

REVIEW

New trends in nanoformulation for vegetable crop pest management: A review

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Abstract

The use of insecticides remains one of the primary methods for controlling species harmful to crops. However, insecticides used for pest control pose hazards to human health and cause environmental damage. Nanotechnology has been used in the agriculture sector to address these problems and increase crop yield. Numerous formulations with various modes of action and applications have been developed, including solid-based nanopesticides, controlled-release formulations, nanoemulsions and nanosuspensions. Nanopesticides provide effective and environment friendly substitutes for controlling insect pests in fields and storage. Nanoparticles can be used to target particular pests, thereby minimizing off target impacts and increasing pest control effectiveness. Nanoformulations enhance the stability and solubility of active ingredients, leading to better absorption and prolonged action, and also allow for the slow and controlled release of pesticides. Recently, green nanotechnology-based nanoparticles and nanoparticle-based RNA pesticides have been used as a recent trend to control vegetable crop pests. This review presents information about recently used nano formulations for vegetable crop pest management and their challenges.

Keywords: agriculture, nanoformulations, nanoparticle, pest, pesticides

Introduction

Agriculture plays a pivotal role in the economies of many countries, providing a foundation for both food security and economic stability. It is essential for sustaining human populations by fulfilling their nutritional needs and continues to be a significant contributor to the global economy (Malik *et al.* 2023). In India, agricultural diversity is particularly pronounced, with approximately 1,097 varieties of vegetables cultivated for human consumption. Despite this extensive crop diversity, the yield of many vegetables remains below the global average. One of the primary factors limiting productivity is the prevalence of biological stressors, such as nematodes, weeds, and insect pests – that hinder crop growth and development (Divekar *et al.* 2024). Globally, pests and pathogens account for substantial yield losses across major crops, with estimated reductions of about 30% in rice, 21.5% in wheat, 17.2%

in potato, 22.5% in maize, and 21.4% in soybean (Savary *et al.* 2019).

In 2022, approximately 3.70 million tons of pesticides were used globally to reduce agricultural output losses caused by various pests, with herbicides accounting for 50%, insecticides for 22%, and fungicides and bactericides for 22% of the global pesticide market (FAO 2024). The widespread use of chemical insecticides intended to control insect pest populations poses significant risks to biodiversity, as they are toxic to non-target organisms and ecosystems (Mahmood *et al.* 2016). Furthermore, these chemicals can accumulate in human tissues, particularly in the colon, and have been associated with a range of serious health issues, including cancer, respiratory disorders, diabetes, reproductive dysfunctions, and neurological impairments (Rani *et al.* 2021).

Botanical pesticides, derived from plant extracts, have been extensively tested for their toxic effects, repellency, antifeedant properties, and impact on oviposition activities to control pests (Yooboon *et al.* 2019). Despite their insecticidal efficacy, the use of certain phytochemicals remains limited due to their rapid degradation, instability, and high volatility.

Recent advancements in nanotechnology have introduced new opportunities for the development of more effective formulations that address these limitations, such as degradation and instability (De Oliveira *et al.* 2018). Nanotechnology enables selective, targeted, and controlled long-term release of pesticides, enhancing their stability and efficacy. Pesticides in the form of nanoparticles, nanogels, nanocapsules, and nanoemulsions can be effectively delivered into plants or insects, ensuring more precise pest control (Zannat *et al.* 2022). Nanopesticides are available in various forms, including micelles and particles, and can consist of both organic (e.g. polymers) and inorganic (e.g. metal oxides) components (Harish *et al.* 2022; Yousef *et al.* 2023). Numerous formulations, incorporating different modes of action and applications, have been developed, including solid-based nanopesticides, controlled-release formulations, nanoemulsions, and nanosuspensions. Due to their small size, nanopesticides demonstrate improved efficacy compared to traditional pesticides, offering better performance and reduced impact on non-target species. Consequently, nanopesticides represent a promising, environmentally friendly alternative for controlling insect pests in both agricultural fields and storage (Jasrotia *et al.* 2022). This review aims to explore various types of nano formulations and recent trends in their applications for pest management in vegetable crops.

Materials and Methods

The present review was conducted to summarize and critically analyze recent advances in nano formulation based pest management strategies with special reference to vegetable crops. A comprehensive literature survey was carried out using electronic databases including PubMed, Scopus, Web of Science, Research Gate, ScienceDirect, and Google Scholar. The keywords used for the search included “nanoparticles,” “nano formulation,” “green synthesis,” “botanical extract nanoparticles,” “pest management,” and “RNAi delivery and insect control” combined with “vegetable crops,” and “toxicity of nanoparticle” in different combinations using Boolean operators. The time frame of the literature considered was primarily from 2010 to 2025, with emphasis on the most recent advancements

reported in the last five years. Both experimental research papers and review articles were examined; however, only original research papers reporting nano formulations tested directly on vegetable crop pests were included for detailed analysis. Articles were screened based on relevance to agricultural pest control, particularly those evaluating laboratory and field bioefficacy of nano formulations against major vegetable crop pests. Only peer-reviewed research and review articles in English were included, while duplicate records, non-agricultural applications (e.g. human medicine), and unpublished thesis were excluded. A total of 400 articles were initially retrieved; after screening and eligibility assessment, 125 papers were finalized for synthesis. Data were categorized according to nanoparticle type, synthesis method, crop pest system, bioefficacy and safety aspects. This approach enabled a critical comparison of different nano formulations and their potential role in sustainable pest management.

To provide clarity, the extracted information has been organized into summary tables and figures, highlighting the nanoparticle formulations, their mode of action, observed efficacy, and associated challenges. In addition, special attention was given to risk assessment, regulatory concerns, and field applicability of nano formulations. This methodological approach allowed for critical evaluation of the strengths and limitations of various nano formulations and for identifying emerging trends and research gaps relevant to sustainable pest management in vegetable crops.

Types of nano formulations for vegetable crop pest management

Formulations are classified based on their structure and intended uses:

Nanocapsules

Nanocapsule is composed of a core-shell configuration, with a polymeric membrane or coating serving as the shell. There are several ways to make pesticide-loaded nanocapsules, like polyelectrolyte complexation and the emulsion-solvent/evaporation method (Nuruzzaman *et al.* 2016). The nanoencapsulation method involves enclosing the active ingredients (AI) in a nanoscale matrix or polymer. The encapsulation enables precise targeting and protects the AI against environmental damage (Manna *et al.* 2023). The AI may be released from the nanocapsules under specific physiological or environmental conditions (Jampilek and Kralova, 2017). Nanoencapsulation gives many benefits, including improved bioavailability and specific targeting of active ingredients (Nuruzzaman *et al.* 2016). Additionally, nanoencapsulation can be used to

prevent the early degradation of pesticides (Shekhar *et al.* 2021). Encapsulation of pesticides is employed to achieve controlled release, which enhances the stability of the active ingredients. The encapsulation of water-soluble pesticides extends their effectiveness, reduces the associated hazards, and slows down issues such as leaching and runoff (Iqbal *et al.* 2021). Similarly, Kumar *et al.* (2013) encapsulated imidacloprid (IMI) into alginate (ALG) nanocapsules using emulsion cross linking technology, optimized through central composite design with sodium alginate concentration (0.1–1.0% w/v) and AOT surfactant concentration (0.05–20% w/v) as variables, and found nanoencapsulated imidacloprid (IMI) to be more effective than free imidacloprid in controlling the leafhopper pest population with sustained effectiveness up to 15 days versus the rapid decline of normal pesticide. Cytotoxicity assays revealed significantly reduced cytotoxicity (34–44% at $10 \mu\text{g} \cdot \text{ml}^{-1}$) compared to the plain pesticide (41–44%), which was attributed to controlled-release mechanisms. However, limitations include potential nanoparticle aggregation affecting size distribution, limited environmental fate studies, absence of soil mobility data, and insufficient investigation of the formulation's impact on non-target organisms and ecosystem balance beyond the controlled field conditions.

Nanoemulsions

Nanoemulsions are transparent or translucent emulsions with droplet sizes ranging from 20 nm to 500 nm (K. and Kumar 2022). Various methods can be used to integrate active ingredients into nanoemulsion, including physical adsorption or chemical bonding. This is an efficient way to reduce the efficacy loss caused by leaching, evaporation, and degradation (Chaud *et al.* 2021). Nanoemulsion formulation has better solubility, stability, and permeability, which results in better efficacy of pesticides (Ali *et al.* 2023; Rani *et al.* 2023). Nanoemulsion pesticidal formulations have unique properties like improved chemical stability, controlled release mechanisms, and increased bioavailability (Yadav *et al.* 2021). Nanoemulsions can be further categorized as (1) thermodynamically stable and (2) kinetically stable nanoemulsions based on the kind and quantity of surfactant utilized (Yadav *et al.* 2021). Recent advancements in nanoemulsion-based delivery systems have significantly enhanced the efficacy of agrochemicals and biopesticides. (Gupta *et al.* 2024) reported a nanoemulsified formulation of fenpropathrin that exhibited increased toxicity against third-instar larvae of *Helicoverpa armigera* while simultaneously protecting the active ingredient, underscoring the potential of nanocarrier systems to augment both

efficacy and stability. Similarly, Sharma *et al.* (2020) demonstrated that essential-oil-based nano formulations outperform conventional insecticides and crude oils in pest control, achieving markedly higher mortality across multiple pest and vector species. These formulations leverage enhanced bioavailability and improved cell penetration; their nanoscale droplets facilitate efficient diffusion of active compounds through insect cuticles, leading to superior absorption compared to bulk formulations (Guan *et al.* 2018; Mustafa and Hussein 2020). Further illustrating this principle, Fernandes *et al.* (2014) synthesized a *Manilkara subsericea* based nanoemulsion using low energy phase inversion, achieving 155 nm droplet size with -47 mV zeta potential, which demonstrated 44% mortality against *Dysdercus peruvianus* without acetylcholinesterase inhibition or murine toxicity at $3\text{g} \times \text{kg}^{-1}$. However, there were some limitations including uncharacterized active compound release kinetics, absence of field validation, and lack of comparative cost-stability analysis with conventional pesticides. Study by Wei *et al.* (2022) reported a nano emulsified formulation of fenpropathrin developed using a low energy emulsification method, with an optimal formula of 10% fenpropathrin, 9% surfactant and 8% solvent (S-200) that exhibited increased toxicity against third instar larvae of *Helicoverpa armigera* also showed low toxicity to earthworms (*Eisenia fetida*) and reduced cytotoxicity to human L02 cells, indicating an improved environmental and safety profile while simultaneously protecting the active ingredient, underscoring the potential of nanocarrier systems to augment both efficacy and stability. However, the study has some limitations as it does not include field trials to validate real-world performance, and restricts ecotoxicity testing to only earthworms and one human cell line, omitting other non-target organisms like bees or aquatic species.

Nanoparticulate

Nanoparticles (NPs) are particulate materials with at least one dimension smaller than 100 nm (Khan *et al.* 2019). Nanoparticles exhibit a range of sizes, shapes, and configurations, including spherical, cylindrical, conical, tubular, hollow core, and spiral forms (Swaminathan *et al.* 2021). Nanoparticles can be either amorphous or crystalline, containing single or multiple crystals, and may exist as loose and agglomerated particles (Joudeh and Linke 2022). Nanoparticles may consist of several layers: (a) surface layer, typically composed of metal ions, polymers, surfactants, and other tiny molecules; (b) shell layer, which has a different composition from the core; (c) core layer, the central portion of the nanoparticle that provides structural support (Khan *et al.* 2019; Joudeh and Linke 2022).

Types of nanoparticles

Metallic nanoparticles

Metallic nanoparticles, typically composed of materials such as copper, gold, and silver, range in size from 1 nm to 100 nm. These nanoparticles are widely utilized due to their unique properties, including large surface area, high reactivity, and antibacterial and insecticidal activities. Commonly used metallic nanoparticles include Nano-Ag, Nano-TiO₂, Nano-Au, and Nano-Zn (Anandhi *et al.* 2020). Silver nanoparticles, in particular, exhibit strong antibacterial, antiviral, and antifungal properties (Dikshit *et al.* 2021). Silver nanoparticles, one of the promising nanomaterials, are used as carriers to deliver agrochemicals to their desired location (Gupta *et al.* 2018; Jasrotia *et al.* 2022). Zinc oxide nanoparticles outstanding antibacterial, physical, and optical properties have led to their applications in the development of pesticides (Akbar *et al.* 2020; Jasrotia *et al.* 2022). Green-synthesized metallic nanoparticles offer significant advantages for pest management through their enhanced antimicrobial and insecticidal properties while maintaining environmental sustainability (Dikshit *et al.* 2021). Information on green-synthesized metallic nanoparticles against different crop pests, including their effective dose and mortality, is summarized in Table 1.

Polymeric nanoparticles

Polymer nanoparticles, ranging in size from 1 nm to 100 nm, are synthesized from natural or synthetic

polymers and serve as nanocarriers for insecticides. They are preferred for their biodegradability, cost-effectiveness, and minimal residue, aligning with increasing concerns about environmental protection (Sun *et al.* 2020). Due to their small size, high surface-to-volume ratio, and biocompatibility, polymeric nanoparticles have found widespread use in agricultural applications (Perumal 2022). There are many benefits of polymer nanoparticles, including their nontoxicity, biodegradability, and biocompatibility, as well as their easy availability from marine resources, such as chitin and chitosan, or agricultural resources, such as starch, cellulose, and pectin (Divya and Jisha 2017). Examples of polymers utilized in the delivery of agrochemicals include polyethylene glycol (PEG), poly(vinyl alcohol) (PVA), and poly(lactide-co-glycolides) (PLGA) (Acharya and Pal 2020). Polysaccharides such as alginates, starch, and chitosan are also used for nano formulation preparation (Yadav *et al.* 2021). One of the most promising polymers for the effective delivery of micronutrients and agrochemicals in nanoparticle form is chitosan (Kashyap *et al.* 2015).

Lipid-based nanoparticles

Lipid-based nanoparticles are naturally occurring bioactive compounds known for their excellent entrapment potential, stability, and well-controlled release systems, which enhance bioavailability (Patel *et al.* 2024). Lipid nanoparticles provides a matrix for encasing lipophilic active compounds without the need for organic solvents (Worrall *et al.* 2018). One

Table 1. List of green synthesized metallic nanoparticles

Nanoformulation	Plant used	Vegetable crop pest	Effective dose/Mortality	References
Silver nanoparticles	<i>Azadirachta indica</i>	<i>Bemisia tabaci</i>	1200 ppm/41.11% at 24 h	(Shahid <i>et al.</i> 2022)
Zinc oxide nanoparticles	<i>Zingiber officinale</i>	<i>Spodoptera litura</i>	500 ppm/100% mortality at 144 h	(Thakur <i>et al.</i> 2022)
Copper oxide nanoparticles	<i>Punica granatum</i>	<i>Myzus persicae</i>	4000 ppm/75% mortality at 24 h	(Ghidan <i>et al.</i> 2016)
Iron oxide nanoparticles (FeNPs)	<i>Trigonella foenum-graecum</i>	<i>Tuta absoluta</i>	100 lg · ml ⁻¹ /72% at 96 h	(Ramkumar <i>et al.</i> 2020)
Zinc oxide nanoparticle	<i>Ocimum basilicum</i>	<i>Spodoptera litura</i>	7 ml/ 53% at 72 h	(Shabir <i>et al.</i> 2023)
Silver nanoparticles	<i>Glycine max</i>	<i>Spodoptera litura</i>	6000 ppm/53.33% at 48 h	(Hosamani <i>et al.</i> 2019)
Silver nanoparticles	<i>Datura stramonium</i>	<i>Spodoptera frugiperda</i>	20 ml per 80 ml water/73.3% at 48 h	(Tahir <i>et al.</i> 2022)
Silver nanoparticles	<i>Ocimum basilicum</i>	<i>Spodoptera litura</i>	1500 mg · l ⁻¹ /96.67% at 72 h	(Jafir <i>et al.</i> 2021)
Silver nanoparticles	<i>Borago officinalis</i>	<i>Spodoptera littoralis</i>	4.0 mg · g ⁻¹ /100% at 24 h	(Hazaa <i>et al.</i> 2021)
Silver nanoparticles	<i>Moringa oleifera</i>	<i>Spodoptera frugiperda</i>	500 ppm/95% at 72 h	(Noreen <i>et al.</i> 2024)
Silica nanoparticles	<i>Oryza sativa</i>	<i>Aphis gossypii</i>	200 ppm/73.33% at 72 h	(Pavitra <i>et al.</i> 2018)
Silver nanoparticles	<i>Euphorbia hirta</i>	<i>Helicoverpa armigera</i>	100 ppm/90% at 24 h	(Devi <i>et al.</i> 2014)
Silver nanoparticles	<i>Artemisia herba-alba</i>	<i>Spodoptera littoralis</i>	0.9 ml · ml ⁻¹ /100% at 30 h	(El-Ashmouny <i>et al.</i> 2022)
Silver nanoparticles	<i>Ocimum tenuiflorum</i>	<i>Helicoverpa armigera</i>	0.75%/83.33% at 24 h	(Qamar <i>et al.</i> 2021)
Silver nanoparticles	<i>Moringa oleifera</i>	<i>Spodoptera frugiperda</i>	500 ppm/95% at 72 h	(Noreen <i>et al.</i> 2024)

of the potential nanocarriers is solid lipid nanoparticles (SLNs), which are made of a lipid matrix with a high melting point, and compared to other nano formulations, they also offer several benefits, including improved transport of lipophilic active components, reduced toxicity, superior biocompatibility, and physical stability (Yadav *et al.* 2021). A study conducted by Ganilho *et al.* (2022) evaluated the safety of lipid nanoparticles containing lambda-cyhalothrin on crops such as *Solanum lycopersicum* and *Zea mays*, and soil invertebrates such as *Folsomia candida* and *Eisenia fetida*, and revealed no toxic effects on crop growth and reproduction of soil invertebrates.

Nanoparticle-based RNA pesticides

As a novel approach to pest management, RNA pesticides provide unparalleled specificity and environmental safety relative to conventional chemicals, and artificial microRNAs, hairpin-structured RNAs, and dsRNAs are examples of RNAi triggers that can be carefully engineered to target particular genes in harmful organisms (Qiao *et al.* 2024). RNA interference (RNAi) harnesses sequence-dependent gene silencing by deploying molecules such as siRNAs, miRNAs, and circRNAs to degrade target mRNAs, thereby suppressing essential genes in insect pests and triggering mortality (Wynant *et al.* 2014; Swaminathan *et al.* 2021). Although RNAi pesticides are efficient and safer than conventional pesticides, there are still challenges, such as environmental degradation and inefficient delivery to target insects, including the breakdown of dsRNA by RNases inside the insect intestinal gut lumen or haemolymph, which decreases its efficiency (Pugsley *et al.* 2021). To address the limitations of physical and metabolic instability of RNAi based pesticides in the field, researchers have engineered diverse nanoparticle carriers encompassing dendrimers, inorganic nanostructures, polymeric self-assemblies, and natural-product-based vectors to protect dsRNA and enhance delivery (Dubelman *et al.* 2014; Whitfield *et al.* 2018; Pugsley *et al.* 2021). Various nanoparticles, including chitosan, liposomes, cationic dendrimers, and quantum dots, have been utilized for RNA-based delivery systems. Despite their potential, issues related to production cost and synthesis complexity remain key challenges (Yan *et al.* 2020).

Several studies have convincingly demonstrated the efficacy of nanoparticle-based RNAi delivery platforms for effective pest management. In one notable investigation, Wang *et al.* (2023) developed chitosan (CS) and star polycation (SPC) nanocarriers loaded with dsRNA targeting the *dskr-h1* gene in *Tuta absoluta*. These formulations, when applied as foliar sprays, effectively protected dsRNA from nuclease degradation, facilitated penetration through the leaf cuticle

into the larval gut, and significantly reduced both pupal weight and adult emergence. Importantly, the dsRNA-loaded complexes exhibited no adverse effects on non-target organisms such as *Nesidiocoris tenuis*, supporting their environmental safety (Wang *et al.* 2023). Another compelling example is provided by Thairu *et al.* (2017), who explored aerosolized siRNA–nanoparticle complexes in three aphid species: *Acyrtosiphon pisum*, *Aphis glycines*, and *Schizaphis graminum*. The researchers observed modest but measurable gene silencing of the pigmentation-related *tor* gene in *A. pisum*, and moderate knockdown of the metabolic *bcat* gene in *A. glycines*, with corresponding phenotypic changes. Crucially, the inclusion of nanoparticles significantly enhanced RNAi efficacy compared to treatments with naked siRNA (Thairu *et al.* 2017).

Nanoparticle-mediated delivery of RNAi agents has shown remarkable potential in disrupting key developmental stages of various insect pests. (Jain *et al.* 2022) demonstrated that foliar application of naked dsRNA encapsulated in layered double hydroxide (LDH) nanosheets marketed as BioClay significantly hindered the development of *Bemisia tabaci*. This BioClay spray not only enhanced dsRNA stability and uptake into plant vascular tissues but also effectively arrested multiple life stages of whitefly larvae, with no evidence of non-target effects, underscoring its sustainability in managing sap-sucking pests.

Different Nano formulations discussed above provide a sustainable solution for pest management, utilizing breakthroughs in targeted delivery, RNAi technology, and biodegradable smart materials to transform agricultural practices. To provide a clearer overview of these innovations, Table 2 summarizes the nano formulations along with their target pests, active ingredients, key findings, and existing limitations.

Mechanisms of action

While the toxicity of NPs against insect pests is well documented, a comprehensive understanding of their mechanisms of action remains comparatively limited. Existing research indicates that nanoparticles can enter an insect's body via ingestion, inhalation, or direct cuticular contact, enabling interaction at both cellular and molecular levels (Rai *et al.* 2014; Athanassiou *et al.* 2018). For instance, nanosilica has been shown to disrupt the insect cuticle by adsorbing surface lipids, leading to desiccation and ultimately insect death (Santos *et al.* 2024). Beyond surface interactions, nanoparticles may penetrate cellular membranes and accumulate within intracellular spaces, where they can bind to essential biomolecules such as phosphorus in DNA or sulfur in proteins. This binding can denature enzymes, compromise cellular organelles, and reduce membrane permeability processes that culminate

Table 2. Summary of different nanoformulations key studies

Type of nanoformulation	Active ingredient	Target pest/crop	Major finding	Limitation/Critical analysis	References
Nanoemulsion	citrus peel oil	<i>Tuta absoluta</i> /Tomato	The essential oil (EO) formulations demonstrated potent insecticidal activity, with emulsions causing high mortality in eggs and larvae upon direct contact, while nanoformulations (EO-NPs) were highly effective when ingested by larvae	Future work must validate these results in field conditions and rigorously assess the impact on beneficial non-target organisms	(Campolo <i>et al.</i> 2017)
Nanosuspension	pyridalyl	<i>Helicoverpa armigera</i> /Tomato	Showed increased insecticidal activity with lower LC ₅₀ values compared to technical material and commercial product	The development of novel agricultural chemicals is a prohibitively expensive and lengthy process.	(Saini <i>et al.</i> 2014)
Nanoemulsion	chlorantraniliprole	<i>Helicoverpa armigera</i>	The nanoemulsion was 3.3 times more effective via contact and 2.2 times more effective via ingestion than its commercial counterpart	Insufficient understanding of nanopesticide development and use, regulatory barriers hindering real-world application and unresolved stability issues for commercialization	(Devi <i>et al.</i> 2025)
Nanoemulsion	neem and peppermint oils	<i>Agrotis ipsilon</i>	Dietary exposure to neem and peppermint oils in <i>Agrotis ipsilon</i> larvae resulted in prolonged larval development, higher mortality rates, and the emergence of physical deformities	Additional studies must evaluate sublethal effects for effective integrated pest management (IPM) implementation	(Amin <i>et al.</i> 2019)
Silica nanoparticles	SiO ₂	<i>Tuta absoluta</i>	Silica nanoparticles were as effective as imidacloprid in controlling <i>T. absoluta</i>	More research is needed to assess environmental risks and impacts on non-target organisms	(El-Samahy <i>et al.</i> 2014)
Nanoemulsion	<i>Mentha piperita</i>	<i>Henosepilachna vigintioctopunctata</i>	The nanoemulsion exhibited 3.8x greater potency (LC ₅₀ : 15.84%) against <i>H. vigintioctopunctata</i> compared to the bulk emulsion (LC ₅₀ : 60.25%)	Essential oils are volatile, water-insoluble and exhibit inconsistent chemical composition due to variations in their plant source and extraction process.	(Livingstone and Iqbal 2021)
Biodegradable nanoparticles poly(ϵ -caprolactone)	<i>Azadirachta indica</i> extracts	<i>Plutella xylostella</i>	The nanoparticles achieved 100% larval mortality against <i>Plutella xylostella</i> and improved stability against UV radiation and dispersion in water	Light/temperature sensitivity, low solubility, and degradation limit azadirachtin, while nanoparticles show erratic release and variable pest control	(Forim <i>et al.</i> 2013)
Silica nanoparticles	protease inhibitors	<i>Helicoverpa armigera</i> /Tomato	Soyabean trypsin inhibitor (STI) functionalized silica nanoparticles (SINPs) were effectively absorbed by tomato plants, causing notable growth inhibition in <i>H. armigera</i> larvae	Further research is needed on silica nanoparticle safety, plant uptake mechanisms, and 3-Aminopropyltriethoxysilane (APTES) insect toxicity	(Bapat <i>et al.</i> 2020)

Table 2. Summary of different nanoformulations key studies – continuation

Type of nanoformulation	Active ingredient	Target pest/crop	Major finding	Limitation/Critical analysis	References
Nanoemulsion	<i>Lippia multiflora</i> essential oil	Aphids and <i>Plutella xylostella</i> /Cabbage	The <i>Lippia multiflora</i> essential oil nanoemulsion demonstrated effective pest control against cabbage aphids and diamondback moths, showing substantially lower pest populations than control groups.	Major gaps remain in understanding nanoparticle characteristics (heat stability, size, shape, oil content) and essential oils long-term effects	(Tia <i>et al.</i> 2023)
Polyethylene glycol nanocapsules	diflubenzuron (DFB)	<i>Helicoverpa armigera</i>	Nano-encapsulation of diflubenzuron in Polyethylene glycol nanoparticles (80 ± 20 nm) significantly improves its insecticidal activity against <i>H. armigera</i> , reducing larval LC ₅₀ from 316.87 to 139.36 µg a.i. · ml ⁻¹ and egg LC ₅₀ from 70.74 to 8.58 µg a.i. · ml ⁻¹ via contact action	Further investigation is necessary to determine optimal field deployment strategies and environmental compatibility	(Saber <i>et al.</i> 2025)
Zein nanoparticles	limonene and carvacrol	<i>Spodoptera frugiperda</i>	Zein nanoparticles with limonene/carvacrol were stable, non-phytotoxic, and enhanced <i>S. frugiperda</i> larval mortality via enzyme-triggered release	Suboptimal lethality (30 ± 12%), restricted scope, missing eco-toxicity data, and no comparative pesticide analysis	(Monteiro <i>et al.</i> 2021)
Chitosan nanoparticle	etofenprox	<i>Bemisia tabaci</i>	Nanoencapsulating etofenprox in chitosan dramatically increased its potency (4x lower LC ₅₀) against whiteflies and resulted in faster degradation (shorter half-life) and lower pesticide residues in eggplant fruits compared to the conventional formulation	Study limited to conventional vs nano comparisons; chitosan Nanoparticle ecotoxicity unexamined	(Sabry <i>et al.</i> 2023)
Silicon dioxide nanoparticles and cellulose nanocrystals	emamectin benzoate	<i>Phenacoccus solenopsis</i>	Both nanoformulations significantly enhanced the insecticidal activity (up to 63x more toxic) and protected the pesticide from UV degradation compared to a commercial formulation	Lab-only study; field performance, environmental fate, and non-target impacts (soil/beneficial insects) unassessed	(Elabasy <i>et al.</i> 2019)
Alginate nanocapsules	imidacloprid (IMI)	leafhoppers	Testing revealed the nanoparticle-based pesticide was more potent against target pests while being less toxic than traditional alternatives	Environmental risks from excessive pesticides; research restricted to imidacloprid-alginate NPs and okra efficacy	(Kumar <i>et al.</i> 2013)
Nanoemulsion	fenpropathrin	<i>Helicoverpa armigera</i>	The formulation demonstrated enhanced pesticidal efficacy, decreased ecotoxicity to earthworms, and reduced cytotoxicity to human cells relative to traditional pesticide formulations	Study evaluated just one species under controlled conditions, leaving field performance and prolonged effects unknown	(Wei <i>et al.</i> 2022)

Table 2. Summary of different nanoformulations key studies – continuation

Type of nanoformulation	Active ingredient	Target pest/crop	Major finding	Limitation/Critical analysis	References
Nanoemulsion	<i>Manilkara subsericea</i>	<i>Dysdercus peruvianus</i>	Unlike conventional pesticides, this stable formulation selectively targeted <i>D. peruvianus</i> without affecting mice or acetylcholinesterase function, demonstrating species-specific action	Long-term environmental impact and effects on a broader range of non-target organisms remain unknown	(Fernandes et al. 2014)
Chitosan/Star Polycation (SPc) Nanocarriers	dsRNA (targeting <i>dskr-h1</i> gene)	<i>Tuta absoluta</i>	Protected dsRNA, facilitated leaf cuticle penetration, reduced pupal weight and adult emergence. No adverse effects on <i>Nesidiocoris tenuis</i>	Must improve dsRNA delivery/stability; need better target genes. Nanomaterial applications limited by metabolic interactions and safety concerns	(Wang et al. 2023)
siRNA-Nanoparticle Complex	siRNA (targeting <i>tor</i> , <i>bcat</i> genes)	<i>Acyrtosiphon pisum</i> , <i>Aphis glycines</i> , <i>Schizaphis graminum</i>	Nanoparticle-mediated siRNA delivery improved gene knockdown efficiency (<i>tor</i> in <i>A. pisum</i> ; modest <i>bcat</i> in <i>A. glycines</i> ; moderate) versus naked siRNA, inducing phenotypic effects in <i>A. glycines</i>	Variable gene knockdown (moderate-moderate) across tissues; requires optimization and uptake mechanism studies	(Thairu et al. 2017)
Layered Double Hydroxide (LDH) Nanosheets (BioClay)	dsRNA	<i>Bemisia tabaci</i>	MgFe-BioClay foliar spray reduces <i>B. tabaci</i> viability; adjuvants enhance dsRNA delivery, inducing RNAi (developmental arrest, vascular uptake). No off-target toxicity	Foliar dsRNA dynamics (uptake, translocation, concatemer performance) and transgenerational impacts remain poorly understood	(Jain et al. 2022)
Nanoemulsion	purslane oil, radish seed oil, rosemary essential oil	<i>Aphis gossypii</i> , <i>Tetranychus urticae</i> , <i>Spodoptera littoralis</i>	Nanoemulsions of purslane, rosemary, and radish oils showed significantly higher insecticidal activity against aphids, mites, and cotton leafworm compared to bulk oils, with purslane nanoformulation being most effective	Study was limited to laboratory conditions only with no field validation, long-term stability data, or environmental safety assessment	(Abd-Elhaby et al. 2025)
Neem gum nano formulation	<i>Azadirachta indica</i>	<i>Spodoptera litura</i> , <i>Helicoverpa armigera</i>	Neem Gum Nanoformulation achieved 100% mortality against <i>H. armigera</i> and <i>S. litura</i> pests at just 100 ppm concentration with very low LC ₅₀ values (10.20–12.49 ppm). It significantly disrupted pest detoxification enzymes while being completely safe for earthworms. The nanoparticles were 20–40 nm in size with oleic acid as the main active component	Study was limited to lab conditions without field testing. Long-term stability, effects on beneficial insects or detailed molecular mechanisms and environmental impact on soil microbiota also remains unexplored	(Kamaraj et al. 2018)

in apoptotic or necrotic cell death (Jiang *et al.* 2015; Benelli 2016, 2018). Among the most studied nanoparticles, silver nanoparticles (AgNPs) are reported to induce cytotoxic effects by generating reactive oxygen species (ROS), altering membrane potential, inhibiting protein synthesis, and disrupting DNA replication (Martínez-Cisterna *et al.* 2024). These multifaceted mechanisms significantly impair cellular function and metabolic activity. Furthermore, nano-based pesticide formulations are reported to enhance the permeability and diffusion of active ingredients across the insect cuticle and gut epithelium. This increases both contact and stomach toxicity, improving the speed and efficacy of pest control (Yang *et al.* 2017). The enhanced bioavailability associated with nano formulations has been linked to higher insecticidal activity, reduced pesticide dosages, and prolonged residual effects in field conditions (Saranya *et al.* 2020). Different modes of action of nanoparticles are illustrated in Figure 1.

Advantages of nano-based pesticides

A summary comparing the key advantages and limitations of different nano formulations is provided in Table 3.

Targeted delivery

Nanoparticles offer the advantage of targeted delivery, allowing pesticides to specifically target pests and minimize off-target effects. This is achieved by loading drugs or pesticides into nanoparticles, which can be recognized by specific receptors or antigens on target cells, thereby limiting non-specific distribution. This targeting can be further enhanced by adding ligands

or through precise structural and chemical engineering (Sun *et al.* 2020). Target-specific nanopesticides help reduce the amount discharged into the environment, thereby minimizing harm to non-target plants (Harish *et al.* 2022).

Nanoencapsulation formulations limit dose compared to conventional pesticides while providing maximum efficacy through more target-oriented pesticide action (Yousef *et al.* 2023). Biopolymer-based nanoparticles, in particular, facilitate localized application of insecticides and fertilizers in agriculture without harming the surrounding environment (Sampathkumar *et al.* 2020). Furthermore, nanoparticle-mediated delivery of AI prevents damage to non-target species and reduces the possibility of resistance development (Wu *et al.* 2019; An *et al.* 2022).

Improved stability and solubility

Many bioactive compounds, particularly those used in pest control, are often unstable and poorly soluble in water, limiting their effectiveness. Nanotechnology addresses these challenges by enhancing the stability and solubility of active ingredients, leading to improved absorption and prolonged action (Cao *et al.* 2023). Nanopesticide delivery systems improve the bioavailability of poorly water-soluble pesticides by increasing water solubility compared to their bulk counterpart and improving stability through nanoencapsulation, which prevents premature degradation of AIs (Balaure *et al.* 2017). For example, Liu *et al.* (2019) encapsulated curcumin in zein nanoparticles to enhance its stability and release profile. Nanopesticides also improve the solubility and fat-soluble compounds in aqueous solutions and limit photodegradation, thereby increasing the

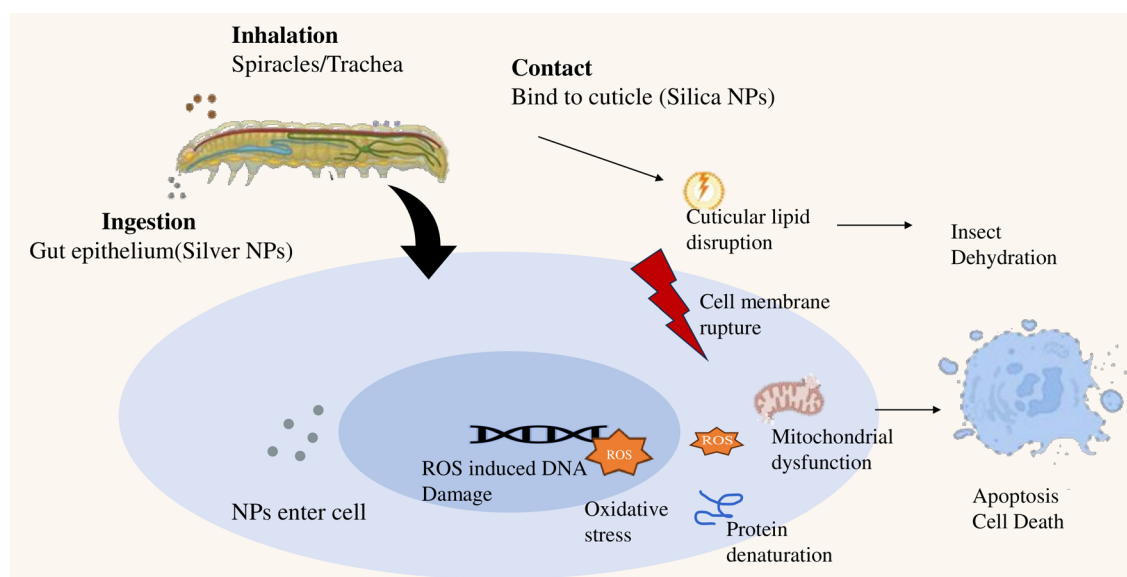


Fig. 1. Different mode of action of Nanoparticles

Table 3. Comparison of different nanoformulation advantages and limitations

Nanoformulation type	Composition/Examples	Key advantages	Key limitations/Drawbacks	References
Nanocapsules	alginate, chitosan, zein. e.g., imidacloprid-alginate nanocapsules	controlled release, protects active ingredients (AIs) from degradation, improves bioavailability	complex synthesis, high production cost, potential polymer toxicity	(Kumar <i>et al.</i> 2013)
Nanoemulsions	oil, water, surfactants, e.g., fenpropathrin nanoemulsion	enhanced solubility, better leaf penetration, improved rain fastness	stability issues (creaming, separation), surfactant phytotoxicity	(Gupta <i>et al.</i> 2024)
Metallic nanoparticles (NPs)	silver, zinc, copper, titanium (e.g., Ag-NPs, ZnO-NPs)	broad-spectrum antimicrobial/insecticidal activity, high reactivity	environmental persistence, soil accumulation, toxicity to non-target organisms	(Gupta <i>et al.</i> 2018; Akbar <i>et al.</i> 2020; Dikshit <i>et al.</i> 2021)
Polymeric nanoparticles	chitosan, polyethylene glycol (PEG), polylactic acid (PLA)	biodegradable, non-toxic, biocompatible, low cost	low encapsulation efficiency for hydrophobic AIs, variable batch to batch quality	(Kashyap <i>et al.</i> 2015)
Lipid based nanoparticles	solid lipids, surfactants	high encapsulation for lipophilic AIs, improved stability, low toxicity	low loading capacity, potential for AI expulsion during storage	(Worrall <i>et al.</i> 2018)
RNAi nanopesticides	chitosan, clay nanosheets (BioClay), cationic polymers	extreme specificity, no residue, targets resistant pests	high cost of dsRNA production, off-target effects, variable efficiency across insect species	(Jain <i>et al.</i> 2022; Wang <i>et al.</i> 2023)

chemical stability of light-sensitive compounds (Zhao *et al.* 2017). Formulating compounds as nanoparticles significantly increases water solubility and dissolution rate without chemically disrupting the pesticide molecule (Margulis-Goshen and Magdassi 2012).

Slow and controlled release

Slow and controlled release nano formulations offer significant agricultural advantages by enabling reduced pesticide dosage, decreased spray frequencies, and minimized environmental contamination through regulated temporal delivery (Kapeleka and Mwema 2024). This sustained-release mechanism reduces the need for frequent pesticide applications, thereby promoting long-term pest management. Furthermore, nanoparticle encapsulation helps extend the shelf life of pesticides by protecting AIs from degradation due to environmental factors, ensuring a consistent and controlled release of AIs over time (An *et al.* 2022). Rather than releasing quickly in a single application, controlled release of nanopesticides increases their efficacy by releasing slowly and remaining active for an extended period (Gupta *et al.* 2023b). Nanopesticide enable controlled release of pesticides to the lowest effective dose to eliminate pest, triggered by specific microenvironmental conditions such as pH, thereby reducing excessive use of harmful pesticides (Balaure *et al.* 2017; Zhao *et al.* 2017).

Challenges and future directions

Toxicity

Metallic nanoparticles are effective for pest control, but their potential toxicity to non-target organisms and humans remains a concern. At high concentrations, nanoparticles can alter plant structure and function, inhibit seed germination and root growth, and decrease biomass production. Their toxicity can lead to membrane breakage, reduced photosynthetic activity, cell damage, and altered gene expression (Muzammil *et al.* 2023). Despite their use in agriculture, the toxicological impacts of nanoparticles on other biological systems, including fungi, insects, and mammals, are not well understood (Paramo *et al.* 2020). Toxicological studies have identified diverse harmful effects, including genotoxicity, oxidative stress through increased ROS production, and DNA damage, which can adversely affect human cells and beneficial environmental microbes (Kumar *et al.* 2018). Specifically, Vannini *et al.* (2014) reported that silver nanoparticles significantly inhibited wheat seed germination and reduced root and shoot lengths, inducing phytotoxic effects that could alter plant development. Similarly, Shaw *et al.* (2014) reported that nano-CuO exposure led to reduced root and shoot growth in Syrian barley seedlings, accompanied by oxidative bursts, highlighting the potential for oxidative damage to plant tissues.

Ghodake *et al.* (2010) also documented cobalt and zinc oxide nanoparticle adsorption in *Allium cepa* roots, disrupting root development, cell division, and chromosomal integrity. Human cell line studies demonstrated acute cytotoxicity of CuO nanoparticles, with an IC_{50} of approximately $2.5 \mu\text{g} \times \text{ml}^{-1}$, observed in human bone marrow mesenchymal stem cells (Mancuso and Cao 2014). In aquatic environments, Gao *et al.* (2017) reported that exposure to nanocadmium prompted elevated activities of antioxidant enzymes including peroxidase, superoxide dismutase, catalase, and anti-superoxide anion enzymes in *Daphnia magna*, indicative of oxidative stress, and caused damage at high concentrations. Collectively, these findings emphasize the necessity for comprehensive risk assessments to evaluate DNA damage, genotoxicity, oxidative stress, phytotoxicity, and ecological impacts, particularly on non-target organisms and ecosystem microbiota, before large-scale application of nanoparticle-based technologies.

Effect on soil and aquatic ecosystem

The widespread application of NPs in agriculture poses significant and complex risks to both soil and aquatic ecosystems, raising serious environmental concerns. Studies consistently demonstrate that metal and metal oxide NPs, such as CuO, ZnO, and AgNPs, exhibit increased toxicity and bioavailability compared to their bulk counterparts (Santos-Rasera *et al.* 2019; Rajput *et al.* 2020). In aquatic environments, NPs induce severe toxicological effects on model organisms. CuO NPs caused oxidative stress, bioaccumulation, and were biotransformed within *Daphnia magna*, disrupting reproduction and survival (Santos-Rasera *et al.* 2019) while AgNPs inflicted significant histopathological damage, oxidative stress, and ionoregulatory dysfunction in zebrafish (*Danio rerio*) by inhibiting gill Na^+/K^+ -ATPase activity (Mitalik *et al.* 2024; Okuthe and Siguba 2025). The terrestrial ecosystem is equally vulnerable, as soil acts as a primary sink for NPs, where they can persist and alter soil chemistry and microbiology. Critical research showed that NPs are readily absorbed by plants, accumulate in root tissues, and translocate to edible parts, thereby entering the food chain and posing a potential threat to higher trophic levels, including humans (Belal and El-Ramady 2016; Rajput *et al.* 2020). For example, CuO NPs accumulated in rice roots and transformed into other copper species, while ZnO NPs negatively impacted soil microbial communities, reducing vital enzymatic activities and disrupting nutrient cycles (Belal and El-Ramady 2016; Rajput *et al.* 2020). This interplay of high persistence, increased uptake, and potential for trophic transfer underscores the urgent need for stringent regulatory frameworks and the development of

eco-friendly, biodegradable nano formulations to mitigate the long-term ecological impact of nanotechnology in agriculture (Belal and El-Ramady 2016; Rajput *et al.* 2020).

Regulatory issues

The regulatory framework governing the application of nanoparticles in agriculture is still at an early stage, requiring robust guidelines to ensure safety for farmers, consumers, and the environment. Tang *et al.* (2023) emphasized the necessity for international collaboration among regulatory authorities to develop unified standards and protocols for nano-agrochemicals. Compared to their bulk counterparts, nanomaterials exhibit unique behaviors and biological interactions that may create novel risks, underlining the importance of thorough evaluation of toxicity, exposure routes, and environmental and human health impacts (Bratovic *et al.* 2023; Kumari *et al.* 2023). These studies highlighted that regulatory authorities must assess the toxicity of nanoparticles to non-target organisms and monitor their environmental accumulation to avoid ecological harm. Ghosh *et al.* (2025) called for the establishment of standardized testing and approval procedures for nanopesticides, stating that coherent guidelines are essential to streamline regulatory processes and facilitate safe adoption. The slow and inconsistent regulatory review and approval landscape, as noted by Rehmanullah *et al.* (2020), eroded confidence among researchers and agricultural practitioners. Atanda *et al.* (2025) pointed out that consumer acceptance is pivotal; effective public outreach, transparency, and trust-building are critical for the large-scale adoption of agricultural nanotechnologies. Collectively, these insights signal an urgent need for coordinated policymaking, harmonized testing standards, and proactive engagement with stakeholders to safely integrate nanopesticides into sustainable agriculture. To address regulatory challenges for nano formulations, a focused approach is essential. Beyond the information about active ingredients, advanced characterization for providing detailed data on nanoparticle size, distribution, surface charge, and composition should also be mandatory. Nanopesticides often face shelf-life challenges like aggregation and degradation, but these can be solved by formulating them as dry powders, using natural stabilizers like lignin, and packaging them in airtight, light-resistant materials. Toxicological studies must expand beyond standard ecotoxicology to include nano-specific risks, such as higher bioavailability, unique mechanisms of action, and long-term sublethal effects on pollinators and soil health. Additionally, new Environmental Risk Assessment (ERA) protocols should be developed to evaluate the distinct exposure routes and potential hazards of

nano formulations in varied vegetable cropping systems. These steps will ensure safer and science-based regulatory approval.

Cost and production

Nanotechnology offers transformative potential for agriculture, yet it is not without significant challenges. Key limitations include steep development and scaling costs, the need for specialized equipment, and the potential for health and environmental hazards (Rana *et al.* 2024). These financial and technical barriers pose adoption hurdles for small-scale farmers, with the expense of large-scale nano formulation production notably limiting accessibility (Jakhar *et al.* 2022; Yadav *et al.* 2023). Moreover, the manufacturing of consistently sized nanoparticles in bulk remains costly and technically demanding (Gupta *et al.* 2023a). Although several companies have patented various nanoproducts, their commercial availability remains limited, indicating that further development is required before widespread agricultural rollout (An *et al.* 2022). To overcome this challenge, government agencies, businesses, and research institutes must work together. Partnerships, research funding, and financial incentives can help lower costs and increase use of nano-agrochemicals by agricultural workers (Tang *et al.* 2023). Moving forward, research should concentrate on scaling up production economically while ensuring that nano-agrochemicals remain affordable and deployable across diverse agricultural communities.

Conclusion

Nano formulations offers an exciting new possibility for sustainable insect pest management. Advances in nanocarriers, nanoemulsions, RNAi delivery systems, smart nanotechnologies, and biodegradable materials are transforming the way pest management is approached. By enhancing pesticide efficacy and minimizing environmental impact, these innovations pave the way for more precise, efficient, and eco-friendly pest management strategies. Despite the effectiveness of nano-based formulations, concerns persist regarding their potential toxicity to non-target organisms, the regulatory framework governing their use, and the cost of large-scale production. Addressing these challenges requires extensive research and the integration of biodegradable materials such as chitosan, PEG, which are cost-effective, environmentally safe, and non-toxic to non-target species and humans. Additionally, encapsulating Nano formulations with insecticidal phytochemicals and implementing them as part of an integrated pest management (IPM) strategy

could enhance their effectiveness in vegetable crop pest management. Future research should focus on optimizing synthesis processes, improving cost effectiveness and evaluating large scale field applications to promote the sustainable and responsible implementation of nanotechnology in agriculture.

Ensuring safety and long-term sustainability requires adopting “safe by design” principles utilizing biodegradable, waste-derived nanocarriers (e.g. chitosan, nanocellulose). This approach inherently addresses scalability and cost-effectiveness by simplifying production and leveraging low-cost materials, while their clear environmental profile can expedite the establishment of a robust, science-based regulatory framework for nano agricultural products.

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