

Research Insight

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Evaluation of Plant-Based Extracts for the Control of *Anopheles gambiae* Mosquitoes under Laboratory Conditions

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Abstract *Anopheles gambiae* is one of the principal vectors of malaria and remains a major target in mosquito control programs. However, the widespread development of insecticide resistance has reduced the effectiveness of conventional chemical interventions, creating an urgent need for alternative control agents. This review summarizes laboratory-based evaluations of plant extracts for the control of *A. gambiae*, with emphasis on their larvicidal, adulticidal, and repellent activities. It also examines the chemical composition of these extracts, including the identification of major bioactive compounds, and discusses their possible mechanisms of action at physiological, enzymatic, and cellular levels. In addition, the review considers safety issues, such as toxicity to non-target organisms and environmental persistence, and compares plant-derived products with synthetic insecticides. Overall, plant extracts show considerable promise as eco-friendly and sustainable tools for mosquito management, although further studies are needed to standardize formulations and validate their field efficacy.

Keywords *Anopheles gambiae*; Plant extracts; Mosquito control; Larvicidal activity; Insecticide resistance

1 Introduction

Anopheles gambiae mosquitoes are the primary vectors responsible for malaria transmission in sub-Saharan Africa, where the disease remains a major public health challenge. Their capacity to transmit Plasmodium parasites is influenced by factors such as their abundance, biting behavior, and longevity, which enable effective parasite development and spread among human populations. Understanding the biology and ecology of *An. gambiae* is crucial for developing targeted interventions to reduce malaria incidence, as these mosquitoes predominantly feed indoors at night and breed in aquatic habitats, making them accessible to control measures (Takken et al., 2024; Simoni et al., 2025).

Current mosquito control strategies largely rely on synthetic insecticides applied through insecticide-treated nets (ITNs) and indoor residual spraying (IRS). While these methods have significantly reduced malaria burden, their effectiveness is increasingly compromised by the rapid emergence of insecticide resistance in *An. gambiae* populations, as well as behavioral adaptations that reduce mosquito contact with treated surfaces. Additionally, concerns about environmental toxicity and sustainability highlight the limitations of chemical-based approaches, necessitating alternative or complementary vector control tools that can overcome resistance and minimize ecological impact (Paton et al., 2022; Simoni et al., 2025).

Plant-based extracts have gained attention as promising alternative agents for controlling *An. gambiae* due to their eco-friendly nature and diverse bioactive compounds with repellent, larvicidal, and adulticidal properties. Various studies have demonstrated that essential oils and phytochemicals from plants such as *Croton macrostachyus*, *Cymbopogon* species, *Azadirachta indica*, and *Ocimum* spp. exhibit significant efficacy against different life stages of *An. gambiae* under laboratory conditions. These natural products offer potential advantages including reduced risk of resistance development and lower environmental toxicity, positioning them as valuable candidates for integrated malaria vector management strategies (Lamuntani et al., 2025; Tadesse et al., 2025).

2 Materials and Methods

2.1 Source of plant materials and extraction procedures

Plant materials used for this study were collected from local sources, ensuring freshness and proper identification before extraction. The extraction process involved selecting appropriate solvents based on the polarity of target bioactive compounds, commonly including polar solvents such as methanol or ethanol, which are effective in extracting a wide range of phytochemicals. Extraction methods such as maceration and Soxhlet extraction were employed to maximize yield; maceration involves soaking plant material in solvent at room temperature for extended periods, while Soxhlet extraction uses continuous solvent reflux to enhance compound recovery. These methods have been widely used in mosquito control research due to their efficiency in isolating larvicidal and adulticidal compounds from plants (Figure 1) (Ravi et al., 2018; Abubakar and Haque, 2020).



Figure 1 Morphological midgut content induced by *Azolla pinnata* plant extract from soxhlet extraction method in larvae of *Ae. Aegypti* (Adopted from Ravi et al., 2018)

Image caption: (A) Control test for midgut content view in early 4th instar larvae of *Ae. Aegypti* (B) *A. pinnata* crude extract for midgut content view in larvae of *Ae. Aegypti*. Arrows indicating the plant extracts (greenish colour), GC: gut content (after 24hours) (Adopted from Ravi et al., 2018)

Following extraction, crude extracts were concentrated under reduced pressure using rotary evaporation to remove solvents without degrading active constituents. The chemical composition of extracts was characterized using chromatographic techniques like gas chromatography-mass spectrometry (GC-MS) to identify major phytochemicals responsible for insecticidal activity. Such characterization is essential for understanding the bioactive profile and guiding further bioassays. Quality control measures included standardizing extract concentrations and storing samples at low temperatures to preserve stability prior to testing (Abutaha and Al-Mekhlafi, 2020; Hafsi et al., 2022).

2.2 Origin of experimental mosquitoes and laboratory rearing conditions

Experimental *Anopheles gambiae* mosquitoes were obtained from established laboratory colonies maintained under controlled environmental conditions to ensure uniformity in age, physiological status, and genetic background. Colonies were typically reared at temperatures between 25-28°C with relative humidity around 70-80%, simulating natural tropical environments conducive for mosquito development. Photoperiods were maintained on a 12:12 hour light-dark cycle to regulate circadian rhythms affecting mosquito behavior and physiology (Ahamd et al., 2023; Dutta and Dey, 2023).

Larvae were fed standardized diets such as finely ground fish food or yeast suspensions to promote consistent growth rates, while adult mosquitoes were provided with sugar solutions for sustenance and periodic blood meals when necessary for egg production. Rearing containers were regularly cleaned to prevent microbial contamination that could affect mosquito health or experimental outcomes. These controlled rearing protocols ensured that test mosquitoes exhibited normal development and behavior suitable for reliable bioassay results (Priya and Jones, 2021; Dutta and Dey, 2023).

2.3 Bioassay methods and experimental design

Bioassays followed standardized World Health Organization (WHO) protocols adapted for evaluating larvicidal and adulticidal effects of plant extracts against *Anopheles gambiae*. Larval bioassays involved exposing early fourth instar larvae to various concentrations of plant extracts diluted in water, with mortality recorded after 24 hours of exposure. Control groups received solvent only to account for any non-specific effects. Concentration-mortality data were analyzed using probit analysis to determine lethal concentration values (LC50 and LC90), indicating the potency of each extract (Ravi et al., 2018; Pavela et al., 2019).

Adulticidal assays entailed topical application or exposure of adult mosquitoes to treated surfaces impregnated with plant extracts, monitoring knockdown rates and mortality over specified time intervals. Experimental designs incorporated replicates per treatment concentration alongside controls to ensure statistical robustness. Additionally, sub-lethal effects such as behavioral changes or reproductive impairments were observed where applicable. This comprehensive approach allowed assessment not only of acute toxicity but also potential impacts on mosquito population dynamics relevant for vector control strategies (Hafsi et al., 2022; Dutta and Dey, 2023).

3 Chemical Composition Analysis of Plant Extracts

3.1 Determination of physicochemical properties of extracts

The physicochemical properties of plant extracts are fundamental for understanding their stability, solubility, and bioactivity, which influence their efficacy as mosquito control agents. Parameters such as pH, viscosity, density, and refractive index are commonly measured to characterize the extracts and ensure consistency across batches. These properties can affect the interaction of bioactive compounds with mosquito targets and their formulation into usable products. For example, pH can influence the ionization state of active molecules, altering their penetration or binding affinity (Godlewska et al., 2023; Zhang et al., 2023).

Additionally, preliminary qualitative tests such as colorimetric assays help identify classes of phytochemicals present in the extracts, including phenols, flavonoids, alkaloids, tannins, and saponins. These compounds often contribute to insecticidal activity through various mechanisms like enzyme inhibition or membrane disruption. Rapid screening methods provide an initial profile that guides more detailed chemical analyses and bioassays. Maintaining standardized physicochemical characteristics is essential for reproducibility in experimental evaluations and potential field applications (Heinrich et al., 2022; Godlewska et al., 2023).

3.2 Identification of active components

Gas chromatography-mass spectrometry (GC-MS) is a widely used analytical technique for identifying volatile and semi-volatile compounds in plant extracts. It separates complex mixtures into individual constituents based on their retention times and mass spectra, allowing precise identification by comparison with spectral libraries. GC-MS analysis typically reveals a diverse array of bioactive molecules such as terpenes, hydrocarbons, alcohols, esters, and fatty acids that may contribute to larvicidal or adulticidal effects against *Anopheles gambiae* (Khdera and Saad, 2024; Dhanaraj et al., 2025).

High-performance liquid chromatography (HPLC) complements GC-MS by enabling the separation and quantification of non-volatile or thermally labile compounds like polyphenols, flavonoids, and alkaloids. Coupled with detectors such as UV-Vis or mass spectrometry (LC-MS), HPLC provides detailed profiles of major phytochemicals responsible for biological activity. Combining these chromatographic techniques ensures comprehensive characterization of plant extracts' chemical composition critical for correlating specific compounds with observed insecticidal properties (Figure 2) (Heinrich et al., 2022; Hodoşan et al., 2025).

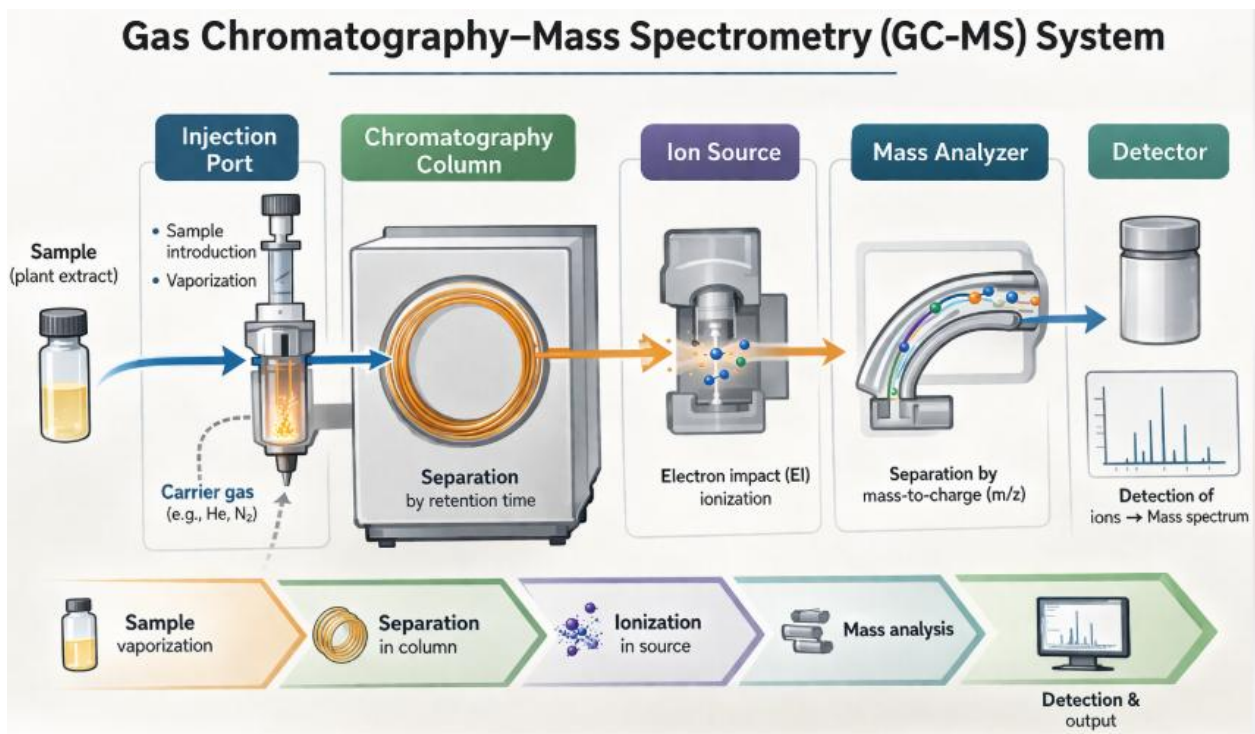


Figure 2 Schematic diagram of the gas chromatography-mass spectrometry (GC-MS) system illustrating sample injection, chromatographic separation, and mass spectral detection. Adapted from general analytical instrumentation principles

3.3 Quantitative analysis of major active compounds

Quantitative determination of key bioactive constituents is essential to standardize plant extracts and evaluate dose-dependent effects on mosquito populations. Techniques such as calibration curve-based HPLC quantification allow accurate measurement of major phenolic acids, flavonoids, or terpenoids known for insecticidal or repellent activities. This quantitative data supports reproducibility in bioassays and facilitates comparisons between different plant species or extraction methods (Dhanaraj et al., 2025; Hodoşan et al., 2025).

Furthermore, advanced mass spectrometry methods including high-resolution MS enable precise quantification even in complex mixtures at low concentrations. Such analyses help identify marker compounds that can serve as quality control indicators during extract production. Understanding the concentration ranges of active components also informs formulation strategies to optimize efficacy while minimizing potential toxicity to non-target organisms or the environment (Heinrich et al., 2022; Kapadia et al., 2022).

4 Larvicidal Activity of Plant Extracts against *Anopheles gambiae*

4.1 Mortality rates under different concentration treatments

The larvicidal efficacy of various plant extracts against *Anopheles gambiae* larvae generally exhibits a clear dose-dependent relationship, with higher concentrations producing increased mortality rates. For instance, methanol crude extracts of *Croton macrostachyus* achieved 100% mortality at 400 ppm, while lower concentrations showed proportionally reduced effects, demonstrating strong larvicidal potential (Tadesse et al., 2025). Similarly, ethanol leaf extracts from *Azadirachta indica*, *Carica papaya*, and *Annona muricata* caused significant larval mortality, with complete mortality observed at concentrations above 10% for *A. indica* and *C. papaya* and above 5% for *A. muricata* (Ekpo et al., 2025).

Other studies confirm this trend across different plant species and extraction methods; for example, methanol leaf extracts of *Ocimum gratissimum* and *Cymbopogon citratus* showed high larvicidal activity with mortality rates reaching up to 100% at the highest tested concentrations (1 000 ppm) after 72 hours exposure (Opoggen et al., 2019). These findings underscore the importance of optimizing extract concentration to maximize larvicidal effects while considering practical application limits in vector control programs (Okbatinsae and Haile, 2017).

4.2 Determination of lethal concentrations (LC50, LC90)

Lethal concentration values such as LC50 and LC90 are critical metrics for quantifying the potency of plant extracts against mosquito larvae. The ethyl acetate fraction of *Croton macrostachyus* exhibited an LC50 of 38.60 ppm and an LC90 of approximately 100 ppm against *Anopheles gambiae* larvae, indicating high efficacy compared to other tested plants (Tadesse et al., 2025). Hexane extracts from *Abutilon bidentatum* also demonstrated potent larvicidal activity with an LC50 value of 40.77 ppm and an LC90 value near 100.54 ppm under semi-field conditions (Muhammed et al., 2024).

In addition, hexane extracts of *Lantana camara* showed remarkable toxicity with an LC50 value as low as 20.19 ppm and an LC90 around 49.29 ppm against local strains of *Anopheles gambiae* larvae (Wangrawa et al., 2016). These quantitative assessments provide essential benchmarks for comparing bioactivity across different plant species and extraction solvents, guiding selection for further development as biopesticides.

4.3 Analysis of time-dose response relationships

Time-dose response studies reveal that both exposure duration and extract concentration significantly influence larval mortality outcomes. For example, methanol extracts from *Momordica foetida*, *Gnidia glauca*, and *Vepris soyauxii* showed increasing mortality rates over time, with LC50 values decreasing after 48 hours compared to 24-hour exposures, indicating enhanced toxicity with prolonged contact (Njuabe et al., 2022). This temporal effect is important for understanding how quickly plant-based larvicides act in practical settings.

Similarly, ethanol extracts from several plants demonstrated higher larval mortality after extended exposure periods; *Jatropha curcas* and *Ricinus communis* ethanol extracts reached near-complete mortality only after 48 hours at high concentrations (1000 ppm) (Okbatinsae and Haile, 2017). These findings highlight the necessity to consider both dose and exposure time when evaluating the effectiveness of plant-derived larvicides to optimize their use in integrated vector management strategies.

5 Effects of Plant Extracts on Adult Mosquitoes

5.1 Evaluation of contact toxicity and repellency

Plant extracts have demonstrated significant contact toxicity against adult *Anopheles gambiae* mosquitoes, with some extracts achieving high mortality rates at relatively low concentrations. For example, methanol crude extracts of *Croton macrostachyus* showed strong adulticidal activity, reaching 100% mortality at 400 ppm and exhibiting LC50 and LC90 values of 55.32 ppm and 86.77 ppm, respectively (Tadesse et al., 2025). Similarly, essential oils from plants such as *Cymbopogon winterianus*, *Cinnamomum zeylanicum*, and *Thymus vulgaris* exhibited combined repellent, irritant, and toxic effects on adult mosquitoes, suggesting multiple modes of action that could reduce mosquito-human contact effectively (Delétré et al., 2013).

Repellency studies further support the potential of plant extracts as alternatives to synthetic insecticides. Extracts from *Eclipta alba* and *Andrographis paniculata* provided dose-dependent protection against mosquito bites without causing allergic reactions in human subjects, indicating their suitability for topical application (Govindarajan and Sivakumar, 2011). Additionally, ethanolic extracts of *Cymbopogon citratus* and *Ocimum basilicum* leaves showed effective repellency against *Culex quinquefasciatus* adults, with *Cymbopogon citratus* demonstrating superior efficacy (Aïzoun et al., 2025). These findings highlight the dual utility of plant extracts in both killing and deterring adult mosquitoes.

5.2 Effects on adult survival rate and longevity

Exposure to certain plant extracts significantly reduces the survival rate and longevity of adult *Anopheles* mosquitoes. For instance, aqueous leaf extracts of *Zehneria scabra* caused notable adult mortality with an LC50 value of 176.20 ppm against *Anopheles stephensi* adults after 24 hours exposure (Muhammed et al., 2022). Similarly, methanol extracts of *Azadirachta indica* achieved 75% adult mortality at 300 ppm against *Anopheles arabiensis*, indicating substantial impact on adult survival (Ejeta et al., 2021). These reductions in lifespan can decrease the likelihood of disease transmission by shortening the period during which mosquitoes remain infectious.

Histopathological studies reveal that some plant-derived compounds induce physiological damage in adult mosquitoes that likely contributes to reduced longevity. Essential oils from *Ageratum conyzoides* caused degeneration in compound eyes, muscular tissues, gut epithelium, *Malpighian tubules*, and ovarian cells in *Aedes aegypti* adults (Pintong et al., 2020). Such tissue damage impairs vital functions including feeding and reproduction, thereby limiting mosquito population growth over time. This evidence supports the use of botanical insecticides not only for immediate toxicity but also for long-term vector control through lifespan reduction (Figure 3).

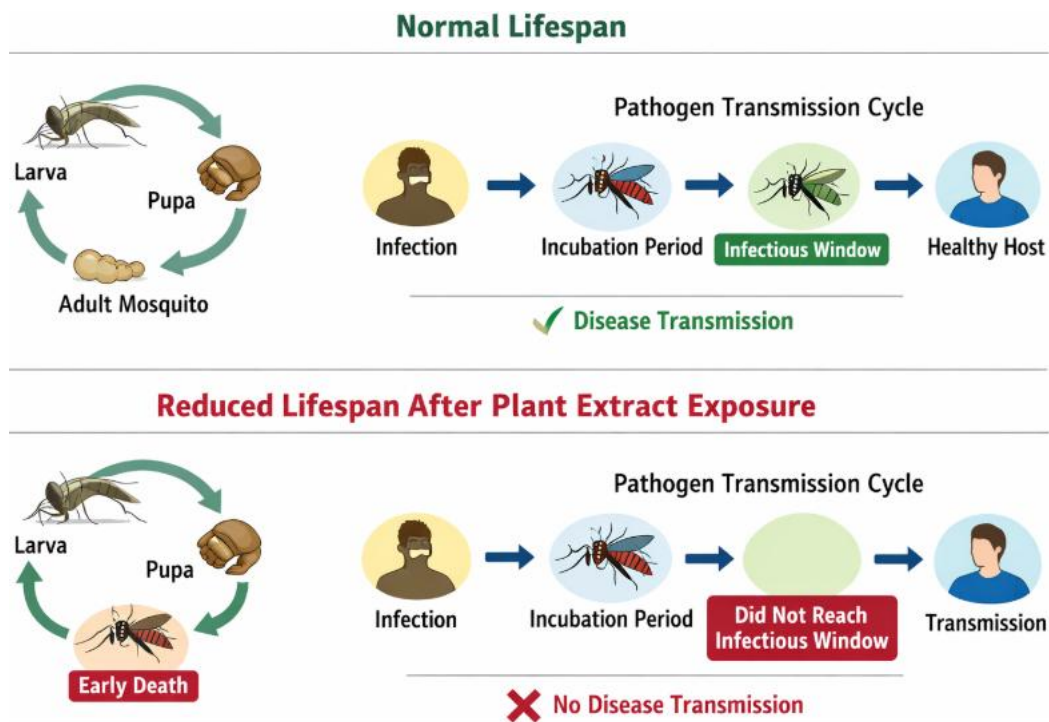


Figure 3 Conceptual diagram illustrating how reduced adult mosquito lifespan limits the transmission potential of malaria parasites by shortening the infectious period

5.3 Effects on blood-feeding behavior and reproductive capacity

Plant extracts can alter blood-feeding behavior in adult mosquitoes by acting as repellents or irritants that reduce host-seeking activity. The irritant and repellent effects observed with essential oils from *Cymbopogon winterianus* and *Thymus vulgaris* suggest disruption of normal feeding patterns in *Anopheles gambiae* adults (Delétré et al., 2013). By decreasing successful blood meals, these extracts may lower pathogen transmission rates indirectly through behavioral modification rather than direct toxicity alone.

Moreover, some botanical compounds negatively affect reproductive capacity by causing ovarian degeneration or reducing egg production. Histopathological alterations induced by *Ageratum conyzoides* essential oils included ovarian cell degeneration in *Aedes aegypti* females (Pintong et al., 2020), which likely translates into decreased fecundity. Although detailed quantitative data on reproductive inhibition are limited for *Anopheles* species specifically, these findings indicate that plant-based products may impair mosquito population growth through multiple physiological pathways beyond immediate lethality.

6 Mechanism of Action Analysis

6.1 Effects on the nervous system

Plant extracts exert significant neurotoxic effects on mosquitoes, primarily targeting their nervous system to disrupt normal physiological functions. Many secondary metabolites found in these extracts, such as alkaloids, flavonoids, and terpenoids, interfere with nerve impulse transmission by affecting ion channels and neurotransmitter receptors, leading to paralysis and death of mosquito larvae and adults (Pavela et al., 2019;

Senthil-Nathan, 2020). Essential oils from various plants have been shown to cause neuroexcitation or inhibition by modulating acetylcholine receptors and other neural targets, which impairs mosquito motor functions and feeding behavior (Duque et al., 2023).

In addition to direct neurotoxicity, some plant compounds disrupt mitochondrial function within nerve cells by inhibiting electron transport chain enzymes, thereby reducing ATP production essential for nerve signal propagation (Duque et al., 2023). This dual action on both synaptic transmission and cellular energy metabolism enhances the overall insecticidal efficacy of botanical extracts. Such neurotoxic mechanisms are crucial for developing plant-based insecticides that can overcome resistance issues associated with synthetic chemicals.

6.2 Inhibition of key enzyme activities

A major mode of action for many plant-derived insecticides involves the inhibition of acetylcholinesterase (AChE), an enzyme critical for terminating nerve impulses by hydrolyzing the neurotransmitter acetylcholine. Several studies have demonstrated that essential oils and phytochemicals bind to AChE active sites, preventing its function and causing accumulation of acetylcholine at synapses, which results in continuous nerve stimulation and eventual paralysis of mosquitoes (Duque et al., 2023; Montaña-Campaz et al., 2025). Molecular docking analyses support these findings by showing stable interactions between plant compounds such as γ -elemene and germacrene D with mosquito AChE enzymes (Montaña-Campaz et al., 2025).

Beyond AChE inhibition, other enzymes involved in detoxification processes like glutathione S-transferase and cytochrome P450 monooxygenases are also targeted by certain plant extracts, impairing the mosquito's ability to metabolize toxic substances (Pavela et al., 2019; Senthil-Nathan, 2020). This multi-enzyme inhibition not only increases toxicity but may also reduce the development of resistance by attacking several biochemical pathways simultaneously.

6.3 Toxicological effects at cellular and tissue levels

At the cellular level, plant extracts induce a range of toxic effects including disruption of cell membranes, oxidative stress, and damage to vital organelles such as mitochondria. These effects compromise cell integrity and function in mosquito larvae and adults (Pavela et al., 2019; Baz et al., 2024). Histopathological examinations reveal degeneration in tissues critical for survival such as midgut epithelium, *Malpighian tubules*, muscles, and reproductive organs following exposure to botanical insecticides (Baz et al., 2024).

Such tissue-level damage impairs digestion, excretion, locomotion, and reproduction in mosquitoes, contributing to reduced population growth beyond immediate mortality effects. For example, essential oils from *Ageratum conyzoides* caused ovarian cell degeneration in adult mosquitoes alongside gut epithelial damage (Baz et al., 2024), indicating that botanical extracts can exert prolonged sublethal impacts that affect vector capacity. These multifaceted toxicological actions highlight the potential of plant-based products as effective tools for integrated mosquito management.

7 Safety and Environmental Impact Assessment

7.1 Toxicity evaluation on non-target organisms

Plant-based extracts used for mosquito control generally exhibit lower toxicity to non-target organisms compared to synthetic insecticides, making them safer alternatives in integrated vector management. Studies have shown that many botanical insecticides, including neem oil and various essential oils, are target-specific and biodegradable, causing minimal harm to beneficial insects, aquatic organisms, and mammals (Demirak and Canpolat, 2022; Chatterjee et al., 2023). For example, methanolic extracts from certain plants demonstrated larvicidal activity against mosquitoes while showing weak or no toxicity in zebrafish embryos, a common model for assessing environmental safety (Figure 4) (Alqurashi et al., 2025). This selective toxicity is attributed to the complex mixtures of bioactive compounds in plant extracts that often act on specific mosquito physiological pathways without broadly affecting other species.

Despite their relative safety, some plant extracts can still pose risks if used improperly or at high concentrations. Therefore, thorough ecotoxicological assessments are necessary before large-scale application to ensure non-target species such as pollinators, aquatic invertebrates, and vertebrates remain unharmed (Pavela et al., 2019; Hillary et al., 2024). The rapid biodegradability of many plant compounds also reduces the risk of bioaccumulation and long-term environmental persistence. Overall, current evidence supports the use of plant-based products as environmentally friendly mosquito control agents with a favorable safety profile for non-target organisms.

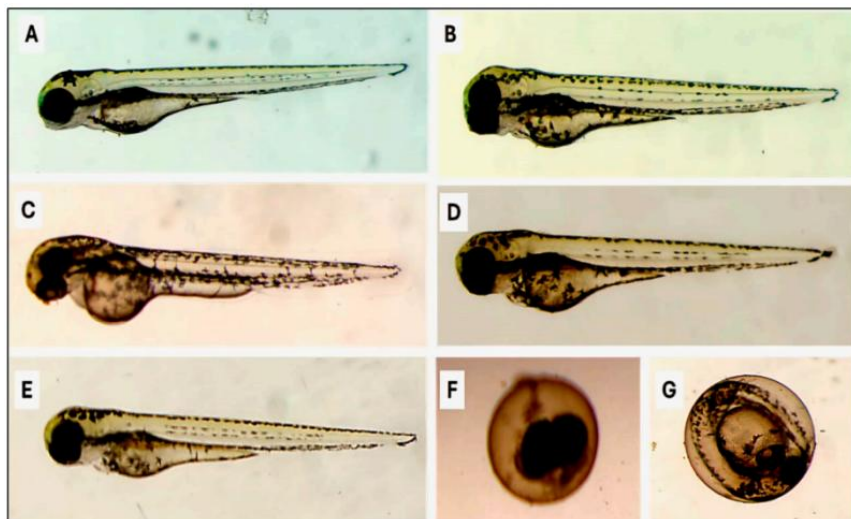


Figure 4 Biosafety evaluation of *H. erectus* in the zebrafish embryos. Representative micrographs of the zebrafish embryos at 3 days post-fertilization were treated with the crude methanolic extract of the marine sponge *H. erectus* and its various fractions. The embryos treated with the crude methanolic extract (B), as well as the n-hexane (<25 µL) (C), chloroform (D), and n-butanol (E) fractions, developed normally with no observable differences in morphology or growth compared to the control group (A). However, the embryos exposed to a higher concentration of n-hexane (>25 µL) showed complete lethality (F). Additionally, unhatched embryos were also observed in some treatments (G) (Adopted from Alqurashi et al., 2025)

7.2 Environmental degradation and residue characteristics of plant extracts

Plant-derived insecticidal compounds typically degrade more rapidly in the environment than conventional chemical insecticides, resulting in lower residual toxicity and reduced ecological impact. Many phytochemicals such as terpenoids, flavonoids, and alkaloids are naturally biodegradable under sunlight and microbial action, which limits their persistence in soil and water bodies (Pavela et al., 2019; Hillary et al., 2024). This rapid degradation helps prevent contamination of aquatic ecosystems and reduces the likelihood of adverse effects on non-target organisms over time.

However, some formulations like neem oil may face challenges related to stability under atmospheric conditions; direct application can lead to quick disintegration reducing efficacy (Chatterjee et al., 2023). Advances in formulation technologies such as nanoemulsions or encapsulation have been developed to enhance stability and prolong residual activity while maintaining environmental safety. These improved formulations balance effective mosquito control with minimal environmental footprint by controlling release rates and protecting active ingredients from rapid degradation.

7.3 Comparison with conventional chemical insecticides

Compared to synthetic chemical insecticides like organophosphates and pyrethroids, plant-based extracts offer several advantages including reduced toxicity to humans and wildlife, lower environmental persistence, and decreased risk of resistance development in mosquito populations (Demirak and Canpolat, 2022; Hillary et al., 2024). Synthetic chemicals often cause pollution through bio-magnification and have been linked to health issues such as neurotoxicity and skin irritation in humans (Hillary et al., 2024). In contrast, botanical insecticides tend to be safer due to their natural origin and complex mixtures of active compounds that reduce the chance of mosquitoes developing resistance.

Nevertheless, plant extracts sometimes exhibit lower immediate potency or shorter duration of action than conventional insecticides, which can limit their standalone effectiveness in some settings (Pavela et al., 2019; Ahamd et al., 2023). Combining botanical products with other control methods or improving formulations can help overcome these limitations while preserving their eco-friendly benefits. Overall, plant-based mosquito control agents represent promising alternatives or complements to chemical insecticides by offering effective vector management with fewer environmental and health risks.

8 Discussion and Conclusion

The experimental evaluation of plant-based extracts against *Anopheles gambiae* mosquitoes demonstrated significant larvicidal and adulticidal activities, confirming the potential of botanical compounds as effective mosquito control agents. Extracts from plants such as *Parthenium hysterophorus* and *Nicotiana tabacum* showed high toxicity with low LC50 values, indicating strong potency even at low concentrations. These findings align with broader literature reporting that secondary metabolites like alkaloids, terpenoids, and flavonoids disrupt mosquito physiology through multiple mechanisms including neurotoxicity and enzyme inhibition. The observed synergistic effects between different plant extracts or when combined with conventional insecticides further enhance their efficacy, suggesting opportunities for integrated approaches to overcome resistance issues. However, while laboratory results are promising, the translation to field conditions remains limited due to factors such as environmental degradation of active compounds and variability in mosquito populations. Stability challenges of some plant extracts under natural conditions can reduce residual activity, necessitating improved formulations or delivery systems to maintain effectiveness over time. Additionally, sublethal effects on mosquito development and reproduction observed in some studies indicate that botanical extracts may contribute to population suppression beyond immediate mortality, which is important for sustainable vector control strategies.

Plant-based extracts offer a valuable alternative or complement to synthetic insecticides due to their biodegradability, lower toxicity to non-target organisms, and reduced risk of resistance development in mosquitoes. Their broad-spectrum activity against various mosquito life stages-including larvae, pupae, and adults-makes them versatile tools for integrated vector management programs. Moreover, the availability of many effective plants locally supports cost-effective production and use in endemic regions where resources are limited. Advances in formulation technologies such as nanoencapsulation and synergistic blends have improved stability and potency, enhancing field applicability. Despite these advantages, challenges remain for large-scale implementation including standardization of extract composition, regulatory approval processes, and ensuring consistent efficacy across diverse ecological settings. Field validation studies are urgently needed to assess epidemiological impacts and optimize application protocols. Combining plant-based products with other control measures like insecticide-treated nets or biological agents could maximize overall effectiveness while minimizing environmental impact. Thus, plant extracts hold considerable promise as eco-friendly components of sustainable mosquito control strategies.

This study's primary limitation lies in its laboratory-based design which may not fully capture the complexities encountered under field conditions such as environmental variability and interactions with other biotic factors. The stability and persistence of active compounds in natural habitats require further investigation to ensure practical utility. Additionally, the potential development of resistance against botanical insecticides has not been extensively studied and warrants long-term monitoring. Future research should focus on large-scale field trials to validate laboratory findings and evaluate the epidemiological benefits of plant-based interventions. Exploring synergistic combinations among different plant extracts or with conventional insecticides could improve efficacy while reducing doses required. Advances in formulation science aimed at enhancing stability, controlled release, and target specificity will be critical for successful deployment. Finally, comprehensive safety assessments on non-target organisms and environmental fate studies must accompany efficacy evaluations to support regulatory approval and public acceptance.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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