# A REVIEW ON OVICIDAL POTENTIAL OF PLANT EXTRACTS AGAINST MOSQUITOES

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## Abstract

Mosquitoes pose significant health impact globally with the pathogens they transmit to living organisms especially humans. With rising annual cases of dengue fever, the need of effective, sustainable and eco-friendly strategies is highly emphasized to control mosquitoes' population. Although commercialized synthetic insecticides are available to control the population, the emergence of insecticides resistance, environmental impact due to chemical cues and toxicity effect again non target organisms have become issues. This review paper explores the potential of plant extracts and their active constituents as alternative repellent, ovicides, larvicides and adulticides against mosquito's species as they are abundant, cost- effective, biodegradable, and exhibit minimal toxicity to beneficial organisms. Having said that there are also limitations on implying these alternatives. Thus, a comparison

between conventional and plant-based, modes of phytochemical action, major plant species used and future recommendations are discussed.

## Introduction

Dengue is a well-known mosquito-borne viral infection that leads to the common complications of rash, body pain, and high fever. This endemic disease is caused by the dengue virus, consisting of four distinct serotypes (DEN 1-4) belonging to the family of Flaviviridae. Dengue emerges when a viral-infected Aedes species mosquito, *Aedes aegypti* or *Aedes albopictus*, transmits the deadly virus into the human bloodstream. These primary arthropod vectors are mostly active early morning and evening as *Aedes* mosquitoes flourish in warmer temperatures, typically highest during the day to favour the transmission conditions. The complications of dengue fever (DF), however are alarming as having said it can appear to be worse and life-threatening which will lead to dengue hemorrhagic fever (DHF) or dengue shock syndrome (DSS). Referring to the past years, Malaysia in cumulative recorded a total of 122,423 dengue cases along with 117 deaths, followed by 123,133 cases with 100 deaths in 2024 and 2023, respectively (Ministry of Health Malaysia, 2025). Despite an increasing number of dengue cases annually, other mosquito-borne diseases such as Zika, Malaria, and Chikungunya are also rising, especially in the high-risk regions. These global burdens of mosquito-borne diseases have constrained human daily activities.

To date, there are no specific antiviral treatments for dengue (Khalid et al., 2025). The episode of dengue cases can be treated only to relieve pain symptoms. Many researchers have designed clinical trials for dengue vaccines. The first licensed dengue vaccine recently is Dengvaxia, which is a live attenuated tetravalent vaccine (LATV). The idea of tetravalent means protecting dengue fever patients against all the four serotypes. However, Dengvaxia vaccine can only be given to people who have previously been infected with dengue (seropositive) as it may increase the risk of severe disease in individuals who have never been infected (seronegative) (Agustina & Alamanda, 2025). Another developing vaccine called TAK-003 has been reported to show effectiveness as a live attenuated tetravalent vaccine against the dengue virus for over three years of clinical study evaluation. Nevertheless, a booster dose is understudied as the efficacy of TAK-003 has decreased over time though it continues to offer powerful protection against severe cases of dengue requiring hospitalization (Rivera et al., 2022).

Dengue fever remains a major public health issue across the globe. According to the World Health Organization (WHO) report, by January 2025, the region of the Americas accounted for the highest number of confirmed cases with a total of 154,841. The second- highest confirmed cases were in the Southeast Asia region with a total of 10,110. Several factors have contributed to the cause of rising dengue cases, including weather conditions, population density, global warming, socioeconomic factors, human mobility, and the most concerning factor is the emergence of resistance against conventional mosquito controls. An extensive use of insecticide has prolonged the mosquito's survival rate by mutations. The drawback throughout this resistance will cause the traditional insecticides to lose their effectiveness; hence, impacting the agricultural sector in maintaining the expenses for the mosquito vector control. From America, Asia, and West Africa, chemical insecticides that are widely used, such as organophosphates and pyrethroids, have been altered in their target sites (voltage-gated sodium channel, VGS) by the mutations of amino acids, reducing their binding ability, thus leading the threatened vector to withstand the insecticides better. In the most recent study, V1016G and F1534C are recognizable as the frequently mutated amino acids that cause pyrethroid resistance in *Aedes aegypti* mosquitoes (Uemura et al., 2024). Also, detoxification has been enhanced, allowing the vector to break down and neutralize the insecticide more efficiently (Moyes et al., 2017).

Alternatively, many researchers have revised to sustainable and eco-friendly mosquito control strategies derived from natural sources, known as biopesticides. Natural sources in pest control management can be sourced from plants, algae, fungi, bacteria, viruses, and pheromones. Biopesticides have been introduced into the world of scientific research for a long time. In agriculture, *Bacilllus thurengiensis* (Bt) was subsequently isolated and tested against *Ostrinia nubilalis* (European corn borer larvae), reported to have a favorable outcome. This report has encouraged the production of the first commercial Bt insecticide, Sporeine, which was invented in 1938 (Luthy, 1982, as cited in Milner, 1994). Apart from that, large- scale commercial production of pyrethrins, which are still utilized in household sprays today, from *Chrysanthemum* flowers started in the mid-19th century (Davies et al., 2007). It has been a promising approach because they pose less pollution to the environment, have low mammalian toxicity, have specific action targets, and can enhance the efficacy of current control strategies. In this review paper, the plant is the subject that will be focused on as a sustainable agent in mosquito control management as plants have established their impactful role and gained prominence as natural and botanical insecticides.

**Mosquito Control Strategies**

Current conventional methods in mosquito control can be categorized into five separate groups that may effectively be working in by group or a combination of them. Biological, physical, chemical, plant-based, and integrated mosquito management methods exist. In Malaysia, there are several techniques used in controlling Aedes population, namely using insecticides, Wolbachia and genetic modified Aedes (GM) as shown is Figure 1.

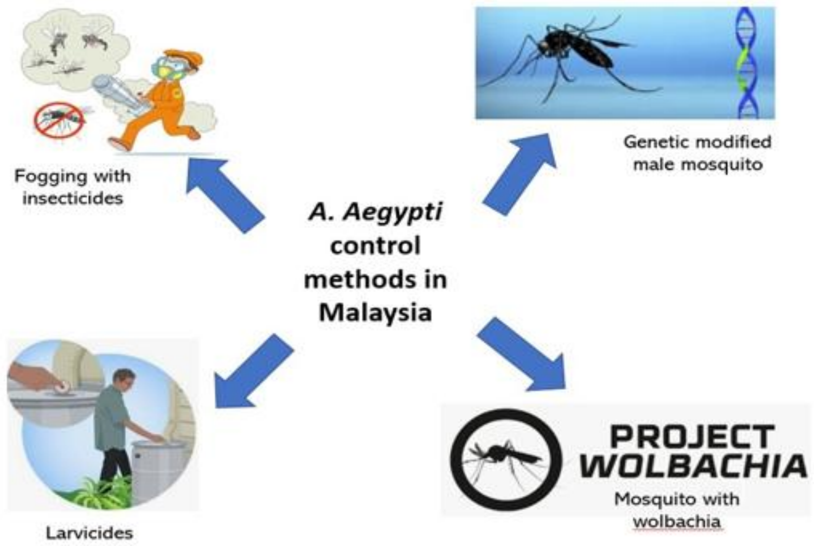


Figure 1: Methods used in Malaysia for controlling Aedes mosquitoes.

Biological strategies involve natural predators or biological agents such as Bt, predatory fish, frogs, and dragonflies. Besides, there is an approach known as the sterile insect technique (SIT), which is a mosquito population control by treating them with ionizing radiation to reduce mating success. The alteration happens when SIT targets enzymes related to detoxification, stress response, and the reproductive part. Glutathione S-transferases (GSTs) in mosquitoes are one of the detoxifications responsible for insecticide resistance. However, a limitation was identified when a study by Da Silva et al. (2025) reported both female and male mosquitoes experienced increasing levels of GST activity after exposure to Gamma radiation. This response encouraged them to become less vulnerable to insecticides and increased their population.

The pressure to develop effective, long-term, sustainable mosquito control strategies is surging. By involving SIT as a basic technique, Wolbachia-based mosquito control has also been introduced to reduce the burden of mosquito-borne diseases by either two strategies: mosquito population modification and population suppression. Generally, in Malaysia, the first application of Wolbachia-based vector-control strategies began in 2017. Keramat AU2, Kuala Lumpur, and Section 7, Shah

Alam, Selangor were selected as the localities of study since these two areas have become dengue hotspot areas (Institute for Medical Research, IMR, 2017). The principle behind Wolbachia-based mosquito control is that the bacteria act as a natural barrier against virus replication by inducing cytoplasmic incompatibility (CI) and are maternally transmitted to local mosquito populations (Zabalou et al., 2004). Malaysia utilized population modification by releasing both Wolbachia-infected female and male *Aedes* (bidirectional CI) to gradually replace the wild *Aedes* population in their natural habitat. As a result, this pilot project has successfully reduced dengue transmission (The Star, 2023). Wolbachia-based strategy is applicable to pose a self-sustaining criterion as it spreads naturally through mosquito populations from female *Aedes*. This supports the idea that no continuous mosquito release is required to maintain the effect. However, having said that this technique only modifies or replaces the mosquito population, it does not do complete elimination and requires microinjection of Wolbachia strains for naturally uninfected mosquitoes especially *Aedes aegypti* (Ogunlade et al., 2021).

Apart from that, genetically modified organisms (GMO) is no longer an unfamiliar practice nowadays. It is believed that the GMO approach can control the mosquito population by targeting reproduction reduction. According to a study by Subramaniam et al. (2012), Malaysia had the first field trial of releasing 6000 genetically modified (GM) mosquitoes on 21st December 2010 in Bentong, Pahang to evaluate the biological traits and survival of GM mosquitoes in the wild for public engagement. From the trial, GM mosquitoes showed limited survival in natural conditions by forming offspring that do not survive beyond the early stages of development. However, public concerns, ethical and costing discussions require additional assessments before considering large-scale implementation. The fundamentals of GM mosquito are still involving SIT as the basis, yet GM mosquito is an improved one (Arham et al., 2022).

Physical-based strategies for mosquito control involve non-chemical techniques by targeting the breeding sites or reducing human-vector contact. One of the simplest methods is to remove stagnant water from flowerpots or wasted containers. This is because the presence of water favors the deposition of eggs by the gravid *Aedes*. Prohibiting more breeding sites, improving drainage systems, and maintaining cleanliness will contribute to lowering the risk of disease transmission and offer better life quality to humans in their daily activities. Next, the installation of mass trapping particularly for larvae or eggs is proven to reduce mosquito population. Based on a study concluded by Jaffal et al. (2023), mass trapping can be effective as integrated into other classical vector control methods with engagement from the public and the community. There is a variety of mosquito trapping designed to preserve human health; for instance, oviposition, light, carbon dioxide, sticky, and insecticide- treated traps (Aguilar-Durán et al., 2024; Lhaosudto et al., 2024; Machange et al., 2024; Roslan et al., 2017; McNamara et al., 2024). Indeed, these model inventions are redesigned day by day to achieve the highest opportunity of eliminating the vectors and reducing the cost of the installation which requires regular replacement or repositioning.

Additionally, chemical insecticides also hold significance in the field of pest management nowadays. It has been synthetically produced and widely used to deter mosquitoes and the diseases (Zika, Malaria, and Dengue) they transmit. One example of a classical chemical insecticide is pyrethroid derived from natural pyrethrin. Due to the fastaction activating neurotoxicity in insects, pyrethroid has been commercialized into household sprays for convenient use. As mentioned, the primary mechanism of pyrethroid is exerted when it binds to VGS in the insect nervous system and causes prolongation of sodium intake. This sodium ion influx will encourage rapid depolarization, from negatively charged to positively charged internal neurons, leading to hyperexcitation. Then, the mosquito will experience paralysis and death. The neurotoxicity mechanism of pyrethroids can be induced via oxidative stress, inflammation, apoptosis, and mitochondria dysfunction (Oyovwi et al., 2025). These events support the point that even though pyrethroids eliminate the mosquito population through alteration in the nervous system, pyrethroids may impact other non-target organisms especially aquatic organisms, and human health as well (Ahamad & Kumar, 2023). According to them again, the need for high specificity and sensitivity biosensors for detecting pyrethroids pesticides in food is growing due to the extensive use of pyrethroids in insecticides in the agriculture sector.

Moreover, targeting the adult stage of mosquitoes can be a straightforward approach to their elimination. In 1854, tetraethylpyrophosphate (TEPP) was identified as an initial organophosphate (OP) compound as a cholinesterase inhibitor (Soltaninejad & Shadnia, 2014). The action of this mosquito-killing agent takes place when the OP compound disrupts the neurotransmitter acetylcholine (ACh) degradation process by blocking acetylcholinesterase enzyme (AChE) via phosphorylation of serine hydroxyl group at the enzyme active site (Mangas et al., 2017). AChE is supposed to offer continuous normal nerve signaling function by hydrolyzing ACh into choline and acetate to be reused. Consequently, the accumulation of nerve signaling by ACh will cause paralysis and eventually kill the mosquito (Bowman et al., 2018). In the context of human health, organophosphate poisoning generally leads to symptoms such as nausea, vomiting, blurred vision, excessive saliva production, increased mucus in the airways, slow heart rate, low blood pressure, and involuntary muscle twitching (Bereda, 2022). Consistent implementation of chemical insecticides against mosquitoes permits resistance to insecticides. *Aedes aegypti* has developed enzyme-mediated resistance, rendering the fenitrothion (OP insecticide) ineffectiveness reported by Atencia-Pineda et al. (2025) which has proven the elevated activity levels of α- and β-esterases have been linked to resistance against fenitrothion. In addition, esterases and GSTs are the common detoxifying enzymes in mosquito resistant chemical insecticides. Esterase itself plays a role in breaking down the ester bond in the OP, resulting in non-toxic OP. Meanwhile, in Riau, Indonesia, Lesmana et al. (2022) explained the genetic factor also contributed to the high resistance level of mosquitoes to organophosphate because the presence of glutathione s transferase gene boosted the esterase performance in *Aedes aegypti* and speed up the detoxification of organophosphate insecticides specifically temephos and malathion.

As resistance intensified, it faced greater challenges, and some insecticides have been phased out because they are no longer effective. As another selection, some opt for pesticide treadmill which refers to a higher dosage use or combination of multiple insecticides (Meier et al., 2022). The effect of these alternatives may lead to ecological burdens caused by the accumulation of chemicals in the environment. Limitations of synthetic insecticides have allowed better alternatives that concern in all aspects. This can be referred to as the plant- based alternative.

**Plant Extracts as Mosquito Control Agents**

The procedure for establishing mosquito control strategies needs to consider various aspects including effectiveness, feasibility, sustainability, community participation, and indeed safety of the ecosystem including public health. Not merely being a food source, producing oxygen, and maintaining environmental balance, but the plants also have attained significance as botanical insecticides since 400 BCE (Silva Aguayo, 2023) as they developed mechanisms that protect themselves from insect attack. The mechanisms are facilitated by the bioactive compounds that are naturally present in the plants which exhibit insecticidal effects and other biological effects on living organisms. Bioactive compounds or pyhtochemicals are present in all parts of the plant including leaves, flowers, fruits, seeds, roots, stems, and latex. Each of the parts can identify multiple classes of bioactive compounds such as essential oils,flavonoids, terpenoids, alkaloids, saponins and others in leaves. Terpenoids are also available in stems for some other plants. These natural compounds offer broad benefits to plants and consumers in the fields of human health, pharmaceutical and therapeutics, agriculture, environment, food industry and pest management. Quercetin, a natural flavonoid identified from *Moringa oleifera*, was reported to potentially be an antiviral for SARS-CoV-2 as the entry inhibitor (Mawaddani et al., 2022). In addition, Xu et al. (2024) added quercetin extracted from *M. oleifera* possess pharmacological activities, such as antioxidant, anti-inflammatory, anti- cancer, hypoglycemic, and hypolipidemic. Indeed, one compound can serve multifunction interventions.

The basic structures and biosynthetic pathways of phytochemicals contributed to their chemical classification. For those with aromatic rings, it is called phenolics. Examples of phenolics are polyphenols, flavonoids, tannins, lignins, and coumarins. They shared similarities by having at least one aromatic benzene ring with hydroxyl (-OH) groups in their chemical structures. Phenolics or phenol can appear as white moisture-absorbing crystalline substances and exhibit a strong odor. The presence of phenolics in plant samples can be tested using phenol test iron (III) chloride test; formation of dark green solution signifies positive phenol. Furthermore, they are moderately soluble in water. However, the solubility may increase due to the presence of -OH which can attract water molecules or may decrease due to the hydrophobic nature of the benzene ring (ScienceInfo, 2022). Next, alkaloids contain a heterocyclic ring with at least a nitrogen atom attached to it. Most of the compounds in alkaloids portray alkaline properties due to the presence of nitrogen. The addition of ester or amide linkages in their chemical structures influences the pharmacological effects. Examples of alkaloids are caffeine and nicotine. To detect the presence of alkaloids in plant samples, Dragendorff's reagent is used to form orange-red precipitation if the sample positive alkaloids.

Phytochemicals exhibit ovicidal, larvicidal, adulticidal, and repellency properties in both early and adult mosquito stages, affecting through their water balance, endocrine, respiratory, and neurological systems. Other key characteristic of phytochemicals, they can either be classified as primary or secondary metabolites.

As promoting insecticidal effect against mosquito, secondary metabolites such as essential oils (EOs) are more applicable as they are naturally made for defense mechanisms. EOs from *Litsea cubeba* (May Chang), showed maximum repellent effectiveness against *Aedes aegypti*, *Anopheles stephensi,* and *Culex quinquefasciatus* (Amer & Mehlhorn, 2006). This finding has highlighted high citral content of *L. cubeba* is potential to be used as natural vector control. The idea of repellency falls behind few fundamentals, i.e. smell-based repellency, taste-based repellency, contact irritation, and neurotoxic behaviour. Hence, selection of volatile constituents in plant agent is an initial benchmark to evaluate the performance of compounds as a potential mosquito control as they will interfere olfactory system of the vector through evaporation.

Furthermore, ovicidal and larvicidal are the optimal stages to be effectively targeted and eliminated before reaching adulthood as they are localized. As a result, the ovicidal and larvicidal effects of various plant compounds have been extensively studied (Şengül Demirak & Canpolat, 2022). By preventing egg hatching, ovicidal agents effectively reduce the emergence of new larvae, thereby disrupting the life cycle of the insect. Ovicidal activity can be evaluated via physical morphology alteration and chemical composition of embryonic in eggs as refer to a study by Suman et al. (2013). They explained that the treatment of insect growth regulator, Azadirachtin, against mosquitoes disrupted the normal growth and progression of an embryo at different points in its development. Insect growth regulators are responsible for causing an imbalance in hormone levels by altering the hormonal titer; thus, interfere with normal embryonic development. For instance, Azadirachtin, which can be primarily found in *Azadirachta indica*, is known to serve as ecdysone agonist that targets premature molting or ecdysis. As a result, the mosquitoes settle over before they evolve as adults.

Meanwhile, targeting the larval stage is particularly effective in mosquito control, as larvae are confined to aquatic habitats and are more accessible than adult mosquitoes. Consideration on larvicidal toxicity level needs to be counted for the non-target aquatic organisms. In addition, evaluation of biological activities of mosquito larvicides need to account for uniform populations (homogenous) of mosquito larvae at a specific instar for accurate assessment. Treatment of larvicides requires different concentrations (ppm) within its effective range for a period of 24 to 48 hours or longer; then, the observations can be made. For agents with delayed effects, evaluation should continue until adult emergence. Ultimately, the lethal concentration (LC) of the larvicide required to cause 50% and 90% mortality (LC50 and LC90, respectively) or to inhibit adult emergence by 50% and 90% (IE50 and IE90) can be determined (World Health Organization, 2005). Determination of LC50 and LC90 for ethanol extract of *Ocimum gratissimum* leaves against *A. aegypti* over 12 hours was calculated by Sharma (2024), obtained for 57.82 mg/l and 331.07 mg/l respectively. On the other hand, *Ocimum gratissimum* is abundant in polyphenols and flavonoids, which are phytochemical constituents with recognized larvicidal properties (Ijinu et al., 2023; Zareiyan & Khajehsharifi, 2022). The extract is effective against *Aedes aegypti* but requires a relatively high concentration to achieve near-total elimination.

Surely, plant-based mosquito control has gained attention for its potential benefits over synthetic insecticides. Firstly, biodegradability should be considered as it involves the environment where all human beings live. A polluted environment will impact human health, unpredictable extreme weather changes, loss of biodiversity, water contamination, and economic consequences. This is why the biodegradability of a source is crucial as it can reduce the repetitive impacts as mentioned. As the ones composing natural organic materials, plants have a high capability of going through natural degradation which prevents the accumulation of toxic waste from chemical substances in the environment. This will protect the ecosystem wisely. Compared to synthetic insecticides, plants have a low risk of allergic reactions, but some consumers might encounter a reaction from the pollen. Many pharmaceutical, food, cosmetics, and therapeutic industries have been relying on plant sources as they exhibit minimal effects on the consumer. Another point of selecting plants as safe alternative-based insecticides is the fact of sustainability. It is significantly cost-efficient because the source can be renewable by reforestation programs and be used again. This has aligned with Malaysia's Sustainable Development Goals agenda, which falls under SDG 13, SDG 15, and SDG 7, coordinated by the Economic Planning Unit (EPU) under the Prime Minister's Department (Ministry of Economy Malaysia, 2024; Ministry of Economy Malaysia, 2021).

## Major Plant Species Used in Mosquito Control

### i. Essential oils and plant-based repellents

Beyond the plant agent as natural insecticides, there are major plant species that are scientifically proven to be used as mosquito population control. According to the life traits of a mosquito, the control of their population can be accomplished through either repellent by essential oils (EOs), pupicidal, larvicidal, and ovicidal. EOs can be considered as adulticidal as they primarily target adult mosquitoes either by repelling or killing them. First and foremost, citronella, *Cymbopogon nardus*, showed a significant positive result as a plant-based repellent against mosquitoes. EOs are secondary metabolites that contain plentiful of monoterpenoids or sesquiterpenoids. As for *C. nardus*, it is identified as rich in caryophyllene as one of the major sesquiterpenoids. Based on the result obtained by Srivastava et al. (2023), *C. nardus* EOs exhibited 77.6% ovicidal effects, 73.33% ovipositional repellency, and 73.6% adulticidal effects against *Culex quinquefasciatus*. It is a reliable result as there was a notable over half percentage of mosquitocidal, even though it requires a higher concentration of 160.29 ppm to achieve 50% of mortality (LC50). According to another similar research in the area, Lopes et al. (2025) justified that the achieved larvicidal activity of *C. blanchetianus* essential oils relies upon the presence of one of the sesquiterpenes, β-caryophyllene, which exhibit strong interactions with the active site of the sterol carrier protein, indicating their potential role in larvicidal activity. In addition, β-caryophyllene can be fractioned using gas chromatography- mass spectrometry since it is volatile and further enhanced for its fractions by Centrifugal Partition Chromatography (CPC) (Liakakou et al., 2021).

Secondly, lemon eucalyptus or *Eucalyptus citriodora* is viable to be used for its essential oils for mosquito repellent. This is because *E. citriodora* contains several active constituents, including citronellal and isopulegol, as observed by Unni et al. (2024). They concluded these two phyto-compounds are responsible for the larvicidal activity achieved by Citriodora oils at 45.36 ppm for LC50, 24 hours post-treatment against *Culex quinquefasciatus*. The repellent mechanism hinges on the natural lipophilicity attribute of the citronellal, facilitating the penetration through the insect's cuticle, leading to toxic effects. Citronella individually blocks the activity of cytochrome P450 and glutathione S-transferase in mosquitoes; hence, increasing their susceptibility to insecticides (Iovinella et al., 2022; Şengül Demirak & Canpolat, 2022). Meanwhile, the strong minty aroma of isopulegol hindered mosquito's ability to perceive human skin scents. Combination of citronellal and its derivatives, such as monoterpene alcohol (isopulegol) in Citriodora oils, poses a potential greater activity of the EOs as mosquito repellent. p-Menthane-3,8-diol (PMD), naturally found in *E. citriodora*, has been formally acknowledged by the Centers for Disease Control and Prevention (CDC) as an effective insect repellent comparable to N, N-Diethyl-meta-toluamide (DEET), a synthetic insect repellent. Moreover, PMD was approved to offer mosquito protection without reported adverse effects in the United States and European countries (Carroll & Loye, 2006 as cited by Le et al., 2023).

Neem oil, from *Azadirachta indica*, also offers multiple benefits as a repellent in mosquito control. Exhibiting both olfactory disruption and contact irritation are the general repellence activity shown by neem oil with its efficacy rooted in its rich composition of bioactive compounds. Neem volatile oil contains limonoids, terpenoids, and sulfur that contribute to mosquito repellence. One of the liminoids and terpenoids examples are azadirachtin and citral, respectively. Triterpenoid and one of the main bioactive compounds of *A. indica*, Azadirachtin presents mostly in the seed of the plants. Other triterpenoids found in the same part are Azadirachtin B, nimbin and salannin. It is recognized as antifeedant. Feeding behavior in mosquito is influenced by neural signals from their chemical senses, including taste receptors on the tarsi, mouthparts, and oral cavity, as well as the central nervous system's processing of these sensory inputs. Azadirachtin activates specific deterrent cells within chemoreceptors while simultaneously inhibiting the activity of sugar receptor cells, which are responsible for triggering feeding responses (Mordue *et al.* 1998; Blaney et al. 1990; Simmonds et al. 1990; Mordue (Luntz) et al. 1999 as cited by Nisbet, 2000). Disrupting feeding activity can impact aninsect's ability to transmit pathogens, potentially reducing disease spread. However, there is also similar study regarding life traits disturbance and disruption by neem seed kernel extract via mechanisms of killing the eggs, hindering immature larval and pupa development (Kaur & Kocher, 2023).

**ii. Larvicidal and adulticidal plant extracts**

On the other hand, larvicidal and adulticidal approach have been extensively study for a long time due to convenient access between researcher and the target vector, mosquitoes. According to Yahaya et al. (2021), there was highly present of saponin (2.88%) and alkaloids (3.2%) in *Nicotiana tabacum*, tobacco, which contributed actively to the larvicidal activity against three mosquito's species (Aedes sp., Anopheles sp. and Culex sp.). Tobacco also contains nicotine. In insects, nicotinic acetylcholine receptors (nAChRs) serve as target sites for various natural and synthetic compounds that demonstrate strong insecticidal effects. The core structure of nicotine is pyridine and pyrrolidine ring which act as nAChRs agonists. Nicotine, in general capable of mimicking acetylcholine (ACh) at central nervous system of the mosquito. Assisted by pyridine moiety, nicotine exerts toxic effect to the mosquito and evetually causes paralysis and death (Yamamoto et al., 1998). Nowadays, this mechanism of nicotine has evolved and become basis for neonicotinoid-like alkaloids. For instance, anabasine extracted from aqueous extract of tobacco exhibits high insecticidal effect which also mimick the neurotransmitter ACh in the nervous system (Ogbalu et al., 2014). Therefore, the plants are potential for either establish as novel treatment or as to optimize the conventional methods to have sustainable and eco-firendly mosquito controls approach.

Papaya used to be famous for dengue fever treatment. It is shown that *Carica papaya* leaves extract is effective as larvicide of Aedes aegypti (Maula & Adi, 2021; Dhenge et al., 2021). Papaya is regarded for its nutritional value in food intake, but papaya leaf extract also contributes to insecticidal activity (larvicidal) influenced by the presence of their secondary metabolites. According to the respective paper, Maula and Adi (2021) reported there was  strong larvicidal activity exerted by papaya leaves extract against instar III of the Ae. aegypti with increasing mortality rates after 24 hours of exposure to treatment. Only at the lowest concentration used (0.5% of papaya leaves extract) already shown 54.8% mortality rates. Meanwhile at the highest concentration used (3%) exhibited 98.8% mortality rates. The observation was furthered into the biological appearance of the larvae. They explained the most phytochemical present in papaya leaves were alkaloid, tannins and flavonoids which play roles in alkaloid poisoning, antifeedant and respiratory inhibitors, respectively.

**iii. Ovicidal plant extracts**

In the case of ovicidal, it is a mechanism of leaving no opportunities for the mosquito eggs to hatch and develop into larvae or adults. Generally, the percent hatchability is inversely proportional to the concentration of plant extract. Any changes deviated from the normal appearance of the eggs by the plant extract treatment recognize the plant as an excellent potential mosquito control agent. From a study by prathiba et al. (2023), *Cinnamomum verum* essential oil exhibited the highest ovicidal activity against Ae. aegypti and Ae. albopictus. As further identification of bioactive compounds carried out through GC-MS analysis, *C. verum* contained at least 14 bioactive compounds, with *trans*-Cinnamaldehyde as the highest yield obtained (73.21 ± 2.73) followed by benzyl alcohol (12.87 ± 0.69) and cinnamyl acetate (2.50 ± 0.53). Among the treatments considered in the experiment, *trans*-Cinnamaldehyde (30,000 ppm) resulted the most potent with 96.7 ± 3.9 eggs inhibition rate as individual treatment. Also, this individual treatment is not significantly different from the combination treatment of 10,000 ppm *Cymbopogon citratus* EO and d-limonene (2:1) which exhibited 94.5 ± 1.6 ovicidal rate against the same species, Ae. aegypti after 48 hours of treatment.

Another evidence showed significant ovicidal activity can be observed through microscopy assessment. Ramkumar et al. (2019) revealed the morphological changes and abnormalities on *Culex quinquefasciatus* eggs viewed from fluorescence microscope. From the analysis, operculum and side wall of the eggshell was damaged after exposure to *Cipadessa baccifera* acetone plant extract leaving no chances for development into larvae and adults.

**Mode of Action of Plant-Based Mosquito Control**

As for the mode of action of plant-based mosquito control, four modes can typically be applied. Firstly, neurotoxicity explains when plant-based insecticides target the mosquito's nervous system. This mode is considered fast and direct, as the nervous system is important in coordinating all the body's functions. In this case, plant-based insecticides that rely upon neurotoxicity modes are known as neurotoxic insecticides. Different strategies of neurotoxic insecticides: Some agents can disrupt neurohormonal regulation, such as Azadirachtin against juvenile, ecdysone, and prothoracicotropic hormones. Others can block gamma- aminobutyric acid (GABA) receptors by being GABA receptor antagonists, which eventually leads to severe neuronal disruption and death. Eugenol in clove (Syzygium aromaticum) is shown to exert this strategy by blocking GABA-gated chloride channels, preventing chloride ion flow preventing neurons from becoming hyperpolarized. It also lowers the threshold for neuronal activation, causing an increase in the generation of action potentials. In addition, disruption of octamine (OA) receptors also contributed to the strategy of neurotoxicity. OA carries responsibilities in regulating mosquito biological processes, physiological functions, and behavioral patterns (Li et al., 2017). The disruption explains when the receptor is blocked or overstimulated by typically monoterpenes in plant agents, which will interfere with mosquito fitness capacity (Finetti et al., 2023).

Secondly, plant-based mosquito control is effective for the disruption of mosquito growth and development. With this strategy, one can focus on larvicidal because the development of instars is prolonged to observe the biological effect of plant agents between the egg and pupa stages. However, it is undeniable that all stages of mosquito growth offer great opportunities to be attacked. Chitin, one of the essential components of mosquito cuticle, is susceptible to being targeted by the plant insecticides. The cuticle is the outermost layer, associated with an inner epidermal monolayer, known as integument. For proper growth and development post-hatching, mosquitoes undergo periodic molting. This process starts with apolysis, the separation of the old cuticle, followed by the formation of a new cuticle, and concludes with ecdysis, the shedding of the old cuticle (Rezende et al., 2008; Snodgrass, 1959). The molting process in mosquitoes is intricately linked to the synthesis and breakdown of chitin, a key polysaccharide made up of N-acetylglucosamine units, which is a major component of the mosquito cuticle (Farnesi et al., 2012). The molting process is important for mosquito early development, and it is facilitated by an enzyme called chitinase. Gurunathan et al. (2016) successfully showed that the anticipated biological activity of oleic acid and eicosyl ester isolated from *Thalictrum javanicum* revealed its potential larvicidal effects against Aedes aegypti and Culex quinquefasciatus, as the chitinase and ecdysone 20- monooxygenase activity resulted in reduction.

Thirdly, plant-based mosquitocidal can impact mosquito behavioral deterrence by becoming antifeedant due to the presence of compounds that deter vectors from feeding. The success of deterrence does not necessarily rely on the complete elimination of mosquitoes but at least reduces their food intake. To observe, the weight of mosquito larvae can be determined after being treated with plant extract (Sharma et al., 1983). Mosquito feeding behavior is controlled by neural signals from taste receptors on various body parts. These receptors detect chemical cues and transmit information to the central nervous system, which processes these signals to guide feeding decisions. The integration and specialization of taste neurons play a crucial role in determining feeding preferences (Nisbet, 2000). The antifeedant effects observed in these species are closely associated with the sensory reactions of chemoreceptors located on their mouthparts.

Finally, reproductive inhibition by plant-based agents can be assessed in a few ways. One of them is the oviposition rate by the gravid female mosquito or pregnant mosquito. Plant parts of *Azadirachta indica* have the potential active constituents of being the oviposition deterrent against mosquitoes, including the seed kernels (Elhag, 1999 as cited by Shaalan & Canyon, 2018), leaves (Fatima et al., 2011), and the seed (Benelli et al., 2014; Benelli et al., 2015). However, other plant parts such as stems, fruits, rhizomes, flowers, or roots also contain compounds that are potentially for oviposition deterrence. Gravid mosquitoes utilize their visual, olfactory, and tactile cues for locating favourable oviposition sites (Bentley & Day, 1989). At this moment, the strong scents from plant-based repellent can interfere during then selection period due to the volatility of crude extract, delaying and discouraging the egg-laying process. In addition, to assess the effectiveness of egg-laying stimulants (plant extracts) oviposition engagement index (OEI) is applied. It is a quantitative method used to evaluate the egg-laying preference of gravid female mosquitoes under different conditions. It helps to understand how certain substances or environmental factors affect their selection. According to an oviposition deterrence assay carried out by Prathibha et al. (2014), they examined the gravid mosquitoes of three different species, *A. stephensi*, *A. aegypti*, and *C. quinquefasciatus*, chose to lay eggs in the control cups more often than in the test cups of *S. mauritiana*, *S. canadensis*, *E. ridleyi*, and *E. jambolana* treatment. The highest OEI obtained after the experiment was by *S. mauritiana*, which exhibited −0.20 repellency value, followed and the least obtained was −0.01 by *E. jambolana*. The more negative the repellency value, the stronger the avoidance of the test condition.

**Challenges and Limitations**

Although plant-based mosquito control provides an environmentally friendly alternative to chemical insecticides, it faces various challenges and limitations. Firstly, plant extracts can take account for variability due to the differences in plant species, growing conditions, extraction methods, solvent selection and target species. The factors will affect in plant extract efficacy. For instance, polar solvents like water, tend to have high plant extract yield for hydrophilic compounds compared to non-polar solvents which capable of dissolving lipophilic compounds more (Nawaz et al., 2020). Thus, polar solvents yield broader range of compounds compared to non-polar solvent. However, isolation of lipid-based compound can be highly effective by using nonpolar solvents. Even for the extraction methods can differ in plant extract total yield due to adverse degradation effect from heat applied. Secondly, plant-based insecticide is lacking standardized formulations. This encountered challenge is incomparable to the synthetic insecticide. Before a large-scale production, a standard formulation is crucial to ensure batch-to-batch consistency and reliability. However, factors such as growth habitats, plant varieties, harvest timing, extraction techniques, storage conditions and regulator approval importantly influence the making of standard dosage insecticide. Ongoing efforts to improve the identification of effective phytochemicals and their concentrations in final products remain challenging due to difficulties in achieving precision and standardization. Thirdly, stability and shelf-life factors should be considered too. Many plant-based compounds encounter degradation quickly when exposed to sunlight, air, or water. Optimization of stability and shelf-life of plant extracts must consider some factors including extraction method, purity level, pH and chemical adjustment, moisture content and drying methods, storage conditions, preservatives & stabilizers, microbial & oxidative protection and regular quality control and testing (Postružnik et al., 2024; Gafner & Bergeron, 2005; Green Sky Bio, 2023; Ansari et al., 2024; Plant Extract Wholesale, 2024). Despite the eco-friendly nature of plant-based insecticides, their widespread acceptance faces several challenges in context of regulatory and commercialization. This could be due to some perspectives of having balanced skepticism, especially in the low-income nations, on plant-based mosquitocidal. Gaining trust in scientific validation is not easy for all society. Moreover, variations of plant are not commercially available in all countries; hence, cross-border operation is acquired. According to the government agency in Malaysia, Malaysian Department of Agriculture (DOA) (1976), Plant Quarantine Act 1976 was established to regulate the import, export, plant products and related materials to eliminate the spread of pest's diseases. Malaysian DOA is also responsible to restrict movement of plants within

Malaysia to prevent disease outbreaks; hence, the plants from other countries unable to simply import to Malaysia. This could be one of the hurdles for commercializing the novel plant-based insecticides approaches. However, it is essential to recognize that prohibitions and restrictions exist to safeguard public safety, protect the environment, and uphold societal standards.

## Conclusion and Recommendations

The field of plant-based insecticides for targeting effective mosquito control offers wide opportunities for exploration and holds great potential due to the plants characters of biodegradability, exhibits lower toxicity, eco-friendly and sustainable. The most highlighted criteria, sustainable and eco-friendly, brings environmental protection and economic benefits in such having the potential to conserve natural sources, reduce enviromental pollution from chemical cues and for the renewable energy. Aiming for the earliest stages of mosquitoes' life history able to begin the reduction of mosquitoe-diseases transmission and outbreaks. Although limitations have accompanied along the journey of exploration including variability, accessibility, regulations, and social acceptance, this review proposes recommendations as follows:

i. Formulate advances in nano-formulations for plant-based mosquito control by optimizing nanoformulation techniques such as nanoemulsification and encapsulation.
ii. Conduct an in-depth analysis for synergistic effects of plant extracts with synthetic or biological agents to increase bioavailability and enhance multiple target actions within synergists.
iii. Implement an integration of plant-based solution into mosquito management programs in the community to reach an adaptive and scalable for each region's settings; additionally, to reduce the tendency of resistance.

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