

NANO PESTICIDES: SYNTHESIS, MECHANISMS, AGRICULTURAL APPLICATIONS, AND ENVIRONMENTAL IMPLICATIONS: A COMPREHENSIVE REVIEW

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ABSTRACT

This review examines the synthesis, classification, mechanisms of action, agricultural efficacy, ecotoxicology, and regulation of nano-pesticides, including metal and metal-oxide nanoparticles, polymer-based nanocarriers (chitosan, PLGA, zein), nanoemulsions, nanocapsules, and clay-based nanosystems such as halloysite nanotubes. Controlled release, increased bioavailability, targeted delivery, lower doses, and reduced environmental persistence give these formulations benefits over conventional pesticides. They act by generating toxic reactive oxygen species (ROS), disrupting membranes, inhibiting enzymes and modulating gene expression. However, impacts on non-target organisms require complete risk assessment. Future directions include stimuli-responsive delivery linked to precision agriculture, and uniform global regulatory policies.

KEYWORDS: Nano-pesticides; Nanoparticles; Nanoencapsulation; Controlled release; Integrated pest management; Ecotoxicology; Green synthesis; Sustainable agriculture

INTRODUCTION

Nano-pesticides harness the physicochemical properties of nanomaterials (structural features of 1-100 nanometres), such as high surface area-to-volume ratios and enhanced reactivity, to overcome the limitations of conventional pesticide formulations and possibly create an entirely new class of pest control agents (Fraceto et al., 2016). Nano-enabled formulations provide a 20–30% improvement in pest control over standard equivalents while reducing active ingredient inputs by 50% (Wang et al., 2026; Santos et al., 2025).

Classification of Nano-Pesticides

The major categories are summarized in Table 1.

Metal Nanoparticle-Based Pesticides:

AgNPs act through sustained release of Ag⁺ ions, which destabilize membranes, inactivate sulphhydryl enzymes and generate reactive oxygen species (ROS) (Rai et al., 2009). AgNPs produced by *Trichoderma harzianum* showed potent antifungal activity against the soil-borne pathogen *Sclerotinia sclerotiorum* (Guilger-Casagrande et al., 2019). CuNPs and their oxides have fungicidal and bactericidal properties against downy mildew and bacterial blights (Giannousi et al., 2013).

Metal Oxide Nanoparticles:

ZnO-NPs and TiO₂-NPs are photocatalysts that produce ROS under UV irradiation. Nanosilica (SiO₂) acts mainly by drying insect cuticles, so resistance is unlikely to develop (Rajiv et al., 2020). CuO nanoparticles have been explored as alternatives to Bordeaux mixture for foliar fungal diseases (Giannousi et al., 2013).

Polymer-Based Nanoencapsulated Pesticides:

Nanoencapsulation envelops the active ingredient in a polymer, forming nanocapsules or nanospheres of 50–500 nm (Nuruzzaman et al., 2016); the sustained release reduces application frequency and peak environmental concentrations. Chitosan, a natural biopolymer, is among the most widely used matrices, being mucoadhesive and intrinsically antimicrobial (Saharan et al., 2013). Solid lipid nanoparticles (SLNs) co-loaded with simazine and atrazine showed greater herbicidal activity than commercial herbicides at equivalent dosage (de Oliveira et al., 2015).

Clay Nanotube-Based Systems:

Halloysite nanotubes (HNTs) are aluminosilicate clay minerals with tubular morphology (inner diameter 15–100 nm; outer diameter 50–200 nm; length 500–1500 nm) that serve as low-cost, biocompatible pesticide carriers (Murphy, 2008). Loaded HNTs can reduce the required dose by 70–80%, lowering costs and water contamination, and slow release reduces applications per season.

Mesoporous Silica Nanoparticles (MSNPs):

MSNPs have tunable pores (2–50 nm) and surface areas of 500–1500 m² g⁻¹, enabling high loading and on-demand release via stimuli-responsive gatekeepers. A hollow mesoporous silica hybrid nanocarrier (CNAP-HMS-PDAAM) loaded with

cyantraniliprole showed enhanced residual activity against *Chilo suppressalis* and *Cnaphalocrocis medinalis* on rice up to 28 days post-application, outperforming commercial Benevia at all tested doses (Gao et al., 2020).

Table 1. Classification and comparative attributes of major nano-pesticide categories

Category	Examples	Mechanism	Key Advantages	Limitations	Citation
Metal NPs	Ag, Cu, Au NPs	ROS generation, ion release, membrane disruption	Broad-spectrum activity, low doses	Ecotoxicity concerns, cost	Aguilar-Garay et al. (2024)
Metal Oxide NPs	ZnO, TiO ₂ , CuO, SiO ₂	Photocatalysis, desiccation, enzyme inhibition	Photostability, UV-activated action	Phytotoxicity at high doses	Pathak et al. (2026)
Nanoencapsulated	Chitosan, PLGA, zein nanocapsules	Controlled active ingredient release	Extended residual, dose reduction	Scale-up complexity, cost	Cao et al. (2016)
Nanoemulsions	O/W nanoemulsions of synthetic & biopesticides	Enhanced penetration & bioavailability	Improved shelf-life, reduced dose	Surfactant toxicity, stability	Mustafa and Hussein (2020)
Clay Nanotubes	Halloysite nanotubes (HNTs)	Sustained release from tubular reservoir	Low cost, 70–80% dose reduction	Variable purity of natural HNTs	Teng et al. (2023) ; Zhong et al. (2017)
Mesoporous Silica	MSNPs, HMS hybrids	High loading, stimuli-responsive release	Programmable release, prolonged efficacy	Synthesis complexity, cost	Cao et al. (2016)

Synthesis of Nano-pesticides

Green Synthesis:

Green synthesis uses phytochemicals from plant extracts, and microbial enzymes and metabolites, for nucleation and capping of metal nanoparticles without hazardous reagents (Dauthal and Mukhopadhyay, 2016). Green-synthesised ZnO-NPs from *Melia azedarach* bark extract showed larvicidal activity against *Holotrichia* spp. and antifungal activity against soybean seed-borne pathogens (Shukla et al., 2020; Lakshmeesha et al., 2020). Preliminary data suggest a 15–40 per cent reduction in cumulative energy demand and GHG emissions at production for green-synthesised nanopesticides (Bist et al., 2025).

Mechanisms of Action

Reactive Oxygen Species (ROS) Generation:

TiO₂-NPs and ZnO-NPs generate ROS (O₂^{•-}, •OH, H₂O₂) upon UV or visible light activation, oxidising lipids, proteins and nucleic acids and causing membrane dysfunction, enzyme denaturation and cell death.

Cell Membrane Disruption:

Cationic nanoparticles interact electrostatically with negatively charged microbial and arthropod membranes, causing depolarization, enhanced permeability and loss of intracellular content. Chitosan nanoparticles show intrinsic antifungal

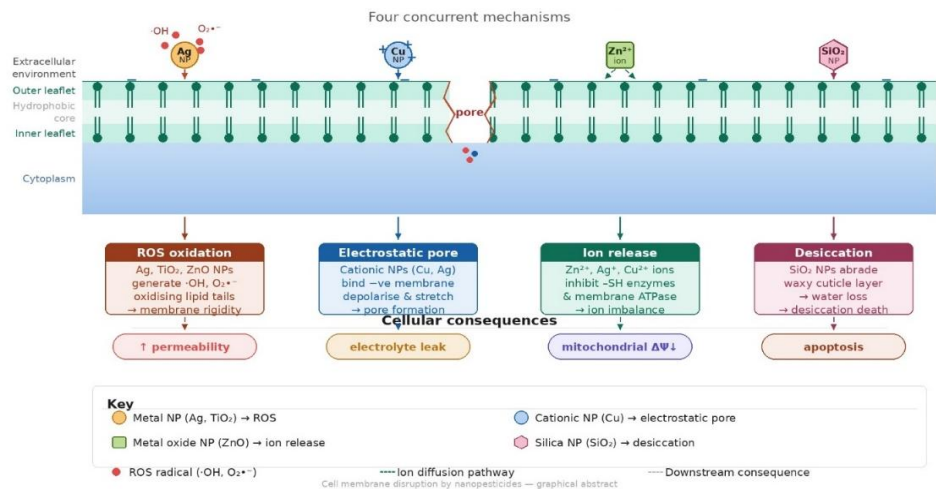


Fig. 1: Mechanism of disruption of cell membrane by nanopesticides

activity via this mode and synergize with encapsulated fungicides (Saharan et al., 2013).

Enzyme Inhibition and Metabolic Disruption:

CuNPs inhibited laccase, cellulase, and protease activities in phytopathogenic fungi, reducing their capacity to degrade

plant cell walls and colonise host tissues (Giannousi et al., 2013). AgNPs release silver ions inside cells, disabling thiol-containing enzymes required for respiration.

Controlled Release Kinetics:

Polymer-encapsulated or clay-hosted nano-pesticides act mainly through sustained, diffusion-controlled desorption, maintaining pest-lethal concentrations with fewer applications and lower peak environmental concentrations that cause acute toxicity to non-target organisms (Grillo et al., 2016).

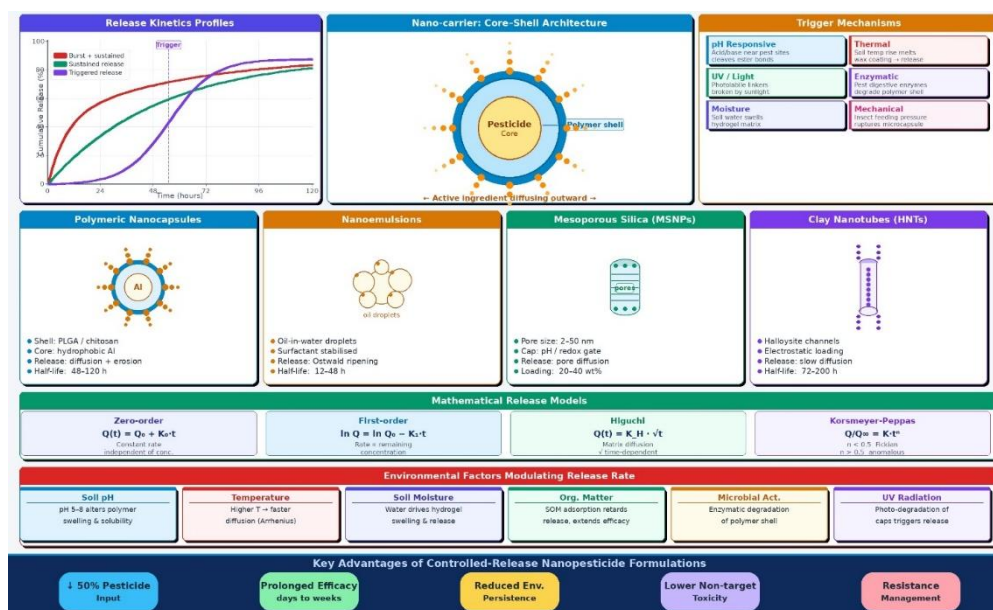


Fig. 2: Mechanism of control release of nano-pesticides

Agricultural Applications and Efficacy

Insect Pest Management:

In *Spodoptera frugiperda* bioassays, a pyrethroid formulated with zein nanoparticles caused greater adult mortality than commercial emulsifiable concentrates owing to improved cuticle penetration (Pérez-de-Luque and Rubiales, 2009). In field trials, CNAP-HMS-PDAAM outperformed Benevia against striped stem borer and rice leaf folder at all rates over 28 days, owing to prolonged release and enhanced leaf adhesion (Gao et al., 2020).

Fungal Disease Management:

Green-synthesised silver and zinc oxide nanoparticles are effective against Fusarium wilt of watermelon caused by *F. oxysporum* f. sp. *niveum* (Elmer et al., 2018).

Environmental and Ecotoxicological Implications

Fate and Behaviour in Soil:

Soil fate depends on interactions of the nanoformulation with soil pH, ionic strength, organic matter, clay mineralogy and microbes; nanoparticles may dissolve, aggregate, or undergo surface passivation or biotransformation, determining bioavailability, mobility and persistence (Kah et al., 2014).

Impacts on Soil Microbial Communities:

In a 90-day mesocosm study of $\text{Cu}(\text{OH})_2$ nanopesticide with and without the isopod *Porcellionides pruinosus*, single and season-representative doses substantially modified soil bacterial and fungal community composition (Peixoto et al., 2021). Exposed soils showed decreased β -glucosidase activity but enhanced functional diversity of carbon substrate utilization.

Aquatic Toxicology:

AgNPs and ZnO-NPs are acutely and sublethally toxic to *Daphnia magna*, zebrafish (*Danio rerio*) and algae at environmentally relevant concentrations, and smaller particles can penetrate gill epithelium and accumulate in tissues.

Effects on Non-Target Terrestrial Arthropods:

Pollinators such as honey bees (*Apis mellifera*) and natural enemies such as parasitoids and predatory beetles are exposed via sprayed surfaces or contaminated pollen and nectar. Sub-lethal TiO_2 -NP exposure affected learning and memory in *A. mellifera* foragers.

Dietary Exposure and Food Safety:

Residues in harvested crops raise health concerns, as dendrimers may penetrate via cuticular or stomatal pathways and reach edible parts via phloem. Their small size hinders chromatographic detection, requiring techniques such as single-particle ICP-MS, and guidance on maximum residue limits for nano-specific residues is almost entirely absent (de Francisco and García-Esteva, 2018).

Regulatory Frameworks and Risk Assessment

Kookana et al. (2014) indicated guiding principles for regulatory assessment of environmental risk, as the current paradigm based on bulk properties and conventional ecotoxicological methods is inadequate for nano-specific assessment. The EU, USA, Canada, and Australia have initiated regulatory reviews, but progress toward harmonised standards remains limited.

Key challenges include agreed definitions and characterisation requirements, validated nanoscale test methods, standardised nano-residue detection methods, and tiered risk assessment frameworks. EFSA guidance on nanoscience and nanotechnologies in food and feed provides a first tier of nano-specific assessment criteria whose implementation in pesticide regulation is ongoing (EFSA Scientific Committee, 2021). EU Regulation (EC) No 1107/2009 is under revision to accommodate nano-specific data requirements, with guidance on physico-chemical characterisation published in 2023 (Wang et al., 2026).

Future Perspectives

Smart and Stimuli-Responsive Nano-Pesticide Systems:

Stimuli-responsive nano-pesticides release their payload on biotic or abiotic signals at the pest-plant interface, such as pH or redox changes from pest feeding, pathogen-secreted proteases or lipases, temperature gradients, or UV intensity (Ragaei and Sabry, 2014), reducing off-target exposure.

RNA Interference (RNAi)-Based Nano-Pesticides:

dsRNA targeting essential insect genes is a highly specific biopesticide class, but is rapidly degraded by environmental nucleases and poorly taken up by cells. Nanocarriers such as chitosan nanoparticles and clay nanosheets protect dsRNA and facilitate endocytic uptake, improving RNAi-mediated gene silencing, with high species specificity, a novel mode of action and minimal resistance risk (Cagliari et al., 2019). Field trials of clay nanosheet-encapsulated dsRNA targeting the voltage-gated sodium channel gene of western corn rootworm recorded 87 percent larval mortality without detectable effects on non-target soil invertebrates (Yin et al., 2023). Sprayable dsRNA nano-formulations conferred gene silencing in *Spodoptera frugiperda* for 14 days in field testing (Santos et al., 2025). Designed for targeted action with reduced environmental risk, nano-pesticides could offer an alternative to other plant protection products for agro-ecosystems under pressure from climate change and high food demand, showing greater effectiveness at much lower active ingredient concentrations through controlled release, improved stability, and possible targeted delivery. However, scientific risk assessment must precede large-scale deployment, as ecotoxicological information on soil microbial communities, beneficial arthropods, aquatic organisms, and dietary residues is limited, and nano-specific regulatory frameworks are an urgent priority. Integration with precision agriculture, digital monitoring, and RNAi presents a pathway towards intelligent pest management.

DECLARATIONS

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