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From conventional to nano

Transforming insect pest control in modern agriculture

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Insect pests are among the most persistent and economically damaging threats to global food production. It is estimated that insect pests destroy between 20 and 40 percent of global crop yields annually, with sucking pests, chewing insects and stored grain pests collectively accounting for losses valued at hundreds of billions of US$ each year. The heavy reliance on conventional synthetic insecticides like organophosphates, pyrethroids, neonicotinoids and carbamates has created a cascade of problems, including widespread insecticide resistance, environmental contamination, harm to non-target organisms (particularly pollinators) and human health risks from residue exposure.

In response to these challenges, nanotechnology has opened a fundamentally new frontier in crop protection. Nano insecticides exploit the unique physicochemical properties that emerge at the nanoscale like dramatically increased surface area, altered solubility and enhanced reactivity to deliver active ingredients with unprecedented precision and efficiency. By encapsulating or dispersing the active ingredient (a.i.) within nanoparticulate carriers, researchers have demonstrated that pest control equivalent to conventional applications can be achieved with a fraction of the chemical load.

Nature and Classification of Nano Insecticides

Definition and Physicochemical Basis: A nano insecticide is defined as a pesticidal formulation in which the active ingredient, carrier or both are engineered to exist at the nanoscale, typically within the range of 1 to 1000 nanometres (nm). At this scale, materials exhibit properties that differ substantially from their bulk counterparts. The surface area to volume ratio increases dramatically as particle size decreases: a particle reduced from 1 mm to 100 nm experiences a ten million fold increase in surface area per unit mass. This transformation underpins the enhanced biological activity of nano insecticides greater contact area means more efficient interaction with target organisms and greater uptake through biological membranes.

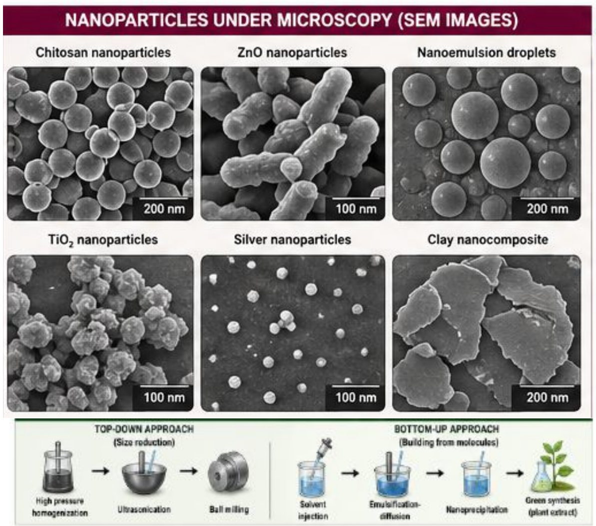
Key physicochemical advantages over conventional formulations include: enhanced aqueous solubility of poorly water soluble a.i., improved adhesion to leaf cuticles and insect body surfaces, extended half-life through protection of the a.i. from UV degradation and hydrolysis and precisely tunable release kinetics governed by particle composition and coating.

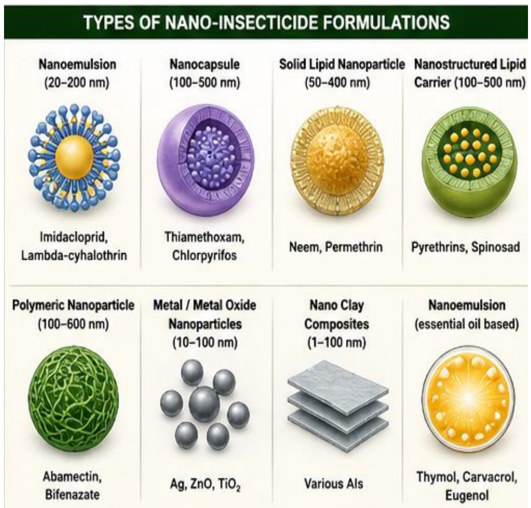
Classification of Nano Insecticide Formulations: Nano insecticides are classified according to the nature of their carrier matrix. The principal types in current research and development are:

Formulation Type	Description	Key Active Ingredients	Notable Advantage
Nanoemulsions (NE)	Oil in water or water in oil emulsions; droplet size 20-200 nm	Imidacloprid, Lambda cyhalothrin	Ultra-fine droplets maximise contact on waxy cuticle
Nanocapsules (NC)	Polymer-shell encapsulation of a.i.;	Thiamethoxam, Chlorpyrifos	Triggered release in insect gut (pH/enzyme-driven)

	size 100-500 nm		
Solid Lipid Nanoparticles (SLN)	Lipid matrix; biodegradable; size 50-400 nm	Neem, Permethrin	Biodegradable, low mammalian toxicity
Nanostructured Lipid Carriers (NLC)	Liquid-solid lipid blend; size 100-500 nm	Pyrethrins, Spinosad	Higher a.i. loading capacity than SLN
Polymeric Nanoparticles	PLGA, chitosan, or zein matrices; size 100-600 nm	Abamectin, Bifenazate	pH-responsive; excellent biopolymer compatibility
Metal/Metal Oxide NPs	Silver (AgNP), zinc oxide (ZnO), TiO_2; size 10-100 nm	Intrinsic toxicant	Dual physical-chemical action; antimicrobial synergy
Nano Clay Composites	Layered silicate matrices; size 1-100 nm	Various a.i.	Extended release; physical pest deterrent

Synthesis Approaches: Nano insecticides are synthesised through two broad strategies. 1. **Top-down methods:** In this method, high-pressure homogenisation, ultrasonication and ball milling physically reduce the size of existing particles. 2. **Bottom-up methods**: this method, such as solvent injection, emulsification-diffusion, nanoprecipitation and green biosynthesis using plant extracts, builds nanostructures from molecular precursors. Green synthesis approaches using plant derived reducing and capping agents are of growing interest due to their low toxicity and environmental compatibility.





Mechanisms of Action Against Insect Pests

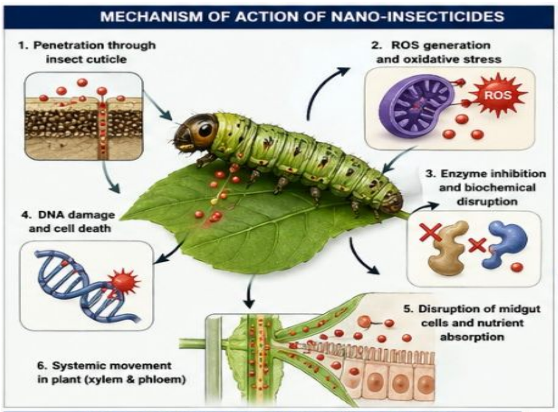
Contact and Physical Action: When nano insecticide formulations are applied to plant surfaces, nanoparticles come into physical contact with the exoskeleton of crawling and resting insects. Unlike conventional particles, nano sized carriers can penetrate the lipid rich epicuticle (outermost waxy layer of the insect integument), which conventionally acts as a barrier to uptake. Once the epicuticle is breached, nano insecticides may cause desiccation by disrupting the waxy layer responsible for maintaining water balance, physical damage to spiracles (respiratory openings) and direct cytotoxicity to underlying epidermal cells. Inorganic metal oxide nanoparticles (e.g., ZnO, SiO_2, Al_2O_3) exert their toxicity primarily through abrasive physical action (adsorbing lipids from the insect cuticle) and through the generation of reactive oxygen species (ROS) that cause oxidative damage to cell membranes, proteins and DNA.

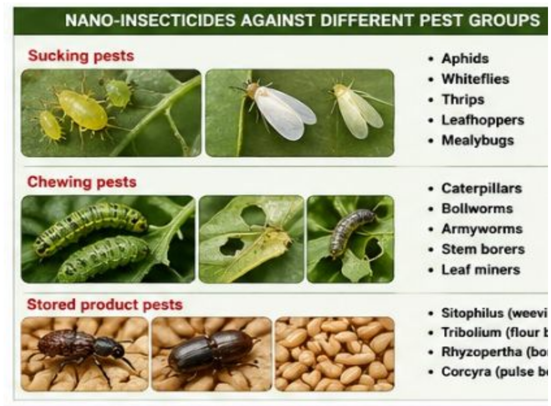
Systemic Uptake: Nano insecticides applied as foliar sprays or soil drenches can be absorbed into the plant's vascular system. Nanoparticulate a.i. are translocated in the phloem and xylem, reaching tissues throughout the plant. Phloem-feeding insects like aphids, whiteflies, mealybugs and leafhoppers ingest the nano insecticide along with plant sap. This route is particularly valuable because it targets pest species that are sheltered beneath leaves or within plant tissues, where spray penetration by conventional formulations is poor. Systemic nano insecticides based on neonicotinoids (imidacloprid, thiamethoxam, clothianidin) disrupt nicotinic acetylcholine receptors (nAChRs) in the insect nervous system, causing continuous nerve stimulation, paralysis and death. The nano formulation approach enhances translocation efficiency and extends systemic persistence.

Gut-Mediated Release and Disruption: Encapsulated nano insecticides that are ingested by target pests release their active payload in response to the specific conditions of the insect midgut. Common triggering mechanisms include the alkaline pH of lepidopteran midguts, the acidic pH of dipteran midguts, gut protease enzymes and elevated temperature. This targeted release maximises the concentration of the a.i. at the site of greatest vulnerability while minimising degradation in the plant or surrounding environment. In sucking pests with piercing and sucking mouthparts, ingested nanocapsules can also mechanically disrupt midgut epithelial cells, impairing nutrient absorption and leading to starvation related mortality in addition to chemical toxicity.

Enzyme Inhibition and Biochemical Disruption: At the molecular level both organic and inorganic nano insecticides interfere with critical enzymatic pathways in insects. Neonicotinoid-loaded nanoparticles inhibit acetylcholinesterase (AChE), the enzyme responsible for terminating nerve impulses at synaptic junctions. Organophosphate nano formulations similarly target AChE but achieve effective inhibition at lower doses due to improved bioavailability. Metal nanoparticles generate ROS that damage mitochondrial membranes, disrupt ATP synthesis and induce apoptosis in insect cells.

Importantly, nano encapsulation can also suppress the activity of detoxification enzymes in insect pests, including mixed function oxidases (MFOs), esterases and glutathione-S-transferases, which are responsible for metabolising conventional insecticides. By overwhelming or evading these resistance mechanisms, nano insecticides offer a potential route to managing populations with established resistance to conventional chemistry.





Efficacy Against Insect Pest Groups

Sucking Pests: Nano insecticides have shown superior efficacy against sucking insect pests due to their small particle size and enhanced penetration ability. They provide controlled release of active ingredients, resulting in higher mortality, longer residual activity and effective control even at lower concentrations. Studies indicate that nano formulations significantly reduce populations of aphids, whiteflies, thrips and leafhoppers by affecting their feeding, survival and reproduction. Additionally, their improved stability and reduced impact on non-target organisms make them suitable for sustainable pest management programs.

Table 1. Efficacy of nano based insecticides on selected sucking insect pest species

Pest Species	Nano formulation	Active Ingredient	Nano Efficacy (%)	Conventional (%)
***Aphis gossypii* (cotton aphid)**	Nanoemulsion	Imidacloprid	88-92	68-74
***Bemisiatabaci* (silverleaf whitefly)**	Nanocapsule	Thiamethoxam	80-85	63-68
***Frankliniella occidentalis* (flower thrips)**	SLN	Neem + Spinosad	73-78	57-63
***Nilaparvata lugens* (brown planthopper)**	Polymeric NP	Chlorpyrifos	85-90	70-75
***Phenacoccus solenopsis* (mealybug)**	NC (PLGA)	Spirotetramat	70-76	56-62
***Empoasca vitis* (grape leafhopper)**	Nano-cypermethrin	Cypermethrin	78-83	62-68

Chewing Pests: Nano insecticides have also demonstrated significant efficacy against chewing pests, which cause direct tissue damage through consumption of leaf, stem, root and fruit tissue. *Bt* toxin (*Bacillus thuringiensis*) encapsulated in chitosan nanoparticles has shown 85-95% mortality against larvae of *Helicoverpa armigera* (cotton bollworm) and *Spodoptera frugiperda* (fall armyworm) in controlled studies, with significantly extended field persistence compared to conventional *Bt* sprays. Nano formulated spinosad achieved 90% control of diamondback moth (*Plutella xylostella*) larvae at doses 40% lower than the conventional label rate. For stem borers such as *Chilo suppressalis* (striped stem borer) in rice, nano encapsulated chlorantraniliprole penetrated into stem tissue more effectively than the conventional formulation, achieving superior larval mortality in systemic challenge bioassays.

Stored Product Pests: In stored grain and commodity protection, nano insecticides based on essential oils (EO), including thymol, carvacrol, eugenol and cinnamaldehyde, have been formulated as nanoemulsions and polymeric nanoparticles. These formulations exhibit potent fumigant and contact activity against *Sitophilus oryzae* (rice weevil), *Tribolium castaneum* (red flour beetle) and *Rhyzopertha dominica* (lesser grain borer). A key advantage is the improved stability of volatile EO compounds when nano encapsulated: EO nanoparticles retained full biological activity for up to 90 days in storage conditions, compared to fewer than 14 days for unencapsulated EO preparations.

Environmental, Safety and Regulatory Considerations

Non-Target Organism Toxicity: The ecological risk profile of nano insecticides is more nuanced than that of conventional pesticides. On one hand, the lower a.i. dose per application reduces total chemical load in the environment. On the other hand, the novel physicochemical properties of nanoparticles can confer unique ecotoxicological effects that are not predicted by testing of the bulk a.i. alone.

Research on non-target organisms presents a mixed picture. Honeybees (Apis mellifera) exposed to nano encapsulated neonicotinoids at field-realistic doses showed lower acute mortality than those exposed to equivalent doses of the conventional formulation, attributed to the slower release of the a.i. from the nanocarrier. However, sub-lethal effects on learning, navigation and colony behaviour have been documented at lower nano insecticide concentrations, raising concerns about chronic colony health. Earthworms (*Eisenia fetida*) and soil microbiota are generally less affected by organic nano carriers (lipid-based, polymeric) but show significant adverse effects from metal oxide NPs, particularly ZnO and CuO nanoparticles, which accumulate in soil and disrupt microbial community structure.

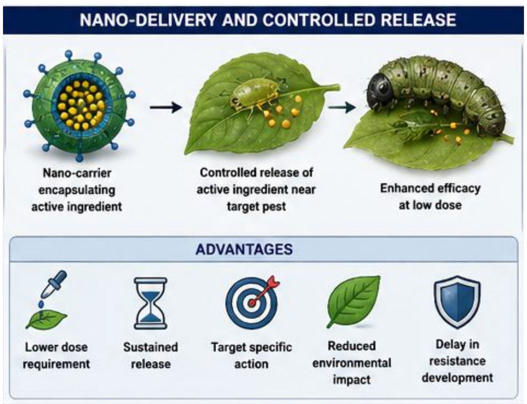
Aquatic ecosystems present heightened concern, particularly in rice agriculture, where field runoff is substantial. Daphnia magna and freshwater fish species show dose dependent toxicity to several nano formulations, underscoring the need for buffer zones and application timing guidelines in flood irrigated cropping systems.

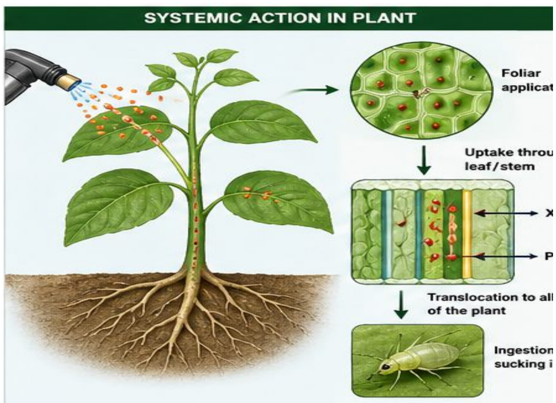
Nanoparticle Fate in the Environment: The environmental persistence of nanoparticles depends strongly on particle composition, surface coating and soil/water chemistry. Organic nano carriers (lipid matrices, biopolymers such as chitosan and zein) are generally biodegradable, breaking down into non-toxic metabolites within weeks to months. Metal and metal oxide nanoparticles, by contrast, are highly persistent and can undergo transformations (aggregation, dissolution, surface modification) that alter their bioavailability and toxicity over time. Silver nanoparticles, for example, may release silver ions in soil, with antimicrobial effects that disrupt nitrogen fixation and organic matter decomposition.

Nano insecticides can also enter food chains through bioaccumulation: nanoparticles taken up by soil invertebrates may be transferred to predatory insects and birds, though current evidence on biomagnification at field-realistic concentrations is limited and warrants further investigation.

Human Health and Food Safety: Consumer exposure to nano insecticide residues on food is a significant regulatory concern. Studies indicate that nano encapsulation does not inherently increase residue levels in edible plant tissue; indeed, controlled release formulations often result in lower residues than conventional applications due to reduce over application. Nonetheless, regulatory agencies including the US EPA, EFSA and India's CIBRC have flagged the need for nano specific residue assessment methods and maximum residue limits (MRLs) that account for nanoparticle-bound vs. dissolved *a.i.* fractions.

Occupational exposure during production and application of nano insecticides presents additional concerns, as inhalation and dermal absorption of nanoparticles may have different toxicological profiles from bulk chemical exposure. Proper personal protective equipment (PPE) guidelines and occupational health standards specific to nanomaterial handling are needed.





Future Directions and Emerging Innovations

Smart and Stimuli Responsive Formulations: The next frontier in nano insecticide design is the development of smart delivery systems that release AIs only in the presence of specific pest associated stimuli. Candidate triggers include the volatile chemical cues emitted by feeding insects, the specific enzymes present in insect saliva (e.g., glucose oxidase in aphid saliva) and temperature gradients created by insect aggregations on plant tissue. Such precision targeted systems would radically reduce off target exposure and are currently under investigation using molecularly imprinted polymer nanoparticles and aptamer functionalized carriers.

RNA Interference (RNAi) Nanoparticles: The silencing of specific insect genes using double stranded RNA (dsRNA) represents a fundamentally new mode of action that is highly target-specific and less prone to cross resistance. However, dsRNA is inherently unstable in the environment and requires effective delivery to insect cells. Nano encapsulation of dsRNA in chitosan, lipid or clay nanoparticles has been shown to protect dsRNA from environmental degradation and facilitate its uptake by target insects, opening the door to ultra selective gene silencing based nano insecticides with negligible non-target toxicity.

Synergistic and Multi-Component Systems: Nano formulations offer unique opportunities for combining multiple modes of action in a single delivery system. Multi-component nanoparticles carrying both a synthetic a.i. and a botanical synergist (e.g., piperonyl butoxide) can inhibit pest detoxification simultaneously with disrupting nerve function, achieving synergistic mortality at doses that would be sub-lethal for either compound alone. Combined nano biopesticide systems pairing *Bt* toxin with plant essential oils have shown promise as high efficacy, low residue alternatives in organic and integrated pest management (IPM) programmes.

Precision Agriculture Integration: The integration of nano, insecticide delivery with precision agriculture technologies like drone application, GPS guided sprayers and remote sensing pest detection offers the prospect of site-specific, real time pest intervention. Nano formulations are particularly suited to ultra-low volume (ULV) drone application due to their superior suspension stability and reduced sedimentation, enabling precise placement of minimal AI quantities at the exact location of pest pressure.

Conclusion

Nano insecticides represent a significant advancement in pest management by offering enhanced efficacy, controlled release and improved stability compared to conventional insecticides. They provide effective control of insect pests at lower doses, contributing to reduced chemical load and better resistance management. However, concerns regarding their environmental fate, potential effects on non-target organisms and regulatory gaps must be carefully addressed through further research and policy development. When integrated with sustainable practices such as biological control and IPM strategies, nano insecticides have strong potential to improve crop protection while minimizing ecological risks and supporting future food security.