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An Evaluation of the Effectiveness of Green Synthesis of Silver Nanoparticles with Plant Extracts Against Mosquito Vectors: A Review

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ABSTRACT: Mosquito-borne diseases remain a critical global public health concern, exacerbated by escalating insecticide resistance, rapid urbanization, and climate-driven alterations in mosquito ecology. Conventional chemical larvicides, though historically effective, have contributed to widespread environmental contamination and resistance in vector populations, underscoring the need for safer, sustainable control tools. In response, plant-derived larvicides and green-synthesized nanoparticles have emerged as promising alternatives due to their biodegradability, eco-compatibility, and multi-target modes of action. This review outlines the historical progression of mosquito control from synthetic larvicides to plant-based and nano-enabled strategies, with particular focus on phytochemicals and plant-mediated silver nanoparticles (AgNPs) as next-generation vector control agents. Green synthesis of AgNPs harnesses phytochemical constituents of plant extracts as reducing, stabilizing, and capping agents, thereby minimizing the use of hazardous reagents and rendering the process environmentally benign. The formation, size, and morphology of these AgNPs are routinely confirmed using techniques such as UV–Vis spectroscopy, X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Accumulating evidence indicates that herbal AgNPs possess potent larvicidal activity, mediated through structural disruption of larval tissues, overproduction of reactive oxygen species, damage to midgut epithelial cells, and interference with key physiological and reproductive pathways. Reported mechanisms further include alterations in larval morphology, perturbation of biochemical profiles, and midgut-targeted toxicity leading to impaired development and survival. The article positions plant-based AgNPs as a potential paradigm shift in vector management, offering an ecologically sustainable alternative to conventional larvicides while highlighting critical knowledge gaps in toxicity profiling, formulation scalability, and field validation that must be addressed before operational deployment. Overall, the evidence supports the progressive integration of botanically synthesized nanoparticles into sustainable mosquito control programmes as part of integrated vector management frameworks. Over the years, mosquito control remains challenged by rising insecticide resistance, ecological risks of non-targeted impact of chemical larvicides, and climate-driven changes in vector ecology as mosquito is rapidly breeding due to conducive environment, undermining progress toward SDG 3, i.e., good health and wellbeing. Alternative environmental friendly benign option is plant-based larvicides and green-synthesized nanoparticles. It offers promising, environmentally compatible alternatives aligned with SDGs 13 (Climate Action) and 15 (Life on land); however, their adoption is limited by gaps in toxicity profiling, regulatory frameworks, scalable formulation, and field validation. Addressing these constraints is essential for integrating nano-enabled botanicals into climate-resilient and biodiversity-sensitive integrated vector management (IVM) strategies.

Keywords: Mosquito-borne diseases, Green-synthesized silver nanoparticles, Plant-based larvicides, Larvicidal mechanisms, Environmental sustainability, Integrated vector management.

INTRODUCTION

Mosquito-borne diseases are still among the most difficult public health problems worldwide that have been around for a long time, and these health issues are mostly found in tropical and subtropical regions. Over half of the global population is still in danger, and the pathogens spread by *Aedes*, *Anopheles*, and *Culex* mosquitoes are the main cause of diseases such as malaria, dengue, chikungunya, Zika virus disease, yellow fever, Japanese encephalitis, lymphatic filariasis, and West Nile fever (Bhatt *et al.*, 2013; World Health Organization 2023). The factors such as the escalation of international travel, rapid urbanisation, unplanned peri-urban growth, and climate-driven shifts in mosquito ecology have significantly influenced the disease transmission dynamics (Githeko *et al.,* 2000; Ryan *et al.,* 2019). Higher temperatures and changes in rainfall patterns are bringing mosquitoes to areas that have never been infected before; this is causing the vectors to proliferate at a faster rate and transmission seasons to be longer (Messina *et al.,* 2016; Mordecai *et al.,* 2019). As a result, the total global burden of mosquito-borne diseases has increased not only in scale but also in geographic distribution, indicating the urgent need for better and coordinated sustainable vector-management strategies.

Mosquito control measures that are traditional depend mostly on the use of synthetic chemical insecticides such as organophosphates, carbamates, pyrethroids, and insect growth regulators. Although these chemicals have been instrumental in reducing vector populations, a massive dependence on them for over 20 years in some areas has led to the emergence of insecticide resistance in vectors, which in turn has greatly hampered their operational effectiveness in endemic regions (Hemingway and Ranson 2000; Moyes *et al.,* 2017). In addition, an over-reliance on chemical insecticides has resulted in several potential problems, such as non-target toxicity, environmental persistence, bioaccumulation, and even a pollution-disrupting ecological balance, which most likely are the adverse effects on insects that serve as pollinators, aquatic organisms, and soil microflora (Nauen, 2007; Pavela, 2016). The high cost associated with repeated insecticide applications, operational and logistical challenges in implementing large-scale spraying programs, and increasing community resistance driven by concerns over human health and environmental safety have collectively limited the sustainability and effectiveness of conventional mosquito control interventions (Hemingway *et al.,* 2016; Moyes *et al.,* 2017; Rivero *et al.,* 2010), which to a great extent make vector control operations inefficient, are the main problems, next to these issues (van den Berg *et al.,* 2012). In summary, these drawbacks show the weaknesses of the current vector-control frameworks and point to the significant gaps that hinder the goal of long-term success.

To address the growing limitations of conventional mosquito control, increasing attention is being focused on the development of novel insecticide formulations that are safe, environmentally sustainable, socially acceptable, and compatible with integrated vector management frameworks. In this regard, plant-derived biopesticides, botanical larvicides, and green-synthesized nanoparticle formulations have gained substantial interest due to their biodegradability, low environmental persistence, phytochemical diversity, multiple and complementary modes of action, and reduced likelihood of resistance development when compared with synthetic insecticides (Govindarajan and Benelli 2016; Isman 2006; Mossa, 2016; Pavela 2015; Regnault-Roger *et al.,* 2012; Saikumar *et al.,* 2025; Singh *et al.,* 2016). Such nature-based methods can be highly effective in limited and targeted mosquito control, especially at the larval stage, so through such intervention cycles the transmission of diseases can be broken (Achee *et al.,* 2019). While global health organizations are supporting the necessity of mosquito management measures that are sustainable, community-based, and ecologically friendly, the finding and perfecting of environmentally friendly insecticide formulations is becoming more and more important (Velayudhan, 2021). This review paper is a contribution to the field who are working on emerging issues by the potential of non-polluting larvicidal agents that can deliver effective, scalable, and sustainable solutions.

CONVENTIONAL AND ALTERNATIVE MOSQUITO CONTROL STRATEGIES

A. Historical and Modern Larvicides

Mosquito larval control has evolved considerably since the early 20th century, beginning with the application of petroleum oils, Paris green, and rudimentary physical methods targeting stagnant water bodies (Becker *et al.,* 2010; Karunaratne and Surendran 2020). These early larvicides were widely applied due to their immediate effectiveness but were later found to be environmentally persistent and harmful to non-target aquatic species (Becker *et al.,* 2010; Brown, 1986). The advent of synthetic insecticides in the mid-20th century marked a major shift, with organophosphates such as temephos becoming the dominant larvicidal agents in global vector-control programmes (Davila-Barboza *et al.,* 2024; Velayudhan, 2021). Although highly effective initially, resistance to temephos was soon reported across *Aedes*, *Culex*, and *Anopheles* populations in multiple countries (Davila-Barboza *et al.,* 2024; Hemingway and Ranson 2000; Saha *et al.,* 2025). To counteract resistance and mitigate ecological impacts, biological larvicides, including *Bacillus thuringiensi sisraelensis* (Bti) and *Bacillus sphaericus* (Bs), gained prominence due to their specificity and reduced environmental toxicity (Shililu *et al.,* 2003). However, limitations such as short field persistence, high operational costs, and the need for repeated application continue to constrain their long-term efficacy (Boyce *et al.,* 2013). These constraints highlight the necessity of integrating more sustainable and ecologically compatible larvicidal approaches into vector management programmes. These limitations stress the importance of the supply of new larvicidal ways that are safe for nature and can be included in the programmes of vector management for the sustainable solution of the problem.

B. Potentials of Plant Compounds and Derived Nanoparticles

The worldwide growth of problems, including insecticide resistance caused by chemical use, environmental contamination by chemicals, and instability of biological insecticides, has led to a revival of interest in orchid-based compounds and the green synthesis of nanoparticles that can be used as agents for mosquito control (Kannan *et al.,* 2023; Weill *et al.,* 2003). Formulations derived from plants exhibit both structural and functional diversity, and possess multiple action modes, which collectively reduce the likelihood of resistance development and minimise toxic effects on non-target organisms (Isman, 2020; Benelli, 2016). Besides that, the use of plants as a source of solutions to the problem of vector control is quite advantageous in terms of availability, it is environmentally friendly and is accepted by the community (Silva Brito *et al.,* 2024). Nanotechnology has by far broadened these possibilities by enabling the creation of biogenic nanoparticles, especially silver nanoparticles (AgNPs), which are produced with the help of plant material used both as a reducing agent and a stabilizing agent (Arjunan *et al.,* 2012; Iravani and Varma 2020). These substances have both the least common feature coming from the plant phytochemicals as well as the increased chemical reactivity and stability coming from the nanosized particles, thus resulting in excellent larvicidal efficiency (Elumalai *et al.,* 2016; Kumari *et al.,* 2019).

(i) Phytochemicals. Phytochemicals are the fundamental bioactive components of plant-based larvicides and cover a broad spectrum of different biochemical classes such as alkaloids, flavonoids, saponins, coumarins, limonoids, terpenoids, and phenolic compounds (Senthil-Nathan, 2020a; Shafeeq *et al.,* 2025). These molecules cause larvicidal effects through various mechanisms, such as breaking of the digestive tract epithelial membranes, inhibition of acetylcholinesterase activity, interference with juvenile hormone pathways, impairment of nutrient assimilation, and inhibition of larval respiration (Basak *et al.,* 2025; Senthil-Nathan 2020b).

The reason why essential oils are pointed out most of all is their very high volatility and very fast knockdown features, and great toxic effects of substances like eugenol, citronellal, thymol, and geraniol toward larvae of *Aedes aegypti* and *Anopheles stephensi* have been demonstrated (Dias and Moraes 2019; Gupta and Gupta 2022).

The extracts of plants from species like *Azadirachta indica*, *Calotropis procera*, *Ocimum sanctum*, and *Syzygium aromaticum* have proven over and again a considerable larvicidal effect, which is attributable to their plentiful phytochemical constituents and the synergistic effect of several bioactive metabolites (Rajasekaran and Duraikannan 2012). However, in spite of their considerable activity, crude plant extracts may show a fluctuation in their potency because of differences in extraction technique, plant chemotype, and environmental factors, thus leading to the necessity of more standardized and stable formulations.

(ii) Nanoparticles and Silver Nanoparticles (AgNPs). With the help of nanotechnology, mosquito control has become easier and more effective by enhancing the delivery, stability, and bioactivity of natural plant compounds. Among these, green-synthesized AgNPs have proved to be highly effective larvicides as they produce reactive oxygen species (ROS), penetrate larval tissues, and disrupt physiological activities at cellular and molecular levels (Iravani *et al.,* 2014). In silver nanoparticle synthesis, plant extracts serve not only as reducing agents but also as capping agents, resulting in nanoparticles that are more biocompatible and less toxic to the environment than those produced chemically (Kuppusamy *et al.,* 2016). Several studies have revealed the tremendous larvicidal potential of silver nanoparticles made from various medicinal plants. The silver nanoparticles obtained from *Excoecaria agallocha, Aervalanata,* and *Diospyros montana* were found to cause a high percentage of death in *Aedes*, *Anopheles*, and *Culex* larvae, respectively, even at very low concentrations (Kumar *et al.,* 2018; Puri and Patil 2022; Raguvaran *et al.,* 2025). Their functioning is through the disruption of the larval cuticle, interference with mitochondria, generation of reactive oxygen species, and damage to midgut and siphon structures, thus leading to quick deaths. Moreover, nanoparticles synthesized from plants show better stability, slow degradation, and prolonged larvicidal effect compared to the arbitrary use of plant extracts, which paves the way for environmentally friendly mosquito-control formulations and corresponds with integrated vector management principles.

GREEN SYNTHESIS AND CHARACTERIZATION OF HERBAL SILVER NANOPARTICLES

AgNPs green synthesis is silver nanoparticles (AgNPs) biologically synthesized, green, and sustainable, attracting great scientific attention over the environmentally harmful and traditionally produced nanoparticles (Hussain *et al.,* 2021; Iravani 2011; Singh *et al.,* 2018). Factories that create nanoparticles chemically and physically usually require high temperatures, the use of toxic reducing agents, or sophisticated equipment (Jadoun *et al.,* 2021; Iravani *et al.,* 2014; Rai *et al.,* 2014). The plant-mediated synthesis, however, takes advantage of plant chemicals that are present in nature and that reduce silver ions and deliver stable nanoparticles with potent biological activity (Ahmed *et al.,* 2016; Mittal *et al.,* 2013; Narayanan and Sakthivel 2010; Varma, 2019). These herbal AgNPs have been revealed as a viable solution for mosquito vector control due to their larvicidal, antimicrobial, and environmentally friendly characteristics, which make them compatible with eco-friendly mosquito-management programs.

A. Synthesis Approaches

Production of nanoparticles is possible either via top-down or bottom-up methods (Iravani, 2011; Jadoun *et al.,* 2021; Rai *et al.,* 2014). To achieve nanoscale silver fragments, top-down methods such as mechanical milling, laser ablation, and lithography physically break the bulk material (Singh *et al.,* 2018; Varma, 2019; Zhang *et al.,* 2016). Although these methods are powerful, they consume a lot of energy and may lead to irregular particle surfaces or the presence of impurities (Hussain *et al.,* 2021; Iravani *et al.,* 2014; Sutradhar *et al.,* 2014).

In opposition to this, bottom-up methods create nanoparticles from atomic or molecular precursors by means of chemical reduction, sol–gel reactions, or biological synthesis (Iravani 2011; Mittal *et al.,* 2013; Narayanan and Sakthivel 2010). Green synthesis: an environmentally-friendly bottom-up method that interacts with metabolites of plants such as flavonoids, phenolics, terpenoids, alkaloids, sugars, and proteins to reduce Ag^+ ions to metallic Ag^0 while the plant components stabilize the nanoparticles, thereby obtaining uniform, biocompatible structures without any harmful chemicals (Ahmed *et al.,* 2016; Jadoun *et al.,* 2021; Kuppusamy *et al.,* 2016; Raveendran and Wallen 2003; Varma, 2019). The method is low cost, fast, reliable and scalable, thus perfect for public health applications (Hussain *et al.,* 2021; Singh *et al.,* 2018; Velayudhan, 2021).

B. Methods for Characterization of AgNPs (UV–Vis, XRD, TEM)

Without a doubt, proper and thorough characterization is important for the identification of AgNPs and the understanding of their physicochemical features that influence their biological reactivity. Among other techniques, UV–visible spectroscopy serves as a first-instance means for the recording of the typical surface plasmon resonance (SPR) band of AgNPs, which is most of the time located between 400 and 450 nm, thus indicating successful silver ion reduction (RebeRaz *et al.,* 2012). The great part of the next step in characterization is done by X-ray diffraction (XRD), whereby the material crystallinity is confirmed by the exclusive peaks shown in the diffractions of the face-centred cubic structure of metallic silver (Mulvaney, 1996). Transmission electron microscope (TEM) gives unlimited information on the shaping of particles, their size range and the patterns of the clusters from which most of the particles are round or nearly round and measure 5-50 nm in size and depend on the plant juices used (Elumalai *et al.,* 2016). Additional tools such as Fourier-transform infrared spectroscopy (FTIR) help identify functional groups responsible for reduction and capping, while dynamic light scattering (DLS) evaluates hydrodynamic size and colloidal stability, ensuring reliable biological performance (Nadagouda *et al.,* 2014).

C. Mechanism of AgNP Synthesis

AgNPs' green synthesis is mainly a result of plant phytochemicals that perform the functions of reducing, stabilizing, and capping agents. In the case of a silver nitrate and plant extract mixture, compounds like phenolics, flavonoids, terpenoids, tannins, alkaloids, and proteins take electrons from Ag^+ ions and thus the ions are reduced to metallic Ag^0, which aggregates and grows to nanoscale structures (Bar *et al.,* 2009; Iravani, 2011). Phenolic compounds and flavonoids, because of their hydroxyl groups, are very powerful reductants, while proteins and polysaccharides provide a protective layer that prevents nanoparticle agglomeration and thus stabilizes them (Shankar *et al.,* 2004). FTIR spectra commonly show the participation of O–H, C=O, and N–H groups in the reduction and stabilization processes, thus pointing to these plant metabolites as the main players in nanoparticle formation (Awwad *et al.,* 2013). The synergistic effect of these phytochemicals results in the production of biologically active and stable AgNPs with enhanced larvicidal potential; thus, herbal nanoparticles are the next generation of mosquito vector control devices.

LARVICIDAL ACTIVITY OF PLANT-DERIVED SILVER NANOPARTICLES

What makes plant-derived silver nanoparticles (AgNPs) a cutting-edge topic in the vector-control research area is the synergistic effect of plant bioactive compounds and nanometallic toxicity, which provides a dual-mode larvicidal strategy that is significantly more effective than either botanical extracts or synthetic insecticides. Green AgNPs are plant-based nanomaterials fabricated using nature-derived reducing and capping agents that are part of plant metabolites, which allows them to be formed in a controlled manner, have a long shelf-life, and can be readily absorbed in the body (Banne *et al.,* 2021). These nanoparticles are potent agents for the broad-spectrum chemical control of the three major mosquito vectors: *Aedes aegypti*, *Anopheles stephensi*, and *Culex quinquefasciatus*, as most of experimental works have been recorded the prompt larval death to be occurring along with the LC_{50} and LC_{90} values that remain constantly low which is the case most for the crude plant extracts (Benelli, 2016; Ochola *et al.,* 2022). Due to their nanoscale size, they are capable of going deeper into the tissue of living organisms, and the phytochemical envelop makes them more soluble, easier to disperse, and they also interact with the biology of the larvae more effectively (Ahmed *et al.,* 2016).

Plant-based AgNPs larvicidal efficacy is mainly explained by the convergence of several mechanisms that operate concurrently (Benelli, 2016; Shahzad and Manzoor 2019; Zhang *et al.,* 2016). The nanoparticles at first come in contact with the larval cuticle as a result of electrostatic attraction and hydrophobic forces and thus initiate fibril breakage, increased permeability, and finally disruption of the protective wax layer, which are the effects of structural abrasions (Armstrong *et al.,* 2013; Fouad *et al.,* 2018; Mao *et al.,* 2018). This structural compromise consequently speeds up the penetration of AgNPs into hemolymph and other tissues (Ishwarya *et al.,* 2017; Meng *et al.,* 2017; Nalini *et al.,* 2017). When AgNPs are present, they initiate excessive production of reactive oxygen species (ROS) that cause oxidative stress and thus the radicals first attack and then oxidize proteins, lipids, and nucleic acids of the cell (Foldbjerg *et al.,* 2015; Mao *et al.,* 2018; Marimuthu *et al.,* 2011; Thivaharan *et al.,* 2018). The excessive ROS caused by AgNPs impair mitochondria; as a consequence, ATP synthesis gets inhibited, and cell death via apoptosis or necrosis is triggered (Ma *et al.,* 2015; Posgai *et al.,* 2011; Raj *et al.,* 2017; Zhang *et al.,* 2016).

The midgut of the larvae is another primary organ that AgNPs damage. The reports on the ultrastructural changes of electron micrographs of larval midgut epithelial cells clearly show severe epithelial degeneration aspects like destruction of microvilli, vacuolization, cytoplasmic leakage, and rupture of midgut epithelial cells (Raj *et al.,* 2017; Dipankar and Murugan 2012). The hindered digestive and absorptive functions make the larvae physically weaker. The disruption of enzymatic activities is also a major factor; exposure to herbal AgNPs can change the activity of detoxifying enzymes such as GST, carboxylesterase and mixed-function oxidases, as well as significantly inhibit neurotransmission-related enzyme, acetylcholinesterase (Subramaniam *et al.,* 2017). The resulting biochemical disorder, which is at the root of symptoms of paralysis, feeding inhibition, and developmental delay, eventually leads to death.

Besides rapid lethality, plant-based AgNPs are capable of a myriad of sublethal effects that, in combination, are instrumental in the vector suppression over a long-time span. There are effects of delayed molting, malformed larvae and pupae, lengthened larval instar stage, and lowered rates of pupation and adult emergence that have been frequently reported in research (AlQahtani *et al.,* 2017; Alomar *et al.,* 2020). These developmental impairments may derive from hormone disruption, interference with ecdysone signalling, and impaired nutrient assimilation, all consequences of nanoparticle-induced physiological stress (Basak *et al.,* 2025; Gürkan 2018; Rajaganesh *et al.,* 2020). Such multi-stage impacts make green-synthesized AgNPs particularly valuable in integrated vector management (IVM), where breaking the mosquito life cycle at the larval stage remains a critical strategy (Benelli *et al.,* 2018; Velayudhan, 2021).

Plant-based AgNPs have a major edge over chemically produced nanoparticles or traditional insecticides in terms of environmental safety. As phytochemicals serve as natural capping agents, the nanomaterials so formed are, in most cases, more biocompatible and have fewer toxic effects on beneficial aquatic organisms like *Daphnia magna* and larvivorous fish (Divekar, 2023). Besides that, green-synthesized AgNPs can also break down quite easily in natural ecosystems due to the presence of weaker metal–organic bonds, thereby reducing their long-term ecological retention compared to synthetic agents (Shreyash *et al.,* 2021). Even so, the risk of ecological damage is not entirely off the table; some research works pinpoint the necessity of dose optimization, chronic toxicity assessment, and controlled field deployment to avert environmental accumulation and unintended effects on non-target organisms (Kumari *et al.,* 2019; Veerakumar *et al.,* 2013; Sundaravadivelan *et al.,* 2013).

The plant-derived AgNPs emerge from the collected research as one of the most effective, rapid-acting, and environmentally benign larvicidal agents with strong potential for practical application in public health initiatives (Kumari *et al.,* 2025; Samidoss *et al.,* 2023; Suthar *et al.,* 2025).

Their multi-targeted mechanisms of action ranging from oxidative stress induction to disruption of digestive and endocrine systems reduce the likelihood of resistance development, a major limitation associated with conventional insecticide-based mosquito control strategies (Mishra *et al.,* 2018; Veerakumar *et al.,* 2013). Nevertheless, several challenges persist, including the lack of standardized green synthesis protocols, variability in phytochemical composition leading to batch-to-batch inconsistency, limited understanding of long-term environmental fate, and constraints related to large-scale production and formulation stability (Kumari *et al.,* 2019; Pai and Shetty 2025; Sundaravadivelan *et al.,* 2013). Addressing these scientific, regulatory, and translational barriers will be essential to move plant-based AgNPs from laboratory-scale evaluations toward field-ready, community-acceptable, and sustainable mosquito control solutions (Benelli *et al.,* 2018; Velayudhan, 2021).

MODE OF ACTION AS LARVICIDAL

The larvicidal capabilities of plant-derived silver nanoparticles (AgNPs) can be explained by the occurrence of morphological changes, histo-pathological alteration, oxidative stress, enzymatic activity change, and developmental progression interruption in mosquito larvae. The first comprehensive set of experiments is coming up with evidence that the effects of these agents on multiple targets are the main reasons for high mortality rates or developmental arrest in the vectors of major diseases.

A. Deterioration or Modifications to Morphology under Nanoparticles

Many scientists have observed major changes in the outward appearance and structural integrity of insect larvae following exposure to biologically produced silver nanoparticles (; Mishra *et al.,* 2018; Murugan *et al.,* 2021). For instance, pronounced external deformities such as body shrinkage, rupture or tearing of the cuticle, alterations in abdominal segmentation, disappearance of anal gills, and loss of lateral hairs have been documented in Culex larvae treated with various plant- and waste-mediated AgNP formulations, particularly at higher concentrations or prolonged exposure durations (Gürkan 2018; Murugan *et al.,* 2021; Rajaganesh *et al.,* 2020).

Progressive darkening or melanization of larval bodies has also been frequently reported, reflecting generalized physiological stress responses associated with cuticular damage, immune activation, and segmental disorganization (Benelli *et al.,* 2018; Haq *et al.,* 2025; Thivaharan *et al.,* 2018).

Histopathological examinations of the midgut of AgNP-treated larvae commonly reveal severe epithelial degeneration, including epithelial disintegration, cellular vacuolization, destruction of microvilli, loss of gut-lining integrity, and extensive necrosis (Basak *et al.,* 2025; Marimuthu *et al.,* 2011). Such internal structural breakdown significantly compromises digestive efficiency, nutrient absorption, and barrier protection, ultimately leading to larval mortality (Mishra *et al.,* 2018; Murugan *et al.,* 2021; Rajaganesh *et al.,* 2020). These morphological and histological disruptions likely exert compounded physiological effects by impairing osmoregulation, weakening cuticle integrity, damaging protective and sensory structures, and thereby severely limiting larval survival potential (Gürkan 2018; Sundaravadivelan *et al.,* 2013; Velayudhan, 2021). Recent evidence further supports these observations, as marine algae–stabilized Mn-doped superparamagnetic iron oxide nanoparticles were shown to induce pronounced midgut tissue degeneration, cellular necrosis, and functional disruption in dengue vector larvae, reinforcing the role of nanoparticle-induced histopathology in mosquito larval mortality (Rajaganesh and Murugan 2024).

B. Changes in Biochemistry and Physiology Caused by Nanoparticles

Besides the structural destruction, plant-based AgNPs also bring drastic biochemical and physiological changes in larvae (Onen *et al.,* 2023; Pathipati and Kanuparthi 2021). The FWH-AgNP research shows that the biochemical reserves were heavily depleted: the carbohydrate content was greatly reduced after the larvae were exposed to the experiment compared to the control group, and this is a clear reflection of the energy metabolism being impaired (Ragheb *et al.,* 2020; Gnanadesigan *et al.,* 2011; Zamboning *et al.,* 2023). The same work also found that activity of acetylcholinesterase (AChE) - an enzyme essential for neural function - was greatly inhibited over time, thus the neurotoxic effects were the most likely cause (Aremu *et al.,* 2023; Awad *et al.,* 2025; Ga'al *et al.,* 2018).

This kind of neurotoxicity may show itself in different ways, for example, the larvae might lose their ability to move properly, their feeding might be interrupted, or they might be unable to sense environmental changes and by this, the death rate is accelerated enormously (Farhan *et al.,* 2024; Farhan *et al.,* 2024; Liu *et al.,* 2009). The researchers who have done the work on the subject of metabolic disruption and enzymatic inhibition have concluded that on the one hand, nanoparticles tamper with energy homeostasis and on the other hand, they cause neurophysiological instability - hence the larvae get a double burden to fight against, which is survival (Ahamed *et al.,* 2008; Chamani *et al.,* 2025; Mao *et al.,* 2016).

What is more, independent research works have revealed that there is a connection between oxidative stress and nanoparticle exposure: the main reason for the latter is the generation of reactive oxygen species (ROS), which in turn results in lipid peroxidation, protein denaturation, and DNA damage (Fouad *et al.,*2018; Puri and Patil 2022). Although ROS-mediated damage has been more intensively studied in microbial or mammalian systems, analogous mechanisms are deemed plausible in insect larvae, especially given the observed histopathological and biochemical damage in treated larvae (Alruhaili *et al.,* 2025; Benelli, 2016). Hence, biochemical and physiological disruption via metabolic exhaustion, neurotoxicity, and oxidative stress constitute central components of AgNPs' larvicidal mode of action.

C. Effects of Nanoparticles on the Midgut, Reproduction, and Development

The midgut, which is the central digestive and absorption organ in larvae, is naturally a main target of AgNP toxicity. Damage to the histologically midgut epithelium (as mentioned above) changes the nutrient assimilation, makes digestion less efficient, and may, by the release of gut contents, cause systemic toxicity (Alruhaili *et al.,* 2025). Disintegration of microvilli and the peritrophic membrane causes a breach in the gut that may ultimately allow nanoparticles to reach the hemocoel, thereby increasing their toxicity. Consequently, their harmful effects can be amplified. Sublethal exposures may disrupt growth and reproduction beyond causing larval death. In the case of AgNPs biosynthesized from *Aervalanata* flower extract, research indicated that injected larvae not only exhibited larval and pupal mortality but also showed significant modulation of antioxidant enzymes (e.g., SOD, GPx) and detoxification enzymes (GST, etc.), leading to chronic stress, developmental impairments, and decreased fitness of surviving individuals (Raguvaran *et al.,* 2025). Such disruptions in enzymatic activities may transform metamorphosis from larva to pupa, adult emergence, or fertility, thus initially reducing the vector population pool further after a certain period of time of exposure.

Furthermore, works compare AgNPs larvicidal efficacy with that of crude plant extracts and reveal that nanoparticle preparations achieve lethal endpoints at lower levels and shorter exposure durations (Dass *et al.,* 2024; Kabtiyal *et al.,* 2022). This implies that uptake, bioavailability, and potency are enhanced, making AgNPs more competent in breaking mosquito life cycles. Therefore, plant-derived AgNPs incorporate a multi-target mechanism combining external morphological injury, internal histopathology, metabolic and enzymatic disruption, oxidative stress, and developmental interference. Their complex mode of action decreases the probability of resistance development and raises their value as sustainable larvicides for vector control.

DISCUSSION

The present article provides evidence for a bright future of silver nanoparticles (AgNPs) obtained from natural sources as effective larvicidal agents against mosquitoes. The use of conventional chemical insecticides, such as organophosphates, carbamates, and pyrethroids, is becoming less effective due to the development of resistance, environmental persistence, and non-target toxicity (Hemingway and Ranson 2000; Velayudhan, 2021). Green-synthesized AgNPs emerge as an excellent alternative that is not only environmentally friendly but also effective, as it harnesses the power of plant phytochemicals as reducing and stabilizing agents in the process of nanoparticle synthesis. A large number of studies report that Nanosilvers possess high larvicidal power with use at quite low levels against *Aedes aegypti* , *Anopheles stephensi*, and *Culexquin quefasciatus* biting midges, while occasionally one combination is less effective (Arjunan *et al.,* 2012; Dhir *et al.,* 2024). The reason for the higher nanoparticles' efficiency is that their size is a lot smaller, the surface area is much larger, and the particles can enter the tissue of the immature stage, which induces different toxic effects, including morphological deformities, midgut tissue damage, oxidative stress, and nutritional metabolism disruption (Feng *et al.,* 2022; Siddiqi *et al.,* 2018). In this multiplicity of mechanisms, the rate of resistance formation is minimized as the compounds of insecticides that are utilized in the classical approach and have a single physiological pathway target (Benelli *et al.,* 2017).

Greensynthesis methods based on either top-down or bottom-up techniques allow for production processes that are kind to the environment and do not use harmful reagents, thus being in line with the vector management principles and local people's willingness to cooperate (Iravani *et al.,* 2014; Mittal *et al.,* 2013). The standardization of nanoparticle size, shape, and stability,which directly affect larvicidal efficiency, relies on the characterization methods such as UV–Vis spectroscopy, X-ray diffraction (XRD), transmission electron microscopy (TEM), and zeta potential analysis (Arjunan *et al.,* 2012; Khan *et al.,* 2021). Besides that, the presence of phytochemical compounds in plant extracts, *i.e.,* flavonoids, terpenoids, alkaloids, and phenolics, not only facilitates nanoparticle synthesis but also liberates the consequent mortality by the larval enzymes inhibition as well as the normal physiological processes (Feng *et al.,* 2022; Siddiqi *et al.,* 2018).

However, a handful of challenges remain even after these promising results. Variability in plant species, extraction methods, and synthesis conditions keeps nanoparticle properties changing, which makes it hard to reproduce and scale up the results (Khan *et al.,* 2021; Mittal *et al.,* 2013). Moreover, there are very few studies that investigate the long-term ecological effects of AgNPs, such as bioaccumulation, non-target aquatic organisms' effects, and potential microbial communities' disruption (Feng *et al.,* 2022; Siddiqi *et al.,* 2018). Their stability under field conditions, interaction with water chemistry, pH, organic matter, and light, as well as formulation for controlled release, are some other aspects that need to be studied systematically (Arjunan *et al.,* 2012). The regulatory frameworks that control nanoparticle use for vector reduction are not yet mature, and public opinion about the use of nanomaterials in aquatic ecosystems may influence the acceptance and deployment of such technologies (Benelli *et al.,* 2017). In addition, mechanistic insights of the uptake, biodistribution, and AgNPs' long-term effects on mosquito physiology, reproduction, and development are still at the initial stage, which therefore calls for more in-depth molecular and biochemical research (Chaudhary *et al.,* 2023; Dhir *et al.,* 2024; Feng *et al.,* 2022).

To summarize, AgNPs from plants could be a powerful and eco-friendly option for larval control agents, guaranteeing a high level of effectiveness, multiple mechanisms of action, biodegradability, and lower environmental risks. The use of such a tool within mosquito management programs might lead to a drastic reduction of larval populations, interruption of disease transmission cycles, and solving the problem of insecticide resistance. Nevertheless, unlocking their full potential is dependent on having standard methods for their synthesis and characterization, ecotoxicological evaluations, optimized formulations for field applications, a regulatory framework, and community involvement. With diligent research, responsible implementation, and ongoing innovation, green nanotechnology has the capacity to become a key element in the success of sustainable vector management strategies and the wider fight against mosquito-borne diseases (Feng *et al.,* 2022; Siddiqi *et al.,* 2018; World Health Organization 2023).

CONCLUSIONS

Vector-borne diseases transmitted by mosquitoes are the main cause of ill health in the world, especially in tropical and subtropical areas; thus, there is a need to develop sustainable and efficient vector control measures. Usage of chemicals in general has been a good solution in the past, but now it shows some problems, such as resistance, environmental pollution, and elevated costs of operational activities. In this scenario, larvicides derived from plants and green fabrication of silver nanoparticles (AgNPs) have appeared as potential environmentally safe alternatives. Phytochemicals not only perform as bioactive agents but also act the reducing and stabilizing agents in the green synthesis of AgNPs, thus providing a sustainable method for nanoparticle production. The characterizations performed by UV-Vis spectroscopy, X-ray diffraction (XRD) and transmission electron microscopy (TEM) validate the syntheses and the stability of such nanoparticles.

Plant-mediated AgNPs inflict potent mosquito larval death by changing the morphological, biochemical, and physiological attributes of larvae. Their utilization- On the surface of the organism damage, midgut epithelial disruption, generation of reactive oxygen species, enzyme inhibition, and reproductive and developmental processes. A multifaceted inhibition mechanism makes it hard for a mosquito population to develop resistance; thus, the problem of resistance to nanoparticle-based interventions is solved. Besides, as a part of integrated vector management and the essence of sustainable pest control, Phyto-synthesized AgNPs' biodegradability, low non-target organism toxicity, and environmental friendliness are worth mentioning.

In short, green-synthesized nanoparticles' use in mosquito control programs is a sound and eco-friendly alternative to the conventional insecticides. Subsequent investigations should prioritise large-scale field trials, synthesis protocol uniformity, and long-term ecological impact evaluation to bridge the gap between laboratory findings and real-world vector management interventions. Hybridizing traditional botanical wisdom and nanotechnology presents new frontiers, scalable, and environmentally viable solutions for the alleviation of the global burden of vector-borne diseases.

FUTURE SCOPE

Vector borne diseases remains a challenge and climatic changes accelerating the speed of spread in newer habitat, which were not occupied by them into the cold regions like Indian Himalayan landscape as recently seen high malaria cases has been reported from there. This opens up a new challenge and arena for researchers to cope up especially with the spread of mosquito and development of environmental friendly approach. AgNPs and green nanotechnology can help in formulation of targeted agents to control the spread of mosquito and some promising experimental results are available in front of scientific community.

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