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 repellent 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
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 repellent 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 repellents 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,
5, 41–48], Ethiopia [49–52], Kenya [53–57], Germany [6], Nigeria [1], USA [58], Tanzania [59], Brazil [60], Sudan [61], Iran [62], Cameroon [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
| 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 (lemon-grass oil)                | 1 ml without dilution | An. culicifacies  | 100          | 11                     |
| Ansari et al.         | 2000 | India   | Field      | D. sissoo oil                               | 1 ml without dilution | An. annularis     | 96.1         | 10.3                   |
|                       |      |         |            | D. sissoo oil                               | 1 ml without dilution | An. annularis     | 100          | 11                     |
| 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 rosaedora) 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            |
| 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/cm² | An. stephensi | 100 | 2 |
| | | 2.5 mg/cm² | An. stephensi | 100 | 2 |
| | | 5.0 mg/cm² | An. stephensi | 100 | 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 Caesalpinia pulcherrima extract | 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/cm² | An. stephensi | 100 | 2.5 |
| | | 5 mg/cm² | An. stephensi | 100 | 3 |
| Govindarajan et al. 2011 India Laboratory | Ervatamia coronaria extract | 1 mg/cm² | An. stephensi | 100 | 2.5 |
| | | 2.5 mg/cm² | An. stephensi | 100 | 3 |
| | | 5 mg/cm² | An. stephensi | 100 | 3.5 |
| | Caesalpinia pulcherrima extract | 1 mg/cm² | An. stephensi | 100 | 2 |
| Govindarajan et al. 2011 India Laboratory | R. officinalis L. essential oil | 2.5 mg/cm² | An. stephensi | 100 | 2.5 |
| | | 5 mg/cm² | An. stephensi | 100 | 3 |
| | | 2.5 mg/cm² | An. subpictus | 100 | 2 |
| | | 5 mg/cm² | An. subpictus | 100 | 2.5 |
| | | 1 mg/cm² | An. subpictus | 100 | 1 |
| | | 2.5 mg/cm² | An. subpictus | 100 | 1 |
| | | 5 mg/cm² | An. subpictus | 100 | 1.5 |
Table 1 (continued)

| Study Authors and Year | Country | Study Type | Plant Extract/ (essential oil) | Concentration dose | Anopheles Species | Repellency % | Protection Time (hours) |
|------------------------|---------|------------|--------------------------------|--------------------|------------------|--------------|------------------------|
| Asadollahi et al. (2019) |         |            | C. citrates Stapf. essential oil | 1 mg/cm²            | An. subpictus     | 100          | 1                      |
|                        |         |            |                                | 2.5 mg/cm²          | An. subpictus     | 100          | 1.5                    |
|                        |         |            |                                | 5 mg/cm²            | An. subpictus     | 100          | 2                      |
| Govindarajan et al. (2016) | India  | Laboratory | C. zeylanicum L. essential oil  | 1 mg/cm²            | An. subpictus     | 100          | 1                      |
|                        |         |            |                                | 2.5 mg/cm²          | An. subpictus     | 100          | 1                      |
|                        |         |            |                                | 5 mg/cm²            | An. subpictus     | 100          | 1.5                    |
| Jeyabalain et al. (2003) | India  | Laboratory | Zingiber nimmonii essential oil | 1 mg/cm²            | An. stephensi     | 100          | 2                      |
|                        |         |            |                                | 2 mg/cm²            | An. stephensi     | 100          | 2.5                    |
|                        |         |            |                                | 5 mg/cm²            | An. stephensi     | 100          | 3                      |
| Karunamoorthi et al. (2008) | Ethiopia | 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. (2010) | 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/cm²            | An. arabiensis     | 100          | 3.2                    |
|                        |         |            |                                | 1.5 mg/cm²          | An. arabiensis     | 100          | 4.4                    |
|                        |         |            |                                | 2 mg/cm²            | An. arabiensis     | 100          | 5.3                    |
|                        |         |            |                                | 2.5 mg/cm²          | An. arabiensis     | 100          | 6.3                    |
| Govindarajan et al. (2016) | India  | Laboratory | Origanum scabrum essential oil | 1 mg/cm²            | An. stephensi     | 100          | 2.5                    |
|                        |         |            |                                | 2 mg/cm²            | An. stephensi     | 100          | 3                      |
|                        |         |            |                                | 5 mg/cm²            | 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                    |
| Study          | Year | Country | Study type | Plant extract/ (essential oil) | Concentration | 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 extract          | 500 mg/m²     | An. gambiae       | 81          | –                      |
|               |      |         |            | Ocimum suave extract         | 500 mg/m²     | An. gambiae       | 81          | –                      |
|               |      |         |            | Ocimum kilimandscharicum extract | 500 mg/m² | An. gambiae       | 73          | –                      |
|               |      |         |            | Citronella                  | 500 mg/m²     | An. arabiensis    | 85          | –                      |
|               |      |         |            | O. suave extract         | 500 mg/m²     | An. arabiensis    | 89          | –                      |
|               |      |         |            | O. kilimandscharicum extract | 500 mg/m² | An. arabiensis    | 75          | –                      |
| Kovendan et al. | 2012 | India   | Laboratory | A. alnifolia extract            | 1 mg/cm²      | An. stephensi    | 100         | 2                      |
|               |      |         |            |                                | 3 mg/cm²      | An. stephensi    | 100         | 2                      |
|               |      |         |            |                                | 5 mg/cm²      | An. stephensi    | 100         | 2.5                    |
| Krishnappa et al. | 2012 | India   | Laboratory | A. digitata crude extract         | 2 mg/cm²     | An. stephensi    | 100         | 3                      |
|               |      |         |            |                                | 4 mg/cm²      | An. stephensi    | 100         | 3.5                    |
|               |      |         |            |                                | 6 mg/cm²      | An. stephensi    | 100         | 3.5                    |
| Naine et al.  | 2014 | India   | Laboratory | Streptomyces sp. VITJS4 extract | 1 mg/cm² | An. stephensi    | 100         | 2                      |
|               |      |         |            |                                | 3 mg/cm²      | An. stephensi    | 100         | 2                      |
|               |      |         |            |                                | 6 mg/cm²      | 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 v/v         | 10%           | 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                   |
| 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                      |
| Panneerselvam et al. | 2013 | India   | Laboratory | Andrographis paniculata methanol leaf extract | 1 mg/cm² | An. stephensi    | 100         | 2                      |
|               |      |         |            |                                | 3 mg/cm²      | An. stephensi    | 100         | 2.5                    |
|               |      |         |            |                                | 6 mg/cm²      | An. stephensi    | 100         | 3                      |
|               |      |         |            | Cassia occidentalis methanol leaf extract | 1 mg/cm² | An. stephensi    | 100         | 2                      |
|               |      |         |            |                                | 3 mg/cm²      | An. stephensi    | 100         | 2.5                    |
|               |      |         |            |                                | 6 mg/cm²      | An. stephensi    | 100         | 5.2                    |
### 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/cm²           | An. stephensi    | 100          | 2                       |
|                              |       |          |            |                                | 3 mg/cm²           | An. stephensi    | 100          | 2                       |
|                              |       |          |            |                                | 6 mg/cm²           | 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/cm²        | An. dirus        | 94           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 92           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | An. dirus        | 92           | –                       |
|                              |       |          |            | C. sinensis oil               | 0.02 mg/cm²        | An. dirus        | 40           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 54           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | An. dirus        | 84           | –                       |
|                              |       |          |            | C. citratus oil               | 0.02 mg/cm²        | An. dirus        | 76           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 82           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | An. dirus        | 98           | –                       |
|                              |       |          |            | Cymbopogon nardus oil         | 0.02 mg/cm²        | An. dirus        | 92           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 92           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | An. dirus        | 98           | –                       |
|                              |       |          |            | E. citriodora oil             | 0.02 mg/cm²        | An. dirus        | 52           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 74           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | An. dirus        | 86           | –                       |
|                              |       |          |            | O. basilicum oil              | 0.02 mg/cm²        | An. dirus        | 66           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 74           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | An. dirus        | 96           | –                       |
|                              |       |          |            | S. aromaticum oil             | 0.02 mg/cm²        | An. dirus        | 82           | –                       |
|                              |       |          |            |                                | 0.10 mg/cm²        | An. dirus        | 92           | –                       |
|                              |       |          |            |                                | 0.21 mg/cm²        | 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           | –                       |
| 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                    |
|                              |       |          |            | Mammordica charan-nia 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                    |
| Study                        | Year | Country    | Study type  | Plant extract/ (essential oil) | Concentration dose | Anopheles species | Repellency % | Protection time (hours) |
|------------------------------|------|------------|-------------|-------------------------------|-------------------|-------------------|--------------|------------------------|
| Rajkumar et al.              | 2005 | India      | Laboratory  | Tridax procumbens essential oil | 2%                | An. stephensi     | –            | 2.33                   |
|                              |      |            |             |                               | 4%                |                   |              |                        |
|                              |      |            |             |                               | 6%                |                   |              |                        |
| Rajkumar et al.              | 2005 | India      | Laboratory  | Tridax procumbens essential oil | 0.001%            | An. stephensi     | 100          | 1.15                   |
|                              |      |            |             |                               | 0.005%            |                   |              |                        |
|                              |      |            |             |                               | 0.01%             |                   |              |                        |
|                              |      |            |             |                               | 0.015%            |                   |              |                        |
| Rawani et al.                | 2012 | India      | Laboratory  | Solanum trilobatum extract    | 1%                | An. stephensi     | 65           | 2.3                    |
|                              |      |            |             |                               |                   |                   |              |                        |
| Rawani et al.                | 2012 | India      | Laboratory  | Solanum trilobatum extract    | 1.50%             | An. stephensi     | 80           | 4                      |
|                              |      |            |             |                               |                   |                   |              |                        |
| Rawani et al.                | 2012 | India      | Laboratory  | Solanum trilobatum extract    | 2%                | An. stephensi     | 90           | 5                      |
| Reegan et al.                | 2015 | India      | Laboratory  | Cliona celata extract         | 1 mg/cm²          | An. stephensi     | 100          | 1.08                   |
|                              |      |            |             |                               | 2.5 mg/cm²        |                   |              |                        |
|                              |      |            |             |                               | 5 mg/cm²          |                   |              |                        |
| Swathi et al.                | 2012 | India      | Laboratory  | Datura stramonium extract     | 0.1%              | An. stephensi     | –            | 0.35                   |
|                              |      |            |             |                               | 0.5%              |                   |              |                        |
|                              |      |            |             |                               | 1%                |                   |              |                        |
| Seyoum et al.                | 2002 | Kenya      | Semi-field  | Neem (A. indica)              | Periodic thermal expulsion | An. gambiae     | 24.5         | –                      |
|                              |      |            |             |                               |                   |                   |              |                        |
|                              |      |            |             |                               |                   |                   |              |                        |
| Sanghong et al.              | 2015 | Thailand   | Laboratory  | L. sinense ethanolic preparations | 25%              | An. minimus      | –            | 11.5                   |
| Das et al.                   | 2003 | India      | Laboratory  | Cymbopogon martini extract     | 1 ml without dilution | An. sundaicus   | 98           | 6                      |
| Nour et al.                  | 2009 | Sudan      | Laboratory  | Basil (O. basilicum L.) essential oil | 0.1 ml            | An. dirus        | –            | 0.66                   |
| Trongtokit et al.            | 2005 | Thailand   | Laboratory  | C. nardus essential oil       | 10%               | An. dirus        | –            | 0.5                    |
|                              |      |            |             |                               | 50%               |                   |              |                        |
|                              |      |            |             |                               | 100%              |                   |              |                        |
|                              |      |            |             |                               |                   |                   |              |                        |
|                              |      |            |             |                               |                   |                   |              |                        |
|                              |      |            |             |                               |                   |                   |              |                        |
### Table 1 (continued)

| Study | Year  | Country      | Study type | Plant extract/ (essential oil) | Concentration dose | Anopheles species | Repellency % | Protection time (hours) |
|-------|-------|--------------|------------|---------------------------------|--------------------|------------------|--------------|-------------------------|
| Mullilam (Zanthoxylum limonella) | 10%  | An. dirus    | –          | 1                              |                    | –                | 1            |                         |
| Clove (Syzygium aromaticum)      | 10%  | An. dirus    | –          | 2                              |                    | –                | 2.16         |                         |
|                                | 50%  | An. dirus    | –          | 2                              |                    | –                | 3.16         |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1.33         |                         |
|                                | 50%  | An. dirus    | –          | 2                              |                    | –                | 2.66         |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 3.5          |                         |
| Yogananth et al.                | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Singh et al.                    | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Trongtokit et al.               | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Kamaraj et al.                  | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Solomon et al.                  | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Soonwera et al.                 | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Sritabutra et al.               | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Sritabutra et al.               | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Birkett et al.                  | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Kamaraj et al.                  | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Soonwera et al.                 | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
| Sritabutra et al.               | 10%  | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |
|                                | 100% | An. dirus    | –          | 2                              |                    | –                | 1            |                         |

Note: Concentration levels are given in mg/cm² or μl for the respective plant extracts/essential oils.
Table 1 (continued)

| Study                      | Year | Country | Study type       | Plant extract/ (essential oil)     | Concentration dose | Anopheles species | Repellency % | Protection time (hours) |
|----------------------------|------|---------|------------------|------------------------------------|--------------------|-------------------|--------------|------------------------|
| Orange (C. sinensis)       |      |         |                  | 0.1 ml An. dirus                    | –                  | 0.83              |             |                        |
| Citronella grass (C. nardus) |      |         |                  | 0.1 ml An. dirus                    | –                  | 0.8              |             |                        |
| Lemongrass (C. citratus)   |      |         |                  | 0.1 ml An. dirus                    | –                  | 1.63             |             |                        |
| Clove (S. aromaticum)      |      |         |                  | 0.1 ml An. dirus                    | –                  | 1                |             |                        |
| Sweet basil (O. basilicum) |      |         |                  | 0.1 ml An. dirus                    | –                  | 0.75             |             |                        |
| Tavassoli et al. 2001 iran| 2001 | Iran    | Laboratory       | Marigold (Calendula officinalis) | 50%                | An. stephensi     | –            | 2.15                   |
| Myrtle essential oil       |      |         |                  | 50% An. stephensi                  | –                  | 4.36             |             |                        |
| Annona senegalensis leaf extract | 2016 | Cameroon | Laboratory | 4.0 mg/cm² An. gambiæ | – | 0.5 | 0.5 |                        |
| Boswellia dalzielii leaf extract | 2011 | India | Laboratory | 4.0 mg/cm² An. gambiæ | – | 1 | 1.5 |                        |
| Govindarajan et al. 2011 | 2011 | India   | Laboratory       | Coccinia indica extract 1 mg/cm²  | An. stephensi      | 100               | 3            |                        |
| Govindarajan et al. 2012 | 2012 | India   | Laboratory       | Cardiospermum halicacabum oil 1 mg/cm²  | An. stephensi      | 100               | 2            |                        |
| Govindarajan et al. 2014 | 2014 | India   | Laboratory       | Asparagus racemosus crude extract 1 mg/cm²  | An. stephensi      | 100               | 2.5          |                        |
| Govindarajan et al. 2015 | 2015 | India   | Laboratory       | Delonix elata crude extract 1 mg/cm²  | An. stephensi      | 100               | 2.5          |                        |
| Innocent et al. 2014 Kenya | 2014 | Kenya   | Laboratory       | Uvariodendron gorgonis essential oil 0.01 w/v An. gambiæ | 29 | – | – |                        |
| Clausena anisata essential oil | 2015 | India | Laboratory       | 0.01 w/v An. gambiæ | 13 | – | – |                        |
| Lantana vibunoides essential oil | 2015 | India | Laboratory       | 0.01 w/v An. gambiæ | 21 | – | – |                        |
|                           |      |         |                  | 0.1 w/v An. gambiæ | 1 | – | – |                        |
|                           |      |         |                  | 10 w/v An. gambiæ | 64 | – | – |                        |
|                           |      |         |                  | 1 w/v An. gambiæ | 42 | – | – |                        |
|                           |      |         |                  | 10 w/v An. gambiæ | 56 | – | – |                        |
|                           |      |         |                  | 0.1 w/v An. gambiæ | 54 | – | – |                        |
|                           |      |         |                  | 10 w/v An. gambiæ | 62 | – | – |                        |
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/cm² showed 1 h protection against *An. subpictus*.

**Catnip (*Nepeta cataria*)**
Catnip is a perennial plant that belongs to the mint family, Lamiaceae. 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) | 1 ml without dilution | An. culicifacies  |
|                         | Citronella (lemongrass oil) | 1 ml without dilution | An. culicifacies  |
|                         | D. sissoo oil | 1 ml without dilution | An. annularis     |
|                         | Peppermint oil | 1 ml without dilution | An. annularis     |
| 8 to < 10               | D. sissoo oil | 1 ml without dilution | An. culicifacies  |
|                         | Peppermint oil | 1 ml without dilution | An. culicifacies  |
|                         | R. mucronata oil | 4 mg/cm² | An. stephensi     |
|                         | R. mucronata oil | 3 mg/cm² | 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     |
|                         | Cinnamom (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/cm² | An. stephensi |
|                         | Thyme (T. serpyllum) essential oils | 20% oil solution | An. stephensi |
|                         | Peppermint oil | 1 ml without dilution | An. subpictus |
|                         | R. mucronata oil | 1 mg/cm² | 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. rosea) 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 |
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 *Anopheles 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 *Anopheles stephensi* for 8 h, had a good effectiveness in preventing *Anopheles 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,

| Protection time (hours) | Plant name                                      | Concentration/dose | Anopheles species |
|------------------------|------------------------------------------------|--------------------|-------------------|
| 6                      | *Helichrysum* (*H. italicum*) essential oil     | 20% oil solution   | *An. stephensi*    |
|                        | *C. martini 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. carica* 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. nobilis*) 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/cm²           | *An. arabiensis*  |
|                        | *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/cm²         | *An. arabiensis*  |
|                        | *Myrtle essential oil*                         | 50%                | *An. stephensi*   |
|                        | *I. carica 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.
Eucalyptus extract is not affective against An. gambiae [54]. 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/cm² 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 (Labiate) 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/cm² 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/cm² 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. Phasomkusolsil et al. [42] also found that orange at 0.02, 0.10, and 0.21 mg/cm², 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 Zingiberaceae 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 flora 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. sisssoo*, 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 citronellol [81]. Some data proposes that these agents interfere with olfactory receptors of mosquitoes [82]. A recent study revealed that *A. 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 pyrethrins another plant based terpene [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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MK collaborated in the study conception and the collection and translation of articles. AA performed collecting of articles and writing the manuscript. All authors read and approved the final manuscript.

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