

# Green Nanotechnology: Innovative Approaches for Sustainable Mosquito Control – A Review

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## Abstract

*Mosquitoes are well-known carriers of various parasites and viruses that can lead to several serious diseases in humans. Illnesses such as malaria, dengue fever, epidemic encephalitis B, and epidemic typhus are among the major health threats transmitted by these insects. Because effective vaccines are lacking for many mosquito-borne viruses (arboviruses), controlling the mosquito population remains the primary method for preventing these diseases. Unfortunately, the increasing resistance of mosquitoes to conventional control methods poses a significant hurdle. As a result, there's a growing need for environmentally friendly alternatives in mosquito control. One promising solution lies in the use of nanoparticles. Thanks to their tiny size and large surface area, nanoparticles have unique features – including strong biological activity, enhanced chemical stability, and the ability to release substances in a controlled manner. These traits make nanotechnology an exciting area of research for developing more effective and sustainable mosquito control methods, especially when green (eco-conscious) synthesis techniques are used. In particular, nanoparticles synthesized using natural, eco-friendly processes have shown strong potential in acting as mosquito-killing agents. These nanomaterials may offer advantages over traditional insecticides, such as improved efficacy and reduced environmental impact. This review explores the potential of green-synthesized nanoparticles in mosquito control, focusing on their types, how they are produced, and how toxic they are to mosquito vectors.*

**Keywords:** Mosquito vectors, eco-friendly control, green nanoparticles, insect resistance, nanotechnology

## INTRODUCTION

In recent years, the rapid advancement of science and technology has sparked a new wave of innovation, reshaping many areas of the scientific landscape [1]. Among the most groundbreaking fields emerging in the 21st century are nanoscience and biotechnology, both of which hold significant promise for transforming diverse sectors [2]. Nanoscience involves the creation, manipulation, and practical use of materials and systems at the nanoscale – typically between 1 and 100 nanometers [3]. In contrast, biotechnology focuses on harnessing biological processes, especially those involving microorganisms,

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Received Date: July 25, 2025

Accepted Date: September 22, 2025

Published Date: September 30, 2025

**Citation:** Alkali, Alhassan, Ezraah, Abba. Green Nanotechnology: Innovative Approaches for Sustainable Mosquito Control – A Review International Journal of Environmental Chemistry. 2025; 11(2): 1–8p.

for a wide range of industrial and scientific applications. One of the exciting crossovers of these fields is the microbial synthesis of metal-based nanomaterials, which bridges biology and nanotechnology to create what is known as nanobiotechnology. Nanobiotechnology represents a fusion of molecular biology and engineering, aiming to develop innovative structures and multifunctional tools for biological, chemical, and medical applications [4]. Its broad scope includes conventional tools as well as novel methods such as molecular self-assembly and atomic-level manipulation [5]. These advances have opened the

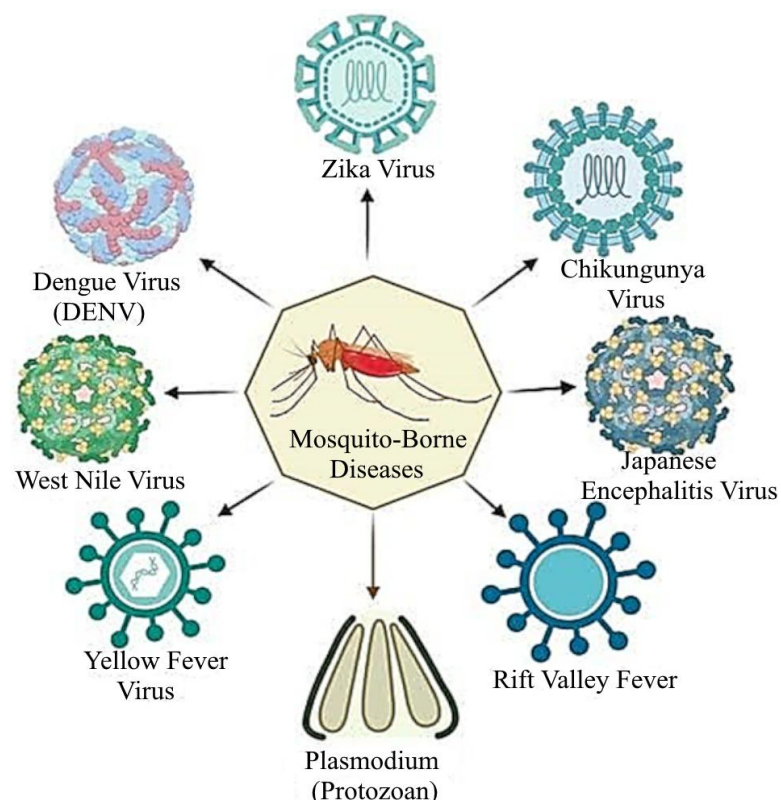
door to transformative uses in fields ranging from medicine and environmental science to agriculture, food production, and insect vector management [6].

When it comes to controlling insect vectors and pests, nanotechnology offers an innovative toolkit. At the nanoscale, materials can be engineered to interact more effectively with biological systems. For instance, nanoparticles can enhance the performance of bio-insecticides by increasing their stability in harsh conditions, protecting them from degradation, and extending their effectiveness through improved adhesion and slow-release properties [7]. This is particularly useful in pest management, where sustained exposure is key to effective control. However, the very properties that make nanomaterials so effective also raise important considerations. Because their dimensions are similar to those of cellular organelles, these materials can enter cells and interfere with critical biological processes, potentially leading to toxic effects [8]. Nevertheless, ongoing improvements in nanoparticle design have enabled scientists to attach useful biomolecules – such as microbial agents, DNA, proteins, and even whole pathogens – to nanomaterials, enhancing their functionality.

Looking ahead, the focus is shifting toward the development of eco-friendly nanotechnologies, particularly green nanoformulations that require only minimal quantities of active agents while ensuring effective delivery [9]. Such innovations are expected to play a key role in sustainable vector control. Key ways nanoscience is being applied in vector management include; larvicidal and adulticidal applications, improved insecticide formulations, and controlled-release systems [10].

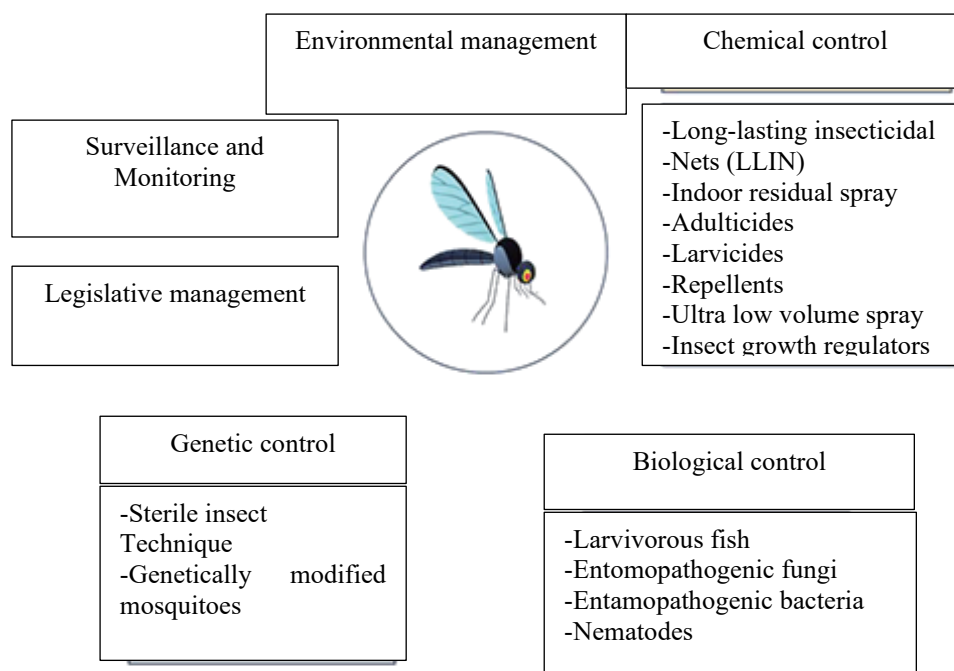
## MOSQUITO-BORNE DISEASES

Mosquito-borne illnesses remain a major global public health challenge due to their potential to cause large-scale outbreaks and long-term impacts on communities [11]. These diseases are transmitted by mosquitoes, which serve as vectors, carrying pathogens from one host to another [12]. Effective control of these diseases has traditionally relied on synthetic insecticides and other conventional control methods (Figure 1 & 2).



**Figure 1.** Mosquito-Borne Diseases.

## Approaches to Mosquito Control and Management



**Figure 2.** Mosquito control strategies.

### Challenges with Conventional Control Methods

Conventional mosquito control techniques – such as chemical insecticides, environmental sanitation, and the use of biological agents – have been widely used for decades. However, these approaches face several significant drawbacks, including development of insecticide resistance in mosquito populations, health, and environmental safety concerns due to toxic residues, high operational costs and limited access in resource-poor settings, short-lived effectiveness of many chemical products and difficulty in achieving consistent community participation [13]. These limitations underscore the urgent need for more sustainable and effective alternatives to mosquito management.

### Nanoscience as an Innovative Approach to Mosquito Control

To overcome these barriers, researchers are exploring advanced techniques – including nanotechnology – to develop safer, more effective mosquito control tools. Nanoscience, a rapidly growing field with applications in medicine, agriculture, and environmental science, offers new possibilities in the fight against vector-borne diseases. Specifically, nanoparticles are being used to create larvicidal and repellent formulations that are more efficient and less harmful to humans and the environment [14, 15]. Compared to conventional insecticides, nanoparticle-based pesticides offer targeted delivery, enhanced stability, and longer-lasting effects. Their small size allows them to remain active in various environmental conditions and reach pest organisms more effectively, without harming non-target species [16]. Additionally, nanomaterials are being explored for their potential use in biosensors for rapid mosquito-borne disease diagnosis [17]. This paper highlights the role of nanoscience in mosquito control, especially considering the limitations of current methods, and its broader implications for public health [18].

### Nanomaterials for Mosquito Management

Nanopesticides represent an eco-friendly shift in pest control technology. They typically require smaller doses, eliminate the need for hazardous solvents, and offer superior efficacy compared to traditional chemical formulations [19]. For instance, modified nanopermethrin has shown improved larvicidal activity and stability against *Aedes aegypti*, with minimal effects on non-target species, unlike

its bulk counterpart [20]. Because of their tiny size, nanoparticles can breach the negatively charged outer membranes of mosquito larvae, reducing the need for high doses of active ingredients. This minimizes risks to humans, animals, and ecosystems, aligning with the principles of One Health. Nanotechnology can also be applied in the development of adulticides, pupicides, ovicides, and repellents, enhancing both the precision and potency of vector control measures [21].

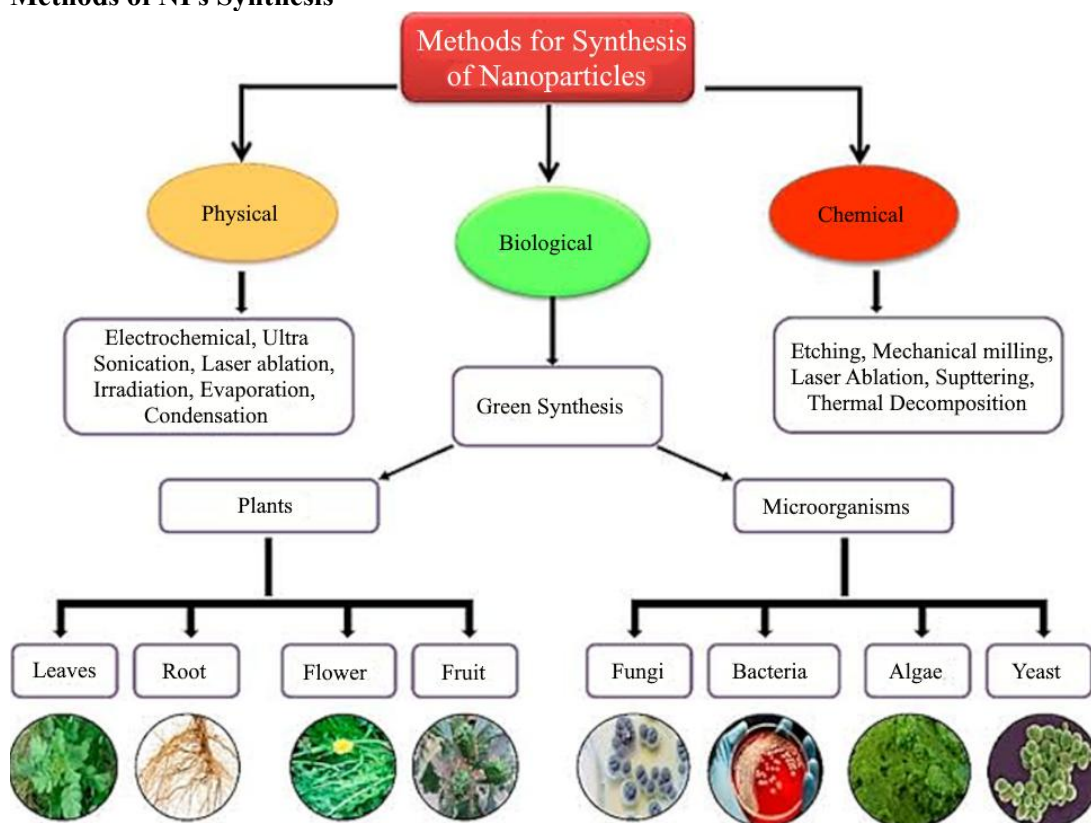
Whereas conventional insecticide products typically consist of active ingredients mixed with inert carriers in forms such as powders, concentrates, or gels, nanoformulations are designed to release their contents in a controlled and targeted manner. This ensures better delivery and sustained mosquito-killing action [22].

### Types of Nanoparticles used against Mosquitoes

Nanoparticles used in insect control can be classified based on their composition, source, or function. The main categories include

- *Organic Nanoparticles*: These carbon-based particles offer versatile structures and functions, including: Polymeric nanoparticles and lipid-based nanoparticles [23].
- *Inorganic Nanoparticles*: Comprising metals, metal oxides, or other non-organic substances, these are known for their strong insecticidal properties.
- *Biological Nanoparticles*: Synthesized using natural sources such as plant extracts, bacteria, or fungi, these nanoparticles are biocompatible and often loaded with naturally occurring bioactive compounds. Green-synthesized nanoparticles are especially valued for being safe, environmentally friendly, and effective [24].
- *Hybrid Nanoparticles*: These are engineered by combining organic and inorganic components. For example, metal nanoparticles coated with polymers can improve environmental stability and minimize toxicity to beneficial organisms [25] (Figure 3) (Tables 1 & 2).

### Methods of NPs Synthesis



**Figure 3.** Method of Nanoparticle Synthesis.

**Table 1.** Advantages and disadvantages of different synthesis methods.

	Advantages	Disadvantages
Physical methods	Simple methodology	Lower yield of NPs, Higher energy-consuming, Higher input cost
Chemical methods	Homogenous NPs with high accuracy, The consumption of less energy	The usage of toxic chemicals
Biological methods	Do not involve toxic chemicals in the preparation protocols	Highly demanding, Time-consuming, Requiring technology and practical microbiological experience to ensure cell culture, and nanoparticle purification under aseptic conditions

Source: Danyue et al., 2023.

**Table 2.** Various NPs with their applicative measures against the different mosquito species.

Nanoparticles	Source	Target's species	Lethal indices (LC50)
Ag	Bacillus marisfavi	Ae. aegypti	13.96 ppm
Ag		Cx. quinquefasciatus	24.54 ppm
Ag		An. stephensi	29.14 ppm
Ag	Ipomoea batatas	Ae. aegypti	17.578 4g/mL
Ag		Cx. quinquefasciatus	10.069 4g/mL
Ag		An. stephensi	12.568 4g/mL
Ag	Cassia roxburghii	Ae. aegypti	26.35 4g/mL
Ag		Cx. quinquefasciatus	28.67 4g/mL
Ag		An. stephensi	31.27 4g/mL
Au	Parmelia sulcata	Ae. aegypti	70.16 ppm
ZnO	Cucurbita	Cx. tritaeniorhynchus	39.007 ppm
ZnO	Cucurbita	Cx. tritaeniorhynchus	44.68 ppm
MgO	Penicillium chrysogenum	An. stephensi	12.5–15.5 ppm
SiO <sub>2</sub>	Chemical method	Cx. quinquefasciatus	27.81 mg/L

Source: Danyue et al., 2023.

### Challenges and Future Prospects of Nanotechnology in Mosquito Vector Control

Nanotechnology presents exciting possibilities for combating mosquito-borne diseases and reducing their global impact [26]. However, despite its potential, there are notable challenges that must be addressed to ensure both the safety and effectiveness of nanotechnology in real-world mosquito control programs.

#### Current Challenges

- **High Production Costs:** Producing nanoparticles—especially through environmentally friendly or “green” synthesis methods—often requires specific biological inputs and precise conditions, which can make large-scale production expensive. Scaling these processes for broad mosquito control efforts presents both financial and operational challenges [27].
- **Environmental and Non-Target Risks:** Although green nanoparticles are generally seen as safer alternatives, high doses or improper use can still harm aquatic life and beneficial organisms like pollinators. Limited data on their long-term environmental effects raise concerns about their widespread deployment [28].
- **Lack of Standardization and Regulation:** There is currently no universally accepted framework for nanoparticle production, application, or safety evaluation. Differences in size, shape, and formulation across studies make it difficult to develop global guidelines or regulatory policies for their use in mosquito control [29].
- **Risk of Resistance Development:** As with chemical insecticides, repeated or incorrect use of nanoparticle-based products could potentially lead to resistance in mosquito populations. Since the resistance mechanisms to nanoparticles are still not fully understood, more research is needed to manage this risk effectively [29].

- *Limited Real-World Testing*: Most nanoparticle-based mosquito control solutions have only been tested in laboratory settings. There is a need for more field trials to assess their performance in natural environments and to understand how external factors affect their stability and efficiency [29].
- *Public Awareness and Acceptance*: Mistrust and lack of knowledge about nanotechnology can hinder its adoption, particularly in areas where vector control is critical. Public education and transparent communication are vital for building trust and encouraging community involvement [29].

### Looking Ahead: Future Opportunities

- *Making Green Synthesis More Affordable*: Ongoing advancements in green nanotechnology may make it more cost-effective. Using abundant natural resources such as agricultural by-products or plant extracts, and adopting scalable biosynthesis technologies, can reduce production costs and make the process more accessible [30].
- *Precision Targeting of Mosquitoes*: Nanoparticles can be designed to deliver active ingredients precisely where needed—for example, directly to mosquito breeding habitats or adhering to mosquito exoskeletons for extended action. This not only improves insecticide effectiveness but also minimizes unintended impacts on non-target organisms [31].
- *Integration with Other Control Methods*: Nanotechnology doesn't have to replace existing strategies—it can work alongside them. For instance, combining nano-based larvicides with biological control agents like *Bacillus thuringiensis* (Bt) can offer a more robust, multi-pronged approach to mosquito management and help delay resistance development [32–38].

### CONCLUSION

Vector control remains one of the most reliable strategies for preventing the spread of infectious diseases. However, new challenges – such as pesticide resistance, climate change, and rapid urbanization – require fresh, innovative solutions. Nanotechnology, particularly when paired with green synthesis methods, offers a promising path forward. These methods are not only environmentally sustainable but also provide flexibility in designing nanopesticides that are both efficient and safe. Nanoparticles (NPs) have been developed from various materials, including metals, nonmetals, and biologically derived substances. They offer dual benefits: some possess inherent insecticidal properties, while others can serve as highly effective carriers for conventional pesticides. By controlling the release rate and preventing rapid evaporation, NPs can help reduce toxicity, improve pesticide efficiency, and minimize environmental impact.

This review has highlighted the broad potential of nanotechnology in vector control. Yet, it also emphasizes the need for more research – particularly into the potential long-term effects of NPs on non-target species, including their possible genetic, physiological, and behavioral impacts. Given the wide range of nanoparticle types and properties, their role in mosquito control is still evolving – but the future looks promising, provided we proceed with caution, scientific rigor, and a strong commitment to environmental safety.

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