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REVIEW

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Effectiveness of plant-based repellents against different *Anopheles* species: a systematic review

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Abstract

Plant-based repellents have been applied for generations in traditional practice as a personal protection approach against different species of *Anopheles*. Knowledge of traditional repellent plants is a significant resource for the development of new natural products as an alternative to chemical repellents. Many studies have reported evidence of repellant activities of plant extracts or essential oils against malaria vectors worldwide. This systematic review aimed to assess the effectiveness of plant-based repellents against *Anopheles* mosquitoes. All eligible studies on the repellency effects of plants against *Anopheles* mosquitoes published up to July 2018 were systematically searched through PubMed/Medline, Scopus and Google scholar databases. Outcomes measures were percentage repellency and protection time. A total of 62 trials met the inclusion criteria. The highest repellency effect was identified from *Ligusticum sinense* extract, followed by citronella, pine, *Dalbergia sissoo*, peppermint and *Rhizophora mucronata* oils with complete protection time ranging from 9.1 to 11.5 h. Furthermore, essential oils from plants such as lavender, camphor, catnip, geranium, jasmine, broad-leaved eucalyptus, lemongrass, lemon-scented eucalyptus, amyris, narrow-leaved eucalyptus, carotin, cedarwood, chamomile, cinnamon oil, juniper, cajeput, soya bean, rosemary, niaouli, olive, tagetes, violet, sandalwood, litsea, galbanum, and *Curcuma longa* also showed good repellency with 8 h complete repellency against different species of *Anopheles*. Essential oils and extracts of some plants could be formulated for the development of eco-friendly repellents against *Anopheles* species. Plant oils may serve as suitable alternatives to synthetic repellents in the future as they are relatively safe, inexpensive, and are readily available in many parts of the world.

Keywords: Plant, Herb, Repellent, Repellency, Systematic review, *Anopheles*

Background

Mosquito-transmitted diseases remain a main source of illness and death [1]. Despite decades of malaria control efforts, malaria continues to be a major worldwide public health issue with 3.3 billion persons at risk in 106 countries and territories in the tropical and subtropical areas [2]. It is one of the significant reasons for maternal and childhood morbidity and mortality, including low birth weight, stillbirths, and early infant death in sub-Saharan Africa [3]. Among 500 species of *Anopheles* mosquitoes known globally, more than 50 species can transmit malaria from the bite of the infected female *Anopheles* spp. [4]. Presently, there is no effective prophylactic anti-malarial vaccine and no suitable preventive measure other than vector control is available [5]. Thus, protection from mosquito bites is one of the best approaches to reduce the disease incidence.

The use of repellents to protect people from bites of mosquitoes previously has been acknowledged as part

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of an overall integrated insect-borne disease control programme [6]. Most commercial repellents are produced by using chemical components such as N, N-diethyl-meta-toluamide (DEET), Allethrin, N, N-diethyl mendelic acid amide, and Dimethyl phthalate [1]. It has been identified that chemical repellents are not safe for public health and should be used with caution because of their detrimental impacts on synthetic fabric and plastic as well as toxic reactions, such as allergy, dermatitis, and cardiovascular and neurological side effects, which have been reported generally after misapplication [4]. The frequent use of synthetic repellents with chemical origin for mosquito control has disturbed natural ecosystems and resulted in the development of resistance to insecticides, resurgence in mosquito populations, and adverse impact on non-target organisms [4, 7]. Accordingly, the idea of using natural mosquito repellent products as an alternative to develop new eco-friendly repellents could be an amicable solution to scale back the undesirable effects on environment and human health.

In recent years, interest in plant-based repellents has been revived, as they contain a rich source of bioactive phytochemicals that are safe and biodegradable into non-toxic by-products, which could be screened for insecticidal activities and mosquito repellent. Many studies have reported evidence of repellant activities of plant extracts or essential oils against malaria vectors around the world. The present systematic review was performed to reveal which plant-based repellent can be relied on to provide a prolonged and predictable protection from species of *Anopheles* mosquitoes without causing side effects on human health.

For this systematic review, all eligible studies on the repellency effects of plant-based repellants against *Anopheles* spp. published up to July 2018 were systematically searched through electronic databases PubMed, MEDLINE, Web of Science, Literature retrieval System of the Armed Forces Pest Management Board, Scopus and Google Scholar using the following Medical Subject Headings (Mesh) and keywords: (((Plant [Title/Abstract]) OR Plants [Title/Abstract]) OR herbal [Title/Abstract]) AND (botanical [Title/Abstract]) AND ((extract [Title/Abstract]) OR extracts [Title/Abstract]) AND ((“essential oil” [Title/Abstract]) OR “essential oils” [Title/Abstract]) AND (((((“Insect repellent” [Mesh]) OR repellents) OR repellent) OR repellence) OR repellency) AND ((“*Anopheles*” [Mesh]) OR “*Anopheles*” [Title/Abstract]). The search was limited to English publications. In addition, a manual search was conducted to identify further pertinent articles using references from retrieved studies.

Eligibility criteria

Studies were included in the present systematic review if they met these criteria: (i) full-text publication was written in English, (ii) inspected the repellency effects of plant extracts and essential oils against malaria vectors, *Anopheles* spp. mosquitoes, and, (iii) reported the percentage of repellency or complete protection time. Following studies were excluded: studies exploring the repellency effect of chemical-based products, studies examining the repellency effect of animal extracts, animal studies (studies not on human subjects), articles without full texts, reviews, duplicate articles, abstracts, republished data, comments, conference papers, editorials, and studies with insufficient data. In addition, studies were excluded if the information could not be extracted. A screening of titles and abstracts followed by a full-text review was performed by two investigators. All titles and abstracts were screened by two independent investigators for eligibility. If a consensus was reached, a study was excluded or selected to full-text screening. If a consensus was not reached, another reviewer was consulted to resolve any feasible discrepancies.

Data extraction

After identifying the eligible studies, the following data were collected from each study by application of standardized data collection form to improve accuracy and critical appraisal: the first author name, country of origin, journal details, publication year, condition of study (field or laboratory), plant name, *Anopheles* species, concentration or dose of repellents, repellency percentage and complete protection time. All data were independently extracted by two reviewers and disagreements were solved by discussion, and if necessary, a third author was involved.

A total of 383 studies were found by the initial literature search of the databases. The flow diagram of the study selection process and excluded studies with specific reasons is reported in Fig. 1. Of the 324 excluded citations, 102 were duplicated studies; 149 were not relevant to the repellency effect of plants on *Anopheles* spp. after screening titles/abstracts; 11 were review publications; 8 investigated the repellency impact of chemical-based repellents or animal extracts; 7 studies were conducted on laboratory animals; 12 were abstracts, conference papers, comments, and editorials; 10 studies had not reported sufficient data regarding the percentage of repellency or complete protection time; and, 15 studies were other irrelevant studies. The primary eligibility process yielded 59 documents and crosscheck of the references of reviews and other databases search provided 3 further articles [8–10]. A total of 62 studies conducted in different countries, including India [7–40], Thailand [4,

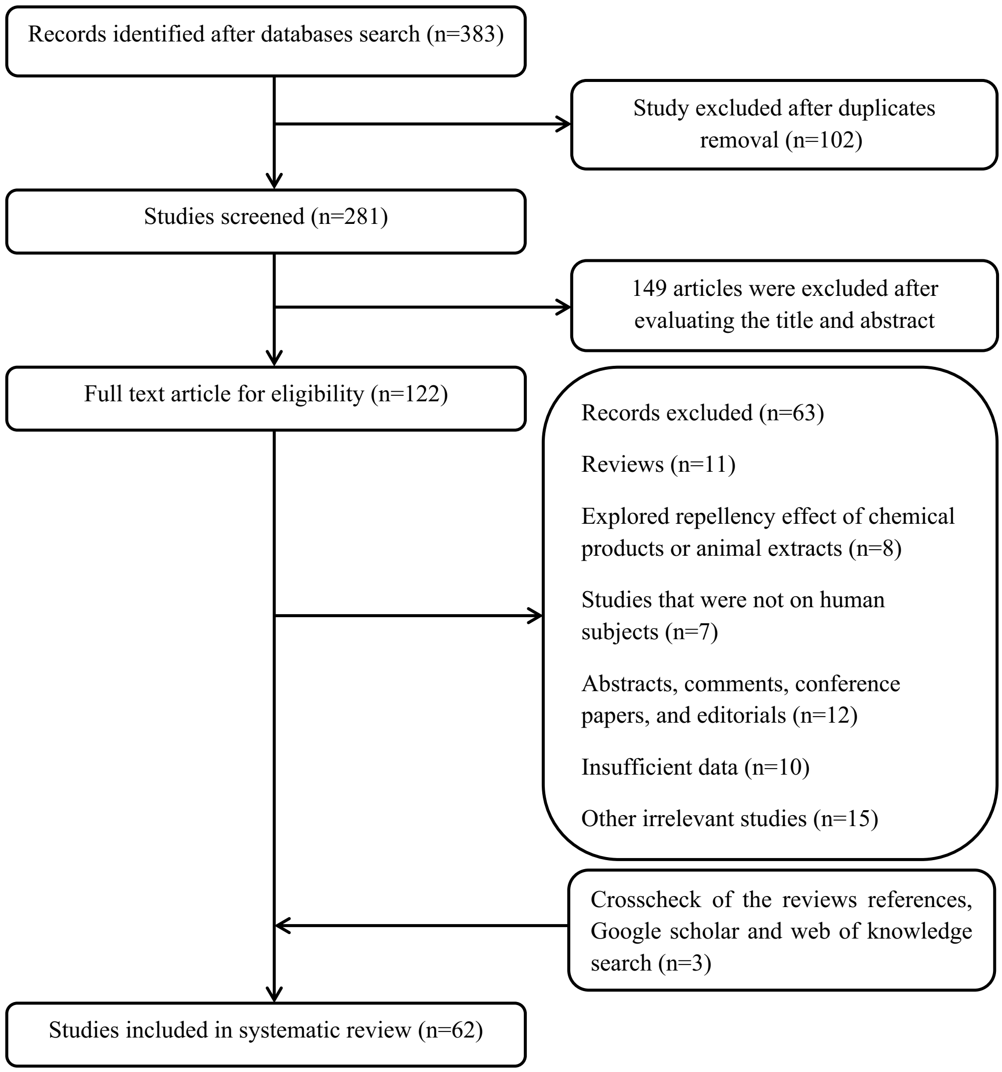

Fig. 1 Study selection process, up to July 2018

5, 41–48], Ethiopia [49–52], Kenya [53–57], Germany [6], Nigeria [1], USA [58], Tanzania [59], Brazil [60], Sudan [61], Iran [62], Cameron [63] and Ivory Coast [64] were eventually included in the systematic review based on the inclusion criteria for the effect of plant-based repellents on species of *Anopheles* mosquitoes. The included studies were published between 1999 and 2018. Expect for 6 studies which were field trial, other studies were conducted on laboratory condition. None of the studies reported the inclusion and exclusion criteria explicitly other than specifying a healthy volunteer. Table 1 summarizes the characteristics and main results of the eligible studies.

Effectiveness of plant-based products against *Anopheles* spp.

Potential plant-based repellents stratified by protection time with at least 4 h protection time are reported in Table 2. The highest repellency effect was identified from *Ligusticum sinense* extract, followed by citronella, pine, *Dalbergia sissoo*, peppermint and *Rhizophora mucronata* oils with complete protection time ranging from 9.1 to 11.5 h. Ethanolic 25% extract of *L. sinense* was able to completely repel *Anopheles minimus* for 11.5 h. Furthermore, essential oils from plants such as lavender, camphor, catnip, geranium, jasmine, broad-leaved

Table 1 Characteristics of studies. Characteristics of studies included in the systematic review, up to July 2018

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
Ansari et al.	2005	India	Field	Pine oil (*Pinus*)	1 ml without dilution	*An. culicifacies*	100	11
				Citronella (lemongrass oil)	1 ml without dilution	*An. culicifacies*	100	11
Ansari et al.	2000	India	Field	*D. sissoo* oil	1 ml without dilution	*An. culicifacies*	96.1	10.3
				D. sissoo oil	1 ml without dilution	*An. annularis*	100	11
				D. sissoo oil	1 ml without dilution	*An. subpictus*	89.7	8
Ansari et al.	2000	India	Field	Peppermint oil	1 ml without dilution	*An. culicifacies*	92.3	9.6
				Peppermint oil	1 ml without dilution	*An. annularis*	100	11
				Peppermint oil	1 ml without dilution	*An. subpictus*	83.1	7.3
Amer et al.	2006	Germany	Laboratory	Citronella (*Cymbopogon winterianus*) essential oils	20% oil solutions	*An. stephensi*	52.4	8
				Rosewood (*Aniba rosaeodora*) essential oils	20% oil solutions	*An. stephensi*	4.8	6.5
				Lavender (*Lavandula angustifolia*) essential oils	20% oil solutions	*An. stephensi*	80.9	8
				Camphor (*C. camphora*) essential oils	20% oil solutions	*An. stephensi*	42.8	8
				Catnip (*N. cataria*) essential oils	20% oil solutions	*An. stephensi*	100	8
				Geranium (*Pelargonium graveolens*) essential oils	20% oil solutions	*An. stephensi*	61.9	8
				Thyme (*T. serpyllum*) essential oils	20% oil solutions	*An. stephensi*	33.3	7.5
				Eucalyptus (*E. globulus*) essential oils	20% oil solutions	*An. stephensi*	28.6	5.5
				Jasmine (*Jasminum grandiflorum*) essential oils	20% oil solutions	*An. stephensi*	100	8
				Broad-leaved eucalyptus (*Eucalyptus dives*) essential oils	20% oil solutions	*An. stephensi*	38.1	8
				Lemongrass (*Cymbopogon citratus*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Lemon-scented eucalyptus (*E. citriodora*) essential oil	20% oil solutions	*An. stephensi*	52.4	8
				Fichtennadel (*Picea excelsa*) essential oil	20% oil solutions	*An. stephensi*	19	3
				Amyris (*Amyris balsamifera*) essential oil	20% oil solutions	*An. stephensi*	100	8

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				Lemon (*Citrus limon*) essential oil	20% oil solutions	*An. stephensi*	9.5	7
				Narrow-leaved eucalyptus (*Eucalyptus radiata*) essential oil	20% oil solutions	*An. stephensi*	42.8	8
				Carotin oil (*Glycina soja*) essential oil	20% oil solutions	*An. stephensi*	9.5	8
				Cedarwood (*Juniperus virginiana*) essential oil	20% oil solutions	*An. stephensi*	38.1	8
				frankincense (*Boswellia carteri*) essential oil	20% oil solutions	*An. stephensi*	19	5
				Dill (*Anethum graveolens*) essential oil	20% oil solutions	*An. stephensi*	71.4	3.5
				Myrtle (*M. communis*) essential oil	20% oil solutions	*An. stephensi*	42.8	6.5
				Chamomile (*Anthemis nobilis*) essential oil	20% oil solutions	*An. stephensi*	76.2	8
				Cinnamon (*C. zeylanicum*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Juniper (*Juniperus communis*) essential oil	20% oil solutions	*An. stephensi*	76.2	8
				Sage (*Salvia sclarea*) essential oil	20% oil solutions	*An. stephensi*	19	5
				Peppermint (*Mentha piperita*) essential oil	20% oil solutions	*An. stephensi*	57.1	6.5
				Basil (*Ocimum basilicum*) essential oil	20% oil solutions	*An. stephensi*	66.7	3.5
				Cajeput (*Melaleuca leucadendron*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Soya bean (*Glycina max*) essential oil	20% oil solutions	*An. stephensi*	76.2	8
				Rosemary (*R. officinalis*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Niaouli (*Melaleuca quinquenervia*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Olive (*O. europaea*) essential oil	20% oil solutions	*An. stephensi*	71.4	8
				Black pepper (*Piper nigrum*) essential oil	20% oil solutions	*An. stephensi*	61.9	3
				Verbena (*Lippia citriodora*) essential oil	20% oil solutions	*An. stephensi*	38.1	5.5
				tagetes (*T. minuta*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Violet (*Viola odorata*) essential oil	20% oil solutions	*An. stephensi*	100	8

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				Sandalwood (*Santalum album*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Litsea (*Litsea cubeba*) Essential oil	20% oil solutions	*An. stephensi*	100	8
				Helichrysum (*Helichrysum italicum*) essential oil	20% oil solutions	*An. stephensi*	47.6	6
				Galbanum (*Ferula galbaniflua*) essential oil	20% oil solutions	*An. stephensi*	100	8
				Chamomile (*Chamaemelum nobile*) essential oil	20% oil solutions	*An. stephensi*	47.6	5.5
Amerasan et al.	2012	India	Laboratory	*Cassia tora* Linn methanol extract	1 mg/cm^2 2.5 mg/cm^2 5.0 mg/cm^2	*An. stephensi*	100 100 100	2 2 2.5
Abiy et al.	2015	Ethiopia	Field	20% neem oil	Neem and chinaberry oils were diluted to 20% using Niger seed (noog abyssinia) oil	*An. arabiensis*	71	3
				20% chinaberry oil	Neem and chinaberry oils were diluted to 20% using Niger seed (noog abyssinia) oil	*An. arabiensis*	70	1
Alayo et al.	2015	Nigeria	Laboratory	*Cassia mimosoides* petroleum ether extract	Cream 0.5% w/w	*An. gambiae*	48	–
					Cream 1% w/w		88	–
					Cream 2% w/w		100	0.08
					Cream 4% w/w		100	0.08
					Cream 6% w/w		100	0.08
Alwala et al.	2010	Kenya	Laboratory	*Mangifera indica* essential Oil	10% solution	*An. gambiae*	100	–
Baskar et al.	2018	India	Laboratory	*Atalantia monophylla* essential oil	50 ppm	*An. stephensi*	–	6.85
Govindarajan et al.	2010	India	Laboratory	*Sida acuta* Burm. F. extract	2.5 mg/cm^2	*An. stephensi*	100	2.5
					5 mg/cm^2	*An. stephensi*	100	3
Govindarajan et al.	2011	India	Laboratory	*Ervatamia coronaria* extract	1 mg/cm^2 2.5 mg/cm^2 5 mg/cm^2	*An. stephensi* *An. stephensi* *An. stephensi*	100 100 100	2.5 3 3.5
				Caesalpinia pulcherrima extract	1 mg/cm^2	*An. stephensi*	100	2
					2.5 mg/cm^2	*An. stephensi*	100	2.5
Govindarajan et al.	2011	India	Laboratory		5 mg/cm^2	*An. stephensi*	100	3
					2.5 mg/cm^2 5 mg/cm^2	*An. subpictus* *An. subpictus*	100 100	2 2.5
				R. officinalis L. essential oil	1 mg/cm^2	*An. subpictus*	100	1
					2.5 mg/cm^2	*An. subpictus*	100	1
					5 mg/cm^2	*An. subpictus*	100	1.5

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				C. citrates Stapf. essential oil	1 mg/cm^2	*An. subpictus*	100	1
					2.5 mg/cm^2	*An. subpictus*	100	1.5
					5 mg/cm^2	*An. subpictus*	100	2
				C. zeylanicum L. essential oil	1 mg/cm^2	*An. subpictus*	100	1
					2.5 mg/cm^2	*An. subpictus*	100	1
					5 mg/cm^2	*An. subpictus*	100	1.5
Govindarajan et al.	2016	India	Laboratory	*Zingiber nimmonii* essential oil	1 mg/cm^2	*An. stephensi*	100	2
					2 mg/cm^2	*An. stephensi*	100	2.5
					5 mg/cm^2	*An. stephensi*	100	3
Jeyabalan et al.	2003	India	Laboratory	*P. citrosa* leaf extract	0.5%	*An. stephensi*	36	–
					1%	*An. stephensi*	51	–
					2%	*An. stephensi*	78	–
					4%	*An. stephensi*	100	–
Karunamoorthi et al.	2008	Ethiopia	Laboratory	Woira (*O. europaea*) smoke	Burning of 25 g of dried plant materials	*An. arabiensis*	79.7	–
				Tinjut (*Ostostegia integrifolia*) smoke	Burning of 25 g of dried plant materials	*An. arabiensis*	90.1	–
				Wogert (*Silene macroserene*) smoke	Burning of 25 g of dried plant materials	*An. arabiensis*	93.6	–
				Kebercho (*Echinops* sp.) extract	Burning of 25 g of dried plant materials	*An. arabiensis*	92.4	–
Karunamoorthi et al.	2010	Ethiopia	Laboratory	*C. citratus* extract	1 mg/cm^2	*An. arabiensis*	100	3.2
					1.5 mg/cm^2	*An. arabiensis*	100	4.4
					2 mg/cm^2	*An. arabiensis*	100	5.3
					2.5 mg/cm^2	*An. arabiensis*	100	6.3
Govindarajan et al.	2016	India	Laboratory	*Origanum scabrum* essential oil	1 mg/cm^2	*An. stephensi*	100	2.5
					2 mg/cm^2	*An. stephensi*	100	3
					5 mg/cm^2	*An. stephensi*	100	3.5
Haldar et al.	2014	India	Laboratory	*Ficus krishnae* smoke	30 mg/l smoked	*An. stephensi*	18	0.16
					60 mg/l smoked	*An. stephensi*	100	0.5
					90 mg/l smoked	*An. stephensi*	100	1
Auysawasdi et al.	2015	Thailand	Laboratory	*Curcuma longa* essential oil	5%	*An. dirus*	100	4
					10%	*An. dirus*	100	5
					15%	*An. dirus*	100	5.5
					20%	*An. dirus*	100	5.5
					25%	*An. dirus*	100	8
				E. globulus essential oil	5%	*An. dirus*	100	1.7
					10%	*An. dirus*	100	2.3
					15%	*An. dirus*	100	3
					20%	*An. dirus*	100	3
					25%	*An. dirus*	100	3.4
				Citrus aurantium essential oil	5%	*An. dirus*	100	1.8
					10%	*An. dirus*	100	2.9
					15%	*An. dirus*	100	2.9
					20%	*An. dirus*	100	3
					25%	*An. dirus*	100	3.5

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
Barnard et al.	1999	USA	Laboratory	Clove essential oil	25%	*An. albimanus*	100	1.25
					50%	*An. albimanus*	100	1.5
					75%	*An. albimanus*	100	2.26
					100%	*An. albimanus*	100	3.55
				Thyme essential oil	25%	*An. albimanus*	100	0.75
					50%	*An. albimanus*	100	0.5
					75%	*An. albimanus*	100	1
					100%	*An. albimanus*	100	1.75
Kweka et al.	2008	Tanzania	Laboratory	Citronella	500 mg/m^2	*An. gambiae*	81	–
				Ocimum suave extract	500 mg/m^2	*An. gambiae*	81	–
				Ocimum kilimandscharicum extract	500 mg/m^2	*An. gambiae*	73	–
				Citronella	500 mg/m^2	*An. arabiensis*	85	–
				O. suave extract	500 mg/m^2	*An. arabiensis*	89	–
				O. kilimandscharicum extract	500 mg/m^2	*An. arabiensis*	75	–
Kovendan et al.	2012	India	Laboratory	*A. alnifolia* extract	1 mg/cm^2	*An. stephensi*	100	2
					3 mg/cm^2	*An. stephensi*	100	2
					5 mg/cm^2	*An. stephensi*	100	2.5
Krishnappa et al.	2012	India	Laboratory	*A. digitata* crude extract	2 mg/cm^2	*An. stephensi*	100	3
					4 mg/cm^2	*An. stephensi*	100	3.5
					6 mg/cm^2	*An. stephensi*	100	3.5
Naine et al.	2014	India	Laboratory	*Streptomyces* sp. VITJS4 extract	1 mg/cm^2	*An. stephensi*	100	2
					3 mg/cm^2	*An. stephensi*	100	2
					6 mg/cm^2	*An. stephensi*	100	2
Murugan et al.	2012	India	Laboratory	Orange peel extract	50 ppm	*An. stephensi*	99	–
					150 ppm	*An. stephensi*	100	0.5
					250 ppm	*An. stephensi*	100	0.05
					350 ppm	*An. stephensi*	100	1.5
					450 ppm	*An. stephensi*	100	2
Padilha et al.	2003	Brazil	Field	*Ocimum selloi* oil	10% v/v	*An. braziliensis*	89	0.5
Konan et al.	2003	Ivory Coast	Laboratory	Karite nut butter oil	75%	*An. gambiae*	100	2
				Palm oil	75%	*An. gambiae*	100	1.38
				Coconut oil	75%	*An. gambiae*	100	0.76
Maheswaran et al.	2013	India	Laboratory	Confertifolin essential oil	0.62 ppm	*An. stephensi*	100	1
					1.25 ppm	*An. stephensi*	100	2.5
					2.5 ppm	*An. stephensi*	100	3
					5 ppm	*An. stephensi*	100	5
					10 ppm	*An. stephensi*	100	5.2
Panneerselvam et al.	2013	India	Laboratory	*Andrographis paniculata* methanol leaf extract	1 mg/cm^2	*An. stephensi*	100	2
					3 mg/cm^2	*An. stephensi*	100	2.5
					6 mg/cm^2	*An. stephensi*	100	3
				Cassia occidentalis methanol leaf extract	1 mg/cm^2	*An. stephensi*	100	2
					3 mg/cm^2	*An. stephensi*	100	2.5
					6 mg/cm^2	*An. stephensi*	100	2.5

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/(essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				Euphorbia hirta methanol leaf extract	1 mg/cm^2	*An. stephensi*	100	2
					3 mg/cm^2	*An. stephensi*	100	2
					6 mg/cm^2	*An. stephensi*	100	2.5
Panneerselvam et al.	2012	India	Laboratory	*Artemisia nilagirica* extract	50 ppm	*An. stephensi*	95	0.5
					150 ppm	*An. stephensi*	98	0.5
					250 ppm	*An. stephensi*	100	0.5
					350 ppm	*An. stephensi*	100	1
					450 ppm	*An. stephensi*	100	2
Phasomkusolsil et al.	2011	Thailand	Laboratory	*Cananga odorata* oil	0.02 mg/cm^2	*An. dirus*	94	–
					0.10 mg/cm^2	*An. dirus*	92	–
					0.21 mg/cm^2	*An. dirus*	92	–
				C. sinensis oil	0.02 mg/cm^2	*An. dirus*	40	–
					0.10 mg/cm^2	*An. dirus*	54	–
					0.21 mg/cm^2	*An. dirus*	84	–
				C. citratus oil	0.02 mg/cm^2	*An. dirus*	76	–
					0.10 mg/cm^2	*An. dirus*	82	–
					0.21 mg/cm^2	*An. dirus*	98	–
				Cymbopogon nardus oil	0.02 mg/cm^2	*An. dirus*	92	–
					0.10 mg/cm^2	*An. dirus*	92	–
					0.21 mg/cm^2	*An. dirus*	98	–
				E. citriodora oil	0.02 mg/cm^2	*An. dirus*	52	–
					0.10 mg/cm^2	*An. dirus*	74	–
					0.21 mg/cm^2	*An. dirus*	86	–
				O. basilicum oil	0.02 mg/cm^2	*An. dirus*	66	–
					0.10 mg/cm^2	*An. dirus*	74	–
					0.21 mg/cm^2	*An. dirus*	96	–
				S. aromaticum oil	0.02 mg/cm^2	*An. dirus*	82	–
					0.10 mg/cm^2	*An. dirus*	92	–
					0.21 mg/cm^2	*An. dirus*	98	–
Prabhu et al.	2011	India	Laboratory	*Moringa oleifera* extract	20%	*An. stephensi*	23	–
					40%	*An. stephensi*	43	–
					60%	*An. stephensi*	58	–
					80%	*An. stephensi*	76	–
					100%	*An. stephensi*	90	–
Rajkumar et al.	2007	India	Laboratory	*Centella asiatica* essential oil	2%	*An. stephensi*	–	1
					4%	*An. stephensi*	–	1.78
					6%	*An. stephensi*	–	2.33
				Ipomoea cairica essential oil	2%	*An. stephensi*	–	2.63
					4%	*An. stephensi*	–	4.13
					6%	*An. stephensi*	–	5.53
				Momordica charantia essential oil	2%	*An. stephensi*	–	2.38
					4%	*An. stephensi*	–	3.93
					6%	*An. stephensi*	–	5.38
				Psidium guajava essential oil	2%	*An. stephensi*	–	0.93
					4%	*An. stephensi*	–	1.48
					6%	*An. stephensi*	–	1.98

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				Tridax procumbens essential oil	2%	*An. stephensi*	–	2.33
					4%	*An. stephensi*	–	3.78
					6%	*An. stephensi*	–	5.28
Rajkumar et al.	2005	India	Laboratory	*Solanum trilobatum* extract	0.001%	*An. stephensi*	100	1.15
					0.005%	*An. stephensi*	100	1.3
					0.01%	*An. stephensi*	100	1.51
					0.015%	*An. stephensi*	100	1.7
					0.02%	*An. stephensi*	100	2.03
Rawani et al.	2012	India	Laboratory	*P. tuberosa* extract	1%	*An. stephensi*	65	2.3
					1.50%	*An. stephensi*	80	4
					2%	*An. stephensi*	90	5
Reegan et al.	2015	India	Laboratory	*Cliona celata* extract	1 mg/cm^2	*An. stephensi*	100	1.08
					2.5 mg/cm^2	*An. stephensi*	100	1.71
					5 mg/cm^2	*An. stephensi*	100	1.21
Swathi et al.	2012	India	Laboratory	*Datura stramonium* extract	0.1%	*An. stephensi*	–	0.35
					0.5%	*An. stephensi*	–	0.72
					1%	*An. stephensi*	–	1.9
Seyoum et al.	2002	Kenya	Semi-field	Neem (*A. indica*)	Periodic thermal expulsion	*An. gambiae*	24.5	–
				Lemon eucalyptus (*Corymbia citriodora*)	Periodic thermal expulsion	*An. gambiae*	74.5	–
				Wild spikenard (*Hyptis suaveolens*)	Periodic thermal expulsion	*An. gambiae*	-13.3	–
				Lantana (*Lantana camara*)	Periodic thermal expulsion	*An. gambiae*	42.4	–
				Fever tea (*Lippia uckambensis*)	Periodic thermal expulsion	*An. gambiae*	45.9	–
				Lime basil (*Ocimum americanum*)	Periodic thermal expulsion	*An. gambiae*	43.1	–
				Rican blue basil (*O. kilimandscharicum*)	Periodic thermal expulsion	*An. gambiae*	52.0	–
				Tree basil (*O. suave*)	Periodic thermal expulsion	*An. gambiae*	53.1	–
				Khaki weed (*T. minuta*)	Placing branches or whole plants inside houses	*An. gambiae*	54.8	–
Sanghong et al.	2015	Thailand	Laboratory	*L. sinense* ethanolic preparations	25%	*An. minimus*	–	11.5
Das et al.	2003	India	Laboratory	*Cymbopogan martinii martinii* var *sofia* oil	1 ml without dilution	*An. sundaicus*	98	6
Nour et al.	2009	Sudan	Laboratory	Basil (*O. basilicum* L.) essential oil	0.1 ml		100	1.5
Trongtokit et al.	2005	Thailand	Laboratory	*C. nardus* essential oil	10%	*An. dirus*	–	0.66
					50%		–	0.5
					100%		–	1.16
				P. cablin essential oil	10%	*An. dirus*	–	1.33
					50%		–	2
					100%		–	2.83

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				Mullilam (*Zanthoxylum limonella*) essential oil	10%	*An. dirus*	–	1
					50%		–	2.16
					100%		–	3.16
				Clove (*Syzygium aromaticum*) essential oil	10%	*An. dirus*	–	1.33
					50%		–	2.66
					100%		–	3.5
Yogananth et al.	2015	India	Laboratory	*R. mucronata* oil	1 mg/cm^2	*An. stephensi*	73	7.2
					2 mg/cm^2	*An. stephensi*	86	7.8
					3 mg/cm^2	*An. stephensi*	92	8.5
					4 mg/cm^2	*An. stephensi*	97	9.1
Tawatsin et al.	2000	Thailand	Laboratory	Turmeric (*C. longa*) volatile oil	3 ml	*An. dirus*	100	6
				Citronella	3 ml	*An. dirus*	100	6
				Hairy basil oil	3 ml	*An. dirus*	100	6
Singh et al.	2005	India	Laboratory	*Cyperus rotundus* Linn hexane extract	2.50%	*An. stephensi*	95	–
					5%	*An. stephensi*	99	–
					10%	*An. stephensi*	100	6
Mayeku et al.	2013	Kenya	laboratory	*Conyza newii* essential oil	0.01 g/ml	*An. gambiae*	38	–
					0.1 g/ml	*An. gambiae*	68	–
					1 g/ml	*An. gambiae*	100	–
Phasomkusolsil et al.	2009	Thailand	Laboratory	Phlai (*Z. cassumunar*) oil	100 µl	*An. minimus*	–	2
				Turmeric (*C. longa*) oil	100 µl	*An. minimus*	–	1
				Mah-Khwuaen (*Z. limonella*) oil	100 µl	*An. minimus*	–	0.66
				Citronella grass (*C. nardus*) oil	100 µl	*An. minimus*	–	2.16
				Orange oil (*Citrus sinensis*) oil	100 µl	*An. minimus*	–	0.83
				Eucalyptus (*E. citriodora*) oil	100 µl	*An. minimus*	–	0.5
				Clove (*S. aromaticum*) oil	100 µl	*An. minimus*	–	2
Trongtokit et al.	2004	Thailand	Laboratory	Clove oil	20% gel	*An. dirus*	–	4.5
					cream 20%	*An. dirus*	–	4.8
Birkett et al.	2011	Kenya	Laboratory	*N. cataria*	0.01 mg	*An. gambiae*	17	–
					0.1 mg	*An. gambiae*	97	–
					1 mg	*An. gambiae*	100	–
Kamaraj et al.	2011	India	Laboratory	*A. concinna* extract	500 ppm	*An. stephensi*	21	–
Solomon et al.	2012	Ethiopia	Laboratory	Citronella extract	20%	*An. Arabiensis*	73	–
Soonwera et al.	2015	Thailand	Laboratory	*C. odorata* oil	1%	*An. dirus*	92	–
					5%	*An. dirus*	92	–
					10%	*An. dirus*	94	–
Sritabutra et al.	2011	Thailand	Laboratory	Eucalyptus (*E. globules*) essencial oil	0.1 ml	*An. dirus*	–	1.58
				Peppermint (*M. piperita*) essencial oil	0.1 ml	*An. dirus*	–	1.08
				Garlic (*A. sativum*) essencial oil	0.1 ml	*An. dirus*	–	0.68

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
				Orange (*C. sinensis*) essencial oil	0.1 ml	*An. dirus*	–	0.83
				Citronella grass (*C. nardus*) essencial oil	0.1 ml	*An. dirus*	–	0.8
				Lemongrass (*C. citratus*) essencial oil	0.1 ml	*An. dirus*	–	1.63
				Clove (*S. aromaticum*) essencial oil	0.1 ml	*An. dirus*	–	1
				Sweet basil (*O. basilicum*) essencial oil	0.1 ml	*An. dirus*	–	0.75
Tavassoli et al.	2001	iran	Laboratory	Marigold (*Calendula officinalis*) essential oil	50%	*An. stephensi*	–	2.15
				Myrtle essential oil	50%	*An. stephensi*	–	4.36
Younoussa et al.	2016	Cameroon	Laboratory	*Annona senegalensis* leaf extract	4.0 mg/cm^2	*An. gambiae*	–	0.5
					8.0 mg/cm^2	*An. gambiae*	–	1
					12.0 mg/cm^2	*An. gambiae*	–	1.5
				Boswellia dalzielii leaf extract	4.0 mg/cm^2	*An. gambiae*	46	
					8.0 mg/cm^2	*An. gambiae*	–	0.5
					12.0 mg/cm^2	*An. gambiae*	–	1
Govindarajan et al.	2011	India	Laboratory	*Coccinia indica* extract	1 mg/cm^2	*An. stephensi*	100	3
					2.5 mg/cm^2	*An. stephensi*	100	3
					5 mg/cm^2	*An. stephensi*	100	3.5
Govindarajan et al.	2012	India	Laboratory	*Cardiospermum halicacabum* oil	1 mg/cm^2	*An. stephensi*	100	2
					2.5 mg/cm^2	*An. stephensi*	100	2.5
					5 mg/cm^2	*An. stephensi*	100	3
Govindarajan et al.	2014	India	Laboratory	*Asparagus racemosus* crude extract	1 mg/cm^2	*An. stephensi*	100	2.5
					2 mg/cm^2	*An. stephensi*	100	2.5
					5 mg/cm^2	*An. stephensi*	100	3
Govindarajan et al.	2015	India	Laboratory	*Delonix elata* crude extract	1 mg/cm^2	*An. stephensi*	100	2.5
					2.5 mg/cm^2	*An. stephensi*	100	3
					5 mg/cm^2	*An. stephensi*	100	3.5
Innocent et al.	2014	Kenya	Laboratory	*Uvariodendron gorgonis* essential oil	0.01 w/v	*An. gambiae*	29	–
					0.1 w/v	*An. gambiae*	48	–
					1 w/v	*An. gambiae*	57	–
					10 w/v	*An. gambiae*	64	–
				Clausena anisata essential oil	0.01 w/v	*An. gambiae*	13	–
					0.1 w/v	*An. gambiae*	21	–
					1 w/v	*An. gambiae*	42	–
					10 w/v	*An. gambiae*	56	–
				Lantana vibunoides essential oil	0.01 w/v	*An. gambiae*	26	–
					0.1 w/v	*An. gambiae*	46	–
					1 w/v	*An. gambiae*	54	–
					10 w/v	*An. gambiae*	62	–

Table 1 (continued)

Study	Year	Country	Study type	Plant extract/ (essential oil)	Concentration dose	*Anopheles* species	Repellency %	Protection time (hours)
Kumar et al.	2012	India	Laboratory	*Sargassum wightii* Greville methanolic extract	2 mg/l	*An. sundaicus*	26	–
					4 mg/l	*An. sundaicus*	40	–
					6 mg/l	*An. sundaicus*	57	–
					8 mg/l	*An. sundaicus*	71	–
					10 mg/l	*An. sundaicus*	89	–
Madhiyazhagan et al.	2014	India	Laboratory	*O. canum* extract	0.49 mg/l	*An. stephensi*	63	–
					0.99 mg/l	*An. stephensi*	77	–
					1.99 mg/l	*An. stephensi*	86	–

eucalyptus, lemongrass, lemon-scented eucalyptus, amyris, narrow-leaved eucalyptus, carotin, cedarwood, chamomile, cinnamon oil, juniper, cajeput, soya bean, rosemary, niaouli, olive, tagetes, violet, sandalwood, litsea, galbanum, and *Curcuma longa* also showed good repellency with 8 h complete repellency against different species of *Anopheles* genus. Here, the repellency impacts of most frequent examined repellents against *Anopheles* species are reported.

Citronella

The repellency effect of citronella was investigated in several studies. Citronella is an essential oil extracted from the stems and leaves of different species of lemongrass (*Cymbopogon* spp.) [65]. Ansari et al. [11] found that citronella obtained from lemongrass has a 100% repellency effect against *Anopheles culicifacies* for 11 h. Amer et al. [6] and Tawatsin et al. [44] also reported that citronella could repel *Anopheles stephensi* and *Anopheles dirus* for 8 and 6 h, respectively. Moreover, 100 µl and 0.1 ml of citronella grass essential oil showed 2.16 and 0.8 h complete protection time against *An. minimus* [45] and *An. dirus* [47], respectively. The percentage repellency of citronella in other studies. [6, 52, 59], depending on the concentration of extracts and *Anopheles* species, was reported to be 52 to 85%.

Peppermint

Peppermint is a hybrid mint from cross-breeding spearmint (*Mentha spicata*) and water mint (*Mentha aquatica*), which contains biologically active constituents and has high menthone, menthol and methyl esters. The plant, indigenous to Europe, is now widespread in cultivation worldwide [66]. The effect of peppermint on *Anopheles* was explored in 3 studies. Ansari et al. [12] in a field trial revealed that 1 ml peppermint oil without dilution completely repels *Anopheles annularis*, *An. culicifacies* and *Anopheles subpictus* for 11, 9.6 and 7.3 h, respectively and the corresponding percentage repellency were 100%, 92.3% and 83.1%. In another study [6], 20% oil solutions of peppermint had 57% repellency and complete protection time for 6.5 h against *An. stephensi*. The study by Sritabutra et al. [47] also found that 0.1 ml of peppermint essential oil protect against *An. dirus* for 1.08 h.

Cinnamomum

Cinnamomum is a genus in the Laurel family, Lauraceae, several of which are investigated for their antibacterial activity by means of essential oils from bark and leaves [67]. Amer et al. [6] reported that 20% oil solutions of both camphor (*Cinnamomum camphora*) and cinnamon (*Cinnamomum zeylanicum*) had 100% repellency affect against *An. stephensi*. While, in the study conducted by Govindarajan et al. [22], *C. zeylanicum* at 1 mg/cm^2 showed 1 h protection against *An. subpictus*.

Catnip (*Nepeta cataria*)

Catnip is a perennial plant that belongs to the mint family, Labiatae. This herb is spread from central Europe to central Asia and the Iranian plateaus [68]. The 20% oil solution of catnip in the study carried out by Amer et al. [6], with 100% protection against *An. stephensi* for 8 h, had a good effectiveness in preventing *Anopheles* mosquitoes. Nevertheless, Birkett et al. [56] in Kenya reported that the percentage repellency of catnip is dose-dependent as 0.01 mg, 0.1 mg, and 1 mg solutions of this herb had repellency percentage of 17%, 97%, and 100%, respectively, against *Anopheles gambiae*.

Thyme (*Thymus serpyllum*)

Thyme is one of nine species belonging to *T. serpyllum*, a perennial aromatic plant of the Mediterranean flora [69]. *Thymus* species have been reported to possess

Table 2 Stratification of potential of plant based repellents

Protection time (hours)	Plant name	Concentration/dose	Anopheles species
11.5	*L. sinense* ethanolic extract	25%	*An. minimus*
11	Pine oil (*Pinus*) Citronella (lemongrass oil) *D. sissoo* oil Peppermint oil	1 ml without dilution 1 ml without dilution 1 ml without dilution 1 ml without dilution	*An. culicifacies* *An. culicifacies* *An. annularis* *An. annularis*
8 < to < 10	*D. sissoo* oil Peppermint oil *R. mucronata* oil *R. mucronata* oil	1 ml without dilution 1 ml without dilution 4 mg/cm^2 3 mg/cm^2	*An. culicifacies* *An. culicifacies* *An. stephensi* *An. stephensi*
8	*D. sissoo* oil	1 ml without dilution	*An. subpictus*
	Citronella (*C. winterianus*) essential oils	20% oil solution	*An. stephensi*
	Lavender (*L. angustifolia*) essential oils	20% oil solution	*An. stephensi*
	Camphor (*C. camphora*) essential oils	20% oil solution	*An. stephensi*
	Catnip (*N. cataria*) essential oils	20% oil solution	*An. stephensi*
	Geranium (*P. graveolens*) essential oils	20% oil solution	*An. stephensi*
	Jasmine (*J. grandiflorum*) essential oils	20% oil solution	*An. stephensi*
	Broad-leaved eucalyptus (*E. dives*) essential oils	20% oil solution	*An. stephensi*
	Lemongrass (*C. citratus*) essential oil	20% oil solution	*An. stephensi*
	Lemon-scented eucalyptus (*E. citriodora*)	20% oil solution	*An. stephensi*
	Amyris (*A. balsamifera*) essential oil	20% oil solution	*An. stephensi*
	Narrow-leaved eucalyptus (*E. radiata*) essential oil	20% oil solution	*An. stephensi*
	Carotin oil (*G. soja*) essential oil	20% oil solution	*An. stephensi*
	Cedarwood (*J. virginiana*) essential oil	20% oil solution	*An. stephensi*
	Chamomile (*A. nobilis*) essential oil	20% oil solution	*An. stephensi*
	Cinnamon (*C. zeylanicum*) essential oil	20% oil solution	*An. stephensi*
	Juniper (*J. communis*) essential oil	20% oil solution	*An. stephensi*
	Cajeput (*M. leucadendron*) essential oil	20% oil solution	*An. stephensi*
	Soya bean (*G. max*) essential oil	20% oil solution	*An. stephensi*
	Rosemary (*R. officinalis*) essential oil	20% oil solution	*An. stephensi*
	Niaouli (*M. quinquenervia*) essential oil	20% oil solution	*An. stephensi*
	Olive (*O. europaea*) essential oil	20% oil solution	*An. stephensi*
	Tagetes (*T. minuta*) essential oil	20% oil solution	*An. stephensi*
	Violet (*V. odorata*) essential oil	20% oil solution	*An. stephensi*
	Sandalwood (*S. album*) essential oil	20% oil solution	*An. stephensi*
	Litsea (*L. cubeba*) essential oil	20% oil solution	*An. stephensi*
	Galbanum (*F. galbaniflua*) essential oil	20% oil solution	*An. stephensi*
	C. longa essential oil	25%	*An. dirus*
7 < to < 8	*R. mucronata* oil	2 mg/cm^2	*An. stephensi*
	Thyme (*T. serpyllum*) essential oils	20% oil solutions	*An. stephensi*
	Peppermint oil	1 ml without dilution	*An. subpictus*
	R. mucronata oil	1 mg/cm^2	*An. stephensi*
7	Lemon (*C. limon*) essential oil	20% oil solution	*An. stephensi*
6 < to < 7	*A. monophylla* essential oil	50 ppm	*An. stephensi*
	rosewood (*A. rosaeodora*) essential oils	20% oil solution	*An. stephensi*
	myrtle (*M. communis*) essential oil	20% oil solution	*An. stephensi*
	peppermint (*M. piperita*) essential oil	20% oil solution	*An. stephensi*

Table 2 (continued)

Protection time (hours)	Plant name	Concentration/dose	Anopheles species
6	*Helichrysum* (*H. italicum*) essential oil	20% oil solution	*An. stephensi*
	C. martinii martinii var *sofia* oil	1 ml without dilution	*An. sundaicus*
	Turmeric (*C. longa*) volatile oil	3 ml	*An. dirus*
	Citronella	3 ml	*An. dirus*
	Hairy basil oil	3 ml	*An. dirus*
	C. rotundus Linn hexane extract	10%	*An. stephensi*
5 < to < 6	*I. cairica* essential oil	6%	*An. stephensi*
	Eucalyptus (*E. globulus*) essential oils	20% oil solution	*An. stephensi*
	Verbena (*L. citriodora*) essential oil	20% oil solution	*An. stephensi*
	Chamomile (*C. nobile*) essential oil	20% oil solution	*An. stephensi*
	C. longa essential oil	15%	*An. dirus*
	C. longa essential oil	20%	*An. dirus*
	M. charantia essential oil	6%	*An. stephensi*
	C. citratus extract	2 mg/cm^2	*An. arabiensis*
	T. procumbens essential oil	6%	*An. stephensl*
	Confertifolin essential oil	10 ppm	*An. stephensi*
5	Frankincense (*B. carteri*) essential oil	20% oil solution	*An. stephensi*
	Sage (*S. sclarea*) essential oil	20% oil solution	*An. stephensi*
	C. longa essential oil	10%	*An. dirus*
	Confertifolin essential oil	5 ppm	*An. stephensi*
	P. tuberosa extract	2%	*An. stephensi*
4 < to < 5	Clove oil	Cream 20%	*An. dirus*
	Clove oil	20% gel	*An. dirus*
	C. citratus extract	1/5 mg/cm^2	*An. arabiensis*
	Myrtle essential oil	50%	*An. stephensi*
	I. cairica essential oil	4%	*An. stephensi*
4	*C. longa* essential oil	5%	*An. dirus*
	P. tuberosa extract	1.5%	*An. stephensi*

Stratification of potential of plant based repellents by complete protection times, up to July 2018

various beneficial effects, such as antiseptic, carminative, antimicrobial, and antioxidant properties [70]. The 20% oil solution of thyme in the study conducted by Amer et al. [6], with 100% protection against *An. stephensi* for 7.5 h, had a good effectiveness in preventing *Anopheles* mosquitoes. Nevertheless, another study [58] reported that the complete protection time of thyme at its maximum concentration (100%) is 1.7 h against *Anopheles albimanus*.

Olive (*Olea europaea*)

Olive (*O. europaea*) is one of the most ancient cultivated fruit tree species in the Mediterranean basin which is a source of several phenolic compounds with important properties [71]. The 20% oil solution of olive in the study conducted by Amer et al. [6], with a mean percentage of repellency (71.4%) and complete protection time against *An. stephensi* for 8 h, had a good effectiveness in preventing *An. stephensi* mosquitoes. Karunamoorthi et al. [50] also supported that burning of 25 g of dried *O. europaea*, comparable to Amer et al. [6], has a percentage repellency of 79.7 against *Anopheles arabiensis*.

Eucalyptus

Eucalyptus is a significant short rotation pulpy woody plant, grown generally in tropical regions [72]. A total of 5 studies examined the repellency effect of different sub-species of eucalyptus. In the laboratory trial by Amer et al. [6], narrow-leaved eucalyptus, lemon-scented eucalyptus, and broad-leaved eucalyptus protected against *An. stephensi* for 8 h, while *Eucalyptus globulus* complete protection time was reported to be 5.5 h. Auysawasdi et al. [41] used *E. globulus* essential oil at 5%, 10%, 15%, 20% and 25% concentrations against *An. dirus*. All concentrations of *E. globulus* provided complete repellency ranging from 1.7 to 3.4 h, depending on the concentration applied. *Eucalyptus globulus* at 0.1 ml dose in a study [47] repelled *An. dirus* for 1.58 h. Besides, 100 µl *Eucalyptus citriodora* repelled *An. minimus* for 0.5 h [45]. In contrast, Seyoum et al. found that lemon eucalyptus extract is not affective against *An. gambiae* [54].

Myrtle (*Myrtus communis*)

Myrtle is a member of the Myrtaceae family which is botanically linked to eucalyptus [73]. In 2 studies, repellency effectiveness of myrtle was investigated. The 20% oil solution of myrtle in the study conducted by Amer et al. [6], with mean percentage repellency of 42.8% and complete protection time against *An. stephensi* for 6.5 h, had a good effectiveness in preventing *Anopheles* mosquitoes. Tavassoli et al. [62] also supported that myrtle at 50% concentration repels *An. stephensi* for 4.36 h.

Basil

Basil is an annual plant of the *Ocimum* genus, which belongs to the Lamiaceae family and is used in traditional medicine in many parts of the world [74]. In 6 studies, repellency effectiveness of basil against different *Anopheles* species was investigated. In the laboratory trial by Amer et al. [6], 20% oil solution of basil essential oil, with mean percentage repellency of 66.7%, had 100% protective impact against *An. stephensi* for 3.5 h. Phasomkusolsil et al. [42] used basil essential oil at 0.02, 0.10, and 0.21 mg/cm^2 concentrations against *An. dirus*. The percentage repellency was dose–response and was reported to be 66%, 74% and 96%, respectively. Basil at 0.1 ml dose in other studies [47, 61] repelled *Anopheles* for 1.5 h and 0.75 h, whereas, Tawatsin et al. [44] found that hairy basil oil provides 100% protection against *An. dirus* for 6 h. In contrast, in the study by Seyoum et al. [54], no remarkable repellency effect against *An. gambiae* was identified.

Tagetes (*Tagetes minuta*)

Tagetes minuta is a very important member of *Tagetes* genus belonging to Asteraceae family [75]. In 2 studies, repellency effectiveness of tagetes was explored. The 20% oil solution of *T. minuta* in the study conducted by Amer et al. [6], with complete protection time for 8 h, had a good effectiveness in preventing against *An. stephensi*. In contrast, Seyoum et al. found that tagetes extract is not affective against *An. gambiae* [54].

Neem (*Azadirachta indica*)

Neem is a versatile tree broadly grown in tropical areas of India [76]. The repellency effect of Neem against different species of *Anopheles* was investigated in 2 studies. The 20% Neem oil in a field trial conducted by Amer et al. [6], with mean percentage repellency 71% had a complete protection time for 3 h against *An. arabiensis*. Nevertheless, Seyoum et al. found that Neem extract is not affective against *An. gambiae* [54].

Rosemary (*Rosmarinus officinalis*)

Rosemary is an evergreen aromatic shrub with a Mediterranean origin, which belongs to Lamiaceae (Labiatae) family [77]. In 2 studies, repellency effectiveness of rosemary was reported. The 20% oil solution of rosemary in the study conducted by Amer et al. [6], with 100% protection against *An. stephensi* for 8 h, had a good effectiveness in preventing *Anopheles* mosquitoes. Govindarajan et al. [22] also supported that rosemary at 1, 2.5 and 5 mg/cm^2 concentrations completely repels *An. subpictus* for 1, 1, and 1.5 h, respectively.

Clove (*Syzygium aromaticum*)

Clove is a naturally occurring spice which has been shown to possess anti-bacterial, anti-oxidant, anti-pyretic, anti-candidal, and aphrodisiac activities [78]. The repellency effect of clove against different species of *Anopheles* was investigated in 6 studies. In the study by Phasomkusolsil et al. [42], clove at 0.02, 0.10 and 0.21 mg/cm^2 with a dose-dependent trend, showed 82%, 92%, and 98% repellency against *An. dirus*. Barnard et al. [58] used clove essential oil at 25%, 50%, 75%, and 100% concentrations against *An. albimanus* and found that all concentrations of clove provided complete repellency ranging from 1.25 to 3.55 h, depending on the concentration applied. Consistently, clove at 10%, 50%, and 100% concentrations, with a dose-dependent trend, showed 1.33, 2.66, and 3.5 h complete repellency against *An. dirus* [43]. *Anopheles dirus* was repelled by clove for 1 h in laboratory conditions in Thailand [47]. Another study [45] reported that clove repels *An. minimus* for 2 h. Moreover, 20% gel of clove protected against *An. dirus* for 4.5 h [46]. All these findings support that clove can be a considered as moderate repellent.

Orange oil (*Citrus sinensis*)

Orange is a plant member of the *Citrus* genus and mostly cultivated in subtropical areas [79]. The repellency effect of orange against different species of *Anopheles* was investigated in 4 studies. In the study by Murugan et al. [27], orange extract at 50, 150 and 250, 350, and 450 ppm showed 0, 0.5, 0.5, 1.5 and 2 h complete protection time repellency (100%) against *An. stephensi*, respectively. While, in another study [45], it repelled *An. minimus* for 0.83 h. Similarly, Sritabutra et al. [47] showed that orange repels *An. dirus* for 0.83 h. Phasomkusolsi et al. [42] also found that orange at 0.02, 0.10, and 0.21 mg/cm^2, with a dose-dependent trend, has 44%, 54%, and 84% repellency against *An. dirus*, respectively.

Turmeric (*C. longa*)

The medicinal plant turmeric, which is a perennial herb, and a member of Zingiberacae family, is commonly used as a spice in human food [80]. In 3 studies, repellency effectiveness of turmeric was examined. Auysawasdi et al. [41] used turmeric essential oil at 5%, 10%, 15%, 20%, and 25% concentrations against *An. dirus*. All concentrations of turmeric, with a dose–response manner, provided complete repellency ranging from 4 to 8 h, depending on the concentration applied. Other studies also found that turmeric oil repels *An. dirus* for 6 h [44] and *An. minimus* [45] for 1 h.

Discussion

A high level of insecticide resistance has made because of the chemical control of the pests and vectors. To overcome this problem, it is essential to research for alternative approaches to vector control. The field of herbal repellents is extremely fertile as people demand mosquitoes' repellents that are safe, pleasant to usage and ecologically maintainable. As cost is a significant factor, examination of the use of local florae as repellents is highly suggested. Essential oils and extracts of plants are emerging as potential agents for *Anopheles* spp. control, with easy-to-administer, low-cost, and risk-free properties. In the present systematic review the highest repellency effect against *Anopheles* mosquitoes was found from *L. sinense* extract, followed by citronella, pine, *D. sissoo*, peppermint and *R. mucronata* oils with complete protection time ranging from 9.1 to 11.5 h. Essential oils from plants such as lavender, camphor, catnip, geranium, jasmine, broad-leaved eucalyptus, lemongrass, lemon-scented eucalyptus, amyris, narrow-leaved eucalyptus, carotin, cedarwood, chamomile, cinnamon oil, juniper, cajeput, soya bean, rosemary, niaouli, olive, tagetes, violet, sandalwood, litsea, galbanum, and *C. longa* also showed good repellency with 8 h complete repellency against different species of *Anopheles* genus.

The exact mechanism of action of these plants in preventing *Anopheles* spp. bites has not yet been completely clarified. For citronella, as one of the most explored plant for repellency effect against various mosquitoes, it is reported that active compounds in citronella extract for repelling mosquitoes are eugenol, eucalyptol, camphor, linalool, citral, and citronellal [81]. Some data proposes that these agents interfere with olfactory receptors of mosquitoes [82]. A recent study revealed that *An. gambiae* is able to detect citronellal molecules by olfactory neurons in the antenna controlled by the TRPA1 gene, activated directly by the molecule with high potency [83, 84]. Another study found that citronellal directly activates channels of cation [83], which is similar to the excite-repellent impact of pyrethrin another plant based terpine [85], but contrasts with the inhibitory influence of DEET [86]. Although the protection time of citronella oil is shorter than that of DEET. Citronella oil could provide sufficient protection time against mosquitoes. For other plants, the underlying mechanism remains to be elucidated. Possibly, the most important aspect in increasing the permanence of such repellents that are effective but volatile is improving formulations of plant extracts to elevate their longevity through the development of nanoemulsions, improved formulations, and fixatives. While alternative uses such as excite-repellency and spatial activity have also been examined [87].

Some caution is important when interpreting the findings. First, a poorly inspected confounding aspect is the effect of sweating on the effectiveness and protection time of repellents, which are approximately all water-soluble, and this might limits the comparability of repellents. Second, in field trial studies, the number of human volunteers as well as the season during which the trial had been performed differed among the included studies. Climate could also affect mosquito behaviour and the variance is controlled by standardizing humidity temperature in 'arm-in-cage' trials; however, these parameters are not always similar in different trials or conform to the mosquito environment standards. Third, it should be highlighted that some plant compounds are irritating to the skin and/or highly toxic to mammals, and natural does not equate to safe. Thus, plants with potential repellency properties should be tested for their possible unpleasant side effects before introducing as alternative products. Fourth, some studies have shown that formulation play a significant role in the effectiveness of a repellents [88]. However, studies have focused more on the search for active compounds than on optimal formulations [8, 29]. Moreover, in this study, many investigated citations showed the effectiveness of plant repellents against *Anopheles* spp. mosquitoes. However, when focusing on *Anopheles* subspecies, there were only a few publications indicating the efficacy of each plant, which resulted in a difficulty to reach a robust conclusion regarding the best herbal candidates to develop new commercial repellents.

This is another area for additional research. Finally, current studies are difficult to be compared and the repellency effectiveness may also differ among subspecies. Unfortunately, a few studies aimed to compare repellency efficacy of a special plant on subspecies of *Anopheles*. The heterogeneity in the results of the previous studies might be stem from differences in compound concentrations, application dosages, mosquito species, formulations and the assessment method of repellency, as in some trials the protection time until mosquitoes landed was recorded, whereas in the majority of studies the time until mosquitoes bite was considered. Given to the sources of heterogeneity in the current systematic review, future research assessing the repellent impacts should provide clear definitions of repellents, characteristics of volunteers in field trials, mosquito species, and outcome measures.

Conclusion

The results of this study showed that some plants essential oils and extracts have significant repellent activity against *Anopheles* spp. mosquitoes. The studies in the last two decades have focused on the search for new natural repellents and some plants displayed good repellent activities, but few natural products have been developed so far [88, 89]. This review calls for the attention of entomologists and people in the field of mosquito-transmitted diseases for understanding the value and potential position of the plant-derived repellents and their role in disease control.

Abbreviation
DEET: N, N-diethyl-meta-toluamide.

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Authors' contributions
MK collaborated in the study conception and the collection and translation of articles. AA performed collecting of articles and writing the manuscript. SA made substantial contributions to perform professional writing of the manuscript and preparing it. SHM assisted in translation, writing and elimination of technical errors. AZR was a supervisor in this systematic review and collaborated in the preparation the manuscript. All authors read and approved the final manuscript.

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