Environ Sci Pollut Res (2018) 25:10307–10316
DOI 10.1007/s11356-017-9093-3

Zingiber cernuum (Zingiberaceae) essential oil as effective larvicide and oviposition deterrent on six mosquito vectors, with little non-target toxicity on four aquatic mosquito predators

Mohan Rajeswary[1] · Marimuthu Govindarajan[1] · Naiyf S. Alharbi[2] · Shine Kadaikunnan[2] · Jamal M. Khaled[2] · Giovanni Benelli[3]

Received: 6 October 2016 / Accepted: 24 April 2017 / Published online: 11 May 2017

Abstract Mosquitoes are responsible for the transmission of many pathogens and parasites, which cause serious diseases in humans and animals. Currently, botanical products have been suggested as alternative tools in the fight against arthropod vectors. In this study, the essential oil (EO) extracted from *Zingiber cernuum* was tested as larvicide and oviposition deterrent on six mosquito species of public health relevance, including malaria and Zika virus vectors. The EO showed high toxicity on third instar larvae of *Anopheles stephensi* (LC_{50} = 41.34 μg/ml), *Aedes aegypti* (LC_{50} = 44.88 μg/ml), *Culex quinquefasciatus* (LC_{50} = 48.44 μg/ml), *Anopheles subpictus* (LC_{50} = 51.42 μg/ml), *Aedes albopictus* (LC_{50} = 55.84 μg/ml), and *Culex tritaeniorhynchus* (LC_{50} = 60.20 μg/ml). In addition, low doses of *Z. cernuum* EO reduced oviposition rates in six mosquito species. The acute toxicity of *Z. cernuum* EO on four mosquito predators was scarce; LC_{50} ranged from 3119 to 11,233 μg/ml. Overall, our results revealed that the *Z. cernuum* EO can be considered for the development of effective and environmental-friendly mosquito larvicides and oviposition deterrents.

Keywords Aquatic toxicology · Biosafety · Dengue · Japanese encephalitis · Malaria · Neglected tropical disease · Zika virus

Responsible editor: Philippe Garrigues

✉ Marimuthu Govindarajan
drgovind1979@gmail.com

✉ Giovanni Benelli
benelli.giovanni@gmail.com

[1] Unit of Vector Control, Phytochemistry and Nanotechnology, Department of Zoology, Annamalai University, Annamalainagar, Tamil Nadu 608002, India

[2] Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia

[3] Department of Agriculture, Food and Environment, University of Pisa, via del Borghetto 80, 56124 Pisa, Italy

Introduction

Arthropods are dangerous vectors of important life-threatening and debilitating diseases. Among them, mosquitoes (Diptera: Culicidae) belonging to the genera *Anopheles*, *Aedes*, and *Culex* act as vectors of pathogens and parasites causing malaria, filariasis, Japanese encephalitis, dengue and dengue hemorrhagic fever, yellow fever, chikungunya, and, very recently, Zika virus (Benelli and Mehlhorn 2016; Ward and Benelli 2017). Several efforts have been made to improve the control of mosquito vectors. Besides the efficacy at low doses, the use of synthetic insecticides can lead to high costs, concerns for environmental sustainability, harmful effects on human health and other non-target populations, and development of insecticide resistance in the targeted pests (Benelli 2015a; Naqqash et al. 2016).

While chemical insecticides are usually based on a single active ingredient, plant-derived pesticides consist of a combination of molecules which can act concertedly on both behavioral and physiological processes (Jain et al. 2001; Pavela 2015). Thus, there is very little chance of resistance development in the treated arthropods. In this scenario, the identification of effective and eco-friendly biopesticides is crucial for the successful management of arthropod vectors (Lucia et al.

2007; Cheng et al. 2003, 2004, 2008, 2009a; Govindarajan and Benelli 2016a, b).

Essential oils (EOs) are complex mixtures of volatile organic compounds produced as secondary metabolites in plants. They include blends of terpenes, sesquiterpenes, and oxygenated compounds, such as alcohols, esters, ethers, aldehydes, ketones, lactones, phenols, and phenol ethers (Chericoni et al. 2004; Astani et al. 2010; Almeida et al. 2011). Plant EOs and their constituents have been proposed as effective pesticides, since they are able to evoke acute toxicity and oviposition and feeding deterrence, as well as repellency (Barnard 1999). The insecticidal properties of EO are widely documented (e.g., Pathak and Dixit 1988; Araujo et al. 2003; Traboulsi et al. 2002; Ansari et al. 2000a, b, 2005; Koul et al. 2008; Rattan 2010; Pavela 2008a, b; Urzúa et al. 2010; Benelli 2015b). To the best of our knowledge, any development of resistance to EOs and their constituents has been reported (Sharma et al. 1992; Cavalcanti et al. 2004; Pavela and Benelli 2016).

A growing number of researchers focused on the effectiveness of plant EOs against young mosquito instars (Pavela 2015). Good examples include *Lippia sidoides* (Carvalho et al. 2003), *Tagetes patula* (Dharmagadda et al. 2005), *Pinus kesiya* (Govindarajan et al. 2016a), *Cordia leucomalloides* and *C. curassavica* (Santos et al. 2006), *Blumea mollis* (Senthilkumar et al. 2008), *Piper klotzschianum* (Do Nascimento et al. 2013), *Tetradium glabrifolium* (Liu et al. 2015), *Chloroxylon swietenia* (Kiran et al. 2006), *Origanum majorana* (El-Akhal et al. 2014), *Thymus vulgaris* (El-Akhal et al. 2015), *T. magnus* (Park et al. 2012), *T. transcaspicus* (Dargahi et al. 2014), *Cinnamomum osmophloeum* (Cheng et al. 2009b), *Clausena excavata* (Cheng et al. 2009c), *Toddalia asiatica* (Liu et al. 2013), *Saussurea lappa* (Liu et al. 2012), *Ipomoea carica* (Thomas et al. 2004), and *Zingiber officinalis* (Pushpanathan et al. 2008). Pitasawata et al. (2007) and Champakaew et al. (2007) reported that *Curcuma zedoaria* EO showed larvicidal toxicity on *Aedes aegypti*, while the *Zingiber zerumbet* rhizome EO had larvicidal and pupicidal activity on anopheline mosquitoes (Tewtrakul et al. 1998). Sutthanont et al. (2010) recommended the use of this EO as mosquito larvicide. Kamaraj et al. (2010) reported that the hexane extract of *Z. zerumbet* had larval toxicity against *Culex quinquefasciatus*.

The family of Zingiberaceae represents a key source of herbal preparations and phytoconstituents of interest for current pharmacology, parasitology, and entomology (Burkill 1966; Negi et al. 1999; Scartezzini and Speroni 2000; Youko et al. 2000; Patricia et al. 2003; Jirovetz et al. 2003; Bendjeddou et al. 2003; Nguefack et al. 2004; Govindarajan et al. 2016b). The *Zingiber officinale* rhizome EO is one of the most studied Zingiberaceae EOs. It contains monoterpenoids and sesquiterpenoids. Main molecules are α-zingiberene, α-curcumene, β-bisabolene, and β-sesquiphellandrene (Menon 2007; Rana et al. 2008; Padmakumari et al. 2009), while *Z. zerumbet* EO shows a high content of the monocyclic sesquiterpene ketone zerumbone, as well as an oxygenated humulene derivative (Srivastava et al. 2000; Bhuiyan et al. 2009).

Zingiber cernuum Dalzell (Zingiberaceae), commonly known as curved-stem ginger, is widely found in the evergreen forests of Western Ghats, India. It is a large perennial herb, 1–2 m tall, with curved stem. The leaves are 15–30 cm in length, narrow-elliptic, and long-pointed. The flowers are borne in spikes 5–10 cm long, directly from the rootstock, rising just above the ground. Bracts are 2–3 cm long, greenish-yellow. The sepal cup is shortly three-lobed. Stamen is single, with a short filament. The style is threadlike. The capsules are 1 cm long, smooth with red, channeled seeds. The flowers are yellow colored, variegated with red, with the lib broad and three-lobed (Sanjay 2015). From a phytochemical point of view, *Z. cernuum* is extremely scarcely studied. Kasarkar and Kulkarni (2011) recently identified flavonoids and tannins in *Z. cernuum* extracts, which showed antioxidant activity (Sanjay 2015). This species is rich in iron and manganese and showed low amounts of molybdenum, sulfur, and nitrate in rhizome and leaves (Kasarkar and Kulkarni 2011). To the best of our knowledge, the composition and mosquitocidal bioactivity of *Z. cernuum* EO have not been explored.

In this research, we analyzed the chemical composition of *Z. cernuum* EO using gas chromatography-mass spectroscopy analysis. Furthermore, we studied the larvicidal and oviposition deterrent activity of the *Z. cernuum* EO on six mosquito species, the malaria vectors *Anopheles stephensi* and *Anopheles subpictus*; the dengue and Zika virus vectors *Aedes aegypti* and *Aedes albopictus*; the filariasis, West Nile virus, and St. Louis encephalitis vector *Culex quinquefasciatus*; and the Japanese encephalitis vector *C. tritaeniorhynchus*. In addition, to assess the biosafety of *Z. cernuum* EO-based treatments in the aquatic environment, we investigated the toxicity of *Z. cernuum* EO on four non-target enemies of mosquito young instars, the insects *Anisops bouvieri* and *Diplonychus indicus* and the fishes *Poecilia reticulata* and *Gambusia affinis*.

Materials and methods

Extraction and GC-MS analysis of the *Z. cernuum* essential oil

Fresh rhizomes of *Z. cernuum* were collected during May 2016 in the Munnar mountains (India 10° 05′ 21″ N 77° 03′ 35″ E, 1700 m a.s.l.). Four hundred grams of fresh rhizomes of *Z. cernuum* was hydrodistillated for 3 h using a modified Clevenger-type apparatus; then, the *Z. cernuum* EO was dried over anhydrous sodium sulfate and stored in the dark at 5 °C. GC and GC-MS analyses were carried out as recently described by Govindarajan and Benelli (2016a). The

constituents of the *Z. cernuum* EO were identified by comparison of their mass spectra and retention indices (Table 1) with the ones indexed in the Wiley library, as well as those available in the literature (Adams 2007).

Larvicidal and oviposition deterrence assays

The six mosquito species were reared as described by Govindarajan and Benelli (2016a). Early third instar larvae and adults were used to evaluate the larvicidal potential and oviposition deterrence, respectively. The larvicidal activity of the *Z. cernuum* EO was studied following the method by WHO (2005). Various doses of the *Z. cernuum* EO were dissolved in 1 ml dimethyl sulfoxide (DMSO) and then diluted in 249 ml of filtered tap water. Control was 1 ml of DMSO diluted in 249 ml of water. Within each replicate, 20 early third instar larvae were tested (WHO 2005); $n = 5$ per each dose.

In oviposition deterrent experiments, *Z. cernuum* EO was evaluated at a dose range of 40–250 μg/ml in DMSO. DMSO diluted in water served as a control. We followed the method by Xue et al. (2001). Twenty gravid females (5–7 days old) of each mosquito species were released in the bioassay cage (60 × 60 × 45 cm). After 24 h, the number of eggs laid in treated and control bowls was counted using a stereomicroscope (Olympus, Japan).

Toxicity on non-target organisms

Toxicity on the four predators was assessed following Sivagnaname and Kalyanasundaram (2004) with minor modifications by Govindarajan and Benelli (2016a). The

Table 1 Chemical composition of *Zingiber cernuum* essential oil

Peak	Component	Retention time (Kovats index)	Composition (%)	Mode of identification
1	α-Thujene	925	0.9	RI, MS
2	α-Pinene	927	1.6	RI, MS
3	Camphene	942	0.8	RI, MS
4	Sabinene	971	4.6	RI, MS
5	β-Pinene	974	1.2	RI, MS
6	Myrcene	987	1.7	RI, MS
7	α-Phellandrene	1002	1.3	RI, MS
8	δ-3-Carene	1005	13.2	RI, MS
9	α-Terpinene	1015	1.2	RI, MS
10	*p*-Cymene	1021	1.9	RI, MS
11	β-Phellandrene	1026	2.6	RI, MS
12	γ-Terpinene	1055	2.3	RI, MS
13	Terpinolene	1081	1.7	RI, MS
14	Terpinen-4-ol	1178	5.8	RI, MS
15	α-Terpineol	1192	1.2	RI, MS
16	β-Elemene	1383	0.9	RI, MS
17	*cis*-Caryophyllene	1397	0.8	RI, MS
18	α-Gurjunene	1402	0.9	RI, MS
19	*trans*-Caryophyllene	1416	31.8	RI, MS
20	α-*trans*-Bergamotene	1431	0.9	RI, MS
21	α-Humulene	1452	10.4	RI, MS
22	BicycloGermacrene	1497	1.2	RI, MS
23	δ-Amorphene	1515	1.6	RI, MS
24	*trans*-Nerolidol	1561	0.9	RI, MS
25	Spathulenol	1573	0.8	RI, MS
26	Caryophyllene oxide	1575	3.6	RI, MS
27	Humulene epoxide II	1601	1.2	RI, MS
28	*epi*-α-Cadinol	1635	0.9	RI, MS
	Total		96.2	

RI retention index, *MS* mass spectra

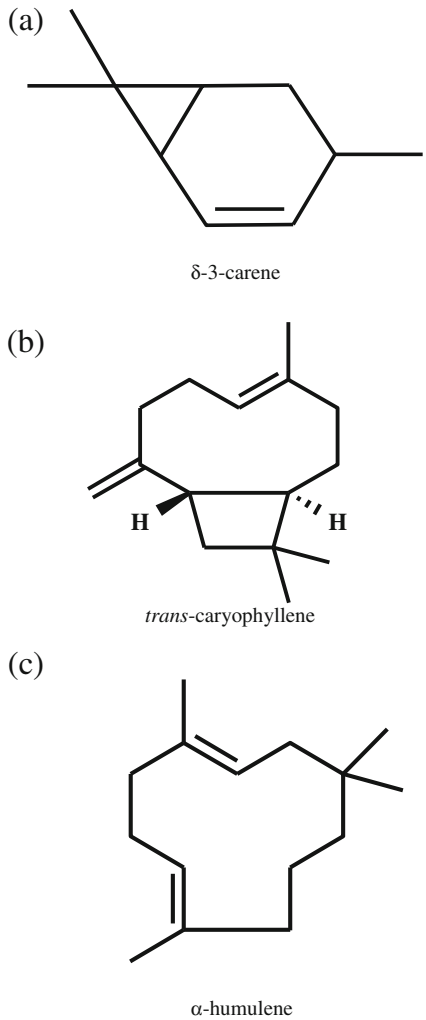

Fig. 1 Chemical structures of the three major constituents of *Zingiber cernuum* essential oil. **a** δ-3-Carene. **b** *trans*-Caryophyllene. **c** α-Humulene

Z. cernuum EO was evaluated at doses of even 50 × LC_{50} values calculated for mosquito larvae studied in the paragraph above, 10 replicates per each dose, plus 4 control replicates (where no EO was added to the water). The mortality of non-target species was assessed 48 h post-treatment.

Data analysis

All data were analyzed using the SPSS Statistical Software Package version 16.0. LC_{50} and LC_{90} were estimated following the method by Finney (1971). The oviposition activity index (OAI) was calculated as indicated by Kramer and Mulla (1979):

$$OAI = (NT-NC)/(NT + NC)$$

Effective repellency (ER %) due to *Z. cernuum* EO was estimated following Xue et al. (2001). In non-target assays, the suitability index (SI) was calculated as described by Deo et al. (1988).

Results

GC and GC-MS of *Z. cernuum* essential oil

The yield of the *Z. cernuum* rhizome EO was 1.8 ml/kg of rhizome fresh weight. Table 1 showed a total of 28 compounds representing 96.2% of the *Z. cernuum* EO. The major constituents of *Z. cernuum* EO were δ-3-carene, *trans*-caryophyllene, and α-humulene (Fig. 1). The other 25 compounds ranged from 0.8 to 5.8%.

Larvicidal and oviposition deterrent activity

The *Z. cernuum* EO showed acute toxicity on third instar larvae of *Anopheles stephensi*, *Aedes aegypti*, *Culex quinquefasciatus*, *Anopheles subpictus*, *Aedes albopictus*, and *Culex tritaeniorhynchus*, with LC_{50} of 41.34, 44.88, 48.44, 51.42, 55.84, and 60.20 μg/ml, respectively (Table 2). No mortality was detected in the control.

The results obtained from the oviposition deterrence experiments testing *Z. cernuum* EO on the six mosquito species are reported in Table 3. The mean number of eggs laid in sites treated with the *Z. cernuum* EO tested at the highest doses (i.e., 200–250 μg/ml) was 44.5, 41.5, and 36.7 eggs per bowl for *Anopheles stephensi*, *Aedes aegypti*, and *Culex quinquefasciatus*, respectively, and 56.2, 52.8, and 47.5 eggs per bowl for *Anopheles subpictus*, *Aedes albopictus*, and *Culex tritaeniorhynchus*, respectively. Significant differences ($P < 0.05$; $P < 0.01$) were detected comparing these values to the respective controls (Table 3). The range of OAI achieved by *Z. cernuum* EO tested against the six mosquito vectors at 200 and 250 μg/ml ranged from −0.79 to −0.84 (Table 3).

Toxicity on non-target predators

Z. cernuum EO toxicity on *A. bouvieri*, *D. indicus*, *P. reticulata*, and *G. affinis* was reported in Table 4. LC_{50} values were 3119, 5273, 10,363, and 11,233 μg/ml, respectively. PSF indicated that the *Z. cernuum* EO showed scarce toxicity on *A. bouvieri*, *D. indicus*, *P. reticulata*, and *G. affinis* (Table 5). Survival and swimming activity of the non-target water bugs and fishes were not affected by the exposure to *Z. cernuum* EO LC_{50} and LC_{90} estimated on the six mosquito species.

Table 2 Larvicidal activity of the essential oil from *Zingiber cernuum* on six mosquito vectors

Mosquito	Concentration (μg/ml)	Mortality (%) ± SD	LC_{50} (μg/ml) (LCL-UCL)	LC_{90} (μg/ml) (LCL-UCL)	Slope	Regression equation	χ^2 (d.f.)
Anopheles stephensi	20	28.5 ± 1.2	41.34 (36.68–45.46)	81.00 (75.13–88.71)	3.11	$y = 10.89 + 0.922x$	5.528 (4) n.s.
	40	46.9 ± 0.8					
	60	67.3 ± 0.6					
	80	88.2 ± 0.4					
	100	100.0 ± 0.0					
Anopheles subpictus	25	29.2 ± 1.2	51.42 (45.49–56.66)	101.86 (94.42–111.66)	3.31	$y = 11.55 + 0.729x$	5.533 (4) n.s.
	50	46.5 ± 0.8					
	75	68.3 ± 0.6					
	100	87.2 ± 0.4					
	125	100.0 ± 0.0					
Aedes aegypti	20	25.2 ± 0.6	44.88 (40.25–49.07)	86.49 (80.24–94.71)	2.86	$y = 6.75 + 0.937x$	3.684 (4) n.s.
	40	43.8 ± 0.8					
	60	62.4 ± 1.2					
	80	85.1 ± 0.4					
	100	98.2 ± 0.8					
Aedes albopictus	25	26.7 ± 0.6	55.84 (49.77–61.27)	110.28 (102.11–121.13)	3.25	$y = 8.16 + 0.73x$	2.467 (4) n.s.
	50	42.6 ± 0.8					
	75	63.8 ± 1.2					
	100	84.2 ± 0.4					
	125	97.1 ± 0.8					
Culex quinquefasciatus	20	22.3 ± 0.4	48.44 (44.00–52.56)	90.15 (83.76–98.56)	2.49	$y = 2.01 + 0.965x$	3.790 (4) n.s.
	40	39.2 ± 1.2					
	60	58.6 ± 0.8					
	80	81.9 ± 0.6					
	100	97.4 ± 1.2					
Culex tritaeniorhynchus	25	23.4 ± 0.4	60.20 (54.45–65.51)	114.22 (105.94–125.18)	2.68	$y = 3.39 + 0.755x$	2.512 (4) n.s.
	50	38.6 ± 1.2					
	75	60.2 ± 0.6					
	100	81.5 ± 0.8					
	125	96.3 ± 0.4					

Discussion

GC and GC-MS of *Z. cernuum* essential oil

Our results showed that 28 compounds were identified in the *Z. cernuum* EO, with δ-3-carene, *trans*-caryophyllene, and α-humulene as main components. This highlighted a quite surprising composition, if compared to EOs extracted from other *Zingiber* species. Indeed, several studies have been conducted on the EOs from other *Zingiber* species, such as *Z. officinale* (Foko et al. 2011), *Z. cassumunar* (Jantan et al. 2003), *Z. zerumbet* (Tewtrakul et al. 1998), *Z. piperitum* (Kamsuk et al. 2006), *Z. limonella* (Somanabandhu et al. 1992), *Z. armatum* (Tiwary et al. 2007), and *Z. monophyllum* (Pavela and Govindarajan 2017). Campbell et al. (2011) pointed out that several mono- and sesquiterpenes, including trans-caryophyllene, α-terpineol, β-pinene, germacrene-D, limonene, and α-zingiberene, present in the EOs evoke responses in *Aedes aegypti* antennae. Sesquiterpenes α-curcumene, β-sesquiphellandrene, zingiberene, and β-bisabolene from *Z. officinale* EO (Campbell 2009), as well as trans-caryophyllene and *Ocimum forskolei* (Dekker et al. 2011), also induced antennal responses by the antennae of *A. aegypti* females.

Larvicidal and oviposition deterrent potential

Essential oils from plants can represent an alternative source of eco-friendly and biodegradable mosquito ovicides (Benelli 2015b), larvicides (Pavela 2015) and adult repellents (Barnard 1999). A growing number of researches concentrated on the effectiveness of plant EOs against mosquito young instars, with special reference to larvae (Sukumar et al. 1991; Benelli 2015b; Pavela 2015). According to Tawatsin et al. (2001), the bioactivity of EOs depends on various factors, including the plant species and cultivar, the growing conditions, the harvesting time, the storage conditions, and the extraction method (see also Pavela and Benelli 2016).

In our assays, the EO extracted from the rhizome of *Z. cernuum* showed high toxicity against third instar larvae of *Anopheles stephensi* (LC_{50} = 41.34 μg/ml), *Aedes aegypti* (LC_{50} = 44.88 μg/ml), *Culex quinquefasciatus* (LC_{50} = 48.44 μg/ml), *Anopheles subpictus* (LC_{50} = 51.42 μg/ml), *Aedes albopictus*

Table 3 Oviposition deterrent activity of the *Zingiber cernuum* essential oil on six mosquito vectors

Mosquito	Concentration (μg/ml)	Eggs laid in bowl (*n*)		Effective repellency (%)	OAI
		Treated	Control		
Anopheles stephensi	40	95.2 ± 1.4**	368.9 ± 2.2	74.10	−0.58
	80	82.6 ± 0.8**	389.6 ± 1.8	78.79	−0.65
	120	65.4 ± 1.2**	433.8 ± 2.4	84.92	−0.73
	160	52.9 ± 1.2*	474.2 ± 2.8	88.84	−0.79
	200	44.5 ± 1.4**	512.7 ± 1.6	91.32	−0.84
Anopheles subpictus	50	94.2 ± 0.8**	375.3 ± 3.2	74.90	−0.59
	100	82.6 ± 1.2**	402.8 ± 2.4	79.49	−0.65
	150	70.7 ± 1.2*	438.9 ± 2.8	83.89	−0.72
	200	64.9 ± 0.8*	465.3 ± 2.2	86.05	−0.75
	250	56.2 ± 1.4**	501.2 ± 3.2	88.78	−0.79
Aedes aegypti	40	91.4 ± 1.2**	375.5 ± 1.8	75.65	−0.60
	80	78.6 ± 0.8**	399.2 ± 2.2	80.31	−0.67
	120	62.7 ± 1.2*	452.7 ± 2.8	86.14	−0.75
	160	46.8 ± 1.4*	488.3 ± 3.2	90.41	−0.82
	200	41.5 ± 1.4**	523.1 ± 1.8	92.06	−0.85
Aedes albopictus	50	92.7 ± 1.2**	388.5 ± 2.8	76.13	−0.61
	100	78.3 ± 1.2**	412.8 ± 2.6	81.03	−0.68
	150	68.9 ± 0.8*	445.7 ± 2.4	84.54	−0.73
	200	61.4 ± 1.4**	476.9 ± 2.8	87.12	−0.77
	250	52.8 ± 1.2**	522.5 ± 2.6	89.89	−0.81
Culex quinquefasciatus	40	87.6 ± 0.8**	388.4 ± 2.4	77.44	−0.63
	80	71.4 ± 1.2**	425.3 ± 18	83.21	−0.71
	120	58.6 ± 1.2*	469.4 ± 2.6	87.51	−0.77
	160	41.8 ± 0.8**	494.2 ± 2.2	91.54	−0.84
	200	36.7 ± 1.4**	544.5 ± 2.8	93.25	−0.87
Culex tritaeniorhynchus	50	87.4 ± 1.6**	396.3 ± 2.2	77.94	−0.63
	100	75.9 ± 1.4*	433.7 ± 2.6	82.49	−0.70
	150	61.3 ± 0.8**	462.9 ± 3.2	86.75	−0.76
	200	55.1 ± 1.2**	497.1 ± 2.6	88.91	−0.80
	250	47.5 ± 0.8**	538.9 ± 2.2	91.18	-0.83

OAI oviposition activity index

t values are significant at $^{*}P < 0.05$; $^{**}P < 0.01$

(LC_{50} = 55.84 μg/ml), and *Culex tritaeniorhynchus* (LC_{50} = 60.20 μg/ml). Concerning the bioactivity of other EOs and extracts from the Zingiberaceae family, Rahuman et al. (2008) evaluated the larvicidal activity of 4-gingerol from *Z. officinalis*, against *A. aegypti* (4.25 ppm) and *C. quinquefasciatus* (5.52 ppm). Sutthanont et al. (2010) reported that *Z. zerumbet* and *Kaempferia galanga* EOs are effective on *A. aegypti*, with LC_{50} of 48.88 and 53.64 ppm, respectively. Tewtrakul et al. (1998) showed the toxicity of *Z. zerumbet* ethanol extract on anopheline larvae, with LD_{50} of 18.9 μg/ml. The *Z. cassumunar* EO is effective against *A. aegypti* larvae (LT_{50} = 1.4 min) (Jantan et al. 2003). Pitasawata et al. (2007) and Champakaew et al. (2007) noted that the *C. zedoaria* EO showed larvicidal activity on *A. aegypti*, with LC_{50} of 33.45 ppm. *Z. zerumbet* EO also showed larvicidal toxicity on *A. aegypti* and *A. nuneztovari*, with LC_{50} of 89.8 and 62.8 μg/ml, respectively (Tewtrakul et al. 1998). Other studies reported that *Z. officinale* EO tested at 20 mg/ml and 700 μl/ml effectively repelled stored product pests, such as *Sitophilus zeamais* and *Prostephanus truncatus* adults (Ogbonna et al. 2014).

The *Z. cernuum* EO tested in this study was mainly composed of δ-3-carene, *trans*-caryophyllene, and α-humulene. Recently, several effective mosquitocidal molecules have been identified in the EOs of other Indian plants. For example, Govindarajan and Benelli (2016a) investigated the toxicity of α-humulene and β-elemene from *Syzygium zeylanicum* EO on *A. albopictus* (LC_{50} = 6.86 and 11.15 μg/ml), *C. tritaeniorhynchus* (LC_{50} = 7.39 and 12.05 μg/ml), and *A. subpictus* (LC_{50} values were 6.19 and 10.26 μg/ml).

Table 4 Toxicity of the *Zingiber cernuum* essential oil on non-target mosquito predators

Non-target species	Concentration (μg/ml)	Mortality (%) ± SD	LC_{50} (μg/ml) (LCL-UCL)	LC_{90} (μg/ml) (LCL-UCL)	Slope	Regression equation	χ^2 (d.f.)
Anisops bouvieri	1500	26.4 ± 1.2	3119.35	6104.44	3.09	$y = 10.52 + 0.012x$	3.146
	3000	48.9 ± 0.8	(2769.42–3429.59)	(5664.60–6681.22)			(4)
	4500	67.2 ± 0.6					n.s.
	6000	88.5 ± 0.4					
	7500	99.1 ± 1.2					
Diplonychus indicus	2500	24.8 ± 0.8	5273.84	10,135.89	2.83	$y = 8.91 + 0.008x$	1.146
	5000	47.2 ± 0.6	(4707.74–5779.89)	(9419.71–11,069.24)			(4)
	7500	68.5 ± 1.2					n.s.
	10,000	89.9 ± 0.4					
	12,500	98.1 ± 1.2					
Gambusia affinis	5000	25.7 ± 0.4	11,233.25	22,026.60	3.12	$y = 7.60 + 0.004x$	2.128
	10,000	42.6 ± 0.6	(10,033.35–12,311.09)	(20,406.96–24,172.77)			(4)
	15,000	64.8 ± 1.2					n.s.
	20,000	83.4 ± 0.8					
	25,000	97.2 ± 1.2					
Poecilia reticulata	5000	28.5 ± 0.6	10,363.75	20,489.41	3.27	$y = 11.05 + 0.004x$	3.533
	10,000	46.3 ± 1.2	(9177.37–11,412.67)	(18,996.93–22,452.17)			(4)
	15,000	67.8 ± 0.4					n.s.
	20,000	88.2 ± 0.8					
	25,000	99.1 ± 1.2					

Further research focusing on potential synergic larvicidal effects occurring among the abovementioned molecules is ongoing.

Concerning the oviposition deterrent potential, we observed that the range of OAI achieved by the *Z. cernuum* EO tested at 200 and 250 μg/ml compared with controls ranged from −0.7 to −0.8. Recently, a growing number of studies focused on the oviposition deterrent activity of plant extracts and EOs against mosquito vectors of economic importance (Elango et al. 2009). However, few of them investigated the oviposition deterrent potential of *Zingiber* species. Coria et al. (2008) reported 100% oviposition deterrent effect obtained with *Melia azedarach* leaf extract tested at 1 g/l concentration against *Aedes aegypti*. Prajapati et al. (2005) noted that the bark EO of *Cinnamomum zeylanicum* reduced the oviposition rates of *A. aegypti* to 50% when tested at 33.5 ppm. Autran et al. (2009) recorded the oviposition deterrent effect of EO obtained from leaves, inflorescences, and stems of *Piper marginatum*; the EOs from leaves and stems of *P. marginatum* exhibited oviposition deterrent effect on *A. aegypti* females at 50 and 100 ppm concentrations and the number of eggs laid was significantly lower (<50%), if compared to control.

Biotoxicity on mosquito predators

It is worthy to note that the toxicity of *Z. cernuum* EO on the mosquito predators *A. bouvieri*, *D. indicus*, *G. affinis*, and *P. reticulata* was very low, with LC_{50} values always higher than 3000 μg/ml. EOs have been recently recognized as novel and reliable biopesticides, which do not induce resistance and have few toxic effects on human health and non-target species. For example, scarce toxicity of *P. kesiya* EO on *A. bouvieri*, *D. indicus*, and *G. affinis* was noted, with LC_{50} from 4135 to 8390 mg/ml, and in agreement with the present results, *G. affinis* has been found less susceptible to EO, if compared to *A. bouvieri* and *D. indicus* (Govindarajan et al. 2016a). *S. zeylanicum* EO tested on *G. affinis* showed LC_{50} = 20,374.26 μg/ml (Govindarajan and Benelli 2016a). Moreover, *Heracleum sprengelianum* EO, lavandulyl acetate

Table 5 Predator safety factor calculated on four mosquito predators and mosquito young instars post-treatment with *Zingiber cernuum* essential oil

Non-target species	*Anopheles stephensi*	*Anopheles subpictus*	*Aedes aegypti*	*Aedes albopictus*	*Culex quinquefasciatus*	*Culex tritaeniorhynchus*
Anisops bouvieri	75.45	60.66	69.50	55.86	64.39	51.81
Diplonychus indicus	127.57	102.56	117.50	94.44	108.87	87.60
Poecilia reticulata	250.69	201.55	230.92	185.59	213.95	172.15
Gambusia affinis	271.72	218.46	250.29	201.16	231.90	186.59

and bicyclogermacrene, tested on *A. bouvieri*, *D. indicus*, and *G. affinis*, led to LC_{50} ranging from 414 to 4219 μg/ml (Govindarajan and Benelli 2016b). Taken together, the data reported above underline the environmental-friendly nature of botanicals from selected Asian plant species, which can be further considered for as larvicides and oviposition deterrents in urban and peri-urban areas.

Conclusions

Overall, the present research sheds light on the chemical composition of the EO of *Z. cernuum*, as well as on its larvicidal and oviposition deterrent activity on six important mosquito species. Notably, really limited non-target effects of *Z. cernuum* EO were found on four important mosquito predators. Therefore, the results from this study supported our hypothesis to consider the *Z. cernuum* EO for the development of effective and eco-friendly larvicides and oviposition deterrents effective against a broad range of mosquito vector species.

Acknowledgements The authors extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this work through research group No RG-1438-074.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

References

Adams RP (2007) 4th Ed. Carol Stream, Illinois: Allured Publishing Corporation; Identification of essential oil components by gas chromatography/mass spectroscopy

Almeida RN, Fátima Agra M, Negromonte Souto Major F, Sousa DP (2011) Essential oils and their constituents: anticonvulsant activity. Molecules 16:2726–2742

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

Ansari MA, Razdan RK, Tandon M, Vasudevan P (2000b) Larvicidal and repellent actions of *Dalbergia sisoo* Roxb. (F. Leguminosae) oil against mosquitoes. Bioresour Technol 73:207–211

Ansari MA, Vasudevan P, Tandon M, Razdan RK (2000a) Larvicidal and mosquito repellent action of peppermint (*Mentha piperita*) oil. Bioresour Technol 71:267–271

Araujo ECC, Silveira ER, Lima MAS, Neto MA, Andrade I, Lima MAA (2003) Insecticidal activity and chemical composition of volatile oils from *Hyptis martiusii* Benth. J Agric Food Chem 51:3760–3762

Astani A, Reichling J, Schnitzler P (2010) Comparative study on the antiviral activity of selected monoterpenes derived from essential oils. Phytother Res 24:673–679

Autran ES, Neves IA, Da Silva CS, Santos GK, Da Câmara CA, Navarro DM (2009) Chemical composition, oviposition deterrent and larvicidal activities against *Aedes aegypti* of essential oils from *Piper marginatum* Jacq. (Piperaceae). Bioresour Technol 100: 2284–2288

Barnard DR (1999) Repellency of essential oils to mosquitoes (Diptera: Culicidae). J Med Entomol 36:625–629

Bendjeddou D, Lalaoui K, Satta D (2003) Immunostimulating activity of the hot water-soluble poly-saccharide extracts of *Anacyclus pyrethrum*, *Alpinia galanga* and *Citrullus colocythis*. J Ethnophamacol 88:155–160

Benelli G (2015a) Research in mosquito control: current challenges for a brighter future. Parasitol Res 114:2801–2805

Benelli G (2015) Plant-borne ovicides in the fight against mosquito vectors of medical and veterinary importance: a systematic review. Parasitol Res 114(9):3201–3212

Benelli G, Mehlhorn H (2016) Declining malaria, rising dengue and Zika virus: insights for mosquito vector control. Parasitol Res 115:1747–1754

Bhuiyan MNI, Chowdhury JU, Begum J (2009) Chemical investigation of the leaf and rhizome essential oils of *Zingiber zerumbet* (L.) Smith. Bangladesh. Aust J Pharm 4:9–12

Burkill IH (1966) A dictionary of the economic products of the Malay Peninsula. Vol I: A-H, Vol II: I-Z; Art Printing Works: Kuala Lumpur, 2402 p.

Campbell C, Gries R, Gries G (2011) Forty-two compounds in eleven essential oils elicit antennal responses from *Aedes aegypti*. Entomol Exp Appl 138:21–32

Campbell CJ (2009) Analyses of essential and edible oils, and constituents therein, as candidate repellents for the yellow fever mosquito *Aedes aegypti* L. (Diptera: Culicidae). Simon Fraser University

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 aegepti* L. Mem Inst Oswaldo Cruz 98:569–571

Cavalcanti ESBC, Morais SM, Lima MAA, Santana EWP (2004) Larvicidal activity of the essential oil from Brazilian plants against *Aedes aegypti*. 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 100:729–737

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 89:99–102

Cheng SS, Chang HT, Lin CY, Chen PS, Huang CG, Chen WJ, Chang ST (2009c) Insecticidal activities of leaf and twig essential oils from *Clausena excavata* against *Aedes aegypti* and *Aedes albopictus* larvae. Pest Manag Sci 65:339–343

Cheng SS, Chua MT, Chang EH, Huang CG, Chen WJ, Chang ST (2009a) Variations in insecticidal activity and chemical composition of leaf essential oils from *Cryptomeria japonica* at different ages. Bioresour Technol 100:465–470

Cheng SS, Huang CG, Chen WJ, Kuo YH, Chang ST (2008) Larvicidal activity of tectoquinone isolation from red heartwood-type *Cryptomeria japonica* against two mosquito species. Bioresour Technol 99:3617–3622

Cheng SS, Liu JY, Huang CG, Hsui YR, Chen WJ, Chang ST (2009b) Insecticidal activities of leaf essential oils from *Cinnamomum osmophloeum* against three mosquito species. Bioresour Technol 100:457–464

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 52:4395–4400

Chericoni S, Flamini G, Campeol E, Cioni PL, Morelli I (2004) GC-MS analysis of the essential oil from the aerial parts of *Artemisia*

verlotiorum: variability during the year. Biochem Sys Ecol 32:423–429

Coria C, Almiron W, Valladares G, Carpinella C, Ludueña F, Defago M (2008) Larvicide and oviposition deterrent effects of fruit and leaf extracts from *Melia azedarach* L. on *Aedes aegypti* (L.) (Diptera: Culicidae). Bioresour Technol 99:3066–3070

Dargahi L, Razavi-Azarkhiavi K, Ramezani M, Reza Abaee M, Behravan J (2014) Insecticidal activity of the essential oil of *Thymus transcaspicus* against *Anopheles stephensi*. Asian Pac J Trop Biomed 4:589–491

Dekker T, Ignell R, Ghebru M, Glinwood R, Hopkins R (2011) Identification of mosquito repellent odours from *Ocimum forskolei*. Parasit Vectors 4:1–7

Deo PG, Hasan SB, Majumdar SK (1988) Toxicity and suitability of some insecticides for household use. Int Pest Control 30:118–129

Dharmagadda VSS, Naik SN, Mittal PK, Vasudevan P (2005) Larvicidal activity of *Tagetus patula* essential oil against three mosquito species. Bioresour Technol 96:1235–1240

Do Nascimento JC, David JM, Barbosa LCA, De Paula VF, Demuner AJ, David JP, Conserva LM, Ferreira JRJC, Guimaraes EF (2013) Larvicidal activities and chemical composition of essential oils from *Piper klotzschianum* (Kunth) C. DC. (Piperaceae). Pest Manag Sci 69:1267–1271

El-Akhal F, El Ouali LA, Ez Zoubi Y, Greche H, Guemmouh R (2014) Chemical composition and larvicidal activity of essential oil of *Origanum majorana* (Lamiaceae) cultivated in Morocco against *Culex pipiens* (Diptera: Culicidae). Asian Pac J Trop Biomed 4: 746–750

El-Akhal F, Greche H, Ouazzani CF, Guemmouh R, El Ouali LA (2015) Chemical composition and larvicidal activity of *Culex pipiens* essential oil of *Thymus vulgaris* grown in Morocco. J Mater Environ Sci 1:214–219

Elango G, Bagavan A, Kamaraj C, Abduz Zahir A, Abdul Rahuman AC (2009) Oviposition-deterrent, ovicidal, and repellent activities of indigenous plant extracts against *Anopheles subpictus* Grassi (Diptera: Culicidae). Parasitol Res 105:1567–1576

Finney DJ (1971) Probit analysis. Cambridge University Press, London, pp 68–72

Foko GA, Tamesse JL, Fekam F (2011) Adulticidal effects of essential oils extracts from *Capsicum annum* (Solanaceae), *Piper nigrum* (Piperaceae) and *Zingiber officinales* (Zingiberaceae) on *Anopheles gambiae* (Diptere-Culicidade), vector of malaria. J Entomol 8:152–163

Govindarajan M, Benelli G (2016a) α-Humulene and β-elemene from *Syzygium zeylanicum* (Myrtaceae) essential oil: highly effective and eco-friendly larvicides against *Anopheles subpictus, Aedes albopictus* and *Culex tritaeniorhynchus* (Diptera: Culicidae). Parasitol Res 115:2771–2778

Govindarajan M, Benelli G (2016b) Eco-friendly larvicides from Indian plants: effectiveness of lavandulyl acetate and bicyclogermacrene on malaria, dengue and Japanese encephalitis mosquito vectors. Ecotoxicol Environ Saf 133:395–402

Govindarajan M, Rajeswary M, Arivoli S, Samuel T, Benelli G (2016b) Larvicidal and repellent potential of *Zingiber nimmonii* (J. Graham) Dalzell (Zingiberaceae) essential oil: an eco-friendly tool against malaria, dengue and lymphatic filariasis mosquito vectors? Parasitol Res 115:1807–1816

Govindarajan M, Rajeswary M, Benelli G (2016a) Chemical composition, toxicity and effects on non-target organisms of *Pinus kesiya* essential oil: an eco-friendly larvicide against mosquito vectors. Ecotoxicol Environ Saf 129:85–90

Jain N, Srivastava SK, Aggarwal LKK, Ramesh S, Kumar S (2001) Essential oil composition of *Zanthoxylum alatum* seeds from northern India. Flavour Frag J 16:408–410

Jantan I, Ping WO, Visuvalingam SD, Ahmad NW (2003) Larvicidal activity of the essential oils and methanol extracts of Malaysian plants on *Aedes aegypti*. Pharm Biol 41:234–246

Jirovetz L, Buchbauer G, Pottachola M, Kalathil N (2003) Analysis of the essential oils of the leaves, stems, rhizomes and roots of the medicinal plant *Alpinia galanga* from southern India. Acta Pharma 53:73–81

Kamaraj C, Rahuman A, Mahapatra A, Bagavan A, Elango G (2010) Insecticidal and larvicidal activities of medicinal plant extracts against mosquitoes. Parasitol Res 107:1337–1349

Kamsuk K, Choochote W, Chaithong U, Jitpakdi A, Tippawangkosol P, Riyong D, Pitasawat B (2006) Effectiveness of *Zanthoxylum piperitum*-derived essential oil as an alternative repellent under laboratory and field applications. Parasitol Res 100:339–345

Kasarkar AR, Kulkarni DK (2011) Phytochemical investigation of the genus *Zingiber* from the family Zingiberaceae. Int J Pharm Res Allied Sci 2:648–649

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 97:2481–2484

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

Kramer WL, Mulla MS (1979) Oviposition attractants and repellents of mosquitoes: oviposition responses of *Culex* mosquitoes to organic infusions. Environ Entomol 8:1111–1114

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 112: 1197–1203

Liu XC, Liu Q, Chen XB, Zhou L, Liu ZL (2015) Larvicidal activity of the essential oil from *Tetradium glabrifolium* fruits and its constituents against *Aedes albopictus*. Pest Manag Sci 71:1582–1586

Liu ZL, He Q, Chu SS, Wang CF, Du SS, Deng ZW (2012) Essential oil composition and larvicidal activity of *Saussurea lappa* roots against the mosquito *Aedes albopictus* (Diptera: Culicidae). Parasitol Res 110:2125–2130

Lucia A, Audino GA, 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 3:299–303

Menon AN (2007) Chemical composition of the essential oils from leaves and roots of ginger (*Zingiber officinale*) from Kerela. J Med Aromatic Pl Sci 29:78–80

Naqqash MN, Gökçe A, Bakhsh A, Salim M (2016) Insecticide resistance and its molecular basis in urban insect pests. Parasitol Res 115: 1363–1373

Negi PS, Jayaprakasha GK, Jagan MRL, Sarariah KK (1999) Antibacterial activity of turmeric oil: a byproduct from *Curcumin manufacture*. J Agric Food Chem 47:4297–4300

Nguefack J, Leth V, Amvam HP, Mathur BS (2004) Evaluation of five essential oil from aromatic plant of Cameroon for controlling food spoilage and mycotoxin producing fungi. Int J Food Microbiol 94: 329–994

Ogbonna CU, Eziah VY, Owusu EO (2014) Bioefficacy of *Zingiber officinale* against *Prostephanus truncates* Horn (Coleoptera: Bostrichidae) infesting maize. J Biopest 7:177–185

Padmakumari KP, Sreekumar MM, Sankarikutty B (2009) Composition of volatile oil of ginger (*Zingiber officinale* Roscoe) varieties from India. Indian Perfum 53:16–20

Park YU, Koo HN, Kim GH (2012) Chemical composition, larvicidal action, and adult repellency of *Thymus magnus* against *Aedes albopictus*. J Am Mosq Control Assoc 28:192–198

Pathak AK, Dixit VK (1988) Insecticidal and insect repellent activity of essential oils of *Tridax procumbens* and *Cyathocline lyrata*. Fitoterapia 59:211–214

Patricia FL, Mera EM, Daisy NS, Joao EC, Maricia OM, Angela AM (2003) Functional properties of spice extracts obtained via supercritical fluid extraction. J Agric Food Chem 51:2520–2525

Pavela R (2008a) Insecticidal properties of several essential oils on the house fly (*Musca domestica* L.) Phytother Res 22:274–278

Pavela R (2008b) Larvicidal effects of various Euro-Asiatic plants against *Culex quinquefasciatus* Say. larvae (Diptera: Culicidae). Parasitol Res 102:555–559

Pavela R (2015) Essential oils for the development of eco-friendly mosquito larvicides: a review. Ind Crop Prod 76:174–187

Pavela R, Benelli G (2016) Essential oils as ecofriendly biopesticides? Challenges and constraints. Tr Plant Sci 21:1000–1007

Pavela R, Govindarajan M (2017) The essential oil from *Zanthoxylum monophyllum* a potential mosquito larvicide with low toxicity to the non-target fish *Gambusia affinis*. J Pest Sci 90:369–378

Pitasawata B, Champakaewa D, Choochotea W, Jitpakdia A, Chaithonga U, Kanjanapothib D (2007) Aromatic plant-derived essential oil: an alternative larvicide for mosquito control. Fitoterapia 78:205–210

Prajapati V, Tripathi AK, Aggarwal KK, Khanuja SP (2005) Insecticidal, repellent and oviposition-deterrent activity of selected essential oils against *Anopheles stephensi*, *Aedes aegypti* and *Culex quinquefasciatus*. Bioresour Technol 96:1749–1757

Pushpanathan T, Jebanesan A, Govindarajan M (2008) The essential oil of *Zingiber officinalis* Linn (Zingiberaceae) as a mosquito larvicidal and repellent agent against the filarial vector *Culex quinquefasciatus* Say (Diptera: Culicidae). Parasitol Res 102:1289–1291

Rahuman AA, Gopalakrishnan G, Venkatesan P, Geetha K (2008) Isolation and identification of mosquito larvicidal compound from *Abutilon indicum* (Linn) Sweet. Parasitol Res 102:981–988

Rana VS, Verdeguer M, Blazquez MA (2008) A comparative study of rhizome essential oils of three *Zingiber* species from Manipur. Indian Perfum 52:17–21

Rattan RS (2010) Mechanism of action of insecticidal secondary metabolites of plant origin. Crop Prot 29:913–920

Sanjay J (2015) Phytochemical screening, antioxidant activity, multielemental and flavonoid analysis of rhizome extracts of *Zingiber cernuum* Dalzell. J Acad Indus Res 4:56–64

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

Scartezzini P, Speroni E (2000) Review on some plants of Indian traditional medicine with antioxidant activity. J Ethnopharmacol 171:23–43

Senthilkumar A, Kannathasan K, Venkatesalu V (2008) Chemical constituents and larvicidal property of the essential oil of *Blumea mollis* (D. Don) Merr. against *Culex quinquefasciatus*. Parasitol Res 103: 959–962

Sharma RN, Gupta AS, Patwardhan SA, Hebbal-ker DS, Tare V, Bhonde SB (1992) Bioactivity of *Lamiaceae* plants against insects. Indian J Exp Biol 30:244–246

Sivagnaname N, Kalyanasundaram M (2004) Laboratory evaluation of methanolic extract of *Atlantia monophylla* (family: Rutaceae) against immature stages of mosquitoes and non-target organisms. Mem Inst Oswaldo Cruz 99:115–118

Somanabandhu A, Ruangrungsi N, Lange GL, Organ MG (1992) Constituents of the stembark of *Zanthoxylum limonella*. J Sci Soc Thailand 18:181–185

Srivastava AK, Srivastava SK, Shah NC (2000) Essential oil composition of *Zingiber zerumbet* (L.) Sm. from India. J Essent Oil Res 12:595–597

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

Sutthanont N, Choochote W, Tuetun B, Junkum A, Jitpakdi A, Chaithong U, Riyong D, Pitasawat B (2010) Chemical composition and larvicidal activity of edible plant-derived essential oils against the pyrethroid-susceptible and -resistant strains of *Aedes aegypti* (Diptera: Culicidae). J Vector Ecol 35:106–115

Tawastin A, Wratten SD, Scott RR, Thavara U, Techadamrongsin Y (2001) Repellency of volatile oils from plants against three mosquito vectors. J Vector Ecol 26:76–82

Tewtrakul S, Itchayapruk J, Chaitongruk P (1998) Mosquito larvicidal activity of *Zingiber zerumbet* Smith rhizomes. Songklanakarin J Sci Technol 20:183–187

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

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

Traboulsi AF, Taoubi K, El-Haj S, Bessiere JM, Rammal S (2002) Insecticidal properties of essential plant oils against the mosquito *Culex pipiens molestus* (Diptera: Culicidae). Pest Manag Sci 58: 491–495

Urzúa A, Santander R, Echeverría J, Cabezas N, Palacios SM, Rossi Y (2010) Insecticide properties of the essential oils from *Haplopappus foliosus* and *Bahia ambrosoides* against the house fly, *Musca domestica* L. J Chil Chem Soc 55:392–395

Ward W, Benelli G (2017) Avian and simian malaria: do they have a cancer connection?. Parasitol Res 116(3):839–845

World Health Organization (2005) Guidelines for laboratory and field testing of mosquito larvicides. Communicable disease control, prevention and eradication, WHO pesticide evaluation scheme. WHO, Geneva, WHO/CDS/WHOPES/GCDPP/1.3

Xue RD, Barnard DR, Ali A (2001) Laboratory and field evaluation of insect repellents as oviposition deterrents against the mosquito *Aedes albopictus*. Med Vet Entomol 15:126–131

Youko S, Kiku K, Akio K (2000) Isolation of novel glucosides related to gingerdiol from ginger and their antioxidative activities. J Agric Food Chem 48:373–377