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Research Article

Larvicidal efficiency of green-synthesised silver nanoparticles against the dengue vector

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ABSTRACT: Mosquitoes are important vectors that transmit life-threatening diseases including malaria, filariasis, dengue, chikungunya, yellow fever, and Zika fever. Increasing resistance to conventional insecticides has created a demand for eco-friendly vector control alternatives. In this study, green synthesised silver nanoparticles using *Coleus aromaticus* were evaluated for larvicidal and pupicidal activity against II, III, IV instars and pupae of one of the dengue *Aedes albopictus*. The synthesised AgNPs were characterised using UV-Vis spectroscopy, FTIR, XRD, and SEM. Bioassays conducted after 24 h of exposure showed LC50 values of 8.77, 14.18, 20.19, and 33.80 ppm for the II, III, IV instars, and pupae, respectively. The findings demonstrate significant larvicidal and pupicidal efficacy of *C. aromaticus* synthesised AgNPs, suggesting their potential as biodegradable and sustainable mosquito control agents. However, further studies on field efficacy, non-target toxicity, biodegradability, and mechanism of action are required before large scale application in vector management programs.

KEYWORDS: *Ae. albopictus, Coleus aromaticus*, good health, green silver nanoparticles, vector controlt

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INTRODUCTION

Mosquitoes, such as, of the *Anopheles, Culex*, and *Aedes*, are medically important vectors of various diseases threatening human health, especially malaria, filariasis, Japanese encephalitis, dengue fever, haemorrhagic fever, yellow fever, chikungunya, and Zika, which are the major health threats in tropical and subtropical areas (Arokiyaraj *et al*., 2025; Vasu *et al*., 2026). Approximately 3,500 species of mosquitoes have been identified and distributed into 41 genera across the world. (Chandra & Bhattacharjee, 2024; Dhiman & Singh, 2024; WHO, 2020). *Aedes* belongs to the genus of significant vectors, which include *Ae. albopictus,* which carries viral diseases, including dengue, yellow fever, chikungunya, and Zika. The diseases are severe and important health problems of the population, particularly in tropical areas. It is important to put measures to curb the population of mosquitoes and the biting of humans to reduce the spread of these viruses (Cheong *et al*., 2025; Zhang *et al*., 2023).

Effective mosquito control is essential for reducing the transmission of vector-borne diseases, particularly in developing countries where disease burden remains high (Estallo *et al*., 2024). Conventional control strategies are primarily based on synthetic insecticides, including organophosphates, carbamates, pyrethroids, and organochlorines, targeting both larval and adult mosquito stages (Chareonviriyaphap *et al*., 2024). Although these substances effectively control the population of mosquitoes, their use has caused many negative effects on human health, non-target animals, and the environment. Moreover, the increasing development of insecticide resistance among mosquito vectors has further limited their long-term effectiveness. Consequently, there is an urgent need to develop novel, sustainable, and eco-friendly alternatives for

mosquito vector management (Dass & Mariappan, 2026; Annamalai, 2026; Dagar & Ramakrishna, 2024).

In these conditions, plant-based insecticides have emerged as promising alternatives due to their biodegradability, effectiveness, and reduced environmental impact (Tchouassi *et al*., 2024). This study focuses on a green synthesis approach to develop an insecticidal agent that is biocompatible, cost-effective, and environmentally sustainable. The method differentiates itself from synthetic chemical insecticides, and the green synthesised nanoparticles minimising ecological toxicity, promoting the use of renewable resources, and harnessing the synergistic bioactivity of compounds derived from plants (Venegas *et al*., 2024).

The green approach has a major role in strengthening sustainable practices of controlling mosquitoes to address the global challenge of insecticide resistance and environmental pollution. Several studies have demonstrated the larvicidal potential of plant derived silver nanoparticles, highlighting their applicability in integrated vector management programs (Cuervo *et al*., 2024; Dass, 2024; Hazarika & Krishnatreyya, 2025). Recent research developments have focused more on the green synthesis of silver nanoparticles that build upon the use of plant products as promising mosquito control agents (Ileke & Atinuke, 2025).

The study plant, *C. aromaticus,* was selected based on its documented medicinal value and its phyto-composition. It is traditionally used to treat a variety of disorders and is rich in bioactive compounds, many of which are volatile in nature (Dass *et al*., 2025; Jimmy, 2021). These volatile constituents possess diverse therapeutic effects, including antioxidant and antimicrobial activities, as well as benefits for respiratory conditions such as throat infections, coughs, and nasal congestion (Anupong *et al*., 2023; Rawat *et al*., 2024). Furthermore, thymol derived from the essential oil of *C. aromaticus* has been shown to be toxic to *Cx. tritaeniorhynchus*, *Ae. albopictus*, and *An. subpictus* species (Nascimento *et al*., 2024; Sanei-Dehkordi *et al*., 2025). Based on these findings, the present study aimed to synthesize silver nanoparticles using *C. aromaticus* and evaluate their larvicidal and pupicidal efficacy against *Ae. albopictus*.

MATERIALS AND METHODS

Collection and preparation of plant extract

The leaves of *C. aromaticus* (Lamiaceae) were collected from urban areas of Thanjavur, Tamil Nadu, India (10°45′23.0″ N, 79°07′40.6″ E). The collected leaves were thoroughly washed with running tap water to remove debris and impurities. Approximately 30 g of leaves were crushed with 100 mL of distilled water to obtain the aqueous extract. The extract was initially filtered through Whatman No. 1 filter paper, followed by a second filtration using a 0.6 µm filter to obtain a clear filtrate for nanoparticle synthesis (Larrañaga-Tapia *et al*., 2024).

Synthesis of silver nanoparticles

A 2 mM aqueous silver nitrate ($AgNO_3$) solution was prepared, and 90 mL of the solution was mixed with 10 mL of *C. aromaticus* leaf extract. The reaction mixture was incubated at room temperature for 5 h to facilitate the reduction of Ag^+ ions. Formation of silver nanoparticles was indicated by a visible colour change from pale yellow to dark brown. The resulting suspension was centrifuged at 3000 rpm, and the obtained pellet was re-suspended in 10 mL of sterile distilled water. This washing and centrifugation rpm process was repeated three times to remove residual impurities. Finally, the purified nanoparticle suspension was freeze-dried to obtain powdered silver nanoparticles, which were subsequently used for bioassay experiments (Kamaraj *et al*., 2023).

Characterisation of green synthesised silver nanoparticles

The synthesised silver nanoparticles were characterised using multiple analytical techniques. UV-visible spectral analysis was performed using a UV-3024 spectrophotometer to confirm nanoparticle formation, while Fourier Transform Infrared Spectroscopy (FTIR) analysis was carried out using a Nicolet 520P spectrometer within the range of 400-4000 cm^{-1} to identify the functional groups involved in nanoparticle synthesis and stabilisation (Zargham *et al*., 2023). Crystalline properties of the synthesised nanoparticles were analysed using an X-ray diffractometer (Rigaku Ultima III) operated at 45 kV and 20 mA with Cu-Kα radiation over a 2θ range of 20°-80°. In addition, the morphology and surface characteristics of the green-synthesised silver nanoparticles were examined using a Vega 3 Tescan Scanning Electron Microscope (SEM) (Madhankumar *et al*., 2020).

Preparation of test concentration

Based on preliminary screening studies, *C. aromaticus* synthesised silver nanoparticles were prepared at concentrations of 5, 10, 20, 30, 40, and 50 ppm for larvicidal and pupicidal bioassays.

Culture and maintenance of the experimental animal

The Vector Control Research Centre in Madurai (VCRC), Tamil Nadu, India, provided the *Ae. albopictus* eggs. After hatching, the larvae were incubated at room temperature (27 ± 2°C) with 75-85% relative humidity. The larvae were fed on fish feed so as to promote growth and development. Bioassays were done using these larvae (Thirumurugan *et al*., 2024)

Larvicidal and pupicidal bioassay

Larvicidal and pupicidal bioassays were conducted following WHO guidelines with slight modifications. Briefly, 200 mL of water was added to 250 mL beakers containing different concentrations (5, 10, 20, 30, 40, and 50 ppm) of *C. aromaticus* synthesised silver nanoparticles. The control consisted of 200 mL of water mixed with 2 mL of *C. aromaticus* aqueous extract without nanoparticles. Thirty larvae or pupae of *Ae. albopictus* were introduced into each concentration, and the experiments were performed in triplicate. Mortality of II, III, and IV instar larvae and pupae were recorded after 24 h of exposure. Percentage mortality was corrected using Abbott's formula (Abbott, 1925; Naveenkumar *et al*., 2024)

$$\text{Mortality (\%)} = \frac{\text{Number of dead larvae}}{\text{Number of treated larvae}} \text{x} 100$$

Statistical analysis

Mortality data were subjected to probit analysis following the method of Finney to determine LC_{50} and LC_{90} values along with their 95% confidence intervals (Finney, 1971). Statistical analyses evaluating the effects of green synthesised silver nanoparticles on larval and pupal mortality were performed using SPSS 2016 (Sathiyaraj *et al*., 2025).

RESULTS

A 10 mL *C. aromaticus* aqueous extract was added to 90 mL of a 2 mM solution of $AgNO_3$ and left to react at room temperature for 5 h. A gradual colour change from pale yellow (A) to dark brown (B) indicated the formation of silver nanoparticles shown in Figure 1. The synthesis of AgNPs was further confirmed by UV-Visible spectroscopy, which showed a characteristic absorption peak at 441 nm, indicating the surface plasmon resonance of *C. aromaticus* synthesised silver nanoparticles (Figure 2).

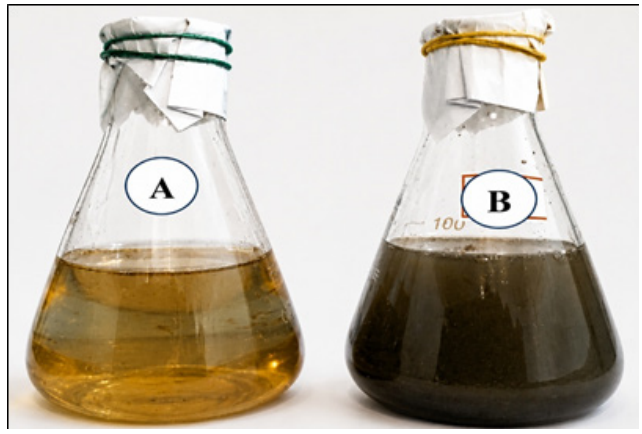


Figure 1. The *C. aromaticus* leaf aqueous extract with **(A).** 2 mM solution of silver nitrate, **(B).** Formation of *C. aromaticus* silver nanoparticles.

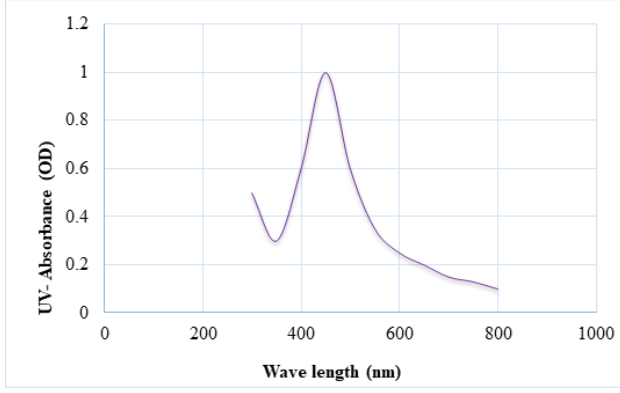


Figure 2. UV-Vis absorption spectra of silver nanoparticles synthesised by *C. aromaticus.*

Table 1. FT-IR functional groups analysis *C. aromaticus* synthesised silver nanoparticles

S. No	Vibrational assignment	Observed wave number (cm^{-1})	Functional group
1	N-H stretching	3336	Amines and amides
2	C-C stretching	1389	Ketones
3	C = O stretching	1692	Aldehydes and ketones
4	N-H wagging	1016	Amide
5	C-C stretching	759	Alkenes
6	C-Br stretching	525	Halocarbon or Alkyl halide

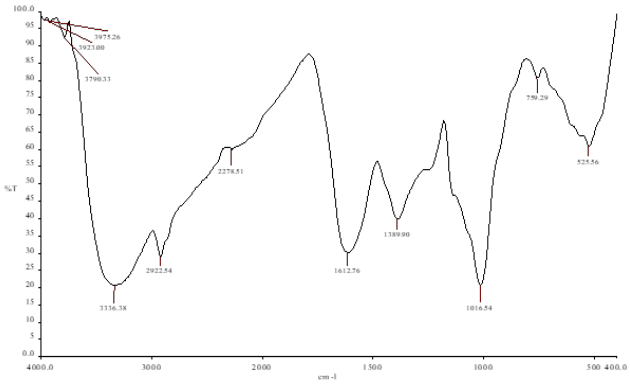


Figure 3. FTIR spectrum of silver nanoparticles synthesised by *C. aromaticus.*

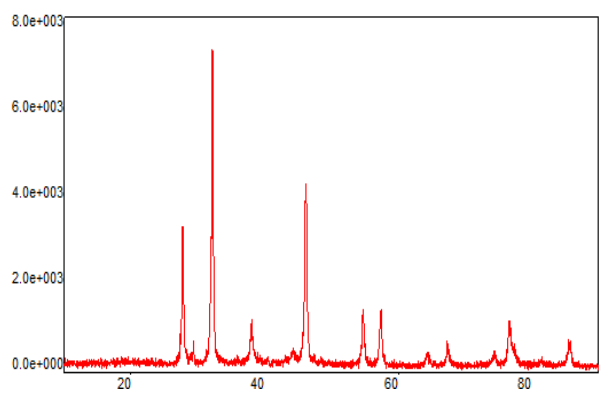


Figure 4. XRD analysis of silver nanoparticles synthesised by *C. aromaticus.*

FTIR was conducted to determine the functional groups that take part in the synthesis of the silver nanoparticles (AgNPs). *C. aromaticus* synthesised silver nanoparticles had characteristic values at 3336, 2922, 1692, 1389, 1016, 759 and 525 cm-^{1}. The band N-H stretch absorbing at 3336 cm-^{1} indicates the presence of N-H stretch of primary amines, whereas the peak at 2922 cm-^{1} is C-H stretching of alkanes. The signal at 1692 cm-^{1} is the C=O signal of diketone groups. Asymmetric C-C stretching is indicated by the band at 1389 cm-^{1}, and the peak at 1016 cm-^{1} is related to N-H bending of secondary amines. Also, absorption at 759 cm-^{1} is associated with C-C scissoring vibrations and the maximum at 525 cm-^{1} is associated with C-Br stretching (Figure 3, Table 1).

The FTIR examination showed that different functional groups such as alcohols, amines, amides, and alkanes, methyl, carbonyl, ketone, aliphatic, and halide groups were present in the prepared AgNPs. These functional groups have been linked with the biomolecules that help in reducing, capping and stabilising the nanoparticles. The results show that the molecules that are bound to the AgNPs have both functional and interconnected functional groups that have led to the stability of the synthesised nanoparticles.

XRD analysis confirmed the crystalline nature of the green-synthesised silver nanoparticles. Distinct diffraction peaks were observed at 2θ values of 27°, 32°, 46°, and 57°, corresponding to the characteristic crystalline planes of Face Centred Cubic (FCC) silver nanoparticles synthesised using *C. aromaticus* (Figure 4). The obtained diffraction pattern verified the successful formation of crystalline AgNPs, and the detailed XRD parameters are presented in Table 2.

SEM analysis revealed that the *C. aromaticus* synthesised AgNPs exhibited relatively homogeneous morphology with particle sizes ranging from 79.46 to 89.39 nm. The observations confirmed that the biological synthesis process produced well-dispersed nanoscale particles with distinct structural and morphological characteristics (Figure 5).

Table 2. XRD patterns of *C. aromaticus* synthesised silver nanoparticles

S. No.	2-theta(deg)	d(ang.)	Height(cps)	FWHM (deg)	Int. I (cps deg)	Int. W(deg)	Asym. factor
1	27.747(7)	3.2125	2904	0.278	1326	0.46	0.63
2	32.165(4)	2.7806	6550	0.283	3038	0.46	0.64
3	46.144(9)	1.9656	3624	0.335	1910	0.53	0.68
4	57.39(3)	1.6043	861	0.45	521	0.61	0.9

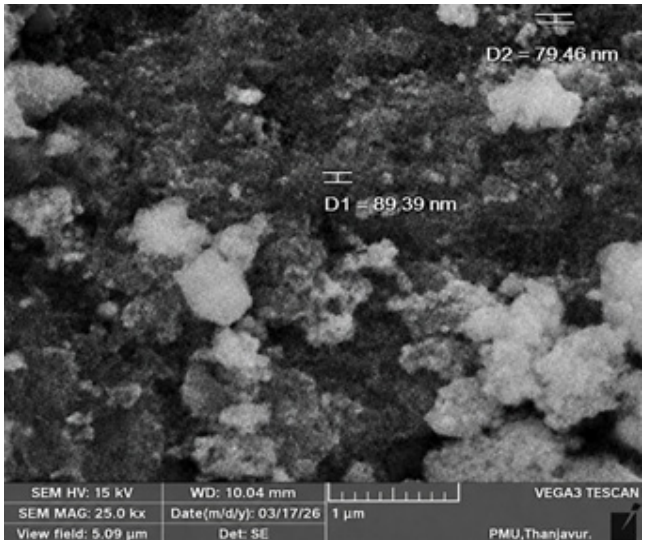


Figure 5. SEM image of silver nanoparticles synthesised by *C. aromaticus.*

The green synthesised silver nanoparticles (AgNPs) of *C. aromaticus* were used in larvicidal and pupicidal bioassays on the second, third and fourth instar larvae and pupae of *Ae. albopictus*. The results of the mortality rates at the end of 24 hrs of exposure are given in Figure 6. LC_{50} of *C. aromaticus* synthesised AgNPs was found to be 8.77 ppm, 14.18 ppm, 20.19 ppm and 33.80 ppm in II, III, IV instar larvae and pupae, respectively. In line with this, the values of the LC_{90} were obtained as 48.66 ppm, 88.72 ppm, 114.39 ppm, and 176.54 ppm. These findings indicate that the silver nanoparticles synthesised using *C. aromaticus* have high larvicidal and pupicidal activities on the dengue vector *Ae. albopictus* (Table 3).

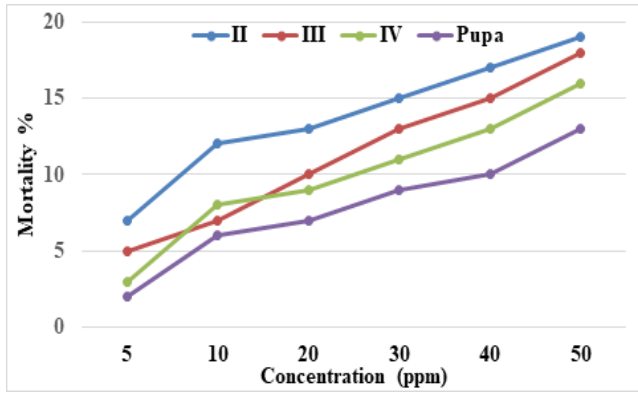


Figure 6. Mortality rate of II, III, IV instar and pupa of *Ae. albopictus* against *C. aromaticus* synthesised silver nanoparticles.

DISCUSSION

The progress of the silver nanoparticles formation in the aqueous solution was observed by UV-Visible spectroscopy. The UV-Vis absorption spectra showed that the colour intensity increased with increased reaction times. The development of a brownish-yellow colouration is believed to be a result of the surface plasmon resonance effect, which proves the creation of the synthesised silver nanoparticles (Siddiqui *et al*., 2023).

Fourier Transform Infrared (FTIR) spectroscopy was used to characterise the synthesised silver nanoparticles to determine the functional groups in the biomolecules that were likely to have contributed to their stabilisation. The X-ray Diffraction (XRD) analysis revealed that metallic silver is crystalline in nature and the presence of

Table 3. The LC_{50} and LC_{90} values of *C. aromaticus* synthesised silver nanoparticles against the II, III, IV instar and pupa of *Ae. albopictus* under 24 hrs exposure

Larval stages	LC_{50} (ppm) (UCL-LCL)	LC_{90} (ppm) (UCL-LCL)	χ^2	Regression equation
II instar	8.77 (13.44-3.33)	48.66 (61.95-23.35)	0.423	Y= -1.45 + 0.14X
III instar	14.18 (19.99-8.73)	88.72 (131.79-51.11)	0.688	Y= 1.72 + 0.08X
IV instar	20.19 (29.68-13.52)	114.39 (143.27-69.56)	0.789	Y= - 1.42 + 0.13X
Pupa	33.80 (67.56-22.59)	176.54 (243.45-109.7)	0.890	Y= - 1.87 + 0.12X

carbonaceous compounds related to the nanoparticle matrix. The analysis of the Scanning Electron Microscopy (SEM) showed that the AgNPs were mostly in a round shape, with the sizes of the particles varying between 79.46 nm and 89.39 nm (Hameed *et al*., 2023).

The findings of the experiment have shown that the second instar larvae were more susceptible to the *C. aromaticus* green-synthesised silver nanoparticles as compared to the other larval stages. The findings confirm that *C. aromaticus* effectively facilitates the synthesis of silver nanoparticles. Statistical analysis further revealed a significant variation in larval mortality among different developmental stages when exposed to the green-synthesised silver nanoparticles.

Although the majority of the earlier investigations support the larvicidal activity against silver nanoparticles (Hameed *et al*., 2023) and other metals, including copper nanoparticles (Abdulwahab *et al*., 2023), zinc nanoparticles (Alamri *et al*., 2024), titanium nanoparticles (Soni & Dhiman, 2020), magnesium nanoparticles (Fouda *et al*., 2023) and gold nanoparticles (Suman *et al*., 2024).

A number of studies have demonstrated that the larvicidal activity of plant-based silver nanoparticles can be used as an integrated measure of control of mosquito species, which highlights its potential application to a set of integrated vector management measures as given in Table 4. AgNPs of *Leonotis nepetifolia* were compared to the Larvicidal and pupicidal actions against the two

Table 4. Green synthesis of silver nanoparticles efficiency of various mosquito species

S. No.	Plant species	Plant part	Mosquito species	Larval stage	LC_{50} (ppm)	References
1	*Ricinus communis*	Leaves	*Ae. aegypti*	II	231.83	Waris *et al*., 2020
				2	455.96	
2	*Azadirachta indica*	Leaves	*Ae. aegypti*	III	1.25	Rasool *et al*., 2020
3	*Citrullus colocynthis*	Fruit	*Ae. aegypti*	III	0.3	
4	*Leonotis nepetifolia*	Leaves	*Ae. aegypti*	IV	47.44	Manimegalai *et a*l., 2020
				IV	35.48	
5	*Nerium oleander*	Leaves	*Ae. aegypti*	III	46.645	Al-Hakimi *et al*., 2022
6	*Echinochloa stagnina*	Leaves	*An. pharoensis*	IV	87.669	Shehabeldine *et al*., 2021
					51.338	
7	Ximenia americana	Leaves	*Ae. aegypti*	IV	0.63	(Madpathi and Bannoth, 2021)
8	*Musa acuminate*	Peel	*Ae. aegypti*	III	88.83	Verma and Preet, 2021
9	*Aegle marmelos*	Leaves	*Ae. aegypti*	II	11.99	Prakash. *et al*., 2022
				13	14.56	
				14	28.42	
				15	44.31	
10	*Colocasia esculenta*	Leaves	*Ae. aegypti*	II	10.39	
				17	13.40	
				18	30.03	
				19	55.61	

Table 4. Continued

11	*Allium sativum*	Bulbs	*Ae. aegypti*	II	44.77	Nasir *et al*., 2022
				21	62.82	
12	*Knoxia sumatrensis*	Leaves	*Cx. quinquefasciatus*	III	0.40	Loganathan *et al*., 2022
13	*Catharanthus roseus*	Flower	*Ae. aegypti*	II	8.963	Mahalingam *et al*., 2023
14	*Azolla pinnata s*	Leaves	*Cx. quinquefasciatus*	IV	4.287	Kamaraj *et a*l., 2023
15	*Laureliopsis philippiana*	Leaves	*Ae. aegypti*	IV	23.915	
				IV	19.457	
16	*Azadirachta indica*	Leaves	*Cx. quinquefasciatus*	III	85.56	Aremu *et al*., 2023
17	*Syzygium aromaticum*	Bud	*Ae. aegypti*	III	4.9	
18	Ocimum gratissimum	Leaves	*Anopheles*	III	0.631	Sunmonu and Ekpunobi, 2023
19	*Aristolochia bracteolata*	Leaves	*An. stephensi*	I	7.9	Chinnasamy *et al*., 2024
				II	12.7	
				III	21.3	
				IV	45.5	
20	*Rhizophora annamalayana*	Leaves	*Ae. aegypti*	III	210.30	Celliah *et al*., 2023
21	*Calotropis procera*	Latex	*Ae. aegypti*	IV	63.05	Harisma *et al*., 2024
22	*Coccinia grandis*	Leaves	*Ae. aegypti*	I	127.8	Saralaya *et al*., 2024
				II	137.7	
				III	165.75	
				IV	193.80	
		Leaves	*Cx. quinquefasciatus*	I	147.9	
				II	177.1	
				III	189.79	
				IV	209.48	
23	*Osbeckia leschenaultiana*	Leaves	*Ae. aegypti*	III	49.17	Thavamurugan *et al*., 2024
24	*Pittosporum undulatum*	Leaves	*An. stephensi*	III	0.4	Narayanan *et al*., 2024
			Cx. quinquefasciatus		4.7	
			Ae. aegypti		1.2	
25	*Aerva lanata*	Flower	*Cx. quinquefasciatus*	III	6.50	Raguvaran *et al*., 2025
			An. stephensi		20.87	
			Ae. aegypti		22.64	

Table 4. Continued

26	*Cymbopogon citratus*	Leaves	*An. stephensi*	III	46.55	Baghela *et al*., 2025
			Ae. aegypti		40.94	
			Cx. quinquefasciatus		41.45	
27	*Coleus aromaticus*	Leaves	*Ae. aegypti*	II	9.13	Dass *et al*., 2025
				III	12.61	
				IV	24.19	
				Pupa	35.76	
28	*Wrightia tinctoria*	Leaves	*Ae. aegypti*	II	11.14	
				III	14.82	
				IV	33.26	
				Pupa	43.72	
29	*Nigella sativa*	Seed	*Cx. quinquefasciatus*	IV	0.52	Jebaseelan *et al*., 2025
30	*Oxalis corniculata*	Leaves	*An. stephensi*	III	4.536	Singh *et al*., 2025
			Ae. aegypti		7.255	
			Cx. quinquefasciatus		6.817	
31	*Enatiocladia prolifera*	Leaves	*Ae. aegypti*	IV	55.6	Gnanaprakasam *et al*., 2026
32	*Indigofera linnaei*	Whole plant	*Cx. quinquefasciatus*	IV	83.02	Prathap *et al*., 2026
33	*Coleus aromaticus*	Leaves	*Ae. aegypti*	IV	5.98	Deepak *et al*., 2026

mosquitoes like *Ae. aegypti* and *Cx. quinquefasciatus*. The AgNPs demonstrated significant larvicidal activity, and LC_{50} were 47.44 ppm, *Ae. aegypti* and 35.48 ppm, *Cx. quinquefasciatus.* These results indicate that the *L. nepetifolia* synthesised silver nanoparticles exhibit an effective and environmentally sustainable approach for mosquito control strategies (Manimegalai *et al*., 2020).

On the same note, the aqueous extracts of *Azadirachta indica* leaf and *Citrullus colocynthis* fruit were used in the biosynthesis of silver nanoparticles, which was followed by the larvicidal activity against *Ae. aegypti* (Rasool *et al*., 2020). The bioassays were checked with different concentrations of the synthesised AgNPs under a 24 h exposure time. The findings showed an LC_{50} of 30 ppm of *C. colocynthis* silver nanoparticles and 1.25ppm of *A. indica* silver nanoparticles. These results suggest that both the plant-synthesised AgNPs have good larvicidal efficacy, with *C. colocynthis* being more effective than *A. indica*. More studies are advisable to clarify the mechanisms involved in their larvicidal effect and to determine their prospective in an environmentally friendly mosquito control program.

Ximenia americana L. synthesised silver nanoparticles demonstrated significant toxicity to *Ae. aegypti* larvae, with an LC_{50} value of 0.63 mg/L and an LC_{90} value of 1.20 mg/L. This study emphasised that AgNPs synthesised by *X. americana* leaves are effective and environmentally friendly agents against dengue mosquitoes (Madpathi & Bannoth, 2021).

The use of *Musa acuminata* L. peel silver nanoparticles was assessed, along with their effectiveness in controlling the dengue vector, *Ae. aegypti*. The bioactivity of AgNPs was investigated against third instar, showing LC_{50} values between 10.69 and 25.15 ppm across different exposure

times. The study concludes by emphasising the hypothetical application of biowaste as an effective larvicide against *Ae. aegypti* (Verma & Preet, 2021).

Prakash *et al*. (2022) conducted experiments on *Ae. aegypti* larvae and pupae using green synthesised silver nanoparticles sourced from *A. marmelos* and *Colocasia esculenta*. The LC_{50} values obtained were 28.42 ppm for *A. marmelos* and 30.03 ppm for *C. esculenta* when evaluated against the IV instar of *Ae. aegypti*. These findings suggest that both plant-derived silver nanoparticles exhibit significant potential as eco-friendly larvicides (Prakash *et al*., 2022).

Methanolic leaf extracts of *Colocasia esculenta* and *Wrightia tinctoria* were tested for their larvicidal and pupicidal effects against the second, third, and fourth instar larvae, as well as pupae, of *Ae. aegypti*. The LC_{50} values of *C. esculenta* extract for these stages were determined to be 101.17 ppm, 126.02 ppm, 161.60 ppm, and 189.28 ppm, respectively. For *W. tinctoria*, the corresponding LC_{50} values were 126.33 ppm, 149.90 ppm, 183.97 ppm, and 228.20 ppm. Among the two species tested, the methanolic extract of *C. esculenta* exhibited greater larvicidal and pupicidal efficacy. These findings suggest that *C. esculenta* could serve as a potential botanical agent for mosquito control, particularly in areas were *Ae. aegypti* poses significant public health risks. Further studies focusing on the identification and characterisation of the bioactive compounds responsible for this activity are recommended to enhance the development of plant-based mosquito control strategies (Dass, 2022).

The ethanolic extract of *Catharanthus roseus* flowers was employed for the green synthesis of silver nanoparticles, which were evaluated for their larvicidal activity against *Ae. aegypti* larvae. The *C. roseus* synthesised AgNPs exhibited strong larvicidal efficacy, with LC_{50} and LC_{90} values of 8.96 ppm and 20.51 ppm, respectively. These results prove the potent bioactivity of the synthesised nanoparticles against mosquito larvae, highlighting the potential of *C. roseus* as a natural and eco-friendly source for the development of plant-based mosquito control agents (Mahalingam *et al*., 2023).

The larvicidal activity of silver and palladium nanoparticles synthesised using *Laureliopsis philippiana* leaf extracts was evaluated against *Ae. aegypti* and *An. stephensi*. The green-synthesised Ag and Pd nanoparticles exhibited concentration-dependent larvicidal effects after 12 and 24 hrs of exposure. The LC_{50} values for *Ae. aegypti* were 29.59, 17.80, 23.91, and 14.87 µg/mL, while those for *An. stephensi* were 23.94, 13.93, 19.45, and 12.87 µg/mL, respectively. These findings suggest that *L. philippiana* Ag and Pd nanoparticles possess strong larvicidal potential and can serve as environmentally friendly alternatives for mosquito control (Kamaraj *et al*., 2023).

Aerva lanata flower silver nanoparticles were tested against *Cx. quinquefasciatus*, *An. stephensi*, and *Ae. aegypti*. The results showed significant larvicidal activity, with LC_{50} values of 6.50, 20.87, and 22.64 ppm, respectively. The results reveal an innovative, plant-based nano-biopesticide with high potential for long-term mosquito control, presenting a sustainable alternative to chemical pesticides. Further research is needed to explore the mechanism of action and potential environmental impacts of these nanoparticles in various ecosystems (Raguvaran *et al*., 2025).

The *Cymbopogon citratus* green-synthesised silver nanoparticles demonstrated notable larvicidal activity against *An. stephensi* (LC_{50} = 46.55 ppm), *Aedes aegypti* (LC_{50} = 40.94 ppm), and *Cx. quinquefasciatus* (LC_{50} = 41.45 ppm). These findings highlight the potential of green-synthesised nanoparticles as an eco-friendly and sustainable alternative to conventional chemical insecticides. Further studies focusing on their mechanism of action, persistence, and long-term effectiveness are essential to fully assess their applicability in integrated vector management programs (Baghela *et al*., 2025).

Silver nanoparticles synthesised from *C. aromaticus* and *W. tinctoria* were evaluated for their larvicidal activity against *Ae. aegypti*. The $LC_{50 \text{ and LC90 values revealed that}}$ *C. aromaticus* synthesised silver nanoparticles exhibited greater efficacy compared to those synthesised from *W. tinctoria*. These findings suggest that green-synthesised silver nanoparticles represent an effective and environmentally sustainable alternative to conventional chemical pesticides. Moreover, the study underscores the potential application of plant-derived nanoparticles in integrated pest management strategies. Future research should focus on elucidating the mechanisms underlying their bioactivity and evaluating their long-term ecological effects on non-target organisms and environmental systems (Dass *et al*., 2025).

The findings of the present study indicate a direct relationship between nanoparticle concentration and larvicidal as well as pupicidal activity, with higher concentrations resulting in increased mortality rates. In agreement with previous reports, silver nanoparticles

synthesised from plant sources exhibited greater efficacy than the crude plant extracts alone. These nanoparticles induced high mortality even at lower concentrations and shorter exposure times, demonstrating enhanced bioactivity compared to the extracts. Overall, the results suggest that the incorporation of green synthesised silver nanoparticles can significantly improve the larvicidal potential of plant-based formulations. Their strong efficacy and eco-friendly nature make them promising candidates for sustainable vector control programs. Future research should aim to optimise synthesis parameters and assess the long-term ecological impacts of these nanoparticles on both target and non-target species.

CONCLUSION

Aqueous extracts of *C. aromaticus* were used for the green synthesis of silver nanoparticles, which were subsequently evaluated against the larvae and pupae of *Ae. albopictus*. The larvicidal bioassay demonstrated that the *C. aromaticus* synthesised silver nanoparticles exhibited greater efficacy. The use of plant materials for nanoparticle synthesis provides a promising and eco-friendly alternative to conventional chemical insecticides for mosquito control. Incorporation of green synthesised silver nanoparticles into mosquito biocontrol programs may improve the effectiveness and sustainability of vector management strategies. Furthermore, understanding the interaction between plant-derived bioactive compounds and nanoparticles offers valuable insights into nanobiotechnology applications in vector control. The findings of the present study may contribute to the development of next-generation biopesticides that provide safe, sustainable, and long-term solutions for disease vector management and public health protection. In addition, the green synthesis approach minimises environmental hazards by avoiding toxic chemicals and utilising renewable plant resources, thereby supporting environmentally sustainable innovation.

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AUTHOR CONTRIBUTION

The sole author was responsible for the conceptualisation, methodology, data collection, analysis, writing, editing, and final approval of the manuscript.