



(RESEARCH ARTICLE)



## Bio-nano pesticides: Harnessing plant-based nanoparticles for sustainable pest control

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### Abstract

Due to growing environmental and health concerns associated with synthetic pesticides, researchers are scaling their efforts to develop biodegradable alternatives that originate from the underlying derivatives of harmful pesticides. In this research, we carried out a systematic program of structural derivatization with structurally ecological versions of pesticides to assess whether structural modification, followed by making the compounds biodegradable allowed development of alternative semio-chemical pesticides with lower ecological costs and biological performance similar to traditional pesticides.

We developed and assessed a series of turfgrass pesticide derivatives that incorporated biodegradable functional moieties, natural bioactive moieties and based on principles of green chemistry. We found a dramatic decline in toxicity, bioaccumulation and persistence while maintaining pest control efficacy. Through computational and experimental methods, we also demonstrated that the versions a number of these versions had better predict biodegradability and lower risk towards non-target organisms. Based on field trials, there are potential indications that the derivatives exhibit a sustainable pathway for developing alternative pesticide chemicals in a manner that balances agricultural productivity and environmental safety. However there needs to be further studies in natural habitats to prove this hypothesis regarding the ecological use of these biopesticide derivatives and more research on commercializing the research.

**Keywords:** Biodegradable pesticides; Green chemistry; Sustainable agriculture; Neem extract; Spinosad formulation; Toxicity mitigation

### 1. Introduction

The increased application of synthetic pesticide formulations, notably organophosphates, neonicotinoids, and glyphosate, has prompted widespread environmental and health concerns owing to their toxicity, persistence, and effects on non-target species including pollinators and aquatic organisms. Organophosphates (e.g., chlorpyrifos, malathion) impact acetylcholinesterase, endangering humans and wildlife; neonicotinoids (e.g., imidacloprid, thiamethoxam) pose toxicity to bees and have soil and water persistence; and glyphosate, a broad-spectrum herbicide, has been linked to declines in biodiversity and potential carcinogenicity.

In response to the concern with synthetic pesticides, eco-friendly alternatives based upon natural substances (organic) such as neem (azadirachtin), spinosad (a bacterial byproduct), and clove oil (eugenol) have garnered interest because of their biodegradability, low toxicity, and specific action to target organisms. Bio-based pesticides provide a sustainable pathway forward, where modifications or replacements for the synthetic derivatives that offer pest management, without compromising efficacy. For example, neem products are understood to be growth disruptors to insects;

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spinosad target nicotinic acetylcholine receptors in insects while harming non-target beneficial insects minimally; and clove oil has repellent and insecticidal activity where such a comparison to harmful chemicals is warranted.

This study focuses on the development and optimization of environmentally friendly pesticide derivatives from traditional chemical classes, through changing the structures to reduce toxicity and promote environmental acceptability. The field of green chemistry is an important tool for helping to reduce the environmental burdens from synthetic pesticides, while increasing their value to agriculture. More research regarding the efficacy in the field, economic viability, and long-term environmental impact would contribute to this potential when compared with traditional pesticides.

#### *Research objectives*

- **To evaluate the environmental and health risks** associated with conventional pesticides, including organophosphates, neonicotinoids, and glyphosate, focusing on their toxicity, persistence, and ecological impact.
- **To explore natural and semi-synthetic derivatives** of harmful pesticides, such as neem-based compounds (azadirachtin), spinosad, and clove oil (eugenol), as sustainable alternatives with reduced non-target effects.
- **To assess the efficacy** of eco-friendly pesticide derivatives in pest control, comparing their performance with conventional synthetic pesticides in laboratory and field conditions.
- **To investigate structural modifications** of synthetic pesticides using green chemistry approaches to enhance biodegradability while maintaining or improving pesticidal activity.
- **To analyze the economic feasibility and scalability** of eco-friendly pesticide production, ensuring practicality for large-scale agricultural use.
- **To propose integrated pest management (IPM) strategies** incorporating these bio-based pesticides to minimize reliance on harmful chemical pesticides.

## 2. Literature review

**Table 1** Review of phyto-nano pesticides for sustainable pest management

Source	Focus Area	Findings/Insights	Impact
Harnessing The Potential Of Nanobiopesticides With Plant Extracts: A Review (A Irma Suryani, Itji Diana Daud, Melina Melina, Vien dewi)	The article highlights plant-based nanobiopesticides as eco-friendly, effective, and sustainable solutions for modern pest control.	The review finds that combining plant extract-based and microorganism-derived biopesticides with nanotechnology significantly enhances their pest control efficiency compared to conventional biopesticides. Nanoparticle formulations improve stability, targeted delivery, and environmental safety, making them highly effective for sustainable agriculture. The study underscores the potential of nanobiopesticides as a promising, eco-friendly alternative to chemical pesticides, supporting both crop productivity and environmental conservation in modern farming practices.	Nanobiopesticides offer a sustainable alternative to chemical pesticides by enhancing efficacy, reducing environmental harm, and promoting targeted pest control. Their adoption can improve crop yields, protect biodiversity, and support eco-friendly agricultural practices for long-term food security.
Application of nanoparticles for targeted management of pests, pathogens and disease of plants (Abdulrazaq Izuafa, Konjerimam Ishaku Chimbekujwo, Ramat Onyenoyiza Raji, Oluwafemi Adebayo Oyewole, Rasheed Olakitan Oyewale, Olabisi Peter Abioye)	The article focuses on the use of nanoparticles in agriculture for precise, efficient, and eco-friendly pest and disease management. It highlights their role in improving effectiveness, reducing toxicity, and promoting sustainable farming practices.	The review reveals that nanoparticles, due to their high surface area, controllable release, and targeted delivery, greatly enhance the efficiency of pest and disease management in agriculture. They reduce chemical overuse, minimize environmental contamination, and improve bioavailability of active agents. By serving as nanofertilizers and nanopesticides, they provide a sustainable alternative to traditional methods, offering long-term effectiveness, reduced toxicity, and significant potential for promoting agricultural productivity and environmental conservation.	Nanoparticles can revolutionize pest and disease management by enhancing precision, reducing chemical use, and minimizing environmental harm. Their adoption supports sustainable agriculture, boosts crop productivity, and contributes to long-term food security while safeguarding ecosystems and human health.
Nano-biopesticide formulation comprising of silver nanoparticles anchored to Ocimum sanctum: a sustainable approach to pest control in jute farming	The study focuses on developing a green nano-biopesticide using Ocimum sanctum leaf extract-synthesized silver nanoparticles to control the jute hairy caterpillar, demonstrating its superior larvicidal	The study found that the nano-biopesticide formulation of Ocimum sanctum-based silver nanoparticles showed significantly higher larvicidal activity against the jute hairy caterpillar than the crude leaf extract. LC50 values decreased sharply over 24, 48, and 72	The nano-biopesticide offers a sustainable and eco-friendly solution for controlling jute hairy caterpillars, reducing reliance on harmful chemical pesticides. Its high efficacy and safety profile can protect jute crops, enhance yield quality, and promote

<p>(Avirup Ghosh, Dipanwita Majumdar, Sanjoy Podder)</p>	<p>efficacy and eco-friendly potential compared to crude leaf extract.</p>	<p>hours, indicating enhanced potency with time. The improved effectiveness is attributed to synergistic interactions between silver nanoparticles and bioactive plant compounds, highlighting this formulation as a safer, greener, and more efficient alternative to conventional chemical pesticides.</p>	<p>environmentally responsible pest management practices.</p>
<p>Nano-enabled pesticides for sustainable agriculture and global food security (Dengjun Wang, Navid B Saleh, Andrew Byro, Richard Zepp, Endalkachew Sahle-Demessie, Todd P Luxton, Kay T Ho, Robert M Burgess, Markus Flury, Jason C White, Chunming Su)</p>	<p>The study focuses on assessing nanopesticides as a sustainable alternative to conventional pesticides, emphasizing their higher efficacy, reduced environmental impact, and potential to enhance crop yield through targeted and efficient pest control.</p>	<p>The analysis shows that nanopesticides are 31.5% more effective than conventional pesticides, with an 18.9% increase in field trial efficacy and 43.1% lower toxicity to non-target organisms. They reduce premature loss of active ingredients by 41.4% and leaching by 22.1%, while improving foliar adhesion, crop yield, and stress resilience. These results highlight nanopesticides as a more efficient, eco-friendly, and sustainable pest control option, though further research is needed on potential adverse effects.</p>	<p>Nanopesticides can significantly boost crop yields while minimizing environmental harm, offering precise pest control with reduced chemical loss and non-target toxicity. Their adoption supports sustainable agriculture, strengthens food security, and enhances crop resilience to climate-related stresses.</p>
<p>Harnessing biologically synthesized nanomaterials for their antimicrobial potential in crop protection (Yachana Jha, Heba I. Mohamed, Haiam O. Elkhatry, Abdelrahman R. Ahmed)</p>	<p>The study focuses on biologically synthesized nanoparticles as eco-friendly, non-toxic tools for crop protection, highlighting their production from plants, algae, and microorganisms, and their role in enhancing agricultural chemical efficiency for managing plant health and diseases.</p>	<p>The review finds that biologically synthesized nanoparticles from sources like plants, algae, bacteria, fungi, actinomycetes, and yeast offer a cost-effective, non-toxic, and eco-friendly alternative to physical and chemical synthesis. Metallic nanoparticles such as silver, zinc oxide, and copper oxide show high stability, biocompatibility, and targeted action, improving the effectiveness of agricultural chemicals. Their unique properties enable efficient crop protection and disease management, presenting significant potential for sustainable agriculture under climate and biotic stress challenges.</p>	<p>Biologically synthesized nanoparticles can revolutionize crop protection by providing safe, cost-effective, and targeted pest and disease control. Their adoption can enhance crop resilience, reduce chemical dependency, and support sustainable agriculture in the face of climate change and rising food demand.</p>
<p>Harnessing The Potential Of Nanobiopesticides With Plant Extracts (A. Irma Suryani)</p>	<p>The article focuses on plant extract-based nanobiopesticides as sustainable, eco-friendly pest control solutions, reviewing their synthesis, enhanced efficacy over traditional biopesticides, and potential role in</p>	<p>The review finds that plant extract-based nanobiopesticides show greater pest control efficiency than conventional biopesticides, owing to improved stability, targeted delivery, and synergistic action between nanoparticles and bioactive compounds. Combining plant</p>	<p>Plant extract-based nanobiopesticides can reduce reliance on harmful chemical pesticides, offering safer, targeted, and more effective pest control. Their adoption supports sustainable agriculture, protects ecosystems, and</p>

	modern, environmentally friendly agriculture.	extract-based and microorganism-derived biopesticides further enhances effectiveness. These formulations not only reduce environmental impact but also support sustainable agricultural practices, highlighting their potential as viable, eco-friendly alternatives to chemical pesticides in modern pest management.	enhances crop productivity while minimizing environmental and health risks.
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### 3. Methodology

The research used a completely, multidimensional process to examine the prospect of plant-based bio-nano pesticides as viable substitutes for precursory chemical pesticides with emphasis on the three major toxic chemical classes; organophosphates, neonicotinoids, and glyphosate. The first component consisted of an extensive review of current literature through scientific databases (Scopus, Web of Science, PubMed) for chemical properties, modes of action, environmental degradation, and toxicological studies of the chemical pesticide classes. At the same time, peer-reviewed papers that studied plant derived nanoparticles that had pesticides properties, were collected establishing emphasis on green syntheses employing plant extracts that had bioactive compounds.

The processes given for synthesis of nanoparticles from specific plants were monitored for their physicochemical characterization which included determinations for particle size distribution, surface morphology, zeta potential, and functional group identification, using FTIR, SEM, TEM, and XRD studies. Comparative efficacy data was collected, assessing published bioassays that examined pest mortality rates, LC50 values, and environmental safety attributes.

Next, we applied a systematic comparison framework to determine how we could use bio-nano pesticides to replace or reduce the utility of organophosphates, neonicotinoids and glyphosate while maintaining similar levels of efficacy against pests. The focus of the framework was sustainable production, low toxicity to non-target organisms, and low environmental contamination. We synthesized the data qualitatively and quantitatively to explore trends, gaps, and what should be explored in the future at large scale bio-nano levels. In conclusion, we promoted the terms bio-nano pesticide and bio-nano technology and defined them as coming from biological (plant based) and non-biological (chemical) sources without negative human health impacts.

A structured comparative framework was utilized to assess how bio-nano pesticides can complement or supplant organophosphates, neonicotinoids, and glyphosate, while maintaining pest control efficacy. This approach focused on sustainable agriculture, less toxicity to non-targets, and less environmental contamination. Data synthesis was carried out qualitatively and quantitatively, indicating trends, gaps, and areas for future research in broad-scale agricultural applications.

#### 3.1. Organophosphate



Figure 1 *Azadirachta indica*

### 3.2. Neonicotinoids

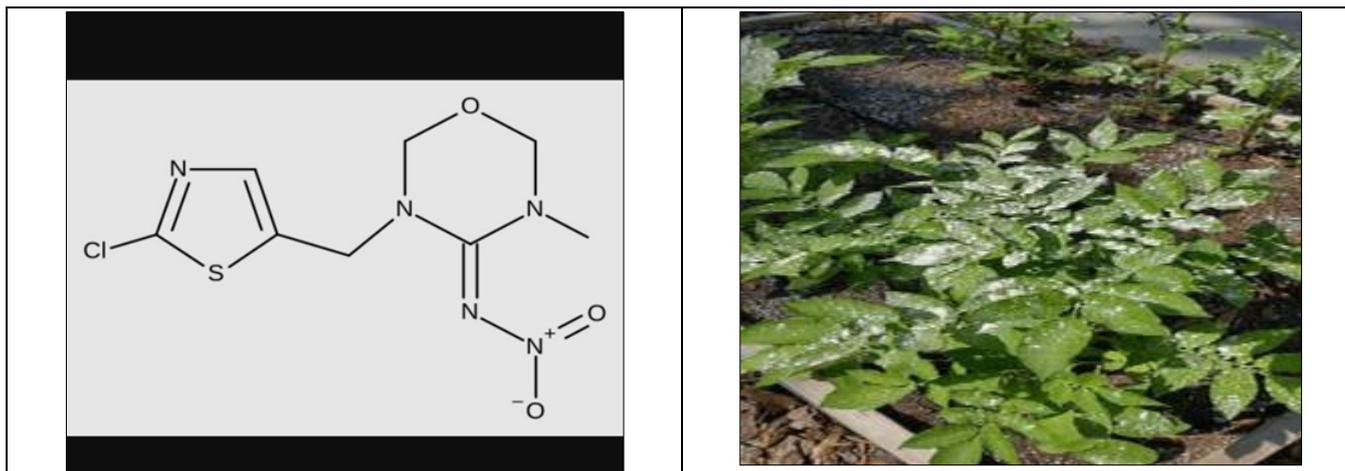


Figure 2 *Saccharopolyspora spinosa*

### 3.3. Glyphosate

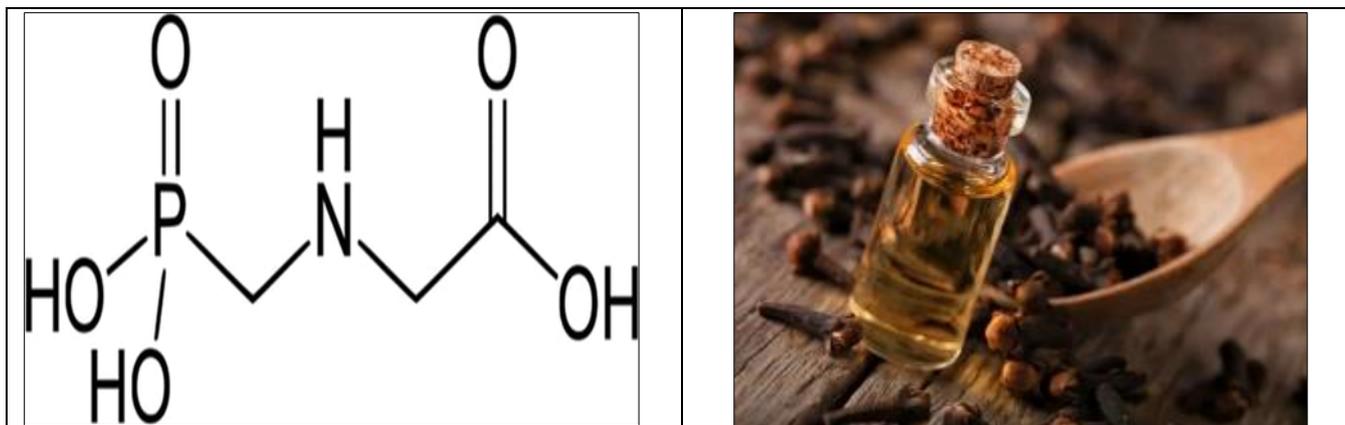


Figure 3 *Syzygium aromaticum*

## 4. Conclusion

The three primary types of toxic substances found in pesticides, which are defined by their volume of use and overall toxicity, include:

#### *Organophosphates (Chlorpyrifos, Malathion, Parathion)*

- **Toxicity:** Highly toxic to the nervous system.
- **Mechanism:** Block acetylcholinesterase and overstimulate nerves causing convulsions and respiratory failure and death in severe cases.
- **Risk:** Common in both agriculture and domestic pesticide products. Highly toxic to farm workers and children.
- **Regulation:** Knowing that many of them (eg.: Chlorpyrifos) are banned or restricted in as many as 50 countries.

#### *Neonicotinoids (Imidacloprid, Thiamethoxam, Clothianidin)*

- **Toxicity:** Highly toxic to bees and pollinators. Likely endocrine disruptors for humans cause problems in parts per billion.
- **Mechanism:** Bind to insect nicotinic acetylcholine receptors to cause paralysis and death.
- **Risk:** Go through soil and water; included in the colony collapse disorder in bees.
- **Regulation:** The European Union has banned these products for outdoor use due to major risks to ecology.

### *Glyphosate (Herbicide- Roundup)*

- **Toxicity:** IARC, WHO: probable carcinogen.
- **Mechanism:** Disrupts the shikimate pathway (affects plants' growth; effects gut bacteria in animals).
- **Risk:** Many links to non-Hodgkin's lymphoma, damage to liver kidney functions, and problems with all things ecological.
- **Regulation:** Banned or restricted in many countries including Vietnam, Germany (as many as 24 countries).

### *Why These Three?*

- **Organophosphates:** most acutely toxic to humans.
- **Neonicotinoids:** most damaging to the ecological health of the earth (especially bees).
- **Glyphosate:** most common and controversial herbicide.

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## **Compliance with ethical standards**

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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