].

Juniperus phoenicea L. leaves contain a high amount of α-pinene (31.3%), followed by δ-3-carene (12.5%), β-phellandrene (13.0%) and α-terpinyl acetate (12.5%) as main constituents [166,167,168,169,170,171,109]. *T. minuta* L. and *Tagetes pusilla* Kunth essential oil is composed mainly of *cis*-anethole (75%) and estragole (24%). *Mendoncia mollis* Lindau essential oil has pulegone (51.2%), mentone (30.7%), and limonene (10.1%) (Gillijet al., 2008). Essential oil of *Rosmarinus officinalis* L. has camphor (34%), verbenone (25%) and (E)-caryophyllene (15%). Camphor in *R. officinalis* L. (33.6%) and in *Baccharis spartioides* (Hook. & Arn. ex DC.) J. Rémy in Gay (50.5%) may be responsible for repellent activity [172].

Limonene was the main component from the essential oil of *Aloysia citrodora* Palau, *Minthostachys mollis* (Benth.) Griseb. and *B. spartioides* (Hook. & Arn. ex DC.) J. Remy in Gay. Other common constituents of essential oil are α-pinene, carvacrol, citronellol, citronellal, camphor and thymol [63,173,59,160,174]. *Artemisia salsoloides* Willd. contains mostly p-cymene (75.1%) and thymol (18.7) [147,175]. Carvone was the major component of the EO of *Aloysia catamarcensis* Moldenke (98.7%), *Aphanamixis polystachya* (Wall.) R. Parker (12%), *Lippia junelliana* (Moldenke) Tronc. (2.2%), and *Lippia integrifolia* (Griseb.) Hieron. (3.1%) [90] (Omolo et al., 2004). *Tagetes filifolia* Lag. had (E)-anethole and methyl chavicol (estragole) as major compounds [66]. *Eupatorium buniifolium* and *Baccharis salicifolia* contained mostly α-pinene [173,140]. *H. suaveolens* (L.) Poit. volatile contained caryophyllene, bergamotene, terpinolene, humulene, sabinene, limonene, β-caryophyllene, sabinene, α-pinene, limonene, β-pinene, bergamotene, terpinolene, δ-elemene and β-phellandrene. *Rhododendron tomentosum* had *p*-cymene, terpinyl acetate, sabinene, α-pinene, bornyl acetate, β-pinene, β-phellandrene, camphene, *Z*-ocimene, γ-terpinene, 2-carene, limonene, linalool, *E*ocimene, terpinolene and myrcene. *Myrica gale* L. contains α-pinene, myrcene, limonene, α-phellandrene and 1, 8-cineole as the main compounds. *Achillea millefolium* L. has (−)-germacrene D, β-pinene, sabinene, α-pinene, 1,8-cineole, camphor, β-caryophyllene, *p*-cymene and δ-elemene [59].

Hemizygia oil contains mosquito-repellent compounds, which are (a) the simple terpenes: 3-pinene (1.5%), myrcene (0.1%) and (+)-limonene (1.2%); (b) the oxygenated terpenoids: cineole (1.3%), linalool (0.6%) and terpinen-4-ol (3.3%); and (c) traces of camphor (<0.05%) [140,176]. *Ocimum selloi* Benth oil has the major constituents of which were estragole (55.3%), isoestragole (or *trans*-anethole) (34.2%) and *cis*-anethole (3.9%) [177]. *Thymus leucospermus* Hartvig oil has p-cymene (64.2%), o-γ-terpinene (7.9%), thymol (4.8%) and borneol (4.7%). *Thymus teucrioides* subsp. *Candilicus* (Beauverd) Hartvig oil has p-cymene (25.5%), γ-terpinene (19.0%), thymol (18.8%), borneol (5.7%) and α-pinene (5.7%). *Origanum vulgare* L. has carvacrol, thymol, γ-terpinene and p-cymene, linalool, α-thujene, α-β-pinene or 1,8-cineole, and 1,8-cineole [178].

IV. FUTURE PROSPECTS

Essential oil from aromatic plants have repellent activity to protect humans from mosquito biting. These essential oils can be used to prepare effective formulations like cream, coil, oil evaporator and other products to repel the mosquitoes. Identification of the specific component present in the essential oil, which is responsible for the repellency, paves the way to prepare new effective formulations for mosquito control. An efficient mosquito repellent could be produced using multiple (synergistic) essential oils. It is the best alternative way to replace the synthetic repellents that cause adverse side effects.

V. FUTURE DIRECTIONS OF THE RESEARCH

In this review, we have mentioned the essential oils that are used as eco-friendly mosquito repellents, so this review should be helpful for a larger-scale research. Furthermore, the repellent activity of these essential oils against other anthropophagous insects should also be studied to establish their possible wider application in controlling human–vector contact. Most of the mosquitoes are sensitive when exposed to the essential oil; however, some essential oils act as repellents only against specific mosquitoes. In future, studies would focus on enhancing the repellent efficacy of any essential oil to all the mosquitoes. It may be useful to finding a potential insect repellent. Furthermore, experiments on repellency of essential oil should also simultaneously evaluate its economic aspects and efficacy under different field conditions. This review would refocus the attention of the research community towards the development and application of known plants rather than screen more plants and isolate novel bioactive molecules that are repellents against mosquitoes. Future investigations should aim at testing essential oils and their mode of action, toxicity of the various biologically active essential oils to the target mechanisms involved and their possible effect on non-target organisms. Repellency approaches of essential oil should be multipronged such as in making of fumigants, sprays, paints, varnishes, incense, candles, etc. In domestic settings, fumigation and spraying in outdoor settings, topical repellents, clothes made of repellent fabrics and repellent wristbands are among other available products for individual protection. Thus, expanded use of essential oils in the eco-friendly insect pest management sector could be of both economic and ecological benefits.

VI. MOLECULAR ASPECTS

The repellent-exposed mosquitoes undergo changes in their life stages. Repellents act on specific targets and ultimately upregulate or downregulate specific gene. Using molecular techniques specific genes can be identified for the biting, flying, and other specific action in the life cycle of mosquitoes [179,180,181,182,183,184,185,186,187,188]. Genetic-based technologies are used to identify functional genomes in the insect. One of the most advanced genetic-based technologies is genome editing. Genome editing uses method such as relies on zinc finger nuclease (ZFN), clustered regulatory interspaced short palindromic repeats (CRISPR), CRISPR-associated protein 9 (Cas9) and transcription activator-like effector nucleases (TALEN). These technologies enable the alteration of specific target genes in mosquitoes. Elimination of specific gene responsible for the biting character of mosquito by using these technologies is one of the measures in the mosquito control program [189,190].

VII. CONCLUSIONS

Rich flora of aromatic plants of wild in nature will certainly be helpful in producing eco-friendly and efficient insecticides to control vector mosquitoes and thus the spread of dreadful diseases. Several studies report that the plant based essential oils exhibit promising repellent activity as against mosquito vectors. Essential oils have also been found to disrupt the host-seeking behavior or disorient the host-seeking mosquito. A mixture of such efficient plant based essential oils in an appropriate ratio would further promise the development of efficacious products towards minimizing the vector born diseases.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

Author's contribution

Pathalam Ganesan, Magesh Daniel, Samuel Rajan and Savarimuthu Ignacimuthu conceived and designed the study. Pathalam Ganesan and Samuel Rajan wrote the manuscript. Micheal Gabriel Paulraj and Savarimuthu Ignacimuthu supervised the study and assisted with writing the manuscript and approved the final edition of the manuscript.

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Table 1 Repellent efficacy of essential oils from various plants with reference to literature

Plant species (Family)	Oil/Parts used/plant material	Test mosquitoes	Concentration used	Repellency		Control	Reference
				Time duration	% protection		
Citrus limon (L.) Osbeck (Rutaceae)	Lemon oil/Fruit	*An. stephensi*	1%		71.16	DEET	[192]
Melissa officinalis L. (Labiatae)	Melissa oil/leaf	*An. stephensi*	1%		60	DEET	[192]
Cymbopogon citratus (DC.) Stapf (Poaceae)	citronella oil	*Ae. albopictus*	15%	3h		DEET	[174]
Eucalyptus globulus Labill. (Myrtaceae)	eucalyptus oil	*Ae. albopictus*	15%	5h		DEET	[174]
Litsea elliptica Blume (Lauraceae)	leaf	*Ae. aegypti*	0.0379 mg cm2		100%	Dimethyl phthalate	[191]
Cinnamomum mollissimum Hook.f. (Lauraceae)	leaf	*Ae. aegypti*	0.0379 mg cm2		100%	Dimethyl phthalate	[191]
Cymbopogon nardus (L.) Rendle (Poaceae)	leaf	*Ae. aegypti*	0.0047 mg cm2		72.2%	Dimethyl phthalate	[191]
Pogostemon cablin (Blanco) Benth. (Lamiaceae)	leaf	*Ae. aegypti*	0.0047 mg cm2		71.4%	Dimethyl phthalate	[191]
Cymbopogon winterianus Jowitt ex Bor (Poaceae)	Citronella	*Ae. aegypti* *An. stephensi* *Cx.*	20%	120min 480min 480min	75.7% 52.4 100	DEET and Bayrepel	[86]

		quinquefasciatus					
Aniba rosaeodora Ducke (Lauraceae)	Rosewood	*Ae. aegypti* *An. Stephensi* *Cx. quinquefasciatus*	20%	80min 390min 480min	89. 4.8 85.7	DEET and Bayrepel	[86]
Lavandula angustifolia Mill. (Lamiaceae)	Lavender	*Ae. aegypti* *An. Stephensi* *Cx. quinquefasciatus*	20%	180min 480min 480min	24.5 80.9 85.7	DEET and Bayrepel	[86]
Cinnamomum camphora (L.) J.Presl (Lauraceae)	Camphor	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 480min 480min	32.4 42.8 57.1	DEET and Bayrepel	[86]
Nepeta cataria L. (Lamiaceae)	Catnip	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	480min 480min 480min	83.8 100 100	DEET and Bayrepel	[86]
Pelargonium graveolens L'Hér. (Geraniaceae)	Geranium	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 480min 480min	78.4 61.9 100	DEET and Bayrepel	[86]
Thymus serpyllum L. (Lamiaceae)	Thyme	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 450min 480min	56.7 33.3 100	DEET and Bayrepel	[86]
Eucalyptus globulus Labill. (Myrtaceae)	Eucalyptus	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	60min 330min 480min	56.7 28.6 100	DEET and Bayrepel	[86]
Jasminum grandiflorum L. (Oleaceae)	Jasmine	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	270min 480min 480min	13.5 100 100	DEET and Bayrepel	[86]
Eucalyptus dives Schauer (Myrtaceae)	Broad-leaved eucalyptus	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	210min 480min 480min	18.9 38.1 100	DEET and Bayrepel	[86]
Cymbopogon citratus (DC.) Stapf (Poaceae)	Lemongrass	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	180min 480min 480min	70.3 100 100	DEET and Bayrepel	[86]
Eucalyptus citriodora Hook. (Myrtaceae)	Lemon-scented eucalyptus	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 480min 480min	59.4 52.4 100	DEET and Bayrepel	[86]
Picea excelsa (Lam.) Link (Pinaceae)	Fichtennadel	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	120min 180min 480min	21.6 19 85.7	DEET and Bayrepel	[86]
Amyris balsamifera L. (Rutaceae)	Amyris	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	240min 480min 480min	29.7 100 100	DEET and Bayrepel	[86]
Citrus limon (L.) Osbeck (Rutaceae)	Lemon	*Ae. aegypti* *An. sephensi* *Cx. quinquefasciatus*	20%	90min 420min 480min	67.6 9.5 100	DEET and Bayrepel	[86]
Eucalyptus radiata A.Cunn. ex DC. (Myrtaceae)	Narrow-leaved eucalyptus	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 480min 480min	64.9 42.8 100	DEET and Bayrepel	[86]
Glycine soja (Fabaceae)	Carotin oil	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	180min 480min 480min	16.2 9.5 100	DEET and Bayrepel	[86]
Juniperus virginiana L. (Cupressaceae)	Cedarwood	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	180min 480min 480min	37.8 38.1 100	DEET and Bayrepel	[86]

Boswellia carteri (Burseraceae)	Frankincense	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	120min 300min 480min	75.7 19 100	DEET and Bayrepel	[86]
Anethum graveolens L. (Apiaceae)	Dill	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	90min 210min 180min	78.4 71.4 57.1	DEET and Bayrepel	[86]
Myrtus communis L. (Myrtaceae)	Myrtle	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 390min 480min	56.7 42.8 85.7	DEET and Bayrepel	[86]
Anthemis nobilis L. (Asteraceae)	Chamomile	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	240min 480min 480min	64.9 76.2 100	DEET and Bayrepel	[86]
Cinnamomum zeylanicum (Lauraceae)	Cinnamon	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	330min 480min 480min	70.3 100 100	DEET and Bayrepel	[86]
Juniperus communis L. (Cupressaceae)	Juniper	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	210min 480min 480min	43.2 76.2 100	DEET and Bayrepel	[86]
Salvia sclarea L. (Lamiaceae)	Sage	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	120min 300min 480min	45.9 19 100	DEET and Bayrepel	[86]
Mentha piperita L. (Lamiaceae)	Peppermint	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	120min 390min 480min	59.4 57.1 100	DEET and Bayrepel	[86]
Ocimum basilicum L. (Lamiaceae)	Basil	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	120min 210min 480min	81.1 66.7 100	DEET and Bayrepel	[86]
Melaleuca leucadendra (L.) L. (Lamiaceae)	Cajeput	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	360min 480min 480min	43.2 100 100	DEET and Bayrepel	[86]
Glycine max (L.) Merr. (Myrtaceae)	Soya bean	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	180min 480min 480min	54 76.2 100	DEET and Bayrepel	[86]
Rosmarinus officinalis L. (Lamiaceae)	Rosemary	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	330min 480min 480min	43.2 100 100	DEET and Bayrepel	[86]
Melaleuca quinquenervia (Cav.) S.T.Blake (Myrtaceae)	Niaouli	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	480min 480min 480min	75.7 100 100	DEET and Bayrepel	[86]
Olea europaea L. (Oleaceae)	Olive	*Ae. aegypti* *An. Stephensi* *Cx.quinquefasciatus*	20%	210min 480min 480min	67.6 71.4 71.4	DEET and Bayrepel	[86]
Piper nigrum L. (Piperaceae)	Black pepper	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	90min 180min 480min	64.9 61.9 100	DEET and Bayrepel	[86]
Lippia citriodora (Palau) Kunth (Verbenaceae)	Verbena	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 330min 480min	70.3 38.1 100	DEET and Bayrepel	[86]
Tagetes minuta L. (Asteraceae)	Tagetes	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	60min 480min 480min	83.8 100 100	DEET and Bayrepel	[86]
Viola odorata L.	Violet	*Ae. aegypti*	20%	360min	67.6	DEET and	[86]

(Violaceae)		*An. stephensi* *Cx. quinquefasciatus*		480min 480min	100 85.7	Bayrepel	
Santalum album L. (Santalaceae)	Sandalwood	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 480min 480min	59.4 100 100	DEET and Bayrepel	[86]
Litsea cubeba (Lour.) Pers. (Lauraceae)	Litsea	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	480min 480min 480min	73 100 100	DEET and Bayrepel	[86]
Helichrysum italicum (Roth) G.Don (Asteraceae)	Helichrysum	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	120min 360min 480min	43.2 47.6 100	DEET and Bayrepel	[86]
Ferula galbaniflua (Apiaceae)	Galbanum	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	150min 480min 480min	70.3 100 100	DEET and Bayrepel	[86]
Chamaemelum nobile (L.) All. (Asteraceae)	Chamomile	*Ae. aegypti* *An. stephensi* *Cx. quinquefasciatus*	20%	60 330 480	70.3 47.6 100	DEET and Bayrepel	[86]
Dalbergia sissoo DC. (Leguminosae)	wood scrapings	*An. culicifacies* *An. annularis* *An. subpictus* *Cx. quinquefasciatus*	1 ml	10h.3min 11h 8h 8h.1min	96.1 100 89.7 91.7	Negative control	[114]
Zanthoxylum piperitum Benn. (Rutaceae)		*Ae. aegypti*	0.1 ml	1h		Negative control	[62]
Anethum graveolens L. (Apiaceae)		*Ae. aegypti*	0.1 ml	0.5h		Negative control	[62]
Kaempferia galanga L. (Zingiberaceae)		*Ae. aegypti*	0.1 ml	0.25h		Negative control	[62]
Hyptis suaveolens (L.) Poit. (Lamiaceae)	Leaf	*A. albopictus*	0.0378µg/cm^2	16 to 135min		Negative control	[67]
Acantholippia seriphioides (A.Gray) Moldenke (Verbenaceae)		*Ae. aegypti*	90%	90min		Negative control	[63]
Achyrocline satureioides (Lam.) DC. (Asteraceae)		*Ae. aegypti*	90%	3h.33 min		Negative control	[63]
Aloysia citriodora Palau (Verbenaceae)		*Ae. aegypti*	90%	50min		Negative control	[63]
Anemia tomentosa (Savigny) Sw. (Anemiaceae)		*Ae. aegypti*	90%	60min		Negative control	[63]
Baccharis spartioides (Hook. & Arn. ex DC.) J.Rémy in Gay (Asteraceae)		*Ae. aegypti*	90%	90min		Negative control	[63]
Chenopodium ambrosioides (Amaranthaceae)		*Ae. aegypti*	90%	60min		Negative control	[63]
Eucalyptus saligna Sm. (Myrtaceae)		*Ae. aegypti*	90%	90min		Negative control	[63]
Hyptis mutabilis (Rich.) Briq. (Lamiaceae)		*Ae. aegypti*	90%	20min		Negative control	[63]
Minthostachys mollis (Benth.) Griseb. (Lamiaceae)		*Ae. aegypti*	90%	90min		Negative control	[63]
Rosmarinus officinalis L. (Lamiaceae)		*Ae. aegypti*	90%	90min		Negative control	[63]
Tagetes minuta L. (Asteraceae)		*Ae. aegypti*	90%	90min		Negative control	[63]
Tagetes pusilla Kunth (Asteraceae)		*Ae. aegypti*	90%	6h.7 min		Negative control	[63]
Acantholippia salsoloides Griseb. (Verbenaceae)		*Ae. aegypti*	0.48 ul per cm^2		significant	Negative control	[66]
Aloysia catamarcensis Moldenke (Verbenaceae)		*Ae. aegypti*	0.48 ul per cm^2		significant	Negative control	[66]
Aloysia polystachya (Griseb.) Moldenke (Verbenaceae)		*Ae. aegypti*	0.48 ul per cm^2		significant	Negative control	[66]
Lippia integrifolia (Griseb.) Hieron. (Verbenaceae)		*Ae. aegypti*	0.96µl/cm^2		100	Negative control	[66]
Lippia junelliana (Moldenke) Tronc.		*Ae. aegypti*	0.0075		76.88	Negative	[66]

(Verbenaceae)			0.015 0.96µl/cm^2		87.65 100	control	
Baccharis salicifolia (Asteraceae)		*Ae. aegypti*	0.48 ul per cm^2		significant	Negative control	[66]
Eupatorium buniifolium (Asteraceae)		*Ae. aegypti*	0.48 ul per cm^2		significant	Negative control	[66]
Tagetes filifolia Lag. (Asteraceae)		*Ae. aegypti*	0.96µl/cm^2		82.22	Negative control	[66]
Artemisia vulgaris L. (Anthemideae)	Whole plant	*Ae. aegypti*	0.4 mg/cm^2		91%	DEET and DMP	[139]
Myrica gale L. (Myricaceae)	leaf	*Ae. aegypti*	10 ml		82.1	DEET	[59]
Rhododendron tomentosum (Ericaceae)	leaf	*Ae. aegypti*	10 ml		83.5	DEET	[59]
Achillea millefolium L. (Asteraceae)	leaf	*Ae. aegypti*	10 ml		78.8	DEET	[59]
Zanthoxylum piperitum Benn. (Rutaceae)	Fruit	*Ae. aegypti*	0.1 ml/30 cm^2	1.5h		Negative control	[68]
Prostanthera melissifolia F.Muell. (Lamiaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Agonis fragrans J.R.Wheeler & N.G.Marchant (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Leptospermum petersonii F.M.Bailey (Myrtaceae)		*Ae. aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Eucalyptus citriodora Hook. (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Eucalyptus polybractea F.Muell. ex R.T.Baker (Myrtaceae)		*A.aegypti* *Cx. Quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Eucalyptus radiata A.Cunn. ex DC. (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Eucalyptus staigeriana F.Muell. ex F.M.Bailey (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Melaleuca alternifolia (Maiden & Betche) Cheel (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Melaleuca ericifolia Sm. (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Melaleuca quinquenervia (Cav.) S.T.Blake (Myrtaceae)		*A.aegypti* *Cx. quinquefasciatus* *Cx. annulirostris*	1ml/ 349.3 cm^2	10-35min 20-100min 25-110min		DEET	[193]
Santalum spicatum (Santalaceae)		*A.aegypti*	1ml/ 349.3	10-35min		DEET	[193]

		Cx. quinquefasciatus *Cx. annulirostris*	cm^2	20-100min 25-110min			
Croton pseudopulchellus Pax (Euphorbiaceae)	whole aerial parts	*An. gambiae*	0.5 ml		More repellent than the control under the experimental conditions	Negative control	[64]
Mkilua fragrans Verdc. (Annonaceae)	whole aerial parts	*An. gambiae*	0.5 ml		More repellent than the control under the experimental conditions	Negative control	[64]
Endostemum tereticaulis (Lamiaceae)	whole aerial parts	*An. gambiae*	0.5 ml		More repellent than the control under the experimental conditions	Negative control	[64]
Ocimum forskolei Benth. (Lamiaceae)	whole aerial parts	*An. gambiae*	0.5 ml		More repellent than the control under the experimental conditions	Negative control	[64]
Ocimum fischeri Gürke (Lamiaceae)	whole aerial parts	*An. gambiae*	0.5 ml		More repellent than the control under the experimental conditions	Negative control	[64]
Plectranthus longipes Baker (Labiateae)	whole aerial parts	*An. gambiae*	0.5 ml		More repellent than the control under the experimental conditions	Negative control	[64]
Conyza newii Oliv. & Hiern (Compositeae)		*An. gambiae*	10^{-1} mg cm^2		100	Negative control	[194]
Plectranthus marrubioides Hochst. ex Benth. (Labiateae)		*An. gambiae*	10^{-1} mg cm^2		100	Negative control	[194]
Lippia javanica (Burm.f.) Spreng. (Verbenaceae)		*An. gambiae*	10^{-1} mg cm^2		90.3	Negative control	[194]
Lippia ukambensis Vatke (Verbenaceae)		*An. gambiae*	10^{-1} mg cm^2		83.9	Negative control	[194]
Tetradenia riparia (Hochst.) Codd (Labiateae)		*An. gambiae*	10^{-1} mg cm^2		79.6	Negative control	[194]
Tarchonanthus camphoratus L. (Compositeae)		*An. gambiae*	10^{-1} mg cm^2		98.5	Negative control	[194]
Ocimum selloi Benth. (Lamiaceae)	leaf	*An. braziliensis*	10%	0-3h	75-100	DEET	[195]
Cymbopogon nardus (L.) Rendle (Poaceae)	Citronella grass	*Ae. aegypti*, *An. minimus* and *Cx. quinquefasciatus*		115min 130min 140min		Negative control	[196]
Citrus sinensis (L.) Osbeck (Rutaceae)	Orange oil	*Ae. aegypti*, *An. minimus* and *Cx. quinquefasciatus*		30min 50min 60min		Negative control	[196]
Eucalyptus citriodora Hook.	Eucalyptus	*Ae. aegypti*,		30min		Negative	[196]

(Myrtaceae)		*An. minimus* and *Cx. quinquefasciatus*		60min 80min		control	
Syzygium aromaticum (L.) Merr. & L.M.Perry (Myrtaceae)	Clove	*Ae. aegypti,* *An. minimus* and *Cx. quinquefasciatus*		80min 120min 90min		Negative control	[196]
Cananga odorata (Lam.) Hook.f. & Thomson (Annonaceae)	ylangylang flowers	*Ae.aegypti* *An.dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		66 92 90	Negative control	[197]
Citrus sinensis (L.) Osbeck (Rutaceae)	Orange fruits	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		48 84 88	Negative control	[197]
Cymbopogon citratus (DC.) Stapf (Poaceae)	Lemon grass leaves and stems	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		100 98 98	Negative control	[197]
Cymbopogon nardus (L.) Rendle (Poaceae)	Citronella grass leaves	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		88 98 94	Negative control	[197]
Eucalyptus citriodora Hook. (Myrtaceae)	Eucalyptus leaves	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		36 86 86	Negative control	[197]
Ocimum basilicum L. (Lamiaceae)	Sweet basil leaves	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		84 96 90	Negative control	[197]
Syzygium aromaticum (L.) Merr. & L.M.Perry (Myrtaceae)	Clove flowers	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.21 mg/cm^2		96 98 92	Negative control	[197]
Cinnamomum zeylanicum (Lauraceae)	Bark	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	53.9 mg/mat 49.6 mg/mat 44.2 mg/mat		95 95 95	Negative control	[103]
Cuminum cyminum L. (Apiaceae)	Seed	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	49.1 mg/mat 44.7 mg/mat 39.9 mg/mat		95 95 95	Negative control	[103]
Curcuma longa L. (Zingiberaceae)	Rhizome	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	110.5 mg/mat 93.7 mg/mat 127.0 mg/mat		95 95 95	Negative control	[103]
Ocimum basilicum L. (Lamiaceae)	leaf	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	82.4 mg/mat 75.0 mg/mat 115.3 mg/mat		95 95 95	Negative control	[103]
Rosmarinus officinalis L. (Lamiaceae)	Shoot	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	57.9 mg/mat 38.9 mg/mat 68.6 mg/mat		95 95 95	Negative control	[103]
Pimpinella anisum L. (Apiaceae)	Seed	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	172.0 mg/mat 154.1 mg/mat 203.4 mg/mat		95 95 95	Negative control	[103])
Zingiber officinale Roscoe (Zingiberaceae)	Rhizome	*Ae. aegypti* *An. stephensi* *Cx quinquefasciatus*	mg/mat mg/mat mg/mat		95 95 95	Negative control	[103]

Cymbopogon citratus (DC.) Stapf (Poaceae)	Lemongrass	*Cx quinquefasciatus*	5.0 mg/cm^2	5h	74.03	Negative control	[201]
Zingiber officinale Roscoe (Zingiberaceae)	Rhizome	*Cx quinquefasciatus*	4.0 mg/cm^2	120min	100	Negative control	[132]
Centella asiatica (L.) Urb. (Apiaceae)	Leaf	*An. stephensi*	6%	140min		Negative control	[197]
Ipomoea cairica (L.) Sweet (Convolvulaceae)	Leaf	*An. stephensi*	6%	332min		Negative control	[197]
Momordica charantia L. (Cucurbitaceae)	Leaf	*An. stephensi*	6%	323min		Negative control	[197]
Psidium guajava L. (Myrtaceae)	Leaf	*An. stephensi*	6%	119min		Negative control	[197]
Tridax procumbens (L.) L. (Asteraceae)	Leaf	*An. stephensi*	6%	317min		Negative control	[197]
Curcuma longa L. (Zingiberaceae)	rhizomes	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.1 ml	6h 6h 6h	60 100 100	DEET	[74]
Citrus hystrix DC. (Rutaceae)	leaf	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.1 ml	3h		DEET	[74]
Cymbopogon winterianus Jowitt ex Bor (Poaceae)	leaf	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.1 ml	6h 6h 6h	100 100 100	DEET	[74]
Ocimum americanum L. (Lamiaceae)	leaf	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	0.1 ml	6h 6h 6h	85.7 100 100	DEET	[74]
Cymbopogon nardus (L.) Rendle (Poaceae)		*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	50%	50 80 30		Negative control	[104]
Pogostemon cablin (Blanco) Benth. (Lamiaceae)		*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	50%	60 90 120		Negative control	[104]
Zanthoxylum limonella (Dennst.) Alston (Rutaceae)	Seed and fruit	*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	50%	80 100 130		Negative control	[104]
Syzygium aromaticum (L.) Merr. & L.M.Perry (Myrtaceae)		*Ae. aegypti* *An. dirus* *Cx quinquefasciatus*	50%	70 120 160		Negative control	[104]
Thymus vulgaris L. (Lamiaceae)	Thyme oil	*Ae. albopictus*	468.5 mg/cm^2	6h	14	Negative control	[148]
Nepeta cataria L. (Lamiaceae)	catnip oil	*Ae. albopictus*	468.5 mg/cm^2	6h	70	Negative control	[148]
Amyris balsamifera L. (Rutaceae)	amyris oil	*Ae .albopictus*	468.5 mg/cm^2	6h	34	Negative control	[148]
Eucalyptus citriodora Hook. (Myrtaceae)	eucalyptus lemon oil	*Ae. albopictus*	468.5 mg/cm^2	1h	3	Negative control	[148]
Cymbopogon citratus (DC.) Stapf (Poaceae)	Leaf	*Cx. tritaeniorhynchus* *An. subpictus*	5.0 mg/cm^2	180 min 180 min	79.4 74.2	Negative control	[200]
Cinnamomum zeylanicum (Lauraceae)	Bark	*Cx. tritaeniorhynchus* *An. subpictus*	5.0 mg/cm^2	180 min 180 min	64.7 61.2	Negative control	[200]
Rosmarinus officinalis L.	Shoot	*Cx. tritaeniorhynchu*	5.0 mg/cm^2	180 min	71.2	Negative control	[200]

(Lauraceae)		*s* *An. subpictus*		180 min	68.2		
Zingiber officinale Roscoe (Zingiberaceae)	Rhizome	*Cx. tritaeniorhynchus* *An. subpictus*	5.0 mg/cm^2	180 min 180 min	88.3 85.6	Negative control	[200]
Zingiber officinale Roscoe (Zingiberaceae)	rhizomes	*Cx. quinquefasciatus*	4.0 mg/cm^2	120 min	100%	Negative control	[132]
Andropogon citratus DC. Stapf (Poaceae)		*Cx. pipiensmolestus*	3%	32 min		Negative control	[178]
Citrus sinensis (L.) Osbeck (Rutaceae)	Leaf	*Cx. pipiensmolestus*	3%	18 min		Negative control	[178]
Eucalyptus spp. (Myrtaceae)	Leaf	*Cx. pipiensmolestus*	3%	39 min		Negative control	[178]
Foeniculum vulgare Mill. (Umbellifers)	Flowers	*Cx. pipiensmolestus*	3%	29 min		Negative control	[178]
Laurus nobilis L. (Lauraceae)	Leaf	*Cx. pipiensmolestus*	3%	29 min		Negative control	[178]
Pinus pinea L. (Pinaceae)	Leaf	*Cx. pipiensmolestus*	3%	28 min		Negative control	[178]
Eucalyptus globulus Labill. (Myrtaceae)	Eucalyptus	*Cx. pipiens pallens*	0.05%	17.8min	70	Negative control	[147]
Lavandula officinalis Chaix (Lamiaceae)	Lavender	*Cx. pipiens pallens*	0.05%	33.2min	65	Negative control	[147]
Rosemarinus officinalis L. (Lamiaceae)	Rosemary	*Cx. pipiens pallens*	0.05%	31min	77	Negative control	[147]
Thymus vulgaris L. (Lamiaceae)	Thymus	*Cx. pipiens pallens*	0.05%	65.4min	91	Negative control	[147]
Hemizygia welwitschii (Lamiaceae)		*Ae. aegypti*	15%	4h	100%	commercial topical mosquito repellent	[199]
Cupressus benthamii Endl. (Cupressaceae)	Aerial parts	*Ae. albopictus*	0.08 mg/cm^2		100%	DEET/negative control	[65]
Chamaecyparis lawsoniana (A.Murray bis) Parl. (Cypress)	Aerial parts	*Ae. albopictus*	0.08 mg/cm^2		100%	DEET/negative control	[65]
Cupressus macrocarpa Hartw. (Cypress)	Aerial parts	*Ae. albopictus*	0.08 mg/cm^2		100%	DEET/negative control	[65]
Thymus leucospermus Hartvig (Lamiaceae)	Aerial parts	*Cx. pipiens*	1mg/cm^2		78.1%	DEET and icaridin	[97]
Thymus teucrioides subsp. *candilicus* (Beauverd) Hartvig (Lamiaceae)	Aerial parts	*Cx. pipiens*	1mg/cm^2		72.9%		[97]