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ORIGINAL PAPER

Essential oils and their compounds as *Aedes aegypti* L. (Diptera: Culicidae) larvicides: review

Clarice Noleto Dias · Denise Fernandes Coutinho Moraes

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Abstract This review aims to describe essential oils and their constituent compounds that exhibit bioactivity against *Aedes aegypti* L. (Diptera: Culicidae) larvae, the immature stage of the primary vector of dengue. This review is based on original articles obtained by searching on major databases. Our literature review revealed that 361 essential oils from 269 plant species have been tested for their larvicidal activity. More than 60 % of these essential oils were considered active (LC_{50}<100 mg/L), and the majority of these active oils were derived from species belonging to Myrtaceae, Lamiaceae, and Rutaceae. The most active essential oils exhibited effective concentrations comparable with the dosage recommended for the use of temephos in container breeding. Approximately 27 % of the plants studied for their larvicidal activity against *A. aegypti* were collected in Brazil. Essential oils rich in phenylpropanoids, oxygenated sesquiterpenes, and monoterpene hydrocarbons were found to be the most active. When the isolates were tested, phenylpropanoids and monoterpene hydrocarbons were the most active compound classes. We describe the plant parts used and the major constituents of the essential oils. In addition, we discuss factors affecting the activity (such as plant parts, age of the plant, chemotypes, larval source, and methods used), structure–activity relationships, and mechanisms of action of the essential oils and their compounds. Essential oils have been widely investigated and show high larvicidal activity against *A. aegypti*. This review reveals that the essential oils are effective alternatives for the production of larvicides, which can be used in vector-borne disease control programmes.

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Introduction

The incidence of dengue has increased 30-fold in recent decades worldwide. In 2012, dengue was considered the most important mosquito-borne viral disease in the world, being endemic in over 100 countries of the tropical and subtropical regions where over 2.5 billion people live. Approximately 40 % of the world's population is now at risk of infection by dengue virus; it is estimated that among this population, 50–100 million are infected annually, with 500,000 cases being severe. Approximately 2.5 % of those affected die and most of them are children living in Asian and Latin American countries (World Health Organization (WHO) 2009a; 2012a, b).

According to the WHO (2012c), *Aedes* (*Stegomyia*) *aegypti* L. (Diptera: Culicidae) is the primary vector of dengue. This mosquito is a highly anthropophilic species. It has adapted to the urban environment and uses man-made containers for oviposition and development of the aquatic stages of its life cycle. Virus transmission to humans occurs through the bites of infected female mosquitoes, which are daytime feeders (Eldridge 2005; Klowden 2007).

Unfortunately, there is no effective vaccine against dengue virus, which would ideally provide protection against all four virus serotypes. As a consequence, controlling the spread of dengue requires that mosquitoes be targeted directly (Konishi 2011; Gupta and Reddy 2013). Although there are no specific drugs available that prevent viral propagation, larvicides have been employed to combat dengue proliferation (Gubler 2011).

The organophosphate temephos is the most appropriate larvicide to be used in public health programmes (Tikar et al. 2008; WHO 2009b). However, the continued and repeated use of temephos has contributed to the development of

resistant strains of vector-borne diseases by different mechanisms (WHO 1992; Braga and Valle 2007; Melo-Santos et al. 2010; Polson et al. 2011).

To circumvent these problems, it is critical to identify novel larvicides with different modes of action in order to increase the available choices of pesticides for use in public health control (Góis et al. 2013; Govindarajan et al. 2013). The ideal insecticide should be effective, ecologically sound, sustainable, and cost effective and exhibit low mammalian toxicity. Additionally, larvicides should not significantly change the characteristics of environmental water (WHO 2006).

For dengue control, an integrated approach should be the best option. To reach effective dengue control measures, it is necessary to consider problems such as unplanned urbanization, inadequate water supply, and poor basic sanitary conditions (Gupta and Reddy 2013). The WHO (2012d) reported four categories of vector control in the *Handbook for Integrated Vector Management*. Among them, botanical preparations are cited as a biological method of control.

Plant–insect relationships are a reason for interest in the search for herbal products. For thousands of years, plants and insects have evolved in parallel. This co-evolution has led to the development, in many plants, of chemical and physical mechanisms of defence against insects (Ryan and Byrne 1988). In addition, plant parts and plant derivatives have been traditionally used by human communities to control pest species of insects (Dharmagadda et al. 2005; Shaalan et al. 2005; Prophiro et al. 2012). Azadirachtin, anabasine, quassia, nicotine, pyrethrins, D-limonene, and carvacrol were important botanical insecticides used before the advent of synthetic chemicals (Wood 2012). Citronella oil is used extensively as an insect repellent (EPA 1999; Kongkaew et al. 2011); similarly, *Eucalyptus* oil is used as an insect repellent or an antifeedant agent against herbivores (Batish et al. 2008).

All these factors have attracted the attention of researchers that aim to identify new plant-based insecticides (Shaalan et al. 2005; Cheah et al. 2013; Kovendan et al. 2013), especially for the control of *A. aegypti* propagation by larvicidal agents (Geris et al. 2012; Warikoo and Kumar, 2013). Some studies have focused on the use of essential oils from plants as potential bioactive agents against *A. aegypti* larvae (Magalhães et al. 2010; Vila et al. 2010; Park et al. 2011; Govindarajan et al. 2012). Essential oils are considered the best alternative for the control of disease vectors (Warikoo et al. 2011; Bilal and Hassan 2012; Maheswaran and Ignacimuthu, 2012; Kumar et al. 2013; Liu et al. 2013). They are complex mixtures of volatile secondary metabolites that can mainly be categorized as phenylpropanoids or mono-, sesqui-, and diterpenes (Baser and Buchbauer 2010).

Literature reviews of plant-based products with biological activity have illustrated a significant contribution to the development of new alternatives for improving human health (Amaral et al. 2006; Krishnaiah et al. 2011; Lang and Buchbauer 2011; Kumar et al. 2012; Unnati et al. 2013). Considering the literature reviews about insecticidal plant extracts (Sukumar et al. 1991; Shaalan et al. 2005; Koul et al. 2008; Zoubiri and Baaliouamer 2011; Ghosh et al. 2012), we limited this review to studies of larvicidal activity of essential oils against *A. aegypti.* We explored the relationship between oil constituents and larvicidal activity with the aim of contributing to the search for new alternatives for dengue control. We present a review based on original articles that were chosen by searching major databases such as Biological Abstracts, Chemical Abstracts, Web of Science, SciFinder, PubMed, Scopus, ScienceDirect, and Scielo. Patents were identified by searching the European Patent Office database. The keywords employed in the literature review were 'essential oils', 'larvicidal activity', 'larvicide', and '*Aedes aegypti*'.

Essential oils and their compounds as larvicides against *A. aegypti*

In 2005, the WHO published the Guidelines for Laboratory and Field Testing of Mosquito Larvicides, aiming to standardize the procedures for testing the mechanisms of action of larvicides. This document defines the sequential phases for evaluating larvicide compounds and their preparation. It is recommended that the studies begin in the laboratory in order to determine the potential of the tested samples. Then, small- and large-scale field trials should be performed to analyse the effects on non-target organisms, as well as the efficacy and residual effects under different ecological settings. These guidelines illustrate that the potency of a chemical against a particular species of mosquito larvae must be compared with other insecticides (WHO 2005).

Several authors developed their own criteria to characterize the potency of mosquito larvicides based of natural products (Chantraine et al. 1998; Massebo et al. 2009; Magalhães et al. 2010). Komalamisra et al. (2005) considered products showing LC_{50}<50 mg/L active, 50 mg/L<LC_{50}<100 mg/L moderately active, 100 mg/L<LC_{50}<750 mg/L effective, and LC_{50}>750 mg/L inactive. Kiran et al. (2006) considered compounds with LC_{50}<100 mg/L as exhibiting a significant larvicidal effect.

As the WHO has not established a standard criterion for determining the larvicidal activity of natural products, in this review, we used the classification established by Cheng et al. (2003) in which the compounds with LC_{50}> 100 mg/L were considered not active, with LC_{50}< 100 mg/L were active, and those with LC_{50}<50 mg/L were highly active. In addition, the samples that had their results expressed as mortality percentage were considered active when they were able to kill almost 100 % of larvae at 100 mg/L.

Our literature review showed that 361 essential oils from 269 plant species have been tested for their larvicidal activity against *A. aegypti*. According to the classification of Cheng et al. (2003), we considered more than 60 % of these essential oils as active (LC_{50}<100 mg/L) in our review. This result confirms the ecological role of essential oils in nature; many essential oils serve to protect plants by defence mechanisms against pathogens and predators (Grodnitzky and Coats 2002; Bakkali et al. 2008). Hence, plant essential oils have great potential in dengue control. Table 1 lists these plant species as well as their essential oil characteristics.

The studies of essential oil as *A. aegypti* larvicide used species distributed among 29 families. Myrtaceae, Zingiberaceae, Asteraceae, and Lamiaceae accounted for 14.5, 12.5, 12, and 12 % of the studied species, respectively. The majority of the active oils are from species that belong to Myrtaceae (13.5 %), Lamiaceae (10.5 %), and Rutaceae (8.2 %). According to Sukumar et al. (1991), Regnault-Roger (1997), Magalhães et al. (2010), and Park et al. (2011), species that belong to Myrtaceae, Apiaceae, Piperaceae, Lamiaceae, Rutaceae, Asteraceae, Meliaceae, and Zingiberaceae have the potential to be used as insecticides.

The most active essential oils were from the woods of *Callitris glaucophylla* Joy (LC_{50}=0.69 mg/L), *Juniperus virginiana* L. (LC_{50}=1 mg/L), *Thymus serpyllum* L. (LC_{50}= 1 mg/L), and *Amyris balsamifera* L. (LC_{50}=1 mg/L) (Amer and Mehlhorn 2006; Shaalan et al. 2006). Their LC_{50} values are comparable with the dosage recommended for the use of temephos (1 mg/L) in container breeding (WHO 2012e).

Essential oils were extracted from the entire plant or from specific parts of the plant. In the analyses, we found that leaves were the most commonly used part of the plant. However, only 50 % of the oils extracted from plant leaves exhibited high larvicidal activity (LC_{50}<50 mg/L), whereas almost 80 % of the essential oils extracted from plant seeds showed high activity.

Approximately 27 % of the plants studied for their larvicidal activity against *A. aegypti* were collected in Brazil, of which 77 % were collected from the northeast of Brazil. Essential oils from these plants have been the most studied. These data support the importance of Brazilian biodiversity. According to Oliveira et al. (2012), 20 % of the plants species of the world are native to Brazil; however, these plants have not been optimally used and should be further studied.

Essential oils rich in phenylpropanoids, oxygenated sesquiterpenes, and monoterpene hydrocarbons were found to be the most active; all phenylpropanoid-rich essential oils exhibited larvicidal activity. The essential oils that were not active according to the criterion used are listed in Table 2. The botanical families Asteraceae and Zingiberaceae showed the highest ratio of inactive species.

To further understand the relationship between essential oils and their larvicidal activity, some authors isolated and tested the major compounds of these oils. In most of these studies, it was observed that the whole essential oil was as active as their isolated compounds. Phenylpropanoids and monoterpene hydrocarbons were the most active compound classes. Table 3 lists the isolated compounds that were considered active (LC_{50}<100 mg/L).

The oxygenated sesquiterpenes β-eudesmol and caryophyllene oxide, which are major compounds of the active essential oils from *Guatteria friesiana* Erkens & Maas and *Guatteria blepharophylla* Mart., respectively (Aciole et al. 2011), were not active when tested isolated, although the whole oil showed high activity (Cheng et al. 2009a, b). This can be explained by the interactions between the constituents present in oils. Other compounds that were considered inactive (LC_{50}>100 mg/L) are listed in Table 4.

The studies performed by Magalhães et al. (2010), Aciole et al. (2011), and Lima et al. (2011) achieved results that demonstrated the high larvicidal activity of oxygenated sesquiterpene-rich essential oil. Lima et al. (2011) correlated the activity of *Spondias purpurea* L. essential oil with the high concentration of these compounds in blend. Simas et al. (2004) noted that oxygenated sesquiterpenes were more effective than monoterpenes and phenylpropanoids. On the basis of these results, the authors hypothesized that lipophilicity is an important tool for the larvicidal activity on *A. aegypti*.

Essential oils are complex chemical mixtures of major and minor compounds. In general, the bioactivity of essential oils is correlated with their major substances. However, it is important to note that these secondary metabolites can facilitate interactions that increase or decrease the larvicidal activity of tested oils compared with the activities of their isolated constituents (Waliwitiya et al. 2009). The synergistic phenomenon exists in botanical preparations by the interaction between molecules that are both major and minor components of the preparations. In some cases, the bioactivity of the blend is higher than those of purified compounds (Lahlou 2004a; Shaalan et al. 2005).

Cheng et al. (2009c) found that the leaf essential oil from *Cryptomeria japonica* (Thunb. ex L. f.) D. Don (LC_{50}= 28.4 mg/L) was more toxic to *A. aegypti* larvae than its major constituents, 16-kaurene (LC_{50}=57.0 mg/L), and elemol (LC_{50}>100.0 mg/L), both of which are present in the samples at proportions approaching 20 %. The authors suggest that the minor compounds 3-carene (LC_{50}=25.3 mg/L), terpinolene (LC_{50}=32.1 mg/L), α-terpinene (LC_{50}=28.1 mg/L), and γ-terpinene (LC_{50}=26.8 mg/L) also contribute to the larvicidal activity, since they exhibited great larvicidal potential.

In a study performed by Silva et al. (2008), β-caryophyllene and caryophyllene oxide were identified as the major compounds of the leaf essential oil of *Hyptis*

Table 1 Plant essential oils considered active (LC_{50}<100 mg/L) against *Aedes aegypti* L. (Diptera: Culicidae) larvae

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Acoraceae					
Acorus calamus L.	Roots	Pakistan	NI	99.41	Manzoor et al. (2013)
Amaranthaceae					
Chenopodium ambrosioides L.	Aerial	Cuba	α-Terpineol	35	Leyva et al. (2009a)
	Aerial	Ethiopia	NI	9.1	Massebo et al. (2009)
Anacardiaceae					
Anacardium humile A. St.-Hil.	Leaves	Brazilian Savanna	NI	20.9	Porto et al. (2008)
Schinus molle L.	Leaves	Ethiopia	NI	9.6	Massebo et al. (2009)
	Seeds	Ethiopia	NI	14.5	Massebo et al. (2009)
	Seeds	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Spondias purpurea L.	Leaves	Northeast of Brazil	Caryophyllene oxide and α-cadinol	39.7	Lima et al. (2011)
Annonaceae					
Guatteria blepharophylla Mart.	Leaves	Brazilian Amazon	Caryophyllene oxide	58.72	Aciole et al. (2011)
Guatteria friesiana Erkens & Maas	Leaves	Brazilian Amazon	β-Eudesmol	52.6	Aciole et al. (2011)
Guatteria hispida (R.E.Fr.) Erkens & Maas	Leaves	Brazilian Amazon	β-Pinene and α-pinene	85.74	Aciole et al. (2011)
Rollinia leptopetala R.E. Fr.	Stems	Northeast of Brazil	Spathulenol	34.7	Feitosa et al. (2009)
Apiaceae					
Anethum graveolens L.	Aerial	Germany	NI	50	Amer and Mehlhorn (2006)
Apium graveolens L.	Seeds	Thailand	(*R*)-(+)-Limonene	42.07	Pitasawat et al. (2007)
	Leaves	South Korea	4-Chloro-4,4-dimethyl-3-(1-imidazolyl)-valerophenone and 1-dodecanol	59.32	Nagella et al. (2012)
Carum carvi L.	Seeds	Thailand	Carvone	54.62	Pitasawat et al. (2007)
	Fruits	South Korea	NI	NI[a]	Lee (2006)
Cuminum cyminum L.	Fruits	South Korea	NI	NI[a]	Lee (2006)
Daucus carota L.	Root	South Korea	NI	NI[a]	Lee (2006)
Eryngium sp. L.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Ferula galbanifera Mill.	Steam bark	South Korea	NI	NI[a]	Lee (2006)
Foeniculum vulgare Mill.	Fruits	Thailand	*trans*-Anethole	49.32	Pitasawat et al. (2007)
	Seeds	Bolivia	NI	24.3	Chantraine et al. (1998)
Heracleum pastinacifolium subsp. *transcaucasicum* P.H. Davis	Fruits	NI	Octyl acetate	69.72	Tabanca et al. (2012a)
Heracleum pastinacifolium subsp. *incanum* P.H. Davis	Fruits	NI	Hexyl butyrate	71.85	Tabanca et al. (2012a)
Pimpinella anisum L.	Seeds	India	NI	<100	Prajapati et al. (2005)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Trachyspermum ammi (L.) Sprague	Seeds	NI	Thymol	NI[a]	Seo et al. (2012)
Araliaceae					
Dendropanax morbifera Leveille	Flower	South Korea	γ-Elemene	62.32	Chung et al. (2009)
Aristolochiaceae					
Asarum heterotropoides Leveille	Root	Korea	Methyleugenol and safrole	23.82	Perumalsamy et al. (2009, 2010)
Asteraceae					
Baccharis sp. L.	Aerial	Bolivia	NI	14.7	Chantraine et al. (1998)
Coreopsis fasciculata Wedd.	Aerial	Bolivia	NI	26.5	Chantraine et al. (1998)
Eupatorium betonicaeforme (DC.) Baker	Root	Northeast of Brazil	β-Caryophyllene	NI[a]	Albuquerque et al. (2004)
Gynoxis sp. Cass.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Helichrysum italicum G. Don f.	NI	France	NI	100	Amer and Mehlhorn (2006)
Pectis oligocephala Baker	Aerial	Northeast of Brazil	*p*-Cymene and thymol	NI[a]	Albuquerque et al. (2007)
Senecio adenophylloides Sch. Bip.	Leaves	Bolivia	NI	43.4	Chantraine et al. (1998)
Tagetes erecta L.	Leaves	India	NI	15.37	Pathak et al. (2000)
	Leaves and Stem	Northeast of Brazil	Piperitone	79.78	Marques et al. (2011)
Tagetes filifolia Lag.	Aerial	Peru	*trans*-Anethole	47.7	Ruiz et al. (2011)
Tagetes minuta L.	Aerial	Peru	*trans*-Ocimenone	52.3	Ruiz et al. (2011)
Tagetes patula L.	Leaves	India	Limonene and terpinolene	13.57	Dharmagadda et al. (2005)
Tagetes pusilla Kunth	Seeds	Bolivia	NI	14.1	Chantraine et al. (1998)
Boraginaceae					
Auxemma glazioviana Taub.	Heartwood	Northeast of Brazil	α-Bisabolol and α-cadinol	2.53	Costa et al. (2004)
	Heartwood	Northeast of Brazil	α-Bisabolol, α-cadinol, and T-muurolol	2.98	Costa et al. (2004)
Cordia curassavica (Jacq.) Roem. & Schult.	Leaves	Southeast of Brazil	*cis*-Isolongifolone	87.70	Aciole (2009)
	Leaves	Northeast of Brazil	α-Pinene	97.7	Santos et al. (2006)
Cordia leucomalloides Taroda	Leaves	Northeast of Brazil	δ-Cadinene and (*E*)- caryophyllene	63.1	Santos et al. (2006)
Burseraceae					
Boswellia carteri Birdw.	Resins	Somalia	NI	10	Amer and Mehlhorn (2006)
Commiphora myrrha (T. Nees) Engl.	Stem bark	South Korea	NI	NI[a]	Lee (2006)
Convolvulaceae					
Ipomoea cairica (L.) Sweet	NI	India	NI	22.3	Thomas et al. (2004)
Cupressaceae					
Callitris glaucophylla Joy Thomps. & L.P. Johnson	Wood	Australia	Guaiol and citronellic acid	0.69	Shaalan et al. (2006)
Calocedrus formosana (Florin) Florin	Heartwood	Taiwan	NI	75.2	Cheng et al. (2003)
	Bark	Taiwan	NI	51.8	Cheng et al. (2003)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
	Leaves	Taiwan	NI	56.3	Cheng et al. (2003)
Chamaecyparis formosensis Matsum.	Wood	Taiwan	Myrtenol	38.6	Kuo et al. (2007)
Cryptomeria japonica (Thunb. ex L. f.) D. Don	Leaves	Taiwan	16-Kaurene and elemol	28.4 – 56.7	Cheng et al. (2009c)
	Leaves	Taiwan	NI	37.6	Cheng et al. (2003)
	Bark	Taiwan	NI	48.1	Cheng et al. (2003)
	Heartwood	Taiwan	NI	72	Cheng et al. (2003)
	Sapwood	Taiwan	NI	82.7	Cheng et al. (2003)
Cunninghamia konishii Hayata	Wood	Taiwan	Cedrol	85.7	Cheng et al. (2013)
	Leaves	Taiwan	α-Pinene	91.7	Cheng et al. (2013)
Cupressus arizonica var. *glabra* (Sudw.) Little	Female cones	USA	α-Pinene	33.7	Ali et al. (2013a)
	Wood-bark	USA	α-Pinene and *epi*-zonarene	44.6	Ali et al. (2013a)
	Male cones	USA	α-Pinene and *epi*-zonarene	53.6	Ali et al. (2013a)
	Needle-twigs	USA	α-Pinene	55.5	Ali et al. (2013a)
Juniperus macropoda Bois.	Fruit	India	NI	< 100	Prajapati et al. (2005)
Juniperus virginiana L.	Wood	USA	NI	1	Amer and Mehlhorn (2006)
	Wood	South Korea	NI	NI[a]	Lee (2006)
Juniperus communis L.	NI	Austria	NI	50	Amer and Mehlhorn (2006)
Taiwania cryptomerioides Hayata	Heartwood	Taiwan	NI	79.8	Cheng et al. (2003)
Euphorbiaceae					
Croton argyrophylloides Müll. Arg.	Aerial	Northeast of Brazil	β-*trans*-Guaiene	94.6	Lima et al. (2013)
Croton nepetaefolius Baill.	Aerial	Northeast of Brazil	Methyleugenol	66.4	Lima et al. (2013)
	Leaves	Northeast of Brazil	Methyleugenol	84	Morais et al. (2006)
Croton regelianus Müll. Arg.	Leaves	Northeast of Brazil	Ascaridole	24.22	Torres et al. (2008)
	Leaves	Northeast of Brazil	*p*-Cymene	66.74	Torres et al. (2008)
Croton sonderianus Müll. Arg.	Aerial	Northeast of Brazil	Spathulenol	54.5	Lima et al. (2013)
Croton zehntneri Pax & K. Hoffm.	Aerial	Northeast of Brazil	(*E*)-Anethole	26.2	Lima et al. (2013)
	Leaves	Northeast of Brazil	(*E*)-Anethole	28	Morais et al. (2006)
	Leaves	Northeast of Brazil	(*E*)-Anethole	56.2	Santos et al. (2007)
	Stalkes	Northeast of Brazil	(*E*)-Anethole and *p*-anisaldehyde	51.3	Santos et al. (2007)
	Inflorescence	Northeast of Brazil	(*E*)-Anethole	57.5	Santos et al. (2007)
Fabaceae					
Bauhinia acuruana Moric	Leaves	Northeast of Brazil	epi-α-Cadinol and spathulenol	56.22	Góis (2010)
Copaifera multijuga Haynet	Resin	Brazilian Amazon	β-Caryophyllene	18	Trindade et al. (2013)
Hymenaea courbaril L.	Ripe fruit peels	Northeast of Brazil	α-Copaene and spathulenol	14.8	Aguiar et al. (2010)
	Unripe fruit peels	Northeast of Brazil	Germacrene D and β-caryophyllene	28.4	Aguiar et al. (2010)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Myroxylon pereirae (Royle) Klotzsch	Resin	NI	Benzyl benzoate	NI[a]	Seo et al. (2012)
Lamiaceae					
Hyptis martiusii Benth.	Leaves	Northeast of Brazil	δ-3-Carene and 1,8-cineol	18.5	Costa et al. (2005)
Lavandula gibsoni J. Graham	Aerial	India	α-Terpinolen and thymol	48.32	Kulkarni et al. (2013)
Lavandula officinalis Chaix	Flowering tops	South Korea	NI	NI[a]	Lee (2006)
Lepechinia meyenii (Walp.) Epling	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Mentha piperita L.	Leaves	India	NI	26.19	Pathak et al. (2000)
	Leaves	India	NI	47.54	Kalaivani et al. (2012)
Mentha spicata L.	Leaves	India	Carvone	56.08	Govindarajan et al. (2012)
	Leaves	Ethiopia	NI	67.8	Massebo et al. (2009)
Nepeta cataria L.	NI	NI	(*E*),(*Z*)-Nepetalactone and (*Z*),(*E*)-nepetalactone	70	Zhu et al. (2006)
Ocimum americanum L.	Leaves and branches	Northeast of Brazil	(*E*)-Methyl-cinnamate	67	Cavalcanti et al. (2004)
Ocimum basilicum L.	Leaves	Pakistan	NI	75.35	Manzoor et al. (2013)
Ocimum gratissimum L.	Aerial	Northeast of Brazil	Eugenol	60	Cavalcanti et al. (2004)
Ocimum lamiifolium Hochst. Ex Benth.	Leaves	Ethiopia	NI	8.6	Massebo et al. (2009)
Ocimum sanctum L.	Leaves	India	NI	29.76	Pathak et al. (2000)
	NI	Nigeria	Methyleugenol	85.11	Gbolade and Lockwood (2008)
	NI	India	NI	92.48	Tennyson et al. (2013)
Ocimum suave Willd.	Leaves	Ethiopia	NI	29.8	Massebo et al. (2009)
Origanum marjorana L.	Leaves	South Korea	NI	NI[a]	Lee (2006)
Plectranthus amboinicus (Lour.) Spreng.	Leaves	Northeast of Brazil	Carvacrol	51.8	Lima et al. (2011)
Plectranthus mollis Spreng.	Aerial	India	Piperitone oxide and fenchone	25.39	Kulkarni et al. (2013)
Pogostemon patchouli Pellet.	Whole plant	NI	NI	NI[a]	Seo et al. (2012)
Thymus serpyllum L.	NI	Turkey	NI	1	Amer and Mehlhorn (2006)
Thymus vulgaris L.	Leaves	Ethiopia	NI	17.3	Massebo et al. (2009)
Lauraceae					
Cinnamomum camphora (L.) J. Presl	NI	Taiwan	NI	10	Amer and Mehlhorn (2006)
Cinnamomum cassia (L.) C. Presl	NI	NI	Cinnamaldehyde	80	Zhu et al. (2006)
Cinnamomum impressicostatum Kosterm.	Leaves	Malaysia	Benzyl benzoate and α-phellandrene	10.7	Jantan et al. (2005)
	Leaves	Malaysia	NI	13.7	Jantan et al. (2003)
Cinnamomum microphyllum Ridl.	Leaves	Malaysia	Benzyl benzoate	6.7	Jantan et al. (2005)
	Leaves	Malaysia	NI	20.6	Jantan et al. (2003)
Cinnamomum mollissimum Hook. F.	Leaves	Malaysia	Benzyl benzoate	10.2	Jantan et al. (2005)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Cinnamomum osmophloeum Kaneh.	Leaves	Taiwan	NI	86.8	Cheng et al. (2003)
	Leaves	Taiwan	*trans*-Cinnamaldehyde	36	Cheng et al. (2004)
	Leaves	Taiwan	*trans*-Cinnamaldehyde and cinnamyl acetate	44	Cheng et al. (2004)
Cinnamomum pubescens Kochummen	Leaves	Malaysia	Benzyl benzoate	12.8	Jantan et al. (2005)
Cinnamomum rhyncophyllum Miq.	Leaves	Malaysia	Benzyl benzoate	6.0	Jantan et al. (2005)
Cinnamomum scortechinii Gamble	Leaves	Malaysia	β-Phellandrene and linalool	21.5	Jantan et al. (2005)
Cinnamomum sintoc Blume	Leaves	Malaysia	Safrole	41	Jantan et al. (2005)
Cinnamomum zeylanicum Blume.	Leaves	Northeast of Brazil	Eugenol	79.75	Mendes (2011)
Meliaceae					
Guarea humaitensis T.D. Penn.	Branches	Brazilian Amazon	Caryophyllene epoxide	48.6	Magalhães et al. (2010)
Guarea scabra A. Juss.	Leaves	Brazilian Amazon	*cis*-Caryophyllene	98.6	Magalhães et al. (2010)
Myristicaceae					
Myristica fragrans Houtt.	NI	India	NI	93.62	Tennyson et al. (2013)
Myrtaceae					
Eucalyptus benthamii var *Benthamii* Maiden & Cambage	Leaves	Argentina	α-Pinene	NI[a]	Lucia et al. (2012)
Eucalyptus botryoides Smith	Leaves	Argentina	*p*-Cymene, α-eudesmol, and 1,8-cineol	NI[a]	Lucia et al. (2012)
Eucalyptus camaldulensis Dehnh.	Leaves	Argentina	1,8-Cineol, *p*-cymene and β-phellandrene	26.75	Lucia et al. (2008)
	Leaves	Taiwan	α-Pinene, *p*-cymene, and α-phellandrene	31	Cheng et al. (2009b)
Eucalyptus citriodora Hook.	Leaves	Ethiopia	NI	38.7	Massebo et al. (2009)
	NI	NI	*p*-Menthane-3,8-diol	58	Zhu et al. (2006)
Eucalyptus dives Schauer	Leaves	Australia	NI	NI[a]	Amer and Mehlhorn (2006)
Eucalyptus dunnii Maiden	Leaves	Argentina	1,8-Cineol and γ-terpinene	25.23	Lucia et al. (2008)
Eucalyptus fastigata Deane & Maiden	Leaves	Argentina	*p*-Cymene	NI[a]	Lucia et al. (2012)
Eucalyptus globulus Labill.	Leaves	Ethiopia	1,8-Cineol	52.9	Massebo et al. (2009)
Eucalyptus grandis W. Hill	Leaves	Argentina	α-Pinene	32.4	Lucia et al. (2007)
Eucalyptus gunnii Hook. F.	Leaves	Argentina	1,8-Cineol and *p*-cymene	21.13	Lucia et al. (2008)
Eucalyptus nobilis L.A.S. Johnson & K.D. Hill	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2012)
Eucalyptus radiata ssp. *radiata* Sieber ex Spreng	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2012)
Eucalyptus robusta Smith	Leaves	Argentina	α-Pinene	NI[a]	Lucia et al. (2012)
Eucalyptus saligna Sm.	Leaves	Argentina	1,8-Cineol and *p*-cymene	22.16	Lucia et al. (2008)
Eucalyptus tereticornis Sm.	Leaves	Argentina	β-Phellandrene and 1,8-cineol	22.14	Lucia et al. (2008)
Eucalyptus urophylla S.T. Blake	Leaves	Taiwan	1,8-Cineol	95.5	Cheng et al. (2009b)
Eugenia melanadenia Krug & Urb.	Leaves	Cuba	1,8-Cineol	85	Aguilera et al. (2003)
Eugenia triquetra O. Berg	Leaves	Venezuela	Linalool and limonene	64.8	Mora et al. (2010)
Melaleuca dissitiflora F. Muell	NI	NI	Terpinen-4-ol	NI[a]	Park et al. (2011)
Melaleuca leucadendron (L.) L.	NI	Cuba	1,8-Cineol, α-pinene, and α-terpineol	41	Leyva et al. (2008)
Melaleuca linariifolia Sm.	NI	NI	Terpinem-4-ol and γ-terpinene	NI[a]	Park et al. (2011)
Melaleuca quinquenervia (Cav.) S. T. Blake	NI	NI	1,8-Cineol and (*E*)-nerolidol	NI[a]	Park et al. (2011)
Melaleuca viridiflora Sol. ex Gaertn.	Leaves	South Korea	NI	NI[a]	Lee (2006)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Myrtus communis L.	Leaves and Twigs	France	NI	50	Amer and Mehlhorn (2006)
Pimenta dioica (L.) Merr.	Leaves	Southeast of Brazil	Eugenol	38.8	Marinho (2010)
Pimenta pseudocaryophyllus (Gomes) Landrum	Leaves	Southeast of Brazil	Chavibetol (m-eugenol)	44.1	Aciole (2009)
Pimenta racemosa (Mill.) J.W. Moore	Leaves	Cuba	Terpinem-4-ol and 1,8-cineol	27	Leyva et al. (2009a)
	Leaves	South Korea	NI	NI[a]	Lee (2006)
Psidium guajava L.	Leaves	Northeast of Brazil	1,8-Cineol and β-caryophyllene	24.7	Lima et al. (2011)
Psidium rotundatum Griseb.	Leaves	Cuba	1,8-Cineol	63	Aguilera et al. (2003)
Syzygium aromaticum (L.) Merr. & L.M. Perry	Flowers	Northeast of Brazil	Eugenol	21.4	Costa et al. (2005)
	NI	NI	Eugenol	62.3	Barbosa et al. (2012a)
	Flowers	NI	Eugenol	63.36	Nascimento (2012)
Pinaceae					
Picea excelsa (Lamb.) Link	NI	Korea	NI	NI[a]	Amer and Mehlhorn (2006)
Pinus caribaea Morelet	Leaves	Cuba	NI	51	Leyva et al. (2009b)
Pinus longifolia Salisb.	NI	India	K-terpineol	82.1	Ansari et al. (2005)
Pinus tropicalis Morelet	Leaves	Cuba	NI	42	Leyva et al. (2009b)
Pinus sp. L. (Turpentine)	Resin	Argentina	α-Pinene and β-pinene	14.7	Lucia et al. (2007)
Piperaceae					
Piper aduncum L.	Fruits	Northeast of Brazil	β-Pinene	30.2	Costa et al. (2010a)
	Aerial	Brazilian Amazon	Dillapiole	54.5	Almeida et al. (2009)
	NI	Cuba	Dillapiole	57	Leyva et al. (2009a)
Piper auritum Kunth.	Leaves	Cuba	Safrole	17	Leyva et al. (2009a)
Piper betle L.	NI	Indonesia	Citronellal	13.1	Wahyuni (2012)
Piper hostmanianum (Miq.) C. DC.	Leaves	Brazilian Amazon	Asaricin and myristicin	54	Morais et al. (2007)
Piper klotzschianum (Kunth) C. DC.	Seeds	Southeast of Brazil	1-Butyl-3,4-methylenedioxybenzene, limonene, and α-phellandrene	13.27	Nascimento et al. (2013)
	Root	Southeast of Brazil	1-Butyl-3,4-methylenedioxybenzene	10.0	Nascimento et al. (2013)
Piper marginatum Jacq.	Leaves	Northeast of Brazil	Isoelemecin and apiole	8.29	Costa et al. (2010a)
	Leaves	Northeast of Brazil	(*Z*)-Asarone	23.8	Autran et al. (2009)
	Stem	Northeast of Brazil	(*E*)-Asarone and patchouli alcohol	19.9	Autran et al. (2009)
	Inflorescence	Northeast of Brazil	Patchouli alcohol and (*E*)-asarone	19.9	Autran et al. (2009)
Piper nigrum L.	Seeds	Ethiopia	NI	9.1	Massebo et al. (2009)
	Seeds	Sri Lanka	(*E*)-Caryophyllene and caryophyllene oxide	50	Amer and Mehlhorn (2006)
	Seeds	Northeast of Brazil	(*E*)-Caryophyllene, caryophyllene oxide, and Sabinene	75.8	Costa et al. (2010a)
Piper permucronatum Yunck.	Leaves	Brazilian Amazon	Dillapiole and myristicin	36	Morais et al. (2007)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Poaceae					
Cymbopogon citratus (DC.) Stapf	Leaves	Northeast of Brazil	Geranial	69	Cavalcanti et al. (2004)
Cymbopogon martini (Roxb.) Will. Watson	NI	India	NI	87.88	Tennyson et al. (2013)
Cymbopogon winterianus Jowitt ex Bor	Leaves	Northeast of Brazil	NI	98	Mendonça et al. (2005)
Vetiveria zizanioides (L.) Nash	Root	Bolivia	NI	31.5	Chantraine et al. (1998)
Ranunculaceae					
Nigella sativa L.	Leaves	Ethiopia	NI	32.1	Massebo et al. (2009)
Rutaceae					
Amyris balsamifera L.	Wood	Haiti	NI	1	Amer and Mehlhorn (2006)
	Wood	Haiti	Elemol and eudesmols	52	Zhu et al. (2006)
Chloroxylon swietenia DC.	Leaves	India	Geijerene	16.5	Kiran et al. (2006)
	Stems	India	Geijerene and limonene	20.4	Kiran et al. (2006)
Citrus bergamia Risso	Fruit peels	South Korea	NI	NI[a]	Lee (2006)
Citrus limon (L.) Osbeck	Fruit peels	Italy	NI	10	Amer and Mehlhorn (2006)
Citrus sinensis (L.) Osbeck	NI	India	NI	85.93	Tennyson et al. (2013)
Ruta graveolens L.	Aerial	NI	Undecan-2-one	21.25	Tabanca et al. (2012b)
Clausena excavata Burm. f.	Leaves	Taiwan	Safrole and terpinolene	37.1	Cheng et al. (2009a)
	Twigs	Taiwan	Safrole	40.1	Cheng et al. (2009a)
Feronia limonia (L.) Swingle	Leaves	India	Estragole and β-pinene	11.59	Senthilkumar et al. (2013)
Murraya koenigii (L.) Spreng.	Leaves	India	NI	29.96	Pathak et al. (2000)
Toddalia asiatica (L.) Lam.	Fruits	Kenya	Linalool	40.6	Nyahanga et al. (2010)
	Leaves	Kenya	Sabinene	99.7	Nyahanga et al. (2010)
Zanthoxylum armatum DC.	Seeds	India	Linalool	54	Tiwary et al. (2007)
Zanthoxylum articulatum Engler	Leaves	Northeast of Brazil	Viridiflorol	77.62	Feitosa et al. (2007)
Zanthoxylum limonella Alston	Fruits	Thailand	(*R*)-(+)-Limonene	24.6	Pitasawat et al. (2007)
Zanthoxylum Oxyphyllum Edgew.	Leaves	India	Methyl heptyl ketone	7.52	Borah et al. (2012)
Santalaceae					
Santalum album L.	Wood	India	Guaiol, elemol, and eudesmol	10	Amer and Mehlhorn (2006)
Scrophulariaceae					
Capraria biflora L.	Leaves	Northeast of Brazil	α-Humulene	73.39	Souza et al. (2012a)
Stemodia maritima L.	Stem	Northeast of Brazil	β-Caryophyllene and caryophyllene oxide	22.9	Arriaga et al. (2007)
	Leaves		β-Caryophyllene	55.4	Arriaga et al. (2007)
Verbenaceae					
Lantana camara L.	Leaves	Northeast of Brazil	Bicyclogermacrene and (*E*)-caryophyllene	42.3	Costa et al. (2010b)

Table 1 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Lippia adoensis Hochst.	Leaves	Ethiopia	NI	47.1	Massebo et al. (2009)
Lippia citriodora Kunth.	NI	France	NI	100	Amer and Mehlhorn (2006)
Lippia gracilis Schauer	Leaves	Northeast of Brazil	Carvacrol	26.3	Santiago et al. (2006)
	Leaves	Northeast of Brazil	Carvacrol	98	Silva et al. (2008)
Lippia sidoides Cham.	Leaves	Northeast of Brazil	Thymol	19.5	Costa et al. (2005)
	NI	Northeast of Brazil	Thymol	25.5	Lima et al. (2013)
	Leaves	Northeast of Brazil	Thymol	56	Morais et al. (2006)
	Leaves	Northeast of Brazil	Thymol	63	Cavalcanti et al. (2004)
Zingiberaceae					
Alpinia purpurata (Viell.) K. Schum.	Red flower	Northeast of Brazil	β-Caryophyllene and β-pinene	80.7	Santos et al. (2012)
	Pink flower	Northeast of Brazil	β-Pinene and β-caryophyllene	71.5	Santos et al. (2012)
Curcuma aromatica Salisb.	Rhizomes	Thailand	1H-3a,7-Methanoazulene and curcumene	36.3	Choochote et al. (2005)
Curcuma domestica Valeton	Rhizomes	Malaysia	NI	20.9	Jantan et al. (2003)
Curcuma longa L.	Rhizomes	Cuba	Turmerone, curcumene, and zingiberene	25	Leyva et al. (2008)
Curcuma xanthorrhiza Roxb.	Rhizomes	Malaysia	NI	74.2	Jantan et al. (2003)
Curcuma zedoaria Roxb.	Rhizomes	Thailand	1,8-Cineol and *p*-cymene	31.87	Pitasawat et al. (2007)
	Rhizomes	Thailand	β-Tumerone	33.45	Champakaew et al. (2007)
Etlingera elatior (Jack) R.M. Sm.	Porcelain flower	NI	Dodecanal	26.62	Silva et al. (2013)
	Red flower	NI	Dodecanal and dodecanol	33.47	Silva et al. (2013)
	Pink flower	NI	Dodecanal, dodecanol, and α-pinene	42.22	Silva et al. (2013)
Hedychium coccineum Buch.-Ham. ex Sm.	Rhizome	USA	Linalool	NI[a]	Sakhanokho et al. (2013)
Hedychium 'Kinkaku'	Rhizome	USA	1,8-Cineol and β-pinene	NI[a]	Sakhanokho et al. (2013)
Hedychium 'Tai Golden Goddess'	Rhizome	USA	1,8-Cineol	NI[a]	Sakhanokho et al. (2013)
Zingiber officinale Roscoe	Rhizome	India	NI	40.5	Kalaivani et al. (2012)
	Rhizome	NI	α-Zingiberene	76.07	Silva (2012)
	Rhizome	India	NI	100	Prajapati et al. (2005)

NI information is not available

[a] Results expressed as percentage of larval mortality

pectinata (L.) Poit. This oil exhibited an LC_{50} value of 366 mg/L against *A. aegypti* larvae, whereas the LC_{50} value of β-caryophyllene was 1,202 mg/L and that of caryophyllene oxide was 125 mg/L.

Through this review, we observed that the lowest LC_{50} values of essential oils were lower than that of their isolated compounds. For example, among the oils tested, the wood essential oil from *C. glaucophylla* (LC_{50}=0.69 mg/L) showed

Table 2 Plant essential oils considered not active (LC_{50}>100 mg/L) against *Aedes aegypti* L. (Diptera: Culicidae) larvae

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Amaranthaceae					
Achyranthes aspera L.	Leaves	India	NI	761	Khandagle et al. (2011)
	Stems	India	NI	668	Khandagle et al. (2011)
Anacardiaceae					
Schinus pearcei Engl.	Leaves	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Schinus polygamous (Cav.) Cabrera	Leaves	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Schinus terebenthifolia Raddi	Fruits	Southeast of Brazil	δ-3-Carene	117.34	Cole (2008)
	Fruits	Southeast of Brazil	δ-3-Carene	NI[a]	Silva et al. (2010)
Annonaceae					
Rollinia leptopetala R.E. Fr.	Leaves	Northeast of Brazil	Linalool and 1,8-cineol	104.7	Feitosa et al. (2009)
Apiaceae					
Coriandrum sativum L.	Seed	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Cuminum cyminum L.	Seed	India	NI	>150	Prajapati et al. (2005)
Asteraceae					
Eupatorium buniifolium Hook. ex Arn.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Ageratum conyzoides L.	Leaves	Northeast of Brazil	NI	148	Mendonça et al. (2005)
Artemisia abrotanum L.	NI	Cuba	NI	193	Leyva et al. (2008)
Artemisia afra Jacq. ex Willd.	Flowering	NI	NI	NI[a]	Seo et al. (2012)
Artemisia vulgaris L.	Leaves	Northeast of Brazil	NI	114.1	Lavor et al. (2012)
Baccharis dracunculifolia DC.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Baccharis genistelloides (Lam.) Pers.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Baccharis latifolia (Ruiz & Pav.) Pers.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Baccharis pentandlii DC.	Leaves	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Baccharis salicifolia (Ruiz & Pav.) Pers.	Leaves	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Chrysanthemum parthenium (L.) Bernh.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Coniza rurigena Neck.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Eupatorium betonicaeforme (DC.) Baker	Aerial	Northeast of Brazil	β-Caryophyllene	NI[a]	Albuquerque et al. (2004)
Gnaphalium gaudichaudianum DC.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Parastrephia lepidophylla (Wedd.) Cabrera	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Pectis apodocephala Baker	Aerial	Northeast of Brazil	Citral	NI[a]	Albuquerque et al. (2007)
Pluchea fastigiata Griseb.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Porophylum ruderale (Jacq.) Cass.	Leaves and flowers	Northeast of Brazil	(*E*)-β-Ocimene	173.65	Fontes-Jr et al. (2012)
Saussurea lappa (Decne.) Sch. Bip.	Roots	Pakistan	NI	128.89	Manzoor et al. (2013)
Senecio hebetatus Wedd.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Tagetes elliptica Sm.	Aerial	Peru	6,7-Epoxy myrcene and dihydrotagetone	111	Ruiz et al. (2011)
Tagetes minuta L.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Cupressaceae					
Calocedrus formosana (Florin) Florin	Sapwood	Taiwan	NI	104.8	Cheng et al. (2003)
Cunninghamia lanceolata (Lamb.) Hook.	Heartwood	Taiwan	NI	106.4	Cheng et al. (2003)
	Sapwood	Taiwan	NI	172.2	Cheng et al. (2003)
Taiwania cryptomerioides Hayata	Sapwood	Taiwan	NI	240	Cheng et al. (2003)

Table 2 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
Cyperaceae					
Cyperus scariosus R. Br.	Flower	India	NI	>250	Prajapati et al. (2005)
Euphorbiaceae					
Croton argyrophylloides Müll. Arg.	Leaves	Northeast of Brazil	α-Pinene	102	Morais et al. (2006)
Croton heliotropiifolius Kunth	Leaves	Northeast of Brazil	β-Caryophyllene	544	Doria et al. (2010)
	Leaves	Northeast of Brazil	β-Caryophyllene	550.68	Silva (2006)
Croton pulegiodorus Baill.	Leaves	Northeast of Brazil	β-Caryophyllene	158.81	Silva (2006); Doria et al. (2010)
Croton sonderianus Müll. Arg.	Leaves	Northeast of Brazil	β-Phelandrene and β-*trans*-guaiene	104	Morais et al. (2006)
Fabaceae					
Copaifera reticulata Ducke	Resin	NI	NI	NI[a]	Seo et al. (2012)
Pterodon polygalaeflorus Benth.	Dried fruits	Northeast of Brazil	β-Caryophyllene	134.9	Pimenta et al. (2006)
Lamiaceae					
Hedeoma mandoniana Wedd.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Hyptis fruticosa Salzm. Ex Benth.	Leaves	Northeast of Brazil	1,8-Cineol	502	Silva et al. (2008)
Hyptis pectinata (L.) Poit.	Leaves	Northeast of Brazil	β-Caryophyllene and caryophyllene oxide	366	Silva et al. (2008)
Hyptis suaveolens (L.) Poit.	Leaves and branches	Northeast of Brazil	1,8-Cineol and *trans*-caryophyllene	261	Cavalcanti et al. (2004)
Lavandula hybrida E. Rev. ex Briq.	Flowering	NI	NI	NI[a]	Seo et al. (2012)
Lepechinia floribunda (Benth.) Epling	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Lepechinia graveolens (Regel) Epling	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Mentha arvensis L.	Leaves	Pakistan	NI	114.33	Manzoor et al. (2013)
	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Mentha piperita L.	Leaves	India	Menthol	111.9	Kumar et al. (2011)
Minthostachys andina (Britton ex Rusby) Epling	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Ocimum basilicum L.	Leaves	India	NI	200	Prajapati et al. (2005)
	Leaves	India	NI	148.5	Kalaivani et al. (2012)
	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Rosmarinus officinalis L.	Shoot	India	NI	>250	Prajapati et al. (2005)
	NI	NI	NI	>500	Waliwitiya et al. (2009)
Salvia hankei E. Peter	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Satureja boliviana (Benth.) Briq.	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Lauraceae					
Aniba duckei Kosterm.	Leaves	Brazilian Amazon	Linalool	250.61	Teles (2009)
Cinnamomum cordatum Kosterm.	Leaves	Malaysia	Linalool and methyl cinnamate	183.6	Jantan et al. (2005)
Cinnamomum osmophloeum Kaneh.	Leaves	Taiwan	T-cadinol and α-cadinol	108	Cheng et al. (2004)
	Leaves	Taiwan	Camphor	115	Cheng et al. (2004)
	Leaves	Taiwan	NI	120	Cheng et al. (2003)
	Leaves	Taiwan	Linalool	177	Cheng et al. (2004)
Cinnamomum zeylanicum Blume.	Bark	India	NI	>150	Prajapati et al. (2005)
Guarea convergens T.D. Penn.	Branches	Brazilian Amazon	α-Santalene and α-copaene	145	Magalhães et al. (2010)
Guarea silvatica C. DC.	Leaves	Brazilian Amazon	Caryophyllene oxide	117.8	Magalhães et al. (2010)

Table 2 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
	Branches	Brazilian Amazon	Spathulenol	273.6	Magalhães et al. (2010)
Myrtaceae					
Eucalyptus cinerea F. Muell. ex Benth.	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2008)
Eucalyptus citriodora Hook	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
	NI	NI	NI	NI[a]	Park et al. (2011)
Eucalyptus dives Schauer	NI	NI	NI	NI[a]	Park et al. (2011)
Eucalyptus globulus Labill.	NI	India	NI	106.21	Tennyson et al. (2013)
	NI	NI	1,8-Cineol	NI[a]	Park et al. (2011)
Eucalyptus globulus subsp. *maidenii* (F. Muell.) J.B. Kirkp.	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2008)
Eucalyptus globulus subsp. *globulus* Labill.	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2008)
Eucalyptus polybractea R. T. Baker	NI	NI	NI	NI[a]	Park et al. (2011)
Eucalyptus radiata Sieber ex DC	NI	NI	NI	NI[a]	Park et al. (2011)
Eucalyptus sideroxylon A. Cunn. ex Woolls	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2008)
Eucalyptus smithii R. T. Baker	NI	NI	NI	NI[a]	Park et al. (2011)
Eucalyptus viminalis Labill.	Leaves	Argentina	1,8-Cineol	NI[a]	Lucia et al. (2008)
Leptospermum petersonii F. M. Bailey	NI	NI	NI	NI[a]	Park et al. (2011)
Melaleuca cajuputi Powell	Leaves	NI	NI	NI[a]	Seo et al. (2012)
Melaleuca uncinata R. Br.	NI	NI	NI	NI[a]	Park et al. (2011)
Myrcia ovata Cambess.	Leaves	Northeast of Brazil	Neral and geranial	192	Lima et al. (2011)
Plinia cerrocampanensis Barrie	Leaves	Panama	α-Bisabolol	NI[a]	Vila et al. (2010)
Syzygium aromaticum (L.) Merr. & L.M. Perry	NI	India	NI	135.20	Tennyson et al. (2013)
Syzygium jambolana (Lam.) DC.	Leaves and branches	Northeast of Brazil	(*Z*)-Ocimene and (*E*)-ocimene	433	Cavalcanti et al. (2004)
Pinaceae					
Cedrus atlantica (Endl.) Manetti ex Carrière	Wood	India	NI	947.09	Tennyson et al. (2013)
Pinus radiata D. Don	NI	India	NI	182.28	Tennyson et al. (2013)
Piperaceae					
Piper gaudichaudianum Kunth	Leaves	Brazilian Amazon	Viridiflorol and aromadendrene	121	Morais et al. (2007)
Piper humaytanum Yunck.	Leaves	Brazilian Amazon	Caryophyllene oxide and β-selinene	156	Morais et al. (2007)
Piper tuberculatum Jacq.	Leaves	Northeast of Brazil	NI	106.3	Lavor et al. (2012)
Poaceae					
Cymbopogon citratus (DC.) Stapf	Leaves	Pakistan	NI	136.28	Manzoor et al. (2013)
	Aerial	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Cymbopogon nardus (L.) Rendle	NI	India	NI	1374.05	Tennyson et al. (2013)
Cymbopogon flexuosus (Nees ex Steud.) Wats.	Leaves	Northeast of Brazil	NI	121.6	Lavor et al. (2012)
	NI	India	NI	138.36	Tennyson et al. (2013)
Ranunculaceae					
Nigella sativa L.	Seed	India	NI	>250	Prajapati et al. (2005)
Rutaceae					
Clausena anisata (Willd.) Hook. f. ex Benth	Leaves	India	β-Pinene and sabinene	130.19	Govindarajan (2010)
Clausena dentata (Willd.) Roem.	Leaves	India	Sabinene, biofloratriene, and borneol	140.2	Rajkumar and Jebanesan (2010)
Citrus limonia (L.) Osbeck	Fruit peels	Northeast of Brazil	Limonene	519	Cavalcanti et al. (2004)
Citrus sinensis (L.) Osbeck	Fruit peels		Limonene	538	Cavalcanti et al. (2004)

Table 2 (continued)

Family and plant species	Part used	Plant origin	Major constituents	LC_{50} (mg/L)	Reference
		Northeast of Brazil			
Verbenaceae					
Aloysia gratíssima (Gillies & Hook.) Tronc.	Leaves	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Lantana montevidensis (Spreng) Briq.	Leaves	Northeast of Brazil	(*Z*)-Caryophyllene and valencene	117	Costa et al. (2010b)
Zingiberaceae					
Alpinia zerumbet (Pers.) B.L. Burtt & R.M. Sm.	Leaves and branches	Northeast of Brazil	1,8-Cineol and terpinen-4-ol	313	Cavalcanti et al. (2004)
Boesenbergia pandurata (Roxb.) Schltr.	Rhizome	Malaysia	NI	149.2	Jantan et al. (2003)
Costus albiflora A. Chev. ex Koechlin	Root	Bolivia	NI	NI[a]	Chantraine et al. (1998)
Curcuma aeruginosa Roxb.	Rhizome	Malaysia	NI	103.1	Jantan et al. (2003)
Curcuma longa L.	Rhizome	India	NI	>100	Prajapati et al. (2005)
	Rhizome	India	NI	115.6	Kalaivani et al. (2012)
Hedychium bousigonianum Pierre ex Gagnep.	Rhizome	USA	1,8-cineol and β-pinene	NI[a]	2013
Hedychium 'Dave Case'	Rhizome	USA	1,8-Cineol and (*E*)-nerolidol	NI[a]	Sakhanokho et al. 2013
Hedychium 'Dr. Moy'	Rhizome	USA	1,8-Cineol	NI[a]	Sakhanokho et al. 2013
Hedychium elatum Horan.	Rhizome	USA	β-Pinene and linalool	NI[a]	Sakhanokho et al. 2013
Hedychium flavescens Carey ex Roscoe	Rhizome	USA	Linalool and β-pinene	NI[a]	Sakhanokho et al. 2013
Hedychium flavum Roxb.	Rhizome	USA	1,8-Cineol and β-pinene	NI[a]	Sakhanokho et al. 2013
Hedychium forrestii Diels	Rhizome	USA	Linalool	NI[a]	Sakhanokho et al. 2013
Hedychium 'Pink Sparks'	Rhizome	USA	1,8-Cineol and α-humulene	NI[a]	Sakhanokho et al. 2013
Hedychium 'Pink V'	Rhizome	USA	1,8-Cineol	NI[a]	Sakhanokho et al. 2013
Hedychium 'Tai Conch Pink'	Rhizome	USA	1,8-Cineol and (*E*)-nerolidol	NI[a]	Sakhanokho et al. 2013
Hedychium 'Tai Emperor'	Rhizome	USA	1,8-Cineol and α-pinene	NI[a]	Sakhanokho et al. 2013
Hedychium 'Tai Empress'	Rhizome	USA	1,8-Cineol	NI[a]	Sakhanokho et al. 2013
Hedychium 'Tai Mammoth'	Rhizome	USA	1,8-Cineol and linalool	NI[a]	Sakhanokho et al. 2013
Hedychium 'Tai Monarch'	Rhizome	USA	Linalool and 1,8-cineol	NI[a]	Sakhanokho et al. 2013
Hedychium thyrsiforme Sm.	Rhizome	USA	1,8-Cineol and β-pinene	NI[a]	Sakhanokho et al. 2013
Hedychium 'White Starburst'	Rhizome	USA	1,8-Cineol and β-pinene	NI[a]	Sakhanokho et al. (2013)
Zingiber cassumunar Roxb.	Rhizome	Malaysia	NI	NI	Jantan et al. (2003)
Zingiber officinale Roscoe	Rhizome	Malaysia	NI	197.2	Jantan et al. (2003)
	Rhizome	India	NI	154	Khandagle et al. (2011)
Zingiber zerumbet (L.) Roscoe ex Sm.	Rhizome	Malaysia	NI	102.6	Jantan et al. (2003)

NI information is not available.

[a] Results expressed as percentage of larval mortality

the highest larvicidal potential, whereas the lowest LC_{50} value exhibited for an isolated compound (phenylpropanoids benzyl benzoate and benzyl salicylate) from essential oil was 6.8 mg/L.

The blends of compounds, rather than isolated ones, confer the ecological role of essential oils on plant defence. This shows us the importance of the complexity of chemical composition of the natural products. Understanding the mechanisms involved in synergistic phenomenon is meaningful for the improvement of essential oil-based larvicidal products.

These results support the idea of using complex natural product without the isolation of the active compound. The production and marketing of essential oil can be much cheaper than that of larvicide compounds since the necessary process for the isolation or synthesis of the latter is more expensive. Therefore, it is possible to obtain an essential oil-based, economically viable larvicidal product obtained from a renewable resource, with greater acceptance by the population. Thus, scientific research in this segment should be encouraged to contribute to the development of such larvicidal products.

Table 3 Metabolites from essential oils considered active (LC_{50}<100 mg/L) against *Aedes aegypti* L. (Diptera: Culicidae) larvae

Classes	Constituents	LC_{50} (mg/L)	Reference
Monoterpene hydrocarbons	δ-3-Carene	25.3	Cheng et al. (2009a)
		19.2	Perumalsamy et al. (2009)
		60	Kim et al. (2008)
	(−)-Camphene	67	Perumalsamy et al. (2009)
	p-Cymene	19.2	Cheng et al. (2009b)
		37.1	Cheng et al. (2009c)
		43.3	Cheng et al. (2009a)
		51	Santos et al. (2010)
		69.4	Cheng et al. (2013)
		NI[a]	Park et al. (2011)
	Fenchene	69.28	Perumalsamy et al. (2009)
	Limonene	18.1	Cheng et al. (2009b)
		19.4	Cheng et al. (2009a)
		12.01	Govindarajan et al. (2012)
	R-(+)-Limonene	27	Santos et al. (2011)
		24.47	Perumalsamy et al. (2009)
		37	Silva et al. (2008)
		71.9	Cheng et al. (2013)
		NI[a]	Park et al. (2011)
	S-(−)-Limonene	30	Santos et al. (2011)
		NI[a]	Park et al. (2011)
	β-Myrcene	27.9	Cheng et al. (2009a)
		35.8	Cheng et al. (2009c, 2013)
		66.42	Perumalsamy et al. (2009)
	α-Phellandrene	16.6	Cheng et al. (2009b)
		23.08	Perumalsamy et al. (2009)
	α-Pinene	15.4	Lucia et al. (2007)
		79.1	Cheng et al. (2009c)
	(+)-α-Pinene	50.92	Perumalsamy et al. (2009)
		74.3	Simas et al. (2004)
	(−)-α-Pinene	64.80	Perumalsamy et al. (2009)
	β-Pinene	27.69	Govindarajan (2010)
		12.1	Lucia et al. (2007)
	(+)-β-Pinene	22.39	Perumalsamy et al. (2009)
		42.5	Simas et al. (2004)
	(−)-β-Pinene	15.40	Perumalsamy et al. (2009)
	Sabinene	21.2	Govindarajan (2010)
		27.3	Rajkumar and Jebanesan (2010)
		74.1	Cheng et al. (2013)
	α-Terpinene	14.7	Cheng et al. (2009b)
		28.1	Cheng et al. (2009c)
		NI[a]	Park et al. (2011)
	γ-Terpinene	17.11	Perumalsamy et al. (2009)
		26.8	Cheng et al. (2009a)
		30.7	Cheng et al. (2009b, c)
		56	Santos et al. (2011)
		95	Silva et al. (2008)
		NI[a]	Park et al. (2011)
	Terpinolene	28.4	Cheng et al. (2009b, c)
		32.1	Cheng et al. (2009a)
		15.32	Perumalsamy et al. (2009)
Oxygenated monoterpenes	Ascaridole	9.6	Torres et al. (2008)
	Borneol	43.5	Rajkumar and Jebanesan (2010)
		94.9	Perumalsamy et al. (2009)
	Camphene	67.02	Perumalsamy et al. (2009)
	Carvacrol	58.9	Lima et al. (2011)
		69	Santos et al. (2010)
		70	Silva et al. (2008)
	cis-Carveol	32.88	Govindarajan et al. (2012)
	RS-Carvone	23.69	Govindarajan et al. (2012)
		118	Santos et al. (2011)
	R-(−)-Carvone	152	Santos et al. (2011)
		43.8	Simas et al. (2004)
	S-(+)-Carvone	124	Santos et al. (2011)
	1,8-Cineol	47.9	Lima et al. (2011)
		57.2	Lucia et al. (2007)
		74.9	Perumalsamy et al. (2009)
	Citronellol	49.9	Ali et al. (2013b)
	Geraniol	49.3	Ali et al. (2013b)
		81.6	Simas et al. (2004)
	Geranyl formate	58.5	Ali et al. (2013b)
	Linalool	38.64	Govindarajan (2010)
		96.6	Perumalsamy et al. (2009)
	Pulegone	48.7	Waliwitiya et al. (2009)

Table 3 (continued)

Classes	Constituents	LC_{50} (mg/L)	Reference
	Terpinen-4-ol	64.76	Perumalsamy et al. (2009)
	Thymol	53.5	Waliwitiya et al. (2009)
		79	Silva et al. (2008)
		81	Santos et al. (2010)
		NI[a]	Carvalho et al. (2003)
	3,5-dimethoxytoluene	64.05	Perumalsamy et al. (2009)
	3,4,5-Trimethoxytoluene	67.13	Perumalsamy et al. (2009)
	Verbenone	93.16	Perumalsamy et al. (2009)
Sesquiterpene hydrocarbons	Germacrene D	18.76	Govindarajan (2010)
		63.6	Kiran et al. (2006)
	Geijerene	43.4	Kiran et al. (2006)
	β-Caryophyllene	88.3	Perumalsamy et al. (2009)
	Pregeijerene	28.3	Kiran et al. (2006)
Oxygenated Sesquiterpenes	β-Bisabolol	33.2	Rajkumar and Jebanesan (2010)
	(*E*),(*E*)-Farnesol	13	Simas et al. (2004)
	(*E*)-Nerolidol	9.0	Chantraine et al. (1998)
		13.4	Ali et al. (2013b)
		17.0	Simas et al. (2004)
		NI[aa]	Park et al. (2011)
Diterpenes	16-Kaurene	57	Cheng et al. (2009c)
Phenylpropanoids	(*E*)-Anethole	14.8	Chantraine et al. (1998)
		42	Cheng et al. (2004)
		88.5	Waliwitiya et al. (2009)
		69.2	Santos et al. (2007)
	(*E*)-Asarone	27	Perumalsamy et al. (2009; 2010)
	(*Z*)-Asarone	16[b]	Ciccia et al. (2000)
	Benzyl benzoate	6.8	Jantan et al. (2005)
	Benzyl salicylate	6.8	Jantan et al. (2005)
	(*E*)-Cinnamaldehyde	24.4	Simas et al. (2004)
		29	Cheng et al. (2004)
		51.3	Kim et al. (2008)
	Cinnamyl acetate	33	Cheng et al. (2004)
	Methyl cinnamate	16.8	Jantan et al. (2005)
		26	Cheng et al. (2004)
	Ethyl cinnamate	39.5	Kim et al. (2008)
		33	Cheng et al. (2004)
	Ethyl-*p*-methoxycinnamate	18.9	Kim et al. (2008)
	p-Methoxycinnamic acid	61	Kim et al. (2008)
	Eugenol	33	Cheng et al. (2004)
		44.5	Simas et al. (2004)
		79.39	Nascimento (2012)
		82.8	Pandey et al. (2013)
		88	Santos et al. (2010)
		89.9	Jantan et al. (2005)
	Methyleugenol	57.65	Perumalsamy et al. (2009, 2010)
	Estragole	12.7	Govindarajan (2010)
		46.4	Perumalsamy et al. (2009)
	Myristicin	72.98	Perumalsamy et al. (2009)
	Safrole	49	Simas et al. (2004)
		32.1	Jantan et al. (2005
		9.88	Perumalsamy et al. (2009)
	2,2-Dimethyl-6-vinylchroman-4-one	NI[a]	Albuquerque et al. (2004)
	2-Senecioyl-4-vinylphe-nol	NI[a]	Albuquerque et al. (2004)
Others	Hexyl butyrate	74.9	Tabanca et al. (2012a)
	Undecan-2-one	14.37	Tabanca et al. (2012b)

NI information is not available

[a] Results expressed as percentage of larval mortality

[b] Result expressed as LC_{90} (in milligrams per litre)

An additional way to develop more effective natural products for use in mosquito control is by adding the synthetic compound piperonyl butoxide (PBO) to natural compounds. PBO is an inhibitor of microsomal mono-oxygenases, which are involved in the metabolism and detoxification of insecticides (Kumar et al. 2002). Waliwitiya et al. (2009) reported the synergistic effect of PBO and phytochemicals. Their study showed that plant-based products containing PBO were more active, such that their required concentrations were comparable to those of conventional larvicides.

Factors affecting the larvicidal potential of essential oils and their compounds

The toxic potential of essential oils and their compounds against *A. aegypti* larvae may vary significantly according to intrinsic and extrinsic factors. Plant species, plant parts, age of

Table 4 Metabolites from essential oils considered not active (LC_{50}>100 mg/L) against *Aedes aegypti* L. (Diptera: Culicidae) larvae

Classes	Constituents	LC_{50} (mg/L)	Reference
Monoterpene hydrocarbons	3-Carene	150	Santos et al. (2010)
	Myrcene	>500	Waliwitiya et al. (2009)
		NI[a]	Chantraine et al. (1998), Park et al. (2011)
	α-Phellandrene	NI[a]	Park et al. (2011)
	α-Pinene	>100	Cheng et al. (2013)
		>500	Waliwitiya et al. (2009)
		NI[a]	Chantraine et al. (1998), Park et al. (2011)
	β-Pinene	>500	Waliwitiya et al. (2009)
		NI[a]	Park et al. (2011)
Oxygenated monoterpenes	(+)-Borneol	>100	Kim et al. (2008)
	(−)-Borneol	>100	Kim et al. (2008)
	Borneol	610	Santos et al. (2010)
		>500	Waliwitiya et al. (2009)
	Borneol acetate	>500	Waliwitiya et al. (2009)
	Isoborneol	598	Santos et al. (2010)
	(−)-Camphene	>100	Kim et al. (2008)
		220	Santos et al. (2010)
	(+)-Camphene	406	Santos et al. (2010)
	Camphor	271.5	Jantan et al. (2005)
		>500	Waliwitiya et al. (2009)
		657	Santos et al. (2010)
	1,4-Cineol	751	Santos et al. (2010)
	1,8-Cineol	>100	Kim et al. (2008)
		642.4	Jantan et al. (2005)
		1,381	Silva et al. (2008)
		1,419	Santos et al. (2010)
		NI[a]	Chantraine et al. (1998), Park et al. (2011)
	Citral	NI	Ali et al. (2013b)
	Citronellal	262.9	Waliwitiya et al. (2009)
		>100	Simas et al. (2004)
	Citronellyl formate	>100	Ali et al. (2013b)
	Eucarvone	130.35	Perumalsamy et al. (2009)
	Geranic acid	>100	Ali et al. (2013b)
	Geraniol	415	Pandey et al. (2013)
	Limonene oxide	517	Santos et al. (2011)
	Linalool	>100	Simas et al. (2004), Ali et al. (2013b)
		157.4	Jantan et al. (2005)
		242.6	Pandey et al. (2013)
		>500	Waliwitiya et al. (2009)
		NI[a]	Chantraine et al. (1998), Park et al. (2011)
	Menthol	>100	Simas et al. (2004)
		365.8	Pandey et al. (2013)
		404	Santos et al. (2011)
	Menthone	508	Santos et al. (2011)
	Isomenthone	NI	Ali et al. (2013b)
	Pulegone	NI[a]	Chantraine et al. (1998)
	Isopulegol	297	Santos et al. (2011)
	Neoisopulegol	554	Santos et al. (2011)
	Terpineol	331.7	Pandey et al. (2013)
	α-Terpineol	>100	Cheng et al. (2013)
		111.78	Perumalsamy et al. 2009
		NI[a]	Chantraine et al. (1998), Park et al. (2011)
	(+)-α-Terpineol	>100	Kim et al. (2008)
	(−)-α-Terpineol	>100	Kim et al. (2008)
	Terpinen-4-ol	220.5	Jantan et al. 2005
		NI[a]	Chantraine et al. (1998), Park et al. (2011)
	(−)-Terpinen-4-ol	>100	Cheng et al. (2009c)
Sesquiterpene hydrocarbons	β-Caryophyllene	1,038	Doria et al. (2010)
		1,202	Silva et al. (2008)
		NI[a]	Park et al. (2011)
	α-Cedrene	>100	Cheng et al. (2013)
	β-Cedrene	>100	Cheng et al. (2013)
	α-Humulene	NI[a]	Park et al. (2011)
Oxygenated sesquiterpenes	α-Cadinol	>100	Cheng et al. (2013)
	Caryophyllene oxide	125	Silva et al. (2008)
	Cedrol	>100	Cheng et al. (2013)
	Elemol	>100	Cheng et al. (2009c)
	β-Eudesmol	>100	Cheng et al. (2009c)
Phenylpropanoids	Eugenol	142.9	Waliwitiya et al. (2009)
	Methyleugenol	350.9	Jantan et al. (2005)
Others	Hexyl isobutyrate	106.3	Tabanca et al. (2012a)
	Hexyl-2-methyl butyrate	107.7	Tabanca et al. (2012a)
	Octyl acetate	148.9	Tabanca et al. (2012a)

NI information is not available

[a] Results expressed as percentage of larval mortality

the plant, chemotypes, and geographic conditions (such as season, rainfall, humidity percentage, temperature, sunlight, and altitude) in which the plant was collected, larval source, and methods used, in general, induce different larval responses (Morais 2009; Barbosa et al. 2012b).

Cheng et al. (2003) demonstrated that essential oils from the heartwood, bark, leaves, and sapwood of *Calocedrus formosana* (Florin) Florin presented different degrees of activity, e.g. essential oil from sapwood was less toxic than essential oil from leaves. Similar results were observed in the same study for heartwood and sapwood oil of *Taiwania*

cryptomerioides Hayata; the essential oil obtained from heartwood was active against *A. aegypti* larvae (LC_{50}=79.8 mg/L) and that from sapwood was inactive (LC_{50}=240 mg/L).

Arriaga et al. (2007) revealed that the essential oil from the stem of *Stemodia maritima* L. exhibited an LC_{50} of 22.9 mg/L, whereas the essential oil from the leaves of this species was less active (LC_{50}=55.4 mg/L). The essential oil from *Rollinia leptopetala* R.E. Fr. stem (LC_{50}=34.7 mg/L) was also more active than that from its leaves (LC_{50}=104.7 mg/L) (Feitosa et al. 2009). These results can be explained by the differences in the chemical composition of essential oils from distinct plant parts.

Cheng et al. (2009c) compared the larvicidal potential of essential oils from leaves of *C. japonica* at different ages (58, 42, and 26 years old). Although the percentage of the two major compounds (16-kaurene and elemol) in the oils were not significantly different among the three samples, their toxicity against *A. aegypti* larvae varied. The 58-year-old tree was the most active, showing a LC_{50} of 28.4 mg/L, compared with the 42-year-old (LC_{50}=39.2 mg/L) and the 26-year-old tree (LC_{50}=56.7 mg/L). These results indicated that essential oils obtained from the trees at different ages have a significant influence on *A. aegypti* larvicidal activity.

Five chemotypes of indigenous *Cinnamomum osmophloeum* Kaneh. exhibited different larvicidal potential; the linalool type, camphor type, and mixed type (T-cadinol and α-cadinol) were considered inactive (LC_{50}>100 mg/L), whereas the cinnamaldehyde type and cinnamaldehyde/cinnamyl acetate types were highly active (LC_{50}<50 mg/L) (Cheng et al. 2004).

Additionally, the different ecological niches of mosquito larvae can influence their susceptibility to toxic compounds. It was hypothesized that the field-collected larvae are more resistant to chemicals than those reared in laboratory because the former are better adapted to adjust to environmental variations and have a higher genetic variability (George and Vincent 2005; Sun et al. 2006). Simas et al. (2004) tested (*R*)-(−)-carvone against larvae reared in laboratory for more than 10 years and showed that this compound has a good larvicidal potential (LC_{50}= 43.8 mg/L). However (*R*)-(−)-carvone was not active (LC_{50}=158 mg/L) when tested against larvae collected in fields that are known to have larvae strains resistant to temephos (Santos et al. 2011).

Barbosa et al. (2012a) tested some compounds and *Syzygium aromaticum* (L.) Merr. essential oil against a field-collected strain that is resistant to temephos and also tested them against the Rockefeller strain, which is susceptible to temephos. It was possible to observe different results for both strains, such as in the case of eugenol, which exhibited LC_{50} values of 93 and 71 mg/L in field-collected and Rockefeller larvae, respectively. However, the results do not illustrate a statistically significant difference. This finding indicates that *S. aromaticum* essential oil and analysed compounds like eugenol do not exhibit cross-resistance with temephos.

Another factor that can change the potential of compounds is the larval instar (Thanigaivel et al. 2012). There are four mosquito larval stages (Consoli and Oliveira 1994). Waliwitiya et al. (2009) investigated the toxicity of several monoterpenes, *trans*-anethole, and *Rosmarinus officinalis* L. essential oil against *A. aegypti* larvae of first to fourth instars; they observed that the activity of the samples decreased according to larval growth. During larval growth, the larvae acquire higher capacity of detoxification and development alterations in cuticle thickness. These larval features may contribute to decreased larvicidal efficacy of a compound.

Different methodologies and analyses used in the experiments can also lead to contradictory results (Santos et al. 2010; Patil et al. 2011; Barbosa et al. 2012a). For example, methyleugenol was reported to be active (LC_{50}=57.6 mg/L) by Perumalsamy et al. (2010) and inactive (LC_{50}=350.9 mg/L) by Jantan et al. (2005). Silva et al. (2008) showed that the LC_{50} value of β-caryophyllene was 1,202 mg/L, whereas Perumalsamy et al. (2009) observed an LC_{50} value of 88.3 mg/L. Likewise, different larvicidal activities against *A. aegypti* larvae have been reported for other compounds such as 1,8-cineol, α-pinene, β-pinene, (−)-camphene, and linalool in different studies. These varying results probably stem from differences in the methodology performed to measure the larvicidal activity (Tables 3 and 4).

According to Lahlou (2004a), the biological tests results are dependent of laboratory conditions (temperature and photoperiod), materials, and models used for the experimentation. Standardization of the testing procedures is desirable in order to provide data, which can be compared and utilized by national authorities, from scientific researchers who carried out analyses in different laboratories and institutions (WHO 2009b).

Structure–activity relationships of essential oil compounds

The relation between larvicidal effect and essential oil chemical composition is difficult to determine because the interactions among the compounds may influence the activity of the mixture. Thus, some authors have identified chemical structural characteristics of major compounds of essential oils that may contribute to the understanding of larvicidal effects (Santos et al. 2010, 2011; Barbosa et al. 2012a).

Lipophilicity plays a key role in modulating larvicidal activity. The association between lipophilic compounds and protein deactivation/enzyme inhibition may be a reasonable explanation for this fact (Ryan and Byrne 1988). It was confirmed in a chemometric study applied to active compounds such as terpenes and phenylpropanoids. In this study, the larvicidal activity was strongly correlated with the independent variables having a hydrophobic profile (Scotti et al.

2013). We will explain in more detail the important structural characteristics for effective larvicidal activity of monoterpenes, sesquiterpenes, and phenylpropanoids and their derivatives.

Phenol (**1**) exhibited an LC_{50} value of 194 mg/L for *A. aegypti* larvae, whereas compounds that have lipophilic groups like CH chains outside a phenyl ring, e.g. thymol (**2**) (LC_{50}= 81 mg/L) and carvacrol (**3**) (LC_{50}=69 mg/L), displayed larvicidal activity higher than phenol (Santos et al. 2010).

The double bonds are important in the larvicidal activity of natural molecules because hydrogenation of these bonds decreases the lipophilic character of these compounds, restricting their passage through the larvae cuticle (Lomonaco et al. 2009). It is interesting to note the importance of exocyclic double bonds, for instance, in the comparison between α-pinene (**4**) and β-pinene (**5**). According to Simas et al. (2004), Lucia et al. (2007), and Peumalsamy et al. (2009), β-pinene, which possesses exocyclic double blond, is more toxic to *A. aegypti* larvae than α-pinene, which has endocyclic double bond (Table 2). Santos et al. (2011) demonstrated that the LC_{50} value of R-limonene (**6**) (with endo- and exocyclic double bonds) was 27 mg/L. The LC_{50} value of γ-terpinene (**8**), a compound with two endocyclic double bonds, was 56 mg/L.

The phenylpropanoids benzyl benzoate and benzyl salicylate were the most active compounds. The higher number of conjugated double bonds in the aromatic ring contributes to their high larvicidal potential. In general, aromatic molecules are more toxic to *A. aegypti* larvae than are aliphatic ones. The electronic density and aromatic ring planarity seem to influence positively the effectiveness of these substances (Santos et al. 2010).

Similarly, a high number of hydroxyl groups decrease potency (Scotti et al. 2013). López et al. (2005) reported that this structural characteristic prevents molecule penetration through the mosquito cuticle, which prevents the compound from reaching its specific targets. Although carvacrol (**3**) and thymol (**4**) have conjugated double bonds in their aromatic rings, they also have a hydroxyl group each and thus do not exhibit high larvicidal activity against *A. aegypti* (Santos et al. 2010). The same chemical structure without the hydroxyl group, represented by *p*-cymene (**9**), was more potent (LC_{50}=51 mg/L).

Barbosa et al. (2012a) evaluated structure–activity relationships of eugenol derivatives (**10**). The lowest potency was observed for the compound in which the double bond on the side chain was removed to add a hydroxyl (**11**) (LC_{50}=1, 415.1 mg/L). The derivative that was more potent than eugenol (LC_{50}=93.3 mg/L) was 1-ethoxy-2-methoxy-4-(2-propen-1-yl)-benzene (**12**) (LC_{50}=67.2 mg/L). This compound is different from eugenol because the phenolic proton of eugenol was removed and an ethyl group was added instead.

In general, acetylation of the hydroxyl group in oxygenated monoterpenes increases their activity (e.g. LC_{50} of eugenyl acetate was 50.2 mg/L). Some structural features such as shape, degree of unsaturation, and functional groups influence their larvicidal activity (Pandey et al. 2013).

A compound having an aliphatic aldehyde conjugated with an aromatic ring is quite potent. This fact was reinforced by comparing the larvicidal activity of (*E*)-cinnamaldehyde (**13**) (LC_{50}=24.4 mg/L) with that of citronellal (**14**), which is not aromatic and was inactive for larvae of *A. aegypti* (Simas et al. 2004). The studies by Cheng et al. (2004) and Santos et al. (2010) have also confirmed this data. The first study illustrated that the LC_{50} of benzaldehyde (**15**) after 48 h was 33 mg/L. The second study compared the bioactivity of phenol (**1**) (LC_{50}=194 mg/L) and salicylaldehyde (**16**) (LC_{50}=136 mg/L).

Some essential oils compounds have stereoisomers. The chiral compounds are recognized by receptors and enzymes in different ways. This influences their mode of action and leads to different biological activity (Lahlou 2004b). Table 2 shows different larvicidal potential for α-pinene and β-pinene enantiomers. In addition, the larvicidal potential of enantiomers (*S*)-(+)-carvone (**17**) (LC_{50}=124 mg/L) and (*R*)-(−)-carvone (**18**) (LC_{50}=152 mg/L) and (+)-camphene (**19**) (LC_{50}= 406 mg/L) and (−)-camphene (**20**) (LC_{50}=220 mg/L) was significantly different. In contrast, (*R*)-(+)-limonene (**6**) (LC_{50}=27 mg/L) and (*S*)-(−)-limonene (**7**) (LC_{50}=30 mg/L) exhibited similar activity profiles (Santos et al. 2010, 2011).

According to Santos et al. (2011), neo-isopulegol (**21**) exhibited an LC_{50} value of 554 mg/L. It was less potent than its diastereoisomer isopulegol (**22**) (LC_{50}=297 mg/L). However, this difference was not observed between borneol (**23**) (LC_{50}=610 mg/L) and isoborneol (**24**) (LC_{50}=598 mg/L) (Fig. 1) (Santos et al. 2010).

The evaluation of structure–activity relationships of larvicidal compounds may contribute to the search for additional compounds with similarly high or even higher activity. This knowledge may indicate synthesis pathways for the production of insecticides more effective and less toxic and, in addition, can promote the understanding of the mode of action of these larvicidal compounds.

Mode of action

Few studies have investigated the larvicidal mechanisms of action of essential oils and their compounds against *A. aegypti* larvae. Essential oils are complex mixtures of chemical compounds. Hence, several mechanisms of toxicity on insects could be involved. Protein denaturalization, enzymatic inhibition, and membrane disintegration are some of the suggested modes (Regnault-Roger 1997; Cavalca et al. 2010).

Insecticides can affect insects by various modes of action. They may be ingested and absorbed through the digestive tract. The respiratory system and the body may be the target by fumigants, suffocants, and desiccants. Furthermore, some

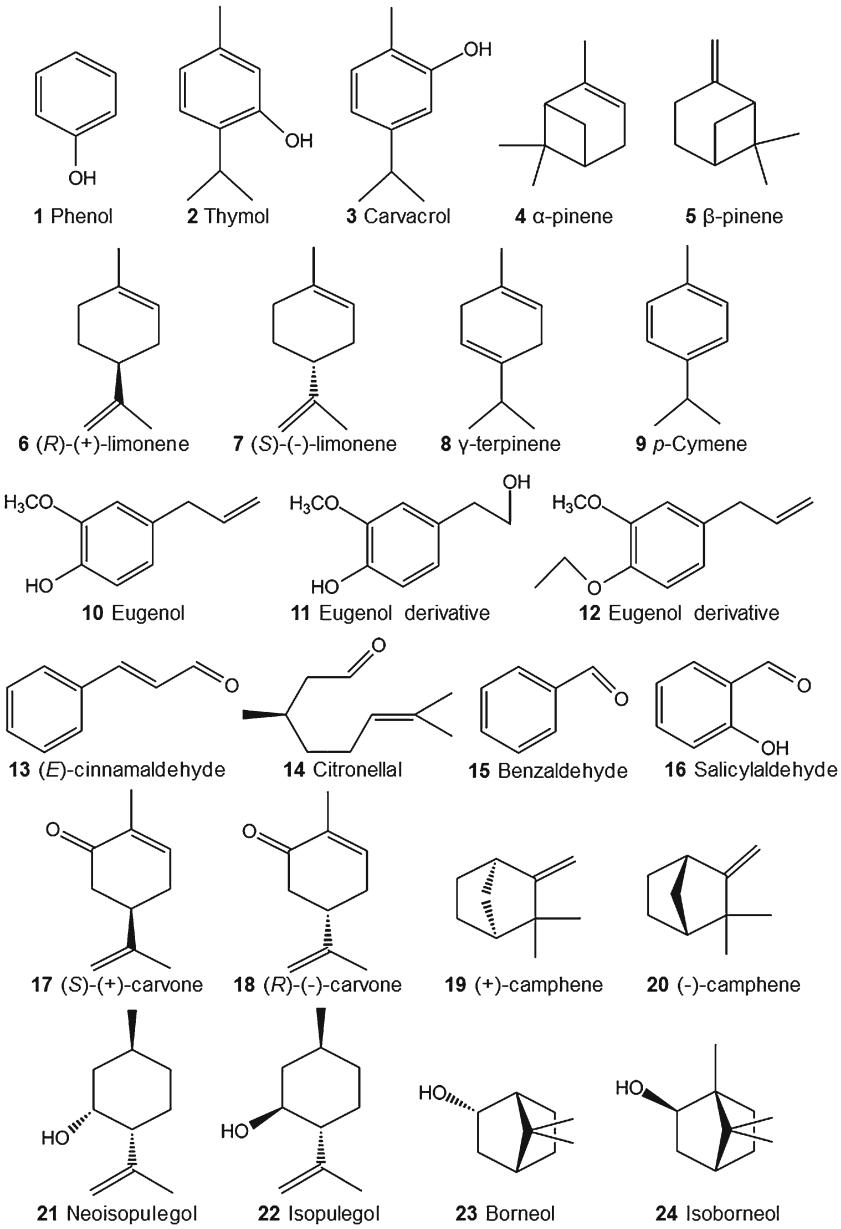

Fig. 1 Chemical structures of some compounds studied for their larvicidal activity against *Aedes aegypti* L. (Diptera: Culicidae)

compounds may act as hormones inhibiting the growth and development of the insect (Hemingway and Ranson 2005).

According to Cantrell et al. (2010), larvicide compounds act by absorption through the cuticle, via the respiratory tract, and/or enter by ingestion via the gastrointestinal tract. Once in the interior of the larva, the substances can reach the site of action or can cause systemic effects by diffusion into different tissues (Souza et al. 2012b).

In addition, the lipophilicity of the essential oils constituents enables disruption and penetration through the lipoprotein matrix of the insect cell membrane (Satyan et al. 2009). Franzios et al. (1997) indicate that many essential oils deter insect feeding, while some others act as insect growth regulators through analogs or antagonistic effects to endogenous hormones.

Some authors have suggested that the rapid effect on some natural larvicides is indicative of their neurotoxic mode of action. The symptoms of most larvae treated with essential oils are caused by toxicity to the neuromuscular system. These symptoms are excitation, convulsions, hyperactivity, and hyperextension of the legs and abdomen, followed by paralysis (fast knock-down) and death (Enan 2001; Isman 2006). According to Kostyukovsky et al. (2002), these effects are similar to those produced by conventional insecticides as temephos, an organophosphate cholinesterase inhibitor used in vector-borne disease control programmes (WHO 2009b).

Ryan and Byrne (1988) reported that five oxygenated monoterpenes were reversible competitive inhibitors of acetylcholinesterase (AChE) isolated from electric eels. Both

in vitro and in vivo experiments confirmed this. Nevertheless, in the studies by Kostyukovsky et al. (2002) and López and Pascual-Villalobos (2010), natural terpenes such as fenchone, γ-terpinene, geraniol, linalool, and (*S*)-carvone only inhibited AChE from *Electrophorus electricus* L. (Gymnotiformes: Gymnotidae) and from *Rhyzopertha dominica* F. (Coleoptera: Bostrichidae) at high concentrations, indicating that the AChE inhibition is not the main mode of action of these essential oil compounds.

Another potential target for the larvicidal activity of essential oil constituents is the octopaminergic system of insects. Octopamine is a biogenic monoamine that is present in neuronal and non-neuronal tissues of invertebrates. This compound acts as a neurotransmitter, neurohormone, and neuromodulator. Its physiological role is analogous to that of norepinephrine in vertebrates, influencing many features of animal physiology and behaviour, such as flight, energy metabolism regulation, and heart rate (Roeder 1999; Pflüger and Stevenson 2005). The octopamine receptors (ORs) are membrane-bound receptors that belong to the family of G protein-coupled receptors. Generally, interactions with ligands modulate effects via changes in intracellular calcium concentrations $[Ca^{2+}]_i$ and via activation or inhibition of adenylyl cyclase (Evans 1984).

Enan (2001) suggested that the toxicity of eugenol and α-terpineol to *Periplaneta americana* L. (Blattaria: Blattidae) (American cockroaches) uses the octopaminergic system as a primary target. The involvement of octopamine/octopamine receptor is indicated by toxicity signs as acceleration of heartbeat, effects on cyclic adenosine monophosphate (cAMP) production in the nervous system, and a decrease in binding octopamine receptors. Kostyukovsky et al. (2002), by in vitro studies using abdominal segments from *Helicoverpa armigera* Hübn (Lepidoptera: Noctuidae) (cotton bollworm moth) as a source of ORs, indicated that the mode of action of two essential oil terpenes on insects was a competitive activation of ORs. Enan (2005) proposed that ORs mediate the toxicity of cinnamic alcohol, eugenol, (*E*)-anethol, and 2-phenylethyl propionate against *Drosophila melanogaster* Meigen (Diptera: Drosophilidae) and *P. americana*, via cellular changes such as receptor binding, cAMP production, and $[Ca^{2+}]_i$ mobilization.

In a recent protein-ligand docking study, eugenol, geraniol, 1,8-cineol, and carvacrol as well as octopamine and acetylcholine were allowed to dock against OR and acetylcholinesterase protein models of *A. aegypti* and *Homo sapiens*. The study objective was to predict and rank the association between the ligands and the target proteins on two animal systems. The compounds docked with all the protein models, although they performed better against the protein models of *A. aegypti* than the human protein models (Khanikor et al. 2013).

Another receptor may be involved with the mode of action of essential oils. The insecticidal activity of the oxygenated monoterpene thymol was mediated by interferences of ionotropic GABA receptors. In addition, thymol was more potent on a recombinant insect GABA receptor than on mammalian $GABA_A$ receptors. However, the thymol-binding site on the GABA receptor has not been identified because thymol did not act via the site of action on the investigated allosteric modulators such as benzodiazepines, β-carbolines, barbiturates, propofol, loreclezole, and steroids (Priestley et al. 2003).

All the aforementioned facts indicate that these compounds may be considered safe to humans. Further studies should be carried out to confirm the mosquito larvicidal modes of action of essential oil constituents. With these data, it will be possible to find pharmacophore models that are necessary for molecular recognition by the receptors. Therefore, these findings can serve as a means to develop products more effective and less toxic to non-target organisms compared with the conventional larvicides used in vector-borne disease control programmes.

Essential oils comprise a complex mixture of constituents, and their larvicidal activity seems to have no specific site of action. Therefore, it is likely very difficult for the insect to develop an adaptation that leads to resistance (Wahyuni 2012).

Patents

The data cited in this paper illustrates the higher larvicidal potential of essential oils and their compounds toward *A. aegypti*. Thus, some patent applications were published with the purpose to regulate the production of formulations for use against *A. aegypti* larvae in the field.

One patent proposed a mosquito larvicide formulation in which the active agent is D-limonene, which is present in orange oil and ethyl lactate (WO2005034631A2). US patent application no. US3954991 also relates to the use of limonene. In this patent, however, limonene is condensed with sesamol to produce two novel compounds that are highly effective at killing mosquito larvae.

Two monoterpenes widely found in essential oils, *p*-cymene and thymol, were incorporated into a formulation that can be used as a larvicide and adulticide against mosquitoes belonging to the genus *Aedes* and *Anopheles* (US2009036547A1). The inventors reported that this composition is also useful against strains resistant to conventional insecticides. Japanese patent application no. 2000026210A includes spathulenol as an active ingredient of a formula insecticide to be used against *A. aegypti* and *Culex pipiens pallens* L. (Diptera: Culicidae).

French patent application no. FR2958500 describes a process for the preparation and use of an insecticide, insect repellent, ovicide, larvicide, and nymphicide composition. This composition comprises at least one essential oil or a mixture of them. These essential oils may originate from *Eucalyptus globulus* Labill., *Juniperus communis* L., *Santalum album* L., *Mentha piperita* L., *Eugenia caryophyllata* Thunb., *Pinus*

sylvestris L., *R. officinalis* L., *Eucalyptus citriodora* Hook., *Annona squamosa* L., among others.

International publication no. WO2011/032892A1 describes a synergistic combination of compounds for use as an ascaricide, insecticide, pupicide, and/or larvicide that comprises at least two active compounds. These may include fatty alcohols and simple oils as well as essential oils of peppermint, tangerine, grapefruit, lemon, and basil.

Although this review highlights the high potential of Brazilian plants, only one Brazilian patent was found in the database. The cited patent reports the use of essential oil from bracts of *Alpinia purpurata* (Viell.) K. Schum. as a larvicide and deterrent against *A. aegypti* (BRPI0805711-7A2).

Conclusion

In the search for alternative larvicides to be used in vector-borne disease control programmes, plant essential oils have demonstrated to be more active than their individual compounds against *A. aegypti*. This highest bioactivity of essential oils shows us the importance of producing a low-cost larvicide without the need to isolate an active compound, which is an expensive process. For this, selection of chemical markers is essential for the quality control of herbal products.

Although these natural products have been widely investigated, a low number of patents have been applied with the purpose of regulating the production of formulations for use against *A. aegypti* larvae in the field. This review demonstrates the need for standardization of methodologies for the evaluation of larvicides against *A. aegypti*.

The research regarding the search for new larvicides should be performed in a standardized manner. The features from plants (collection, extraction, chemical constitution) and insects (collection, age) and the methodological procedures must be well defined in research. We need to overcome the barriers to commercialization of new botanical insecticides. There has to be a paradigm shift in natural product research, in which studies are conducted with the ultimate goal of producing plant-based larvicides for use in public health programmes.

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References

Aciole SDG (2009) Avaliação da atividade inseticida dos óleos essenciais das plantas amazônicas Annonaceae, Boraginaceae e de mata atlântica Myrtaceae como alternativa de controle às larvas de *Aedes aegypti* (Linnaeus, 1762) (Diptera: Culicidae). Dissertation, University of Lisbon

Aciole SDG, Piccoli CF, Duquel JE, Costa EV, Navarro-Silva MA, Marques FA, Maia BLNS, Pinheiro MLB, Rebelo MT (2011) Insecticidal activity of three species of *Guatteria* (Annonaceae) against *Aedes aegypti* (Diptera: Culicidae). Rev Colomb Entomol 37:262–268

Aguiar JCD, Santiago GMP, Lavor PL et al (2010) Chemical constituents and larvicidal activity of *Hymenaea courbaril* fruit peel. Nat Prod Commun 5:1977–1980

Aguilera L, Navarro A, Tacoronte JE, Leyva M, Marquetti MC (2003) Efecto letal de myrtaceas cubanas sobre *Aedes aegypti* (Diptera: Culicidae). Rev Cuba Med Trop 55:100–104

Albuquerque MRJR, Silveira ER, Uchoa DEA (2004) Chemical composition and larvicidal activity of the essential oils from *Eupatorium betonicaeforme* (D.C.) Baker (Asteraceae). J Agric Food Chem. doi:10.1021/jf0352881

Albuquerque MRJR, Costa SMO, Bandeira PN, Santiago GMP, Andrade-Neto M, Silveira ER, Pessoa ODL (2007) Nematicidal and larvicidal activities of the essential oils from aerial parts of *Pectis oligocephala* and *Pectis apodocephala* Baker. An Acad Bras Cienc. doi:10.1590/S0001-37652007000200003

Ali A, Tabanca N, Demirci B, Baser KH, Ellis J, Gray S, Lackey BR, Murphy C, Khan IA, Wedge DE (2013a) Composition, mosquito larvicidal, biting deterrent and antifungal activity of essential oils of different plant parts of *Cupressus arizonica* var. *glabra* ('Carolina Sapphire'). Nat Prod Commun 8:257–260

Ali A, Murphy CC, Demirci B, Wedge DE, Sampson BJ, Khan IA, Baser KHC, Tabanca N (2013b) Insecticidal and biting deterrent activity of rose-scented geranium (*Pelargonium* spp.) essential oils and individual compounds against *Stephanitis pyrioides* and *Aedes aegypti*. Pest Manag Sci. doi:10.1002/ps.3518

Almeida RRP, Souto RNP, Bastos CN, Silva MHL, Maia JGS (2009) Chemical variation in *Piper aduncum* and biological properties of its dillapiole-rich essential oil. Chem Biodivers. doi:10.1002/cbdv.200800212

Amaral FMM, Ribeiro MNS, Barbosa-Filho JM, Reis AS, Nascimento FRF, Macedo RO (2006) Plants and chemical constituents with giardicidal activity. Bras J Pharmacogn 16:696–720

Amer A, Mehlhorn H (2006) Larvicidal effects of various essential oils against *Aedes*, *Anopheles*, and *Culex larvae* (Diptera, Culicidae). Parasitol Res. doi:10.1007/s00436-006-0182-3

Ansari MA, Mittal PK, Razdan RK, Sreehari U (2005) Larvicidal and mosquito repellent activities of pine (*Pinus longifolia*, Family: Pinaceae) oil. J Vector Borne Dis 42:95–99

Arriaga AMC, Rodrigues FEA, Lemos TLG, Oliveira MCF, Lima JQ, Santiago GMP, Braz-Filho R, Mafezoli J (2007) Composition and larvicidal activity of essential oil from *Stemodia maritima* L. Nat Prod Commun 2:1237–1239

Autran ES, Neves IA, Silva CSB, Santos GKN, Câmara CAG, Navarro DMAF (2009) Chemical composition, oviposition deterrent and larvicidal activities against *Aedes aegypti* of essential oils from *Piper marginatum* Jacq. (Piperaceae). Bioresour Technol. doi:10.1016/j.biortech.2008.10.055

Bakkali F, Averbeck S, Averbeck D, Idaomar M (2008) Biological effects of essential oils—a review. Food Chem Toxicol. doi:10.1016/j.fct.2007.09.106

Barbosa JDF, Silva VB, Alves PB, Gumina G, Santos RLC, Sousa DP, Cavalcanti SCH (2012a) Structure–activity relationships of eugenol derivatives against *Aedes aegypti* (Diptera: Culicidae) larvae. Pest Manag Sci. doi:10.1002/ps.3331

Barbosa PCS, Medeiros RS, Sampaio PTB, Vieira G, Wiedemann LSM, Veiga-Junior VF (2012b) Influence of abiotic factors on the chemical composition of Copaiba oil (*Copaifera multijuga* Hayne): soil composition, seasonality and diameter at breast height. J Braz Chem Soc 23:1823–1833

Baser KHC, Buchbauer G (2010) Handbook of essential oils: science, technology, and applications. CRC, Boca Raton

Batish DR, Singh HP, Kohli RK, Kaur S (2008) *Eucalyptus* essential oil as a natural pesticide. For Ecol Manag 256:2166–2174

Bilal H, Hassan SA (2012) Plants secondary metabolites for mosquito control. Asian Pac J Trop Dis 168–168

Borah R, Saikia K, Talukdar AK, Kalita MC (2012) Chemical composition and biological activity of the leaf essential oil of *Zanthoxylum oxyphyllum*. Planta Med. doi:10.1055/s-0032-1307608

Braga IA, Valle D (2007) *Aedes Aegypti*: insecticides, mechanisms of action and resistance. Epidemiol Serv Saúde 16:279–293

Cantrell CL, Pridgeon JW, Fronczek FR, Becnel JJ (2010) Structure–activity relationship studies on derivatives of Eudesmanolides from *Inula helenium* as toxicants against *Aedes aegypti* larvae and adults. Chem Biodivers 7:1681–1697

Carvalho AFU, Melo VMM, Craveiro AA, Machado MIL, Bantim MB, Rabelo EF (2003) Larvicidal activity of the essential oil from *Lippia sidoides* Cham. against *Aedes aegypti* Linn. Mem Inst Oswaldo Cruz 98:569–571

Cavalca PAM, Lolis MIGA, Reis B, Bonato CM (2010) Homeopathic and larvicide effect of *Eucalyptus cinerea* essential oil against *Aedes aegypti*. Braz Arch Biol Tech 53:835–843

Cavalcanti ESB, Morais SM, Lima MAA, Santana EWP (2004) Larvicidal activity of essential oils from Brazilian plants against *Aedes aegypti* L. Mem Inst Oswaldo Cruz 99:541–544

Champakaew D, Choochote W, Pongpaibul Y, Chaithong U, Jitpakdi A, Tuetun B, Pitasawat B (2007) Larvicidal efficacy and biological stability of a botanical natural product, zedoary oil-impregnated sand granules, against *Aedes aegypti* (Diptera, Culicidae). Parasitol Res. doi:10.1007/s00436-006-0350-5

Chantraine JM, Laurent D, Ballivian C, Saavedra G, Ibañez R, Vilaseca LA (1998) Insecticidal activity of essential oils on *Aedes aegypti* larvae. Phytoterap Res 12:350–354

Cheah S-X, Tay J-W, Chan L-K, Jaal Z (2013) Larvicidal, oviposition, and ovicidal effects of *Artemisia annua* (Asterales: Asteraceae) against *Aedes aegypti*, *Anopheles sinensis*, and *Culex quinquefasciatus* (Diptera: Culicidae). Parasitol Res. doi:10.1007/s00436-013-3506-0

Cheng SS, Chang HT, Chang ST, Tsai KH, Chen WJ (2003) Bioactivity of selected plant essential oils against the yellow fever mosquito *Aedes aegypti* larvae. Bioresour Technol. doi:10.1016/S0960-8524(03)00008-7

Cheng SS, Liu JY, Tsai KH, Chen WJ, Chang ST (2004) Chemical composition and mosquito larvicidal activity of essential oils from leaves of different *Cinnamomum osmophloeum* provenances. J Agric Food Chem. doi:10.1021/jf0497152

Cheng SS, Chang HT, Lin CY, Chen PS, Huang CG, Chend WJ, Chang ST (2009a) Insecticidal activities of leaf and twig essential oils from *Clausena excavata* against *Aedes aegypti* and *Aedes albopictus* larvae. Pest Manag Sci. doi:10.1002/ps.1693

Cheng SS, Huang CG, Chen YJ, Yu JJ, Chen WJ, Chang ST (2009b) Chemical compositions and larvicidal activities of leaf essential oils from two *Eucalyptus* species. Bioresour Technol. doi:10.1016/j.biortech.2008.02.038

Cheng SS, Chua MT, Chang EH, Huang CG, Chen WJ, Chang ST (2009c) Variations in insecticidal activity and chemical compositions of leaf essential oils from *Cryptomeria japonica* at different ages. Bioresour Technol. doi:10.1016/j.biortech.2007.11.060

Cheng SS, Lin CY, Chung MJ, Liu YH, Huang CG, Chang ST (2013) Larvicidal activities of wood and leaf essential oils and ethanolic extracts from *Cunninghamia konishii* Hayata against the dengue mosquitoes. Ind Crops Prod. doi:10.1016/j.indcrop.2013.03.016

Choochote W, Chaiyasit D, Kanjanapothi D, Rattanachanpichai E, Jitpakdi A, Tuetun B, Pitasawat B (2005) Chemical composition and anti-mosquito potential of rhizome extract and volatile oil derived from *Curcuma aromatica* against *Aedes aegypti* (Diptera: Culicidae). J Vector Ecol 30:302–309

Chung IM, Seo SH, Kang EY, Park SD, Park WH, Moon HI (2009) Chemical composition and larvicidal effects of essential oil of *Dendropanax morbifera* against *Aedes aegypti* L. Biochem Syst Ecol. doi:10.1016/j.bse.2009.06.004

Ciccia G, Coussio J, Mongelli E (2000) Insecticidal activity against *Aedes aegypti* larvae of some medicinal South American plants. J Ethnopharmacol 72:185–189

Cole ER (2008) Estudo fitoquímico do óleo essencial dos frutos da aroeira (*Schinus terebinthifolius* RADDI) e sua eficácia no combate ao dengue. Dissertation, Federal University of Espírito Santo

Consoli RAGB, Oliveira RL (1994) Principais mosquitos de importância sanitária no Brasil. Editora Fiocruz, Rio de Janeiro

Costa JGM, Pessoa ODL, Menezes EA, Santiago GMP, Lemos TLG (2004) Composition and larvicidal activity of essential oils from heartwood of *Auxemma glazioviana* Taub. (Boraginaceae). Flavour Fragr J. doi:10.1002/ffj.1332

Costa JGM, Rodrigues FFG, Angélico EC et al (2005) Chemical-biological study of the essential oils of *Hyptis martiusii*, *Lippia sidoides* and *Syzigium aromaticum* against larvae of *Aedes aegypti* and *Culex quinquefasciatus*. Braz J Pharmacogn 15:304–309

Costa JGM, Santos PF, Brito SA, Rodrigues FFG, Coutinho HDM, Botelho MA, Lima SG (2010a) Composição química e toxicidade de óleos essenciais de espécies de *Piper* frente a larvas de *Aedes aegypti* L. (Diptera: Culicidae). Lat Am J Pharm 29:463–467

Costa JGM, Rodrigues FFG, Sousa EO, Junior DMS, Campos AR, Coutinho HDM, Lima SG (2010b) Composition and larvicidal activity of the essential oils of *Lantana camara* and *Lantana montevidensis*. Chem Nat Comp 46:313–315

Dharmagadda VSS, Naik SN, Mittal PK, Vasudevan P (2005) Larvicidal activity of *Tagetes patula* essential oil against three mosquito species. Bioresour Technol. doi:10.1016/j.biortech.2004.10.020

Doria GAA, Silva WJ, Carvalho GA, Alves PB, Cavalcanti SCH (2010) A study of the larvicidal activity of two *Croton* species from northeastern Brazil against *Aedes aegypti*. Pharm Biol 48:615–620

Eldridge BF (2005) Mosquitoes, the Culicidae. In: Marquardt WC (ed) Biology of disease vectors, 2nd edn. Elsevier, Amsterdam, pp 95–111

Enan EE (2001) Insecticidal activity of essential oils: octopaminergic sites of action. Comp Biochem Physiol C 130:325–337

Enan EE (2005) Molecular and pharmacological analysis of an octopamine receptor from American cockroach and fruit fly in response to plant essential oils. Arch Insect Biochem Physiol 59:161–171

Evans PD (1984) A modulatory octopaminergic neurone increases cyclic nucleotide levels in locust skeletal muscle. J Physiol 348:307–324

Feitosa EM, Arriaga AMC, Lemos TLG, Lima JQ, Vasconcelos JN, Oliveira MCF, Santiago GMP, Nascimento RF (2007) *Zanthoxylum articulatum* Engler (Rutaceae) essential oil: chemical composition and larvicidal activity. J Essent Oil Res. doi:10.1080/10412905.2007.9699311

Feitosa EMA, Arriaga AMC, Santiago GMP, Lemos TLG, Oliveira MCF, Vasconcelos JN, Lima JQ, Malcher GT, Nascimento RF, Braz-Filho R (2009) Chemical composition and larvicidal activity of *Rollinia leptopetala* (Annonaceae). J Braz Chem Soc 20:375–378

Fontes UR Jr, Ramos CS, Serafini MR, Cavalcanti SCH, Alves PB, Lima GM, Andrade PHS, Bonjardim LR, Quintans LJ Jr, Araújo AAS (2012) Evaluation of the lethality of *Porophyllum ruderale* essential oil against *Biomphalaria glabrata*, *Aedes aegypti* and *Artemia salina*. Afr J Biotechnol 11:3169–3172

Franzios G, Mirotsou M, Hatziapostolou E, Kral J, Scouras ZG, Mavragani-Tsipidou P (1997) Insecticidal and genotoxic activities of mint essential oils. J Agric Food Chem 45:2690–2694

Gbolade AA, Lockwood GB (2008) Toxicity of *Ocimum sanctum* L. essential oil to *Aedes aegypti* larvae and its chemical composition. J Essent Oil-Bear Plants. doi:10.1080/0972060X.2008.10643611

George S, Vincent S (2005) Comparative efficacy of *Annona squamosa* Linn. and *Pongamia glabra* Vent. to *Azadirachta indica* A. Juss against mosquitoes. J Vector Borne Dis 42:159–163

Geris R, Ribeiro PR, Brandão MS, Silva HHG, Silva IG (2012) Bioactive natural products as potential candidates to control *Aedes aegypti*, the vector of dengue. In: Atta-ur-Rahman FRS (ed) Studies in natural products chemistry, vol 37. Elsevier, Amsterdam, pp 277–376

Ghosh A, Chowdhury N, Chandra G (2012) Plant extracts as potential mosquito larvicides. Indian J Med Res 135:581–598

Góis RWS (2010) Estudo fitoquímico e biológico de *Bauhinia acuruana* Moric. Dissertation, Federal University of Ceará

Góis RWS, Sousa LM, Santiago GMP, Romero NR, Lemos TLG, Arriaga AMC, Braz-Filho R (2013) Larvicidal activity against *Aedes aegypti* of pacharin from *Bauhinia acuruana*. Parasitol Res. doi:10.1007/s00436-013-3407-2

Govindarajan M (2010) Chemical composition and larvicidal activity of leaf essential oil from *Clausena anisata* (Willd.) Hook. f. ex Benth (Rutaceae) against three mosquito species. Asian Pac J Trop Med. doi:10.1016/S1995-7645(10)60210-6

Govindarajan M, Sivakumar R, Rajeswari M, Yogalakshmi K (2012) Chemical composition and larvicidal activity of essential oil from *Mentha spicata* (Linn.) against three mosquito species. Parasitol Res. doi:10.1007/s00436-011-2731-7

Govindarajan M, Sivakumar R, Rajeswari M, Veerakumar K (2013) Mosquito larvicidal activity of thymol from essential oil of *Coleus aromaticus* Benth. against *Culex tritaeniorhynchus*, *Aedes albopictus*, and *Anopheles subpictus* (Diptera: Culicidae). Parasitol Res. doi:10.1007/s00436-013-3557-2

Grodnitzky J, Coats J (2002) QSAR evaluation of monoterpenoids' insecticidal activity. J Agric Food Chem. doi:10.1021/jf0201475

Gubler DJ (2011) Dengue, urbanization and globalization: the unholy trinity of the 21st century. Trop Med Health. doi:10.2149/tmh.2011-S05

Gupta B, Reddy BPN (2013) Fight against dengue in India: progresses and challenges. Parasitol Res. doi:10.1007/s00436-013-3342-2

Hemingway J, Ranson H (2005) Chemical control of vectors and mechanisms of resistance. In: Marquardt WC (ed) Biology of disease vectors, 2nd edn. Elsevier, Amsterdam, pp 627–637

Isman MB (2006) Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu Rev Entomol. doi:10.1146/annurev.ento.51.110104.151146

Jantan I, Ping WO, Visuvalingam SD, Ahmad NW (2003) Larvicidal activity of essential oils and methanol extracts of Malaysian plants on *Aedes aegypti*. Pharm Biol 41:234–236

Jantan I, Yalvema MF, Ahmad NW, Jamal JA (2005) Insecticidal activities of the leaf oils of eight *Cinnamomum* species against *Aedes aegypti* and *Aedes albopictus*. Pharm Biol. doi:10.1080/13880200500220771

Kalaivani K, Senthil-Nathan S, Murugesan AG (2012) Biological activity of selected Lamiaceae and Zingiberaceae plant essential oils against the dengue vector *Aedes aegypti* L. (Diptera: Culicidae). Parasitol Res. doi:10.1007/s00436-011-2623-x

Khandagle AJ, Tare VS, Raut KD, Morey RA (2011) Bioactivity of essential oils of *Zingiber officinalis* and *Achyranthes aspera* against mosquitoes. Parasitol Res. doi:10.1007/s00436-011-2261-3

Khanikor B, Parida P, Yadav RNS, Bora D (2013) Comparative mode of action of some terpene compounds against octopamine receptor and acetyl cholinesterase of mosquito and human system by the help of homology modeling and docking studies. J Appl Pharm Sci. doi:10.7324/JAPS.2013.30202

Kim NJ, Byun SG, Cho JE, Chung K, Ahn YJ (2008) Larvicidal activity of *Kaempferia galanga* rhizome phenylpropanoids towards three mosquito species. Pest Manag Sci 64:857–862

Kiran SR, Bhavani K, Devi PS, Rao BRR, Reddy KJ (2006) Composition and larvicidal activity of leaves and stem essential oils of *Chloroxylon swietenia* DC against *Aedes aegypti* and *Anopheles stephensi*. Bioresour Technol. doi:10.1016/j.biortech.2005.10.003

Klowden MJ (2007) Making generalizations about vectors: is there a physiology of "the mosquito"? Entomol Res. doi:10.1111/j.1748-5967.2007.00044.x

Komalamisra N, Trongtokit Y, Rongsriyam Y, Apiwathnasorn C (2005) Screening for larvicidal activity in some Thai plants against four mosquito vector species. Southeast Asian J Trop Med Public Health 36:1412–1422

Kongkaew C, Sakunrag I, Chaiyakunapruk N, Tawatsin A (2011) Effectiveness of citronella preparations in preventing mosquito bites: systematic review of controlled laboratory experimental studies. Trop Med Int Health. doi:10.1111/j.1365-3156.2011.02781.x

Konishi E (2011) Issues related to recent dengue vaccine development. Trop Med Health. doi:10.2149/tmh.2011-S01

Kostyukovsky M, Rafaeli A, Gileadi C, Demchenko N, Eli S (2002) Activation of octopaminergic receptors by essential oil constituents isolated from aromatic plants: possible mode of action against insect pests. Pest Manag Sci. doi:10.1002/ps.548

Koul O, Walia S, Dhaliwal GS (2008) Essential oils as green pesticides: potential and constraints. Biopestic Int 4:63–84

Kovendan K, Murugan K, Kumar PM, Thiyagarajan P, William SJ (2013) Ovicidal, repellent, adulticidal and field evaluations of plant extract against dengue, malaria and filarial vectors. Parasitol Res. doi:10.1007/s00436-012-3252-8

Krishnaiah D, Sarbatly R, Nithyanandam R (2011) A review of the antioxidant potential of medicinal plant species. Food Bioprod Process. doi:10.1016/j.fbp.2010.04.008

Kulkarni RR, Pawar PV, Joseph MP, Akulwad AK, Sen A, Joshi SP (2013) *Lavandula gibsoni* and *Plectranthus mollis* essential oils: chemical analysis and insect control activities against *Aedes aegypti*, *Anopheles stephensi* and *Culex quinquefasciatus*. J Pest Sci. doi:10.1007/s10340-013-0502-1

Kumar D, Kumar A, Prakash O (2012) Potential antifertility agents from plants: a comprehensive review. J Ethnopharmacol. doi:10.1016/j.jep.2011.12.039

Kumar P, Mishra S, Malik A, Satya S (2013) Housefly (*Musca domestica* L.) control potential of *Cymbopogon citratus* Stapf. (Poales: Poaceae) essential oil and monoterpenes (citral and 1,8-cineole). Parasitol Res. doi:10.1007/s00436-012-3105-5

Kumar S, Thomas A, Sahgal A, Verma A, Samuel T, Pillai MKK (2002) Effect of the synergist, piperonyl butoxide, on the development of deltamethrin resistance in yellow fever mosquito, *Aedes aegypti* L. (Diptera: Culicidae). Arch Insect Biochem Physiol. doi:10.1002/arch.10021

Kumar S, Wahab N, Warikoo R (2011) Bioefficacy of *Mentha piperita* essential oil against dengue fever mosquito *Aedes aegypti* L. Asian Pac J Trop Biomed 2:85–88

Kuo PM, Chu FH, Chang ST, Hsiao WF, Wang SY (2007) Insecticidal activity of essential oil from *Chamaecyparis formosensis* Matsum. Holzforschung. doi:10.1515/HF.2007.087

Lahlou M (2004a) Methods to study the phytochemistry and bioactivity of essential oils. Phytoterap Res. doi:10.1002/ptr.1465

Lahlou M (2004b) Essential oils and fragrance compounds: bioactivity and mechanisms of action. Flavour Fragr J. doi:10.1002/ffj.1288

Lang G, Buchbauer G (2011) A review on recent research results (2008–2010) on essential oils as antimicrobials and antifungals. A review. Flavour Fragr J. doi:10.1002/ffj.2082

Lavor PL, Santiago GM, Gois RW, Sousa LM, Bezerra GP, Romero NR, Arriaga AM, Lemos TL, Alves PB, Gomes PC (2012) Larvicidal activity against *Aedes aegypti* of essential oils from northeast Brazil. Nat Prod Commun 7:1391–1392

Lee HS (2006) Mosquito larvicidal activity of aromatic medicinal plant oils against *Aedes aegypti* and *Culex pipiens pallens*. J Am Mosq Control Assoc. doi:10.2987/8756-971X%282006%2922%5B292%3AMLAOAM%5D2.0.CO%3B2

Leyva M, Tacoronte JE, Marquetti MC, Scull R, Montada D, Rodriguez Y, Bruzón RY (2008) Actividad insecticida de aceites esenciales de plantas en larvas de *Aedes aegypti* (Diptera: Culicidae). Rev Cubana Med Trop 60:78–82

Leyva M, Marquetti MC, Tacoronte JE, Scull R, Tiomno O, Mesa A, Montada D (2009a) Actividad larvicida de aceites esenciales de plantas contra *Aedes aegypti* (L.) (Diptera: Culicidae). Rev Biomed 20:5–13

Leyva M, Tacoronte JE, Marquetti MC, Scull R, Tiomno O, Mesa A, Montada D (2009b) Utilización de aceites esenciales de pinaceas endémicas como una alternativa en el control del *Aedes aegypti*. Ver Cuban Med Trop 61:239–243

Lima MAA, Oliveira FFM, Gomes GA et al (2011) Evaluation of larvicidal activity of the essential oils of plants species from Brazil against *Aedes aegypti* (Diptera: Culicidae). Afr J Biotechnol 10: 11716–11720

Lima GPG, Souza TM, Freire GP, Farias DF, Cunha AP, Ricardo NMPS, Morais SM, Carvalho AFU (2013) Further insecticidal activities of essential oils from *Lippia sidoides* and *Croton* species against *Aedes aegypti* L. Parasitol Res. doi:10.1007/s00436-013-3351-1

Liu XC, Dong HW, Zhou L, Du SS, Liu ZL (2013) Essential oil composition and larvicidal activity of *Toddalia asiatica* roots against the mosquito *Aedes albopictus* (Diptera: Culicidae). Parasitol Res. doi: 10.1007/s00436-012-3251-9

Lomonaco D, Santiago GMP, Ferreira YS, Arriaga AMC, Mazzetto SE, Melec G, Vasapollo G (2009) Study of technical CNSL and its main components as new green larvicides. Green Chem. doi:10.1039/b811504d

López O, Fernández-Bolaños JG, Gil MV (2005) New trends in pest control: the search for greener insecticides. Green Chem. doi:10.1039/b500733j

López MD, Pascual-Villalobos MJ (2010) Mode of inhibition of acetylcholinesterase by monoterpenoids and implications for pest control. Ind Crops Prod. doi:10.1016/j.indcrop.2009.11.005

Lucia A, Audino PG, 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. J Am Mosq Control Assoc. doi:10.2987/8756-971X%282007%2923%5B299%3ALEOEGE%5D2.0.CO%3B2

Lucia A, Licastro S, Zerba E, Masuh H (2008) Yield, chemical composition, and bioactivity of essential oils from 12 species of *Eucalyptus* on *Aedes aegypti* larvae. Entomol Exp Appl. doi:10.1111/j.1570-7458.2008.00757.x

Lucia A, Juan LW, Zerba EN, Harrand L, Marcó M, Masuh HM (2012) Validation of models to estimate the fumigant and larvicidal activity of *Eucalyptus* essential oils against *Aedes aegypti* (Diptera: Culicidae). Parasitol Res. doi:10.1007/s00436-011-2685-9

Magalhães LAM, Lima MP, Marques MOM, Facanali R, Pinto ACS, Tadei WP (2010) Chemical composition and larvicidal activity against *Aedes aegypti* larvae of essential oils from four *Guarea* species. Molecules. doi:10.3390/molecules15085734

Maheswaran R, Ignacimuthu S (2012) A novel herbal formulation against dengue vector mosquitoes *Aedes aegypti* and *Aedes albopictus*. Parasitol Res. doi:10.1007/s00436-011-2702-z

Manzoor F, Samreen KB, Parveen Z (2013) Larvicidal activity of essential oils against *Aedes aegypti* and *Culex quinquefasciatus* larvae (Diptera: Culicidae). J Anim Plant Sci 23:420–424

Marinho SC (2010) Chemical study, electrochemical evaluation and larvicidal activity of essential oil from leaves of *Pimenta dioica* Lindl front of *Aedes aegypti* (Linnaeus, 1762). Dissertation, Federal University of Paraíba

Marques MMM, Morais SM, Vieira ÍGP, Vieira MGS, Silva ARA, Almeida RR, Guedes MIF (2011) Larvicidal a activity of *Tagetes erecta* against *Aedes aegypti*. J Am Mosq Control Assoc. doi:10.2987/10-6056.1

Massebo F, Tadesse M, Bekele T, Balkew M, Gebre-Michael T (2009) Evaluation on larvicidal effects of essential oils of some local plants against *Anopheles arabiensis* Patton and *Aedes aegypti Linnaeus* (Diptera, Culicidae) in Ethiopia. Afr J Biotechnol 8:4183–4188

Melo-Santos MAV, Varjal-Melo JJM, Araújo AP, Gomes TCS, Paiva MHS, Regis LN, Furtado AF, Magalhaes T, Macoris MLG, Andrighetti MTM, Ayres CFJ (2010) Resistance to the organophosphate temephos: mechanisms, evolution and reversion in an *Aedes aegypti* laboratory strain from Brazil. Acta Trop. doi:10.1016/j.actatropica.2009.10.015

Mendes LSS (2011) Estudo químico e atividade larvicida frente a *Aedes aegypti* do óleo essencial das folhas de *Cinnamomum zeylanicum* Breyn (canela). Dissertation, Federal University of Maranhão

Mendonça FAC, Silva KFS, Santos KK, Ribeiro-Jr KAL, Sant'Ana AEG (2005) Activities of some Brazilian plants against larvae of the mosquito *Aedes aegypti*. Fitoterapia. doi:10.1016/j.fitote.2005.06.013

Mora FD, Avila JL, Rojas LB, Ramirez R, Usubillaga A, Segnini S, Carmona J, Silva B (2010) Chemical composition and larvicidal activity of *Eugenia triquetra* essential oil from Venezuelan Andes. Nat Prod Commun 5:965–968

Morais SM, Cavalcanti ESB, Bertini LM, Oliveira CLL, Rodrigues JRB, Cardoso JHL (2006) Larvicidal activity of essential oils from Brazilian *Croton* species against *Aedes aegypti* L. J Am Mosq Control Assoc. doi:10.2987/8756-971X%282006%2922%5B161%3ALAOEOF%5D2.0.CO%3B2

Morais SM, Facundo VA, Bertini LM et al (2007) Chemical composition and larvicidal activity of essential oils from *Piper* species. Biochem Syst Ecol. doi:10.1016/j.bse.2007.05.002

Morais LAS (2009) Influência dos fatores abióticos na composição química dos óleos essenciais. Hortic Bras 27:S4050–S4063

Nagella P, Ahmad A, Kim SJ, Chung IM (2012) Chemical composition, antioxidant activity and larvicidal effects of essential oil from leaves of *Apium graveolens*. Immunopharmacol Immunotoxicol. doi:10.3109/08923973.2011.592534

Nascimento AA (2012) Óleo essencial dos botões florais do cravo-da-índia (*Syzygium aromaticum*): extração, caracterização e atividade larvicida frente ao *Aedes aegypti* (Linnaeus, 1762). Dissertation, Federal University of Maranhão

Nascimento JC, David JM, Barbosa LCA, Paula VF, Demuner AJ, David JP, Conserva LM, Ferreira-Jr JC, Guimarães EF (2013) Larvicidal activities and chemical composition of essential oils from *Piper klotzschianum* (Kunth) C DC. (Piperaceae). Pest Manag Sci. doi: 10.1002/ps.3495

Nyahanga T, Jondika JI, Manguro LOA, Orwa JA (2010) Chemical composition, antiplasmodial, larvicidal and antimicrobial activities of essential oils of *Toddalia asiatica* leaves and fruits. Int J Essent Oil Ther 4:54–58

Oliveira VB, Yamada LT, Fagg CW, Brandão MGL (2012) Native foods from Brazilian biodiversity as a source of bioactive compounds. Food Res Intern. doi:10.1016/j.foodres.2012.03.011

Pandey SK, Tandon S, Ahmad A, Singh AK, Tripathi AK (2013) Structure–activity relationships of monoterpenes and acetyl derivatives against *Aedes aegypti* (Diptera: Culicidae) larvae. Pest Manag Sci. doi:10.1002/ps.3488

Park HM, Kim J, Chang KS, Kim BS, Yang YJ, Kim GH, Shin SC, Park IK (2011) Larvicidal activity of Myrtaceae essential oils and their components against *Aedes aegypti*, acute toxicity on *Daphnia magna*, and aqueous residue. J Med Entomol. doi:10.1603/ME10108

Pathak N, Mittal PK, Singh OP, Sagar DV, Vasudevan P (2000) Larvicidal action of essential oils from plants against the vector mosquitoes *Anopheles stephensi* (Liston), *Culex quinquefasciatus* (Say) and *Aedes aegypti* (L.). Int Pest Control 42:53–55

Patil CD, Patil SV, Salunke BK, Salunkhe RB (2011) Bioefficacy of *Plumbago zeylanica* (Plumbaginaceae) and *Cestrum nocturnum* (Solanaceae) plant extracts against *Aedes aegypti* (Diptera: Culicide) and nontarget fish Poecilia reticulata. Parasitol Res. doi: 10.1007/s00436-010-2174-6

Perumalsamy H, Chang KS, Park C, Ahn YJ (2010) Larvicidal activity of *Asarum heterotropoides* root constituents against insecticide-susceptible

and -resistant *Culex pipiens pallens* and *Aedes aegypti* and *Ochlerotatus togoi*. J Agric Food Chem. doi:10.1021/jf102193k

Perumalsamy H, Kim NJ, Ahn AJ (2009) Larvicidal activity of compounds isolated from *Asarum heterotropoides* against *Culex pipiens pallens*, *Aedes aegypti*, and *Ochlerotatus togoi* (Diptera: Culicidae). J Med Entomol 46:1420–1423

Pflüger HJ, Stevenson PA (2005) Evolutionary aspects of octopaminergic systems with emphasis on arthropods. Arthropod Struct Dev 34: 379–396

Pimenta ATA, Santiago GMP, Arriaga AMC, Menezes GHA, Bezerra SB (2006) Phytotochemical study and evaluation of larvicidal activity of *Pterodon polygalaeflorus* Benth (Leguminosae) against *Aedes aegypti*. Braz J Pharmacogn 16:501–505

Pitasawat B, Champakaew D, Choochote W (2007) Aromatic plant-derived essential oil: an alternative larvicide for mosquito control. Fitoterapia. doi:10.1016/j.fitote.2007.01.003

Polson KA, Brogdon WG, Rawlins SC, Chadee DD (2011) Characterization of insecticide resistance in Trinidadian strains of *Aedes aegypti* mosquitoes. Acta Trop. doi:10.1016/j.actatropica.2010.09.005

Porto KRA, Roel AR, Silva MM, Coelho RM, Scheleder EJD, Jeller AH (2008) Atividade larvicida do óleo de Anacardium humile Saint Hill sobre *Aedes aegypti* (Linnaeus, 1762) (Diptera, Culicidae). Rev Soc Bras Med Trop 41:586–589

Prajapati V, Tripathi AK, Aggarwal KK, Khanuja SPS (2005) Insecticidal, repellent and oviposition-deterrent activity of selected essential oils against *Anopheles stephensi*, *Aedes aegypti* and *Culex quinquefasciatus*. Bioresour Technol. doi:10.1016/j.biortech.2005.01.007

Priestley CM, Williamson EM, Wafford KA, Sattelle DB (2003) Thymol, a constituent of thyme essential oil, is a positive allosteric modulator of human $GABA_A$ receptors and a homo-oligomeric GABA receptor from *Drosophila melanogaster*. Br J Pharmacol 140:1363–1372

Prophiro JS, Silva MAN, Kanis LA, Silva BM, Duque-Luna JE, Silva OS (2012) Evaluation of time toxicity, residual effect, and growth-inhibiting property of *Carapa guianensis* and *Copaifera* sp. in *Aedes aegypti*. Parasitol Res. doi:10.1007/s00436-011-2547-5

Rajkumar S, Jebanesan A (2010) Chemical composition and larvicidal activity of leaf essential oil from *Clausena dentata* (Willd) M. Roam. (Rutaceae) against the chikungunya vector, *Aedes aegypti* Linn. (Diptera: Culicidae). J Asia Pac Entomol. doi:10.1016/j.aspen.2010.02.001

Regnault-Roger C (1997) The potential of botanical essential oils for insect pest control. Integr Pest Manag Rev 2:25–34

Roeder T (1999) Octopamine in invertebrates. Prog Neurobiol 59:533–561

Ruiz C, Cachay M, Domínguez M, Velásquez C, Espinoza G, Ventosilla P, Rojas R (2011) Chemical composition, antioxidant and mosquito larvicidal activities of essential oils from *Tagetes filifolia*, *Tagetes minuta* and *Tagetes elliptica* from Perú. Planta Med. doi:10.1055/s-0031-1282361

Ryan MF, Byrne O (1988) Plant-insect coevolution and inhibition of acetylcholinesterase. J Chem Ecol 14:1965–1975

Sakhanokho HF, Sampson BJ, Tabanca N, Wedge DE, Demirci B, Baser KHC, Bernier UR, Tsikolia M, Agramonte NM, Becnel JJ, Chen J, Rajasekaran K, Spiers JM (2013) Chemical composition, antifungal and insecticidal activities of *Hedychium* essential oils. Molecules. doi:10.3390/molecules18044308

Santiago GMP, Lemos TLG, Pessoa ODL et al (2006) Larvicidal activity against *Aedes aegypti* L. (Diptera: Culicidae) of essential oils of *Lippia* species from Brazil. Nat Prod Commun 1:573–576

Santos RP, Nunes EP, Nascimento RF, Santiago GMP, Menezes GHA, Silveira ER, Pessoa ODL (2006) Chemical composition and larvicidal activity of the essential oils of *Cordia leucomalloides* and *Cordia curassavica* from the northeast of Brazil. J Braz Chem Soc 17:1027–1030

Santos HS, Santiago GMP, Oliveira JPP, Arriaga AMC, Marques DD, Lemos TLG (2007) Chemical composition and larvicidal activity against *Aedes aegypti* of essential oils from *Croton zehntneri*. Nat Prod Commun 2:1233–1236

Santos SRL, Melo MA, Cardoso AV, Santos RLC, Sousa DP, Cavalcanti SCH (2011) Structure–activity relationships of larvicidal monoterpenes and derivatives against *Aedes aegypti* Linn. Chemosphere. doi:10.1016/j.chemosphere.2011.02.018

Santos SRL, Silva VB, Melo MA, Barbosa JDF, Santos RLC, Sousa DP, Cavalcanti SCH (2010) Toxic effects on and structure-toxicity relationships of phenylpropanoids, terpenes, and related Compounds in *Aedes aegypti* larvae. Vector-Borne Zoonotic Dis. doi:10.1089/vbz.2009.0158

Santos GKN, Dutra KA, Barros RA, Câmara CAG, Lira DD, Gusmão NB, Navarro DMAF (2012) Essential oils from *Alpinia purpurata* (Zingiberaceae): chemical composition, oviposition deterrence, larvicidal and antibacterial activity. Ind Crops Prod. doi:10.1016/j.indcrop.2012.03.020

Satyan RS, Malarvannan S, Eganathan P, Rajalakshmi S, Parida A (2009) Growth inhibitory activity of fatty acid methyl esters in the whole seed oil of Madagascar periwinkle (Apocyanaceae) against *Helicoverpa armigera* (Lepidoptera: Noctuidae). J Econ Entomol. doi:10.1603/029.102.0344

Scotti L, Scotti MT, Silva VB, Santos SRL, Cavalcanti SCH, Mendonça-Jr FJB (2013) Chemometric studies on potential larvicidal compounds against *Aedes aegypti*. Med Chem 9:1–10

Senthilkumar A, Jayaraman M, Venkatesalu V (2013) Chemical constituents and larvicidal potential of *Feronia limonia* leaf essential oil against *Anopheles stephensi*, *Aedes aegypti* and *Culex quinquefasciatus*. Parasitol Res. doi:10.1007/s00436-012-3188-z

Seo SM, Park HM, Park IK (2012) Larvicidal activity of ajowan (*Trachyspermum ammi*) and Peru balsam (*Myroxylon pereira*) oils and blends of their constituents against mosquito, *Aedes aegypti*, acute toxicity on water flea, *Daphnia magna*, and aqueous residue. J Agric Food Chem. doi:10.1021/jf301296d

Shaalan EAS, Canyon DV, Bowden B, Younes MWF, Abdel-Wahab H, Mansour AH (2006) Efficacy of botanical extracts from *Callitris glaucophylla*, against *Aedes aegypti* and *Culex annulirostris* mosquitoes. Trop Biomed 23:180–185

Shaalan EAS, Canyon D, Younes MWF, Abdel-Wahab H, Mansour AH (2005) A review of botanical phytochemicals with mosquitocidal potential. Environ Int. doi:10.1016/j.envint.2005.03.003

Silva AG, Almeida DL, Ronchi SN, Bento AC, Scherer R, Ramos AC, Cruz ZMA (2010) The essential oil of Brazilian pepper, *Schinus terebinthifolia* Raddi in larval control of *Stegomyia aegypti* (Linnaeus, 1762). Parasites Vectors. doi:10.1186/1756-3305-3-79

Silva ALS (2012) Caracterização e avaliação da atividade larvicida do óleo essencial do *Zingiger officinale* Rocoe (Gengibre) frente ao mosquito *Aedes aegypti*. Dissertation, Federal University of Maranhão

Silva PC, Navarro DM, Dutra K, Santos GK (2013) Composition, larvicidal, and deterrence oviposition activity of *Etlingera elatior* essential oils against *Aedes aegypti* L. (Diptera: Culicidae). Abstracts of Papers of 245th ACS National Meeting & Exposition AGFD-215.

Silva WJ (2006) Atividade larvicida do óleo essencial de plantas existentes no estado de Sergipe contra *Aedes aegypti* Linn. Dissertation, Federal University of Sergipe

Silva WJ, Dória GAA, Maia RT, Nunes RS, Carvalho GA, Blank AF, Alves PB, Marçal RM, Cavalcanti SCH (2008) Effects of essential oils on *Aedes aegypti* larvae: alternatives to environmentally safe insecticides. Bioresour Technol. doi:10.1016/j.biortech.2007.05.064

Simas NK, Lima EC, Conceição SR, Kuster RM, Oliveira-Filho AM (2004) Produtos naturais para o controle da transmissão da dengue—atividade larvicida de Myroxylon balsamum

(óleo vermelho) e de terpenóides e fenilpropanóides. Quim Nova 27:46–49

Souza LGS, Almeida MCS, Monte FJQ, Santiago GMP, Braz-Filho R, Lemos TLG, Gomes CL, Nascimento RF (2012a) Chemical constituents of *Capraria biflora* (Scrophulariaceae) and larvicidal activity of essential oil. Quim Nova 35:2258–2262

Souza TM, Cunha AP, Farias DF, Machado LK, Morais SM, Ricardo NMPS, Carvalho AFU (2012b) Insecticidal activity against *Aedes aegypti* of m-pentadecadienyl-phenol isolated from *Myracrodruon urundeuva* seeds. Pest Manag Sci. doi:10.1002/ps.3316

Sukumar K, Perich MJ, Boobar LW (1991) Botanical derivatives in mosquito control: a review. J Am Mosq Control Assoc 7:210–237

Sun L, Dong H, Guo C, Qian J, Sun J, Ma L, Zhu C (2006) Larvicidal activity of extracts of *Ginkgo biloba* exocarp for three different strains of *Culex pipiens pallens*. J Med Entomol. doi:10.1603/0022-2585(2006)043[0258:LAOEOG]2.0.CO;2

Tabanca N, Özek G, Ali A, Duran A, Hamzaoğlu E, Baser KHC, Khan IA (2012a) Chemical composition of *Heracleum pastinacifolium* subsp. *transcaucasicum* and subsp. *incanum* essential oils, and their biting deterrent and larvicidal activity against *Aedes aegypti*. Planta Med. doi:10.1055/s-0032-1307597

Tabanca N, Demirci B, Kiyan HT, Ali A, Bernier UR, Wedge DE, Khan IA, Baser KHC (2012b) Repellent and larvicidal activity of *Ruta graveolens* essential oil and its major individual constituents against *Aedes aegypti*. Planta Med. doi:10.1055/s-0032-1307598

Teles RM (2009) Caracterização química, avaliação térmica e atividade larvicida frente ao *Aedes aegypti* do óleo essencial da *Aniba duckei* Kostermans. Dissertation, Federal University of Paraíba

Tennyson S, Samraj DA, Jeyasundar D, Chalieu K (2013) Larvicidal efficacy of plant oils against the dengue vector *Aedes aegypti* (L.) (Diptera: Culicidae). Middle-East J Sci Res. doi:10.5829/idosi.mejsr.2013.13.1.64107

Thanigaivel A, Chandrasekaran R, Revathi K, Nisha S, Sathish-Narayanan S, Kirubakaran SA, Senthil-Nathan S (2012) Larvicidal efficacy of *Adhatoda vasica* (L.) Nees against the bancroftian filariasis vector *Culex quinquefasciatus* Say and dengue vector *Aedes aegypti* L. in in vitro condition. Parasitol Res. doi:10.1007/s00436-011-2728-2

Thomas TG, Rao S, Lal S (2004) Mosquito larvicidal properties of essential oil of an indigenous plant, *Ipomoea cairica* Linn. Jpn J Infect Dis 57:176–177

Tikar SN, Mendki MJ, Chandel K, Parashar BD, Prakash S (2008) Susceptibility of immature stages of *Aedes* (Stegomyia) *aegypti*; vector of dengue and chikungunya to insecticides from India. Parasitol Res. doi:10.1007/s00436-007-0848-5

Tiwary M, Naik SN, Tewary DK, Mittal PK, Yadav S (2007) Chemical composition and larvicidal activities of the essential oil of *Zanthoxylum armatum* DC (Rutaceae) against three mosquito vectors. J Vect Borne Dis 44:198–204

Torres MCM, Assunção JC, Santiago GMP et al (2008) Larvicidal and nematicidal activities of the leaf essential oil of *Croton regelianus*. Chem Biodivers 5:2724–2728

Trindade FTT, Stabeli RG, Pereira AA, Facundo VA, Silva AA (2013) *Copaifera multijuga* ethanolic extracts, oil-resin, and its derivatives display larvicidal activity against *Anopheles* darling and *Aedes aegypti* (Diptera: Culicidae). Braz J Pharmacogn. doi:10.1590/S0102-695X2013005000038

United States Environmental Protection Agency (EPA) (1999) Citronella (oil of citronella) (021901) fact sheet. http://www.epa.gov/opp00001/chem_search/reg_actions/registration/fs_PC-021901_01-Nov-99.pdf. Accessed 2 Dec 2012

Unnati S, Ripal S, Sanjeev A, Niyati A (2013) Novel anticancer agents from plant sources. Chin J Nat Med 11:16–23

Vila R, Santana AI, Pérez-Rosés R et al (2010) Composition and biological activity of the essential oil from leaves of *Plinia cerrocampanensis*, a new source of α-bisabolol. Bioresour Technol. doi:10.1016/j.biortech.2009.11.021

Wahyuni D (2012) Larvicidal activity of essential oils of Piper betle from the Indonesian plants against *Aedes aegypti* L. J Appl Environ Biol Sci 2:249–254

Waliwitiya R, Kennedy CJ, Lowenberger CA (2009) Larvicidal and oviposition-altering activity of monoterpenoids, trans-anethole and rosemary oil to the yellow fever mosquito *Aedes aegypti* (Diptera: Culicidae). Pest Manag Sci. doi:10.1002/ps.1675

Warikoo R, Wahab N, Kumar S (2011) Oviposition-altering and ovicidal potentials of five essential oils against female adults of the dengue vector. *Aedes aegypti* L. Parasitol Res. doi:10.1007/s00436-011-2355-y

Warikoo R, Kumar S (2013) Impact of *Argemone mexicana* extracts on the cidal, morphological, and behavioral response of dengue vector, *Aedes aegypti* L. (Diptera: Culicidae). Parasitol Res. doi:10.1007/s00436-013-3528-7

WHO (1992) Vector resistance to pesticides: fifteenth report of the WHO expert committee on vector biology and control. WHO Technical Report Series 818, Geneva

WHO (2005) Guidelines for laboratory and field testing of mosquito larvicides. WHO, Geneva

WHO (2006) Pesticides and their application for the control of vectors and pests of public health importance, 6th edn. WHO, Geneva

WHO (2009a) Dengue: guidelines for diagnosis, treatment, prevention and control. WHO, Geneva

WHO (2009b) Temephos in drinking-water: use for vector control in drinking-water sources and containers. WHO, Geneva

WHO (2012) Impact of dengue. Global alert and response (GAR). http://www.who.int/csr/disease/dengue/impact/en/index.html. Accessed 14 Apr 2012

WHO (2012b) Global strategy for dengue prevention and control 2012–2020. WHO, Geneva

WHO (2012) Dengue and severe dengue. Factsheet no. 117. http://www.who.int/mediacentre/factsheets/fs117/en/. Accessed 15 Apr 2012

WHO ((2012) Handbook for integrated vector management. WHO, Geneva

WHO (2012) Recommended compounds and formulations for control of mosquito larvae. WHOPES. http://www.who.int/whopes/Mosquito_Larvicides_Sept_2012.pdf. Accessed 28 Sep 2012

Wood A (2012) Compendium of pesticide common names: insecticides. http://www.alanwood.net/pesticides/index.html. Accessed 16 Dec 2012

Zhu J, Zeng X, O'neal M, Schultz G, Tucker B, Coats J, Bartholomay L, Xue RD (2006) Mosquito larvicidal activity of botanical-based mosquito repellents. J Am Mosq Control Assoc. doi:10.2987/8756-971X%282008%2924%5B161%3AMLAOBM%5D2.0.CO%3B2

Zoubiri S, Baaliouamer A (2011) Potentiality of plants as source of insecticide principles. J Saudi Chem Soc. doi:10.1016/j.jscs.2011.11.015