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Application of nanoparticles for targeted management of pests, pathogens and disease of plants

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ABSTRACT

Pest and disease infestations pose a significant threat to global food security, drastically lowering plant health and agricultural productivity. Conventional pest management methods, primary reliant on chemical pesticides and fertilizers, often present limited long-term effectiveness and are associated with significant environmental and health risks. In response to these challenges, nanotechnology has arisen as a revolutionary instrument in modern agriculture. Nanoparticles (NPs) have unique physical and chemical properties such as high surface area, adjustable surface charge, and controlled release patterns. These properties enable precise delivery of farm chemicals to specific plant tissues or pest targets. This approach improves effectiveness and reduces unintended environmental exposure. Nanoparticles application in the form of nanofertilizers and nanopesticides provides a sustainable alternative to traditional agricultural inputs, offering controlled release, increased bioavailability, and decreased toxicity. This method not only promotes pest and disease control in plants but reduce toxicity. This review explores the role of nanoparticles in pest and disease managements, their mechanisms of action, and their potential contributions to environmental conservation and agricultural sustainability.

1. Introduction

The global population is expanding rapidly, and by 2050, it is projected that food production must increase by approximately 60 % to meet the needs of over 10 billion people. However, achieving this goal is increasingly challenging due to the substantial crop losses already caused by pests and diseases (Falcon et al., 2022; Sridhar et al., 2023). These biotic stresses remain among the most formidable barriers to agricultural productivity. Each year, plant pests and diseases are responsible for the destruction of up to 40 % of key staple crops such as maize, potatoes, rice, soybeans, and wheat, resulting in annual economic losses estimated at around 220 billion USD (Begna, 2020). The impact of plant diseases varies widely depending on the crop and geographic region, with certain diseases posing serious threats to global food security. For instance, the fungal pathogen responsible for rice blast can reduce yields by 10–35 %. Similarly, *Fusarium graminearum*, a notorious fungus affecting wheat, not only diminishes crop yields but also contaminates grains with harmful mycotoxins, rendering them unsafe for consumption (Islam et al., 2022; Singh et al., 2023). Viral infections also contribute significantly to crop losses. A notable example is the cassava mosaic virus, which leads to the loss of approximately 25 million tons of cassava annually, thereby threatening the food security of nearly 500 million people who rely on cassava as a dietary staple. These figures highlight the urgent need for innovative, effective, and sustainable plant disease management strategies that can overcome the limitations of conventional approaches (Torkpo and Amponsah, 2023). Although traditional chemical pesticides have been widely used to control diseases in major crops, their application raises serious concerns regarding environmental safety and human health. Excessive and indiscriminate use of synthetic fertilizers and pesticides has led to significant environmental degradation, including reduced soil fertility, water contamination, and harm to non-target organisms such as

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pollinators and beneficial insects. Moreover, conventional pesticides often degrade or leach into the environment before reaching their intended targets, with sunlight, water, and soil conditions reducing their efficacy. These shortcomings underscore the pressing need for more targeted, efficient, and environmentally friendly solutions in plant disease management (Souto et al., 2021; Kaur et al., 2021).

The application of nanotechnology in agriculture, particularly for plant disease management, represents a promising and innovative strategy that leverages the distinctive properties of nanoscale materials to overcome longstanding challenges in crop protection. Nanomaterials such as metallic nanoparticles, metal oxides, organic nanoparticles, and composite materials are gaining recognition as powerful tools for managing a wide range of plant pathogens, including bacteria, fungi, viruses, and nematodes (Fu et al., 2020; Li et al., 2020). This approach not only enhances disease control but also contributes to improved crop yield, thereby addressing the growing global demand for food. Nanopesticides, a subset of this technology, are designed to release active ingredients precisely where and when they are needed, thus reducing off-target effects and environmental impact (Abdollahdokht et al., 2022; World Health Organization, 2023). In addition to pest control, some formulations also promote plant growth, supporting integrated and sustainable crop management. Recent technological advances have provided compelling evidence of the efficacy of nanoparticles. For instance, soursop (*Annona muricata*) leaf extract formulated as nanoparticles was shown to reduce locust populations by over 70 % at concentrations as low as 250 g/L in *Pterocarpus indicus* fields (Santos et al., 2023; Irwan et al., 2021). Similarly, Datura stramonium extract, when used at 65 % nanoparticle strength, yielded 80 % healthy cucumber fruits and harvests of 250 kg per hectare comparable to the 254 kg per hectare achieved with conventional chemical pesticides (Tavares et al., 2021). Studies by El-Baky and Amara (2021) demonstrated that treatments based on organic nanoparticles can control up to 75 % of fungal diseases and 67 % of pests, while humic substances showed 74 % effectiveness against fungal and bacterial infections (Ma et al., 2024). These findings highlight that nanoparticle-based and botanical formulations can achieve high efficacy at lower dosages, offering both environmental benefits and economic advantages by lowering production costs and improving benefit-cost ratios (Mittal et al., 2020). Furthermore, the rapid biodegradability and targeted activity of nanoparticles make them safer for non-target organisms such as pollinators, reinforcing their value as sustainable solutions. Collectively, these advancements underscore the technical effectiveness and environmental compatibility of nanotechnology-based plant disease and pest control, positioning it as a transformative tool in modern agricultural practices (Côa et al., 2020).

Scientists have engineered smart nano-based delivery systems capable of releasing pesticides with remarkable precision, guided by specific environmental and biological stimuli. These advanced systems are designed to respond to factors such as pH fluctuations, temperature changes, light exposure, redox conditions, and the presence of certain enzymes, allowing for the controlled release of active ingredients at the most effective time and location. This targeted approach enhances pest control efficacy while significantly minimizing chemical waste and environmental contamination. The biocompatibility and relatively straightforward synthesis of many nanomaterials further support their suitability for agricultural applications; nonetheless, thorough evaluation of their toxicological and ecological safety remains essential before widespread deployment (Shen et al., 2023; Ullah et al., 2024). As depicted in Fig. 1, the disease triangle framework highlights the critical interplay among a susceptible host, a virulent pathogen, and favorable environmental conditions in the onset and progression of plant diseases, providing a foundational context for precision-targeted interventions.

This study highlights recent scientific advances in nanotechnology for plant disease management, while critically assessing safety concerns to support informed decision-making on its integration into agriculture. It identifies key research gaps and regulatory challenges that must be

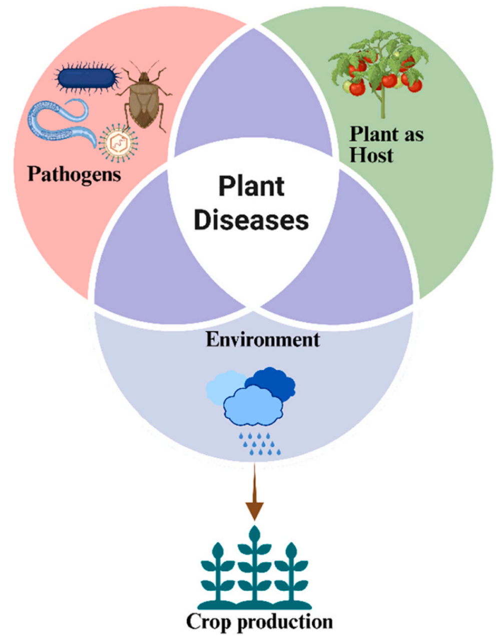

Fig. 1. The Disease Triangle: Interactions among host, pathogen, and environment in plant disease development (Created in https://biorender.com).

addressed to enable the global commercialization of smart nanopesticides. The review explores the mechanisms, by which different nanoparticles such as metallic, metal oxide, organic, and hybrid, which interact with plant pathogens and host systems, providing a basis for evaluating their efficacy across diverse crops. It further examines nanoparticle applications against bacterial, fungal, viral, and nematode diseases, tailoring strategies to the specific challenges posed by each pathogen type. Emerging innovations such as stimuli-responsive delivery systems and multifunctional nanoparticles are also discussed for their dual role in disease control and plant growth enhancement. The review concludes with an evaluation of environmental and toxicological safety, regulatory frameworks, and global guidelines (e.g., FAO, WHO, EPA), emphasizing the need for policy harmonization. Current commercialization efforts, remaining research priorities, and practical deployment considerations are summarized to provide a comprehensive understanding of this fast-evolving field.

1.1. Advances in nanotechnology for pest detection and targeted delivery

Nanoparticles (NPs) serves as transformative tools in modern agriculture, addressing critical challenges in pest management, crop production, and environmental sustainability. Harnessing their unique physicochemical properties, NPs provide precision-based solutions that improve the effectiveness of traditional methods while reducing ecological impact (Singh et al., 2024a, 2024b; B.V. Singh et al., 2024; G. Singh et al., 2024; M. Singh et al., 2024; N.B. Singh et al., 2024). This review synthesizes recent advances in NP applications for plant protection, focusing on smart pest monitoring, targeted delivery systems, RNA interference (RNAi) technologies, and nano-enhanced pesticides. Supported by multidisciplinary research, these innovations offer scalable strategies to mitigate biotic stresses and promote sustainable agricultural practices (Kumar et al., 2023; Jafir et al., 2023). Fig. 2 illustrates the application of nanotechnology in agriculture, highlighting three key domains where nanomaterials contribute to improved crop health and productivity.

Conventional pest monitoring methods, which largely depend on visual inspections or the routine application of broad-spectrum pesticides, often fail to detect infestations at their incipient stages, leading to delayed responses and excessive chemical use. In contrast, nanosensors

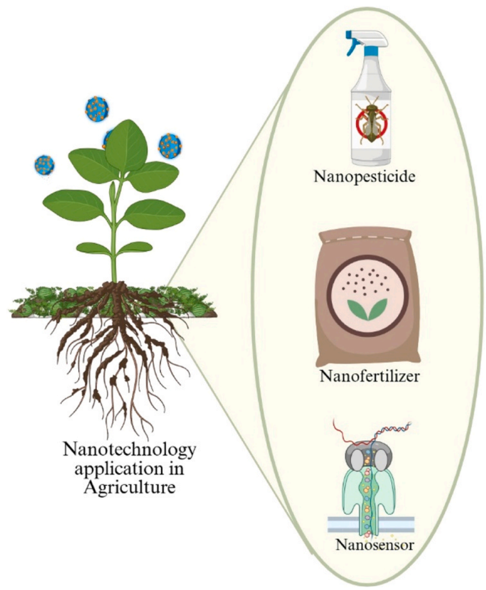

Fig. 2. Schematic representation of key applications of nanotechnology in agriculture (Created with BioRender.com).

offer highly sensitive and specific detection by recognizing chemical cues or signaling molecules emitted by pests, enabling earlier intervention and reducing crop losses (Farnum, 2023). For instance, silicon dioxide-based microelectromechanical system (MEMS) sensors can selectively detect female sex pheromones of *Helicoverpa armigera* and *Bactrocera oleae*, which are two globally significant pests responsible for infesting over 150 crop species. These sensors function in real time, equipping farmers with timely data to implement proactive measures such as crop rotation or targeted pesticide application before pest populations proliferate (Shi et al., 2023; Wu et al., 2022). Complementary advancements include carbon nanotube (CNT)-based sensors capable of detecting volatile organic compounds (VOCs) released by aphids at concentrations as low as 1 part per billion (ppb), and gold nanoparticles functionalized with antibodies that recognize proteins secreted by *H. armigera* larvae for species-specific detection. These innovations have been shown to reduce premature pesticide applications by 30–50 %, thereby mitigating the risk of resistance development and environmental degradation (Yu et al., 2024; Kumar et al., 2023; Chen et al., 2021).

Nanosensors are increasingly integrated into smart trapping systems that combine attractants such as ultraviolet light and pheromones with real-time communication capabilities. A good example is traps embedded with VOC-detecting nanosensors that can differentiate among pest species, significantly reducing the capture of non-target organisms. When networked through the Internet of Things (IoT), these smart traps enable geospatial mapping of pest activity, supporting dynamic, site-specific pest management. A field study on cotton farms demonstrated that sensor-equipped traps reduced pesticide costs by 40 % (Tiwari et al., 2024; Martinazzo et al., 2022). In tandem with detection technologies, nanoencapsulation techniques enhance pesticide delivery by enclosing active ingredients within polymeric coatings such as polyethylene glycol (PEG) or chitosan that stabilize the compound and permit controlled release. For instance, acetamiprid encapsulated in PEG-aluminum nanoparticles showed a 2.3-fold increase in contact toxicity against *Aphis gossypii* relative to its conventional formulation. The polymer matrix responds to environmental triggers, such as pH shifts or enzymatic activity, ensuring that the pesticide is released only under pest-related conditions (Mondéjar-López et al., 2024). Further breakthroughs include the use of graphene oxide sheets to encapsulate potassium nitrate (KNO_3), enabling a 72-hour delayed release tailored to the nutrient uptake cycles of crops. Additionally, copper selenide-chitosan nanocomposites have been used to develop chalcogenic insecticides that increase larval mortality in *Spodoptera litura* by 35 % (Fu et al., 2023). Stimuli-responsive nanoparticles (NPs) release their payloads in response to specific biotic or abiotic cues. For example, chlorpyrifos-loaded alginate nanoparticles disintegrate in the alkaline midgut of *Aedes aegypti* larvae, ensuring site-specific toxicity. Ligand-functionalized nanoparticles further refine this specificity; folic acid-conjugated nanoparticles, for instance, preferentially bind to *Plutella xylostella* larvae, which overexpress folate receptors, thereby minimizing collateral damage to beneficial pollinators (Maan et al., 2024; Schorr et al., 2025). Table 1 provides an overview of these nanoparticle delivery systems, including the types of nanomaterials used, targeted pests, and measurable improvements in pest management outcomes.

RNAi technology silences pest genes by delivering double-stranded RNA (dsRNA) to disrupt key physiological functions. However, dsRNA degradation in plant tissues and insect stomachs limits its efficacy. Carbon dots (CDs), nanoparticles smaller than 5 nm, sidestep these problems by complexing with dsRNA and penetrating plant cell walls. In Nicotiana benthamiana, CD-dsRNA sprays repressed GFP transgenes with 90 % efficiency, whereas tomato tests achieved 70 % suppression of magnesium chelatase genes, generating chlorosis (Lu et al., 2023; Siddique et al., 2025). In cotton, dsRNA targeting the P450 monooxygenase gene of *Helicoverpa armigera* was delivered using layered double hydroxide (LDH) nanoparticles. The gene responsible for detoxifying gossypol was inhibited, resulting in a 65 % decrease in larval survival. Similarly, the delivery of CD-mediated dsRNA targeting chitin synthase genes in *Tribolium castaneum* led to 80 % mortality among stored grain pests. In contrast to traditional insecticides, RNA interference (RNAi) demonstrates species selectivity, thereby protecting beneficial insects such as *Apis mellifera* (Tang et al., 2023; Zou et al., 2025).

Nanoformulations increase traditional insecticides by enhancing solubility, bioavailability, and residual action. Avermectin B1, a macrocyclic lactone, was encapsulated in silica nanocapsules to lengthen its half-life from 6 h to 14 days under UV exposure. Field experiments against *Tetranychus urticae* demonstrated 31.5 % increased mite mortality compared to emulsifiable concentrates. Nanogels, such as poly(N-isopropylacrylamide)-imidacloprid composites, release pesticides in response to temperature changes, matching with pest activity peaks. This reduced spray frequency by 50 % in soybean aphid control (Jiang et al., 2022; Safar et al., 2022). Physicochemical properties driving efficacy NPs boost pesticide performance through high surface area-to-volume ratio, which increases interaction with insect cuticles or digestive systems. Silver nanoparticles (AgNPs) with 10 nm diameters demonstrate 3 × greater antifungal activity than bulk silver due to enhanced reactive oxygen species (ROS) production (Wang et al., 2024). Mesoporous silica nanoparticles (MSNs) loaded with abamectin demonstrate effective systemic movement in plants, translocating from tomato roots to leaves via both apoplastic and symplastic pathways, thereby providing whole-plant protection. Additionally, chitosan-coated zinc oxide (ZnO) nanoparticles enable slow and sustained release of tebuconazole over 21 days, maintaining fungicidal concentrations below groundwater contamination thresholds. These nanoformulations enhance efficacy, reduce application frequency, and minimize

Table 1
Delivery mechanism of nanoparticles.

Delivery mechanism	Example nanoparticle	Target pest	Efficacy improvement
pH-Responsive Release	Alginate-chlorpyrifos NPs	*Aedes aegypti*	40 % larval mortality (Dos-Santos et al., 2023)
Ligand-Conjugated NPs	Folic acid-pesticide NPs	*Plutella xylostella*	55 % specificity (Wu et al., 2021)
Polymer Nanoencapsulation	PEG-aluminum-acetamiprid NPs	*Aphis gossypii*	2.3 × contact toxicity (Ikawati et al., 2024)

environmental impact (Banerjee et al., 2021; Abd-Ellatif et al., 2022; Daqa et al., 2023).

1.2. Objective of targeted delivery systems using nanoparticles

The main purpose of nanotechnology for pest management is creating better techniques to deliver active substances more accurately and control their substance release. Nanoformulation technology involves encapsulating pesticidal agents within nanoparticles to enable targeted delivery and improved pest control efficiency (Hajji-Hedfi and Chhipa, 2021). Nanoencapsulation enhances the lifespan and effectiveness of pesticides by improving their stability and controlled release. This technology reduces labor costs, increases delivery precision, and improves the dispersion of active ingredients, as demonstrated in studies by Kumar et al. (2019) and An et al. (2022). Nanoencapsulation technology delivers four major advantages by boosting water-insoluble active component distribution, strengthening formulation stability, removing traditional pesticide harmful organic solvents, and extending duration of efficacy (Sasson et al., 2007). Nanotechnology reduces pesticide usage during pest control, thereby minimizing the environmental impact of pest management activities (Zannat et al., 2022). This approach aims to prevent pesticide-induced damage to soil health and biodiversity by promoting the formation of optimal nitrifying and denitrifying bacterial populations (Zhang et al., 2021).

2. Mechanisms and applications of nanoparticles

The integration of nanoparticles into plant protection strategies offers advanced solutions for managing pests and diseases. Due to their distinct nanoscale attributes, nanoparticles enable precise intervention at the molecular and cellular levels (Hu et al., 2020). This section describes the fundamental mechanisms by which nanoparticles engage with plant systems and pathogens while also reviewing their practical applications in managing agricultural diseases and pests.

2.1. Applications of nanoparticles in plant disease and pest management

The revolutionary integration of nanotechnology into agricultural disease and pest management represents a paradigm shift towards sustainable and precision-based crop protection strategies (Javaid et al., 2024). Nanoparticles help counter rising pesticide resistance, lessen environmental contamination, and cut chemical inputs in crop production (Acharya and Pal, 2020). The efficacy of nanoparticles in plant protection stems from their unique physicochemical properties, including enhanced surface area-to-volume ratios, time-regulated delivery profiles, and improved bioavailability of active compounds (Akpinar et al., 2021).

2.1.1. Nanoparticles for disease control

Engineered nanoparticles now play pivotal roles in plant disease control due to their unique physicochemical properties, such as high surface area and controlled release capabilities (Kumar, 2020). These nanoparticles are targeted at specific pathogens, including bacteria, fungi, viruses, and nematodes, enhancing the precision and efficacy of disease management strategies (Bang et al., 2009). Metallic nanoparticles (such as silver, copper, and zinc oxide), organic nanoparticles, and composite formulations have demonstrated strong antimicrobial activity and the ability to inhibit pathogen growth and disrupt infection processes (Sánchez-López et al., 2020). Nanoparticles help deliver active compounds directly where needed and release them slowly, which means fewer chemical applications, less harm to the environment, and better practices for protecting crops sustainably (Chen et al., 2021).

2.1.1.1. Silver nanoparticles. Silver nanoparticles (AgNPs) are among the most intensively studied antimicrobial materials in crop protection, increasingly recognized as effective and eco-compatible substitutes to conventional fungicides (Ogbogo et al., 2022). These nanoparticles, ranging from 1 to 5 nanometers in size, demonstrate wide-ranging antimicrobial activity against fungal, bacterial, and viral plant pathogens through multiple synergistic mechanisms that enable close interaction with pathogens and disruption of their growth before infections can establish (El-Baky and Amara, 2021). The antimicrobial efficacy of AgNPs operates primarily through membrane disruption, generation of reactive oxygen species (ROS), interference with enzymatic processes, and the release of silver ions that penetrate microbial cell membranes, disrupt important cellular functions, and ultimately cause cell death (More et al., 2023). Studies have shown that AgNPs at concentrations as low as 50–100 ppm can significantly inhibit mycelial growth of major soil-borne pathogens including *Rhizoctonia solani*, *Fusarium oxysporum*, *Sclerotinia sclerotiorum*, and *Sclerotium rolfsii*, achieving inhibition rates exceeding 67 % against these devastating fungal pathogens (Dutta et al., 2023). AgNPs are especially effective against harmful fungi such as *Bipolaris sorokiniana* and *Magnaporthe grisea*, which cause serious crop losses. Against bacterial pathogens, AgNPs exhibit remarkable effectiveness in controlling diseases such as pepper anthracnose caused by *Colletotrichum* species, demonstrating their utility across a range of bacterial pathogens and making them valuable in integrated disease management (Bibi et al., 2023). Field trials have demonstrated that AgNPs applied at 50 ppm before disease outbreak achieved only 9.7 % disease incidence compared to 84.1 % in untreated controls, significantly outperforming commercial fungicides (Jahan et al., 2024). The nanoparticles cause detrimental effects on mycelial growth and induce morphological disruptions in pathogen structures as observed through scanning electron microscopy (Jo et al., 2009). Applying silver nanoparticles (AgNPs) early in the infection cycle enhances disease control by effectively inhibiting pathogen development, which reduces the need for repeated chemical applications (Tariq et al., 2022). This approach supports sustainable farming practices by minimizing chemical inputs and lowering environmental impact, thereby promoting an overall sustainable environment.

Fig. 3 shows how silver nanoparticles attack bacteria by releasing silver ions that damage bacterial cells and stop infections.

2.1.1.2. Copper nanoparticles. Copper nanoparticles (CuNPs) are economical and eco-friendly substitute for conventional copper-based fungicides (Abd-Elsalam, 2022). Their nanoscale dimensions markedly improve antifungal and antibacterial effectiveness by augmenting surface area and reactivity, resulting in superior pathogen suppression at reduced dosages. The antifungal mechanisms of CuNPs involve induction of oxidative stress, disruption of cell membranes, interference with cellular metabolism, and inhibition of ergosterol biosynthesis, which compromises fungal cell wall integrity and increases susceptibility to oxidative damage (Ali et al., 2024). RNA-sequencing studies have further revealed that CuNPs modulate fungal detoxification pathways,

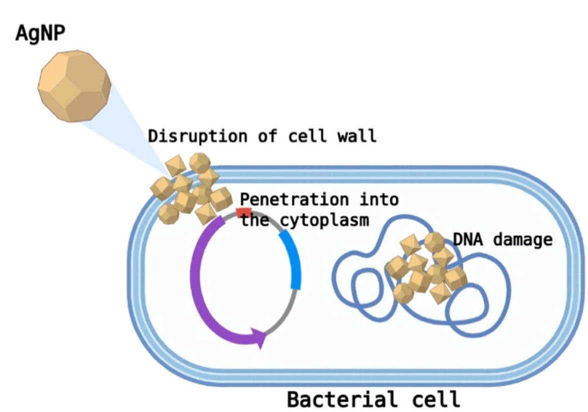

Fig. 3. AgNp antimicrobial action (Created in https://biorender.com).

including copper transporter activity and endosomal sorting complexes, contributing to their potent bioactivity (Hernadi, 2020). Biogenically synthesized CuNPs, produced via green synthesis methods using plant extracts or fungal species such as *Aspergillus flavus*, exhibit superior antifungal efficacy compared to chemically synthesized counterparts (Vincent et al., 2022). These nanoparticles, typically ranging from 5 to 12 nm in size, have demonstrated significant inhibitory effects against major phytopathogens including *Fusarium oxysporum*, *Fusarium culmorum*, *Fusarium equiseti*, *Aspergillus niger*, and *Alternaria alternata*, which are responsible for devastating diseases such as root rot and wilt across diverse crops (Vera-Reyes et al., 2022).

In addition to their antifungal activity, CuNPs possess substantial antibacterial effects against pathogens like *Pseudomonas syringae*, a deadly agent of plant diseases. Importantly, CuNPs exhibit selective toxicity by sparing beneficial soil microorganisms such as *Rhizobium* species and *Trichoderma harzianum,* which play critical roles in nutrient cycling, plant growth promotion, and soil health maintenance (Ma et al., 2022). This selective inhibition supports targeted disease control strategies that preserve the balance of the soil microbial community. The enhanced bioavailability and improved cellular uptake of CuNPs compared to bulk copper compounds underlie their increased antimicrobial potency (Woźniak-Budych et al., 2023). Green synthesis approaches not only improve the stability and efficacy of CuNPs but also enhance their environmental compatibility, reducing potential phytotoxic effects and supporting sustainable agricultural practices (Manjula et al., 2022).

2.1.1.3. Zinc oxide nanoparticles. Zinc oxide nanoparticles (ZnO NPs) combine strong antimicrobial activity with high biocompatibility and low environmental persistence. Their potent antifungal and antibacterial activities arise from multiple mechanisms, including photocatalytic generation of reactive oxygen species (ROS), direct cellular contact, and metal ion release, which collectively disrupt pathogen cell integrity and metabolic functions (Jin and Jin, 2021). The antifungal efficacy of ZnO NPs has been extensively demonstrated against a broad spectrum of plant pathogenic fungi. Green synthesis approaches utilizing plant extracts such as neem, marigold, and ginger have produced ZnO NPs with remarkable inhibitory effects (Abomuti et al., 2021; Farooq et al., 2022). According to research by de Alba et al. (2023) and Farooq et al. (2022), neem-derived ZnO NPs at 500 ppm achieved 83.33 % growth inhibition against *Sclerotium rolfsii*, while marigold-derived particles inhibited *Colletotrichum lindemuthianum* by 68.88 %. Moreover, mycosynthesized ZnO NPs using *Trichoderma harzianum* exhibited superior antifungal activity against *Alternaria brassicae* (91.48 % inhibition at 200 μg/mL), outperforming chemically synthesized particles (79.62 %) and the commercial fungicide mancozeb (82.96 %) (Shobha et al., 2020). The antimicrobial efficacy of ZnO NPs is strongly influenced by particle size, with smaller nanoparticles (12–41 nm) demonstrating enhanced penetration and increased surface interactions with fungal cells, thereby improving pathogen suppression (Jin and Jin, 2021). In addition to controlling pathogens, ZnO NPs serve as vital micronutrients that promote plant growth by enhancing photosynthetic efficiency, stress tolerance, and overall vigor (Singh et al., 2024a, 2024b; B.V. Singh et al., 2024; G. Singh et al., 2024; M. Singh et al., 2024; N.B. Singh et al., 2024). Beyond disease management, ZnO nanoparticles exhibit significant potential in postharvest crop protection. Their ROS-mediated antimicrobial action effectively degrades fungal pathogens such as *Botrytis cinerea* and *Penicillium expansum*, inhibiting the formation of reproductive structures like conidiophores and conidia (Sharifan et al., 2021; Christ et al., 2025). This targeted inhibition reduces disease spread during storage and transit, thereby preserving crop quality and extending shelf life. Consequently, ZnO NPs contribute to reducing reliance on conventional chemical fungicides, aligning with sustainable and health-conscious approaches to food preservation (Lisboa et al., 2024).

2.1.1.4. Chitosan nanoparticles. Chitosan nanoparticles (ChNPs) are biodegradable, biocompatible nanomaterials derived from chitosan that provide multiple antimicrobial functions. Its intrinsic antimicrobial properties, combined with the ability to stimulate plant defense responses, make it highly effective tools for sustainable disease management in agriculture (Jafernik et al., 2023). The antimicrobial mechanisms of ChNPs primarily involve electrostatic interactions between the positively charged (polycationic) chitosan molecules and the negatively charged microbial cell surfaces, including bacterial lipopolysaccharides and fungal cell wall components (Yan et al., 2021). This interaction leads to membrane permeabilization, disruption of membrane integrity, leakage of intracellular contents, and interference with essential cellular processes such as DNA transcription and enzyme synthesis, ultimately restricting pathogen development (Sahu et al., 2022). ChNPs can infiltrate fungal cell walls, further interfering with fungal growth and viability. ChNPs can also activate plant defense systems by enhancing the activity of key enzymes involved in resistance, such as superoxide dismutase, peroxidase, and phenylalanine ammonia lyase (Iqbal et al., 2024). This dual protective effect which entails combining pathogen inhibition with boosted host immunity has been demonstrated across a range of plant diseases, including fungal pathogens like *Pyricularia grisea* (causal agent of blast disease in finger millet), bacterial pathogens affecting tomato and other crops, and viral infections (Dehbi et al., 2023). The antiviral efficacy of ChNPs is particularly notable against plant viruses such as Bean yellow mosaic virus (BYMV) (El Gamal et al., 2022). At concentrations of 300–400 mg/L, ChNPs completely inhibit viral infectivity and accumulation by producing defective viral particles, disrupting replication cycles, and significantly upregulating plant defense genes, including pathogenesis-related (PR-1) proteins (Abdelkhalek et al., 2021).

ChNPs also serve as versatile carriers for bioactive compounds, enabling controlled release and targeted delivery of antimicrobial agents. The ionic gelation synthesis method allows incorporation of various active ingredients such as copper, zinc, salicylic acid, hexaconazole, and thymol (Jafernik et al., 2023). For example, thymol-loaded chitosan nanoparticles (TCNPs), sized between 54 and 250 nm, exhibit potent antibacterial activity against *Xanthomonas campestris pv. campestris*, the causative agent of black rot in cruciferous crops, by inhibiting biofilm formation, reducing exopolysaccharide production, and damaging bacterial membranes (Sreelatha et al., 2022). Metabolomic analyses reveal that TCNPs induce comprehensive disruption of bacterial cellular metabolism. The advantage properties of ChNPs to the external environment, includes biodegradability, biocompatibility, and low toxicity, which underscore their promise as sustainable alternatives to conventional agrochemicals (Sreelatha et al., 2022; Kirubakaran et al., 2025). Its multifunctionality, combining direct antimicrobial action, plant defense stimulation, and efficient delivery of bioactive molecules, positions chitosan nanoparticles as a powerful tool for integrated and eco-friendly plant disease management (Ali et al., 2023).

2.1.1.5. Polymeric nanoparticles. Polymeric nanoparticles are revolutionizing agrochemical delivery by delivering precise and sustained release of pesticides, fungicides, and insecticides (Singh et al., 2020). These nanosystems are manufactured employing biodegradable polymers such as poly epsilon caprolactone (PCL), chitosan, and polylactic acid (PLA), which bind to plant surfaces and assist in minimizing chemical losses from runoff (Guha et al., 2020). The release of active molecules is carefully managed by methods like diffusion, polymer breakdown, or environmental triggers like fluctuations in pH or enzyme activity, ensuring that the chemicals are supplied at the correct site and time (Biondo et al., 2022). For instance, PCL-based nanocapsules delivering herbicides such as atrazine have exhibited prolonged weed control, avoiding the demand for frequent reapplication (Prajapati et al., 2022).

Chitosan nanoparticles, on the other hand, may be engineered to release copper ions in acidic situations, effectively targeting fungal infections in the root zone (Machado et al., 2023; Wahab et al., 2023). This strategy not only enhances the precision of pest and disease control but also decreases environmental pollution and lowers threats to non-target species, fitting well with the goals of sustainable agriculture (Homaeigohar and Boccaccini, 2022). Table 2 below categorizes the modes of activity of different nanoparticles (NPs) in plants, indicating their diverse processes of interaction, absorption paths, and physiological impacts.

2.1.2. Nanoparticle-based strategies for disease management

Nanomaterials have revolutionized plant disease management by offering precise control at atomic and molecular scales, enabling targeted interventions that traditional methods cannot achieve (Li et al., 2020). These nanomaterials encompass a broad range of types, including organic vesicles such as liposomes and polymer-based carriers, inorganic metals, metal oxides, ceramics, and pure carbon-based nanomaterials (Wan et al., 2023). Among these, nanomaterials synthesized through green chemistry approaches are increasingly favored due to their reduced environmental toxicity and enhanced biocompatibility, aligning with sustainable agricultural practices (Dos-Santos et al., 2023).

2.1.2.1. Management of fungal pathogens. Fungal pathogens represent the largest and most devastating group of plant pathogens, accounting for approximately 85 % of all recorded plant diseases worldwide (Thambugala et al., 2020). The conventional management of fungal diseases heavily relies on synthetic fungicides, which are often applied in excessive quantities during crop production cycles. This overreliance has led to the rapid emergence of fungicide-resistant strains, severely limiting the efficacy of available chemical controls and posing a significant threat to global food security (Avelino et al., 2015; Corkley et al., 2022). Consequently, the exploration of nanomaterials as alternative antifungal agents has gained momentum due to their unique physicochemical properties and modes of action (Sousa et al., 2020). Biologically synthesized silver nanoparticles (AgNPs) have demonstrated potent antifungal effects against major soilborne pathogens such as *Penicillium expansum*, *Fusarium graminearum, Fusarium solani*, and *Fusarium oxysporum*. Studies report that AgNPs at concentrations between 15 and 30 ppm can reduce fungal proliferation by 50–90 %, indicating strong inhibitory potential (Ali et al., 2021). In practical applications, AgNPs significantly suppressed powdery mildew development on cucumbers and pumpkins by disrupting fungal cell membranes and degrading spores and mycelia, thereby preventing disease progression (Mansoor et al., 2021).

In addition to silver, various metal oxide nanoparticles such as copper oxide (CuO), manganese oxide (MnO), and zinc oxide (ZnO) have been evaluated for their antifungal properties (Mohamed et al., 2021). For instance, tomato plants grown in soilless systems and infected with *Fusarium oxysporum* showed disease suppression rates of 31 %, 28 %, and 28 % when treated with CuO, MnO, and ZnO nanoparticles, respectively, without exhibiting phytotoxic effects (Elmer and White, 2018). Similarly, eggplants treated with CuO and ZnO nanoparticles exhibited reduced severity of *Verticillium dahliae* wilt, though other tested nanoparticles failed to show significant effects (Abdelaziz et al., 2022). Furthermore, in vitro assays demonstrated that both AgNPs and ZnO nanoparticles effectively inhibited *Sclerotinia homoeocarpa*, the causative agent of dollar spot disease in turfgrass, confirming their broad-spectrum antifungal activity (Li et al., 2018).

Innovative integrated approaches combining bacterial biocontrol agents with nanosilica, diatomaceous earth, and conventional fungicides such as tetraconazole have been employed to manage *Cercospora* leaf blight in sugar beet, yielding enhanced disease control (Elmer and White, 2018). A two-year field study applying foliar nano-Zn treatments at 500 μg/mL improved root yield, increased sugar content, enhanced leaf biomass, and reduced disease severity, with results second only to tetraconazole applications (Derbalah et al., 2013). These findings highlight nanomaterials' potential to supplement or replace existing fungicides, therefore providing long-term solutions for fungal disease control.

2.1.2.2. Suppression of bacterial pathogens. Bacterial diseases, alongside fungal infections, cause substantial agricultural losses globally. While some bacteria promote plant growth and productivity, phytopathogenic bacteria such as *Xanthomonas*, *Pseudomonas*, and *Ralstonia* species pose serious threats to crop health (El-Saadony et al., 2022). Nanotechnology has emerged as a promising avenue for combating bacterial pathogens, with laboratory studies demonstrating significant antibacterial effects of various nanoparticles (Hetta et al., 2023).

Silver nanoparticles have been particularly effective in controlling soft rot disease caused by *Pectobacterium carotovorum* in pepper plants (*Capsicum annuum*) (Ayisigi et al., 2020). The minimum inhibitory concentration (MIC) was established at 0.0625 mg/mL, and treated seedlings exhibited a markedly reduced infection rate of 15 %, highlighting the potent antibacterial activity of AgNPs (Davidova et al., 2024). Copper oxide nanoparticles also demonstrated strong antibacterial properties, inhibiting *Ralstonia solanacearum* and *Erwinia amylovora* with inhibition zones of 22 mm and 19 mm, respectively, in vitro (Swaroop, 2023). Additionally, AgNPs were effective against a range of other phytopathogens, including *Burkholderia gladioli*, *Xanthomonas axonopodis*, and *Pseudomonas syringae* (Tortella et al., 2020; Jha and Mayanovic, 2023).

Zinc nanoparticles exhibited moderate antibacterial activity by reducing *Xanthomonas axonopodis* growth by approximately 50 %, although they were ineffective against *Pseudomonas syringae* and *Erwinia amylovora* (dos Santos et al., 2024). Magnesium oxide nanoparticles showed limited bactericidal effects against *Ralstonia solanacearum* (Khan, 2020). The antibacterial efficacy of nanoparticles is influenced by factors such as microbial metabolism, nanoparticle concentration, cell membrane permeability, and microbial physiology (Khan and Rizvi, 2014). Given their broad-spectrum activity, nanoparticles are particularly valuable for managing complex infections involving multiple pathogens, as primary infections often compromise plant defenses and increase vulnerability to secondary infections (Noman et al., 2023).

2.1.2.3. Antibiotic delivery and targeted control. Nanoparticles have transformed antimicrobial therapy by serving both as direct antimicrobial agents and as sophisticated antibiotic delivery systems. Their unique physical and chemical properties enable enhanced antibacterial activity and improved pharmacokinetics, addressing challenges associated with conventional antibiotic treatments (Li et al., 2020).

Table 2
Mode of activity of different nanoparticles.

Nanoparticles	Mode of action	References
Silver	Penetrates microbial cell membranes and internal components, affecting crucial cellular operations and resulting in cell death.	El-Baky and Amara (2021).
Copper	High levels of catalase, peroxidase, lipid peroxidase	Chukwuebuka et al. (2021).
Zinc	High level of catalase activity	Zhao et al. (2019).
Chitosan	Increasing protective genes like different antioxidant enzymes as well as Elevation of the levels of total phenolics	Prasad et al. (2017).
Polymeric	Ensure breakdown, or environmental triggers like fluctuations in pH or enzyme activity.	Guha et al. (2020).

Nanoparticles synthesized from metals, chitosan, and surfactants exert bactericidal effects through multiple mechanisms, including membrane disruption and oxidative stress induction (Hurdle et al., 2017; Sharifi-Rad et al., 2022). Encapsulation of antibiotics within nanocarriers offers dual benefits: it increases drug stability and bioavailability while minimizing systemic side effects (Aires et al., 2023; Oliveira et al., 2023). The nanoscale size allows these carriers to penetrate endothelial tissues and reach infection sites inaccessible to standard antibiotics, enabling precise drug delivery and reducing the development of resistance (Shah et al., 2021).

Nanoparticles use both passive and active targeting strategies to enhance specificity. Passive targeting exploits the enhanced permeability of infected tissues, while active targeting involves functionalizing nanoparticles with ligands that bind bacterial surface components, improving localization and efficacy (Andersson and Hughes, 2018). Smart nanosystems have been engineered to respond to internal stimuli such as pH changes, enzymes, or infection-related chemicals, releasing antibiotics selectively at infection sites (Borges et al., 2024). External stimuli like electromagnetic fields, light, and ultrasound can also trigger controlled drug release, providing additional precision in treatment. Bacterial biofilms and intracellular reservoirs pose significant barriers to antibiotic efficacy. Biofilms, composed of extracellular polymeric substances, protect bacteria from antimicrobial agents and immune responses (Blair et al., 2015). Nanoparticles can penetrate and disrupt biofilms, enhancing antibiotic access to bacterial communities (Nowak et al., 2021). Functionalized nanomaterials also facilitate intracellular delivery, targeting bacteria residing within host cells that conventional antibiotics cannot reach effectively (Guo et al., 2012). Reflecting their therapeutic potential, 51 nanomedicines have received FDA approval, including antibacterial formulations that advance the fight against resistant infections (Eleraky et al., 2020).

2.1.2.4. Antiviral applications. Viral infections significantly reduce crop yields and quality. Nanoparticles have been investigated for their antiviral properties, including direct viral inhibition and enhanced delivery of antiviral agents (Gurunathan et al., 2020). Silver nanoparticles, for example, reduced viral loads of tomato mosaic virus and potato virus Y by approximately 18–20 % at 50 ppm concentrations (Seukep et al., 2020). Foliar applications of zinc oxide and silicon dioxide nanoparticles suppressed tobacco mosaic virus proliferation by directly inactivating viral particles and stimulating plant defense mechanisms via reactive oxygen species production and upregulation of defense genes (Fu et al., 2023). Beyond pathogen control, nanoparticles improve plant resilience to abiotic stresses such as drought, salinity, and temperature extremes. Nanocomposites combining fertilizers, insecticides, and beneficial microbes on a single delivery platform enhance nutrient use efficiency and stress tolerance (Chew et al., 2022; Seukep et al., 2020). Nano-biofertilizers encapsulate essential nutrients and organic compounds, promoting sustained nutrient release and improving plant growth under adverse conditions (Mombe et al., 2023). Environmentally friendly synthesis methods using plant, fungal, or algal extracts reduce toxicity and environmental impact compared to chemical methods (Balandrin et al., 2023).

The nanoscale size (<100 nm) and large surface area of nanoparticles facilitate their penetration into plant tissues via roots or leaves, allowing targeted delivery of active compounds to intracellular sites (Seukep et al., 2020). Clay-based nanomaterials enhance nutrient delivery and stimulate plant defense responses due to their high permeability and ability to protect encapsulated substances from degradation (Magalhães et al., 2022; Costa et al., 2022). Hollow nanostructures further improve stability and prolong activity in soil and plant systems (Magalhães et al., 2022). Nanoparticles promote plant adaptation to stress by increasing the synthesis of growth regulators and protective secondary metabolites, activating innate defense mechanisms, and providing sustained protection with minimal resource waste (Khan et al., 2022; Doğan and Ayaz, 2019; Shah et al., 2021). This integrated approach offers a promising pathway to address future agricultural challenges, including climate change, resource limitations, and the growing demand for food production.

2.1.3. Nanoparticle-based strategies for pest management

This section highlights key applications of nanoparticles in the targeted management of insect pest, emphasizing their mechanisms of action, efficacy, and potential for sustainable agriculture.

2.1.3.1. Insect pest control mechanisms. Nanoparticle-based insect pest control represents a revolutionary approach that combines precision targeting, enhanced bioavailability, and reduced environmental impact compared to conventional insecticides (Kannan et al., 2024). These nanoscale materials exploit multiple mechanisms that collectively compromise insect survival while minimizing harm to non-target organisms and supporting sustainable pest management (Yousef et al., 2023). The primary insecticidal actions of nanoparticles include generation of reactive oxygen species (ROS), penetration of the insect cuticle, desiccation, disruption of cellular processes, and interference with enzymatic functions (Saranya et al., 2020). Metal-based nanoparticles such as silver (AgNPs) and zinc oxide (ZnO NPs) have demonstrated potent activity against major pests including aphids, whiteflies, *Spodoptera litura*, *Aedes aegypti*, and various lepidopteran species (Bihal et al., 2023). AgNPs induce mortality rates exceeding 80 % at low concentrations by causing membrane disruption, DNA damage, protein synthesis inhibition, and acetylcholinesterase enzyme suppression, which impairs nerve function leading to paralysis and death (Choudhary et al., 2022). ZnO nanoparticles additionally exhibit repellent effects by disrupting insect sensory systems, reducing feeding and reproduction, and preventing plant colonization (Tripathi and Goshisht, 2022).

The nanoscale size, typically below 100 nm, enables enhanced penetration through insect exoskeleton barriers, allowing direct contact with internal tissues and organs (Shahzad and Manzoor, 2021). This size-dependent penetration is especially valuable for controlling resistant pest populations that have developed tolerance to conventional insecticides. Silica nanoparticles employ unique physical mechanisms such as abrasion, spiracle blockage, and disruption of the protective wax layer of insect cuticles, causing rapid dehydration and mortality without chemical toxicity (Wang et al., 2022). This physical mode of action reduces the risk of resistance development, making silica nanoparticles important components of integrated pest management (IPM) systems. Beyond lethal effects, nanoparticles disrupt insect sensory receptors in respiratory organs, impairing host plant recognition and colonization (Goswami et al., 2022). Some nanoparticle formulations act as repellents, further lowering pest infestations and reducing reliance on chemical insecticides. These targeted actions minimize adverse effects on beneficial insects and non-target species, promoting environmentally friendly pest control (Sarmah et al., 2025). Advanced nanoplatforms incorporate stimuli-responsive mechanisms for intelligent pest management. For example, redox- and near-infrared light-responsive nanoparticles loaded with insecticides like nitenpyram have enhanced mortality rates against *Nilaparvata lugens* from 62 % to 88 % compared to conventional formulations (Zong et al., 2023). Controlled-release and smart delivery systems enable precise temporal and spatial release of active agents, preserving chemical stability and reducing off-target exposure (Manzari et al., 2021). Essential oil-based polymeric nanoparticles (EOPNs) encapsulating palmarosa, geranium, and peppermint oils have shown enhanced insecticidal activity against pests such as *Plodia interpunctella*. These formulations exhibit high encapsulation efficiency (>90 %), improved stability, and controlled release, offering sustainable alternatives to synthetic pesticides (Jesser et al., 2020).

Recent studies highlight the efficacy of nanoparticle-based treatments against aphids, whiteflies, and caterpillars (Karthik Raja et al., 2025). Silver nanoparticles penetrate aphid exoskeletons inducing oxidative stress and significantly reducing populations (Amjad et al., 2022). Zinc oxide nanoparticles demonstrate both insecticidal and repellent effects by disrupting aphid sensory systems and improving absorption in nanoemulsion formulations, thereby preserving beneficial insects and maintaining ecological balance (Vishnu et al., 2024). Nanosuspension pesticides enhance control of *Spodoptera littoralis* caterpillars by improving tissue penetration and toxicity, while silica nanoparticles inhibit caterpillar feeding, contributing to effective pest suppression (Zong et al., 2025). The combined destructive and preventive actions of nanoparticles offer significant environmental benefits. Controlled-release formulations extend protection duration, reducing the frequency and quantity of chemical applications needed. These advances support eco-friendly pest management strategies that maintain crop productivity while lowering chemical inputs and mitigating environmental contamination (Li et al., 2021). Fig. 4 illustrates the mode of action of chitosan nanoparticles, which penetrate insect cuticles by damaging membranes, inhibiting essential enzymes, and inducing oxidative stress, collectively causing pest mortality.

2.1.3.2. Nematode control approaches. Nanoparticle-based nematode management represents an innovative and environmentally sustainable approach to controlling plant-parasitic nematodes, which cause billions of dollars in crop losses annually (Zinovieva et al., 2023). The nanoscale interventions offer targeted delivery, enhanced bioavailability, and reduced environmental persistence compared to conventional nematicides. Silver nanoparticles have demonstrated exceptional nematicidal activity against root-knot nematodes (*Meloidogyne* species) at remarkably low concentrations (Arumugam et al., 2024). Studies by Baronia et al. (2020) and Ajith et al. (2024), using *M. graminicola* in rice showed 100 % nematode mortality at 0.1 μg/mL in water screening tests and 2 μg/mL in sand screening assays. Field soil applications required only 3 μg/mL for effective control, significantly lower than previously reported concentrations of 150 μg/mL.

The nematicidal mechanisms of AgNPs involve direct cytotoxicity, membrane disruption, and interference with reproductive processes (Abd-Elgawad, 2024). Against *M. javanica* infecting Swiss chard, AgNPs at 3 μg/mL significantly reduced egg masses, juvenile populations, and reproduction factors without adverse effects on plant growth (Daramola et al., 2023). The negative correlation between nanoparticle concentration and nematode reproduction demonstrates dose-dependent efficacy. Zinc oxide nanoparticles offer dual benefits of nematode suppression and plant growth promotion (El-Qurashi et al., 2023). Green-synthesized ZnO NPs using various plant extracts showed effective control against multiple nematode species while enhancing plant defense mechanisms. The nanoparticles stimulate plant defense enzyme activities including superoxide dismutase (SOD) and catalase (CAT), providing systemic protection against nematode infection (Ulaş et al., 2025).

As shown in Fig. 5, chitosan nanoparticles protect roots by targeting and eliminating nematodes in the root zone, thereby enhancing plant health and yield.

Chitosan nanoparticles, typically synthesized via ionic gelation to produce uniform nanospheres averaging around 380 nanometers, have proven highly effective in targeting soil-borne parasitic nematodes by acting directly in nematode-infested root zones (Alehosseini et al., 2022). For example, Zheng et al. (2023) reported strong nematicidal activity of chitosan nanospheres against *Meloidogyne incognita*, significantly reducing nematode populations in both the rhizosphere and surrounding soil. In one study, a 1 % chitosan nanoparticle solution reduced root galls by 83.68 %, egg masses by 83.85 %, adult female nematodes by 66.56 %, and second-stage juveniles by 73.20 % (Chakraborty et al., 2020), while also increasing fruit yield by 18.75 % compared to conventional treatments (Fan et al., 2023). The nematicidal efficacy of chitosan nanoparticles arises from multiple biological mechanisms. A key action involves activation of chitinase enzymes that degrade essential components of nematode eggshells, reducing egg viability and hatch rates (Khan and Mohiddin, 2023). Additionally, their application triggers plant defense responses, including elevated production of jasmonic acid and salicylic acid hormones and generation of reactive oxygen species (ROS), which collectively enhance the plant's resistance to nematode infection and mitigate infestation severity (Jha et al., 2024).

Chitosan also promotes the parasitic activity of biocontrol fungi such as *Pochonia chlamydosporia* by facilitating the formation of appressoria, specialized structures required to penetrate nematode eggs thereby enhancing biological control effectiveness (Afridi et al., 2022; Kumar, 2020). This synergy between chitosan nanoparticles and biocontrol agents supports environmentally safe and sustainable pest management strategies. Environmental safety is a major advantage of chitosan nanoparticles (Benettayeb et al., 2023). They biodegrade rapidly and exhibit low toxicity toward beneficial soil organisms, including *Eudrilus euginea* earthworms and *Heterorhabditis indica* entomopathogenic nematodes, remaining non-toxic even at concentrations exceeding 10, 000 ppm (Basem et al., 2024; Remya et al., 2022). Field trials confirm that chitosan nanoparticles effectively suppress root-knot nematodes while promoting plant growth in crops such as tomatoes by combining direct nematicidal toxicity with stimulation of plant defense pathways (Fan et al., 2023). This dual action, combined with compatibility with beneficial organisms, makes chitosan nanoparticles ideal components of integrated pest management (IPM) programs.

Currently, chitosan nanoparticles are widely recognized as safe and effective against Meloidogyne incognita and similar nematodes (Remya

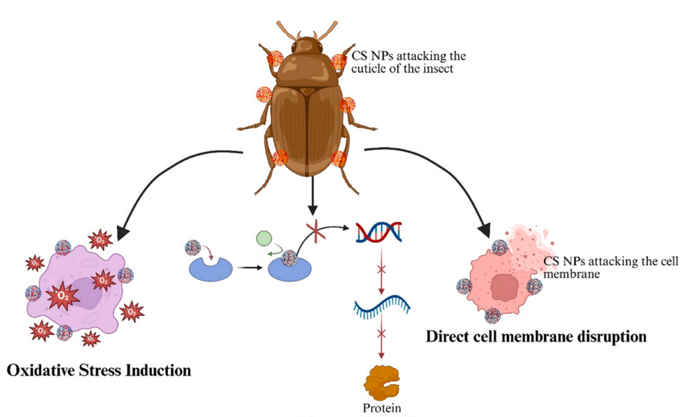

Fig. 4. Insect Pest Management Mechanisms (Created in https://biorender.com).

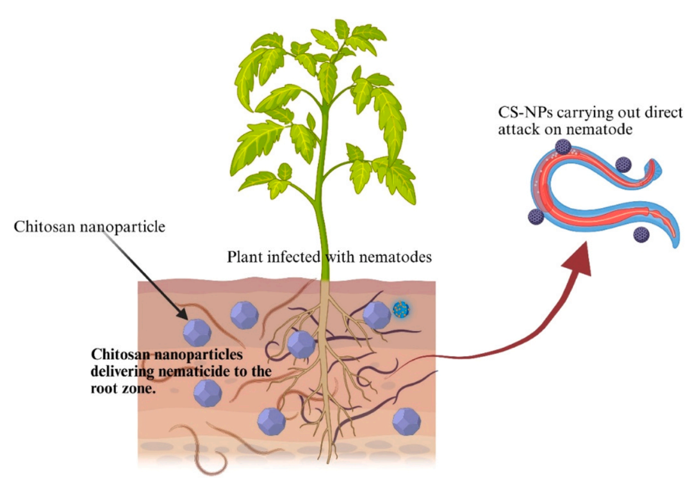

Fig. 5. Chitosan nanoparticles target and affect nematodes near the root zone (Created in https://biorender.com).

et al., 2022). Their ability to penetrate plant roots without harming beneficial organisms underscores their suitability for integrated agricultural systems. Ongoing research continues to optimize nanoparticle formulations, emphasizing their vital role in advancing sustainable and environmentally responsible nematode management (Afzal and Mukhtar, 2024). The nanoparticles act by disrupting and degrading nematode eggshells, as shown in Fig. 6, effectively suppressing nematode populations.

2.1.3.3. Role in integrated pest management (IPM). The integration of nanoparticle-based technologies into integrated pest management (IPM) systems represents a paradigmatic advancement toward sustainable and precision agriculture. Nanotechnology offers tools that complement and enhance traditional IPM components while addressing environmental and resistance concerns associated with conventional pest control methods (Mishra et al., 2024). Nanoparticles function as precision delivery systems that enable site-specific pest control and reduced non-target effects. The targeted delivery mechanisms ensure that active ingredients reach specific pest habitats while minimizing exposure to beneficial organisms (Alemu, 2020). This precision approach aligns with IPM principles of selective pest control and ecological balance preservation. The controlled release mechanisms of nanoformulated pesticides provide sustained protection with reduced application frequency (Mondéjar-López et al., 2024). Studies demonstrate that nano-encapsulated pesticides maintain efficacy for extended periods, reducing the need for frequent applications and lowering overall chemical inputs (Abdollahdokht et al., 2022; Singh et al., 2024a, 2024b; B.V. Singh et al., 2024; G. Singh et al., 2024; M. Singh et al., 2024; N.B. Singh et al., 2024). This approach supports IPM goals of reducing pesticide dependence while maintaining effective pest control.

Nano-biosensors represent innovative tools for early pest detection and monitoring within IPM frameworks. These systems enable real-time surveillance of pest populations, allowing for timely intervention before economic thresholds are reached (Pugsley et al., 2021). The integration of sensing and control technologies facilitates data-driven decision making in pest management strategies. The compatibility of nanoparticles with biological control agents enhances IPM effectiveness (Uniyal et al., 2024). Biodegradable polymer-based nanoparticles such as chitosan and alginate demonstrate compatibility with beneficial microorganisms and natural enemies. These systems can protect and deliver biocontrol agents while providing additional pest control mechanisms (Pugsley et al., 2021; Mondéjar-López et al., 2024). Resistance management benefits significantly from nanoparticle integration into IPM systems. The multiple modes of action provided by different nanoparticle types reduce selection pressure for resistance development (Khan et al., 2023). Physical modes of action, such as those exhibited by silica nanoparticles, provide resistance-proof alternatives that complement biological and chemical control methods. The environmental sustainability of nano-enabled IPM systems addresses growing concerns about agricultural impacts on ecosystems (Abdollahdokht et al., 2022; Pugsley et al., 2021). Biodegradable nanoformulations reduce persistence in environmental compartments while maintaining pest control efficacy (Khan et al., 2023). Green synthesis approaches using plant extracts and microorganisms further enhance environmental compatibility. Economic benefits of nanoparticle-enhanced IPM include reduced pesticide costs, improved crop yields, and decreased environmental remediation expenses (Yousef et al., 2023). The enhanced efficacy of nano-formulated pesticides enables lower application rates while maintaining or improving control levels (Jacquet et al., 2022). Long-term sustainability benefits include preserved beneficial organism populations and reduced resistance management costs. The future development of nano-enabled IPM systems requires regulatory frameworks, safety assessments, and farmer education programs (Bakshi and Abhilash, 2020). Comprehensive evaluation of nanoparticle fate and transport in agricultural systems ensures safe implementation. Participatory approaches involving stakeholders facilitate successful adoption and integration of nanotechnology into existing IPM practices (Khan et al., 2023).

3. Advantages of nanoparticle-based approaches

Nanoparticle-based approaches improve sustainable pest control due to their unique physicochemical properties and versatile interactions with biological systems. Their distinct characteristics enhance dissolution and absorption efficiency while reducing material use, resulting in better outcomes compared to conventional pesticides (Zainab et al., 2024).

3.1. Enhanced solubility and bioavailability

Nanoparticle formulations significantly increase the water solubility and stability of active ingredients, especially those with poor inherent solubility. Conventional pesticides often require higher doses to be effective, contributing to environmental chemical loads (Edo et al., 2024). In contrast, nanoparticles' high surface-area-to-volume ratio promotes closer interaction with pests and more uniform distribution of active compounds. Nanoemulsions and nanocapsules boost efficacy by protecting active molecules from environmental degradation such as UV radiation and oxidation (Khan et al., 2024). Advanced delivery systems also provide controlled, sustained release, ensuring precise timing and location of chemical release (Chaudhari et al., 2021). This results in longer-lasting effects and reduces the frequency and amount of pesticide applications needed (Zhao et al., 2022). Nanopesticides can reduce chemical inputs dramatically while maintaining effectiveness. Their nanoscale size allows better penetration of biological barriers, enabling precise delivery to pest targets (Deka et al., 2021). Incorporating ligands and specific compounds into nanoparticles enhances selective binding to pest receptors, improving uptake and minimizing harm to beneficial insects and soil microorganisms (Chaud et al., 2021). Silver nanoparticles (AgNPs) effectively control pests like aphids and whiteflies with minimal environmental impact (Pathipati and Kanuparthi, 2021). Studies show nanopesticide formulations can reduce active chemical use by up to 50 % without losing efficacy compared to traditional pesticides (Shekhar et al., 2021). This reduction also lowers pesticide residues in soil and water and cuts application costs (Kalia et al., 2020).

Controlled-release nanoparticles gradually release active agents triggered by environmental factors such as temperature or pH changes (Kashkooli et al., 2020). For example, pH-sensitive nanoparticles release

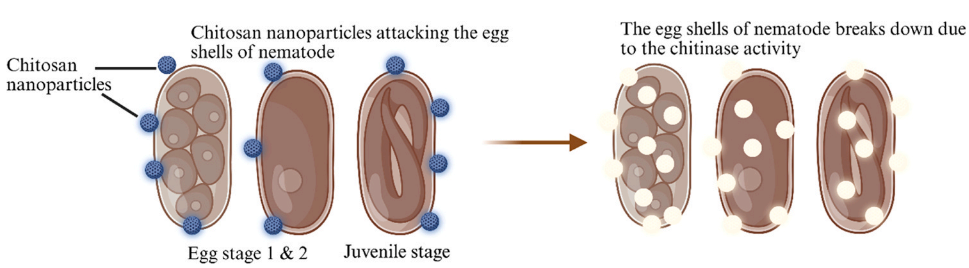

Fig. 6. Chitosan Nanoparticle Eggshell Degradation (Created in https://biorender.com).

chemicals specifically in acidic pest habitats, enhancing targeted delivery and protecting non-target species (Geszke-Moritz and Moritz, 2024). This controlled release improves cost efficiency and resource use in pesticide application (Kalia et al., 2020). Nanopesticides offer environmental benefits by reducing pesticide volumes and their harmful ecosystem effects. They require fewer hazardous organic solvents than conventional pesticides, making them safer for the environment (Babu et al., 2022). Reduced pesticide use leads to lower chemical runoff, preserving aquatic ecosystems and biodiversity. Their lower environmental persistence and reduced soil degradation help protect beneficial microbial populations (Chaud et al., 2021). The unique properties of nanoparticles improve solution dispersion and availability, allowing dose reductions while maintaining prolonged release through controlled delivery (Wang et al., 2022). These advances support both operational efficiency and ecological sustainability by minimizing environmental impacts and conserving natural resources. Recent research highlights nanopesticides as key components of modern, sustainable agricultural pest management systems (Vasseghian et al., 2022).

3.2. Environmental and economic benefits

Nanoparticles used in pest management offer two main benefits: environmental conservation and cost savings, making them superior to conventional insecticides. Nanopesticides promote sustainable agriculture by reducing chemical use and lowering water pollution (Chaud et al., 2021). Although the initial cost of nanotechnology may be higher, farmers and the agricultural sector gain long-term savings through reduced inputs and improved efficiency (Ali et al., 2023). Environmentally, nanopesticides minimize chemical runoff and help preserve soil health. Unlike broad-spectrum conventional insecticides that can harm beneficial organisms like pollinators and soil microbes (An et al., 2022), nanopesticides deliver active ingredients precisely to pest sites. This targeted delivery reduces harm to non-target species and lowers residual chemical contamination (Boregowda et al., 2022), protecting ecosystems while effectively controlling pests.

Nanoparticles also stabilize active compounds by shielding them from sunlight and moisture degradation. Encapsulation ensures pesticides remain potent until they reach their targets (Abbas et al., 2020). Studies show nanopesticides can reduce soil and water pesticide pollution by up to 50 % compared to traditional formulations, improving soil quality and preserving essential microbial communities for nutrient cycling (Wang et al., 2022; An et al., 2022). For farmers, nanopesticides offer practical advantages such as longer-lasting effects and fewer applications. Controlled-release technologies maintain pest suppression over extended periods, simplifying management and reducing labor costs (An et al., 2022). Lower dosages also decrease input expenses, making nanopesticides cost-effective over time (Ali et al., 2023; Abbas et al., 2020). Additionally, nanopesticides help farmers comply with stricter pesticide regulations by reducing environmental pollution and risks to human health and wildlife. This regulatory benefit aids market access for sustainably produced food (Wang et al., 2022). Integrating nanoparticles into pest management, farmers can achieve both ecological protection and economic gains. The precision of nanopesticide delivery lowers environmental chemical loads while maintaining effective pest control. With smaller doses and longer-lasting action, nanopesticides represent a promising alternative for modern agriculture. Ongoing research continues to expand nanotechnology's role in enabling sustainable and efficient pest management (Mittal et al., 2020; Prasad et al., 2024).

3.3. Nanotechnology in sustainable and organic agriculture

Research increasingly shows that nanoparticles can boost crop production while promoting sustainability and reducing environmental impact. Two key areas highlight how these technologies support organic agriculture and conserve beneficial organisms and biodiversity (Mittal et al., 2020; Wang et al., 2022). Nanotechnology offers unique solutions aligned with organic farming principles. Nanoparticles improve pest management efficacy while complying with organic regulations that prohibit synthetic pesticides (Mittal et al., 2020; Singh et al., 2020). They enable precise delivery of biopesticides and natural insecticides to target sites. Using minimal active ingredients is an essential feature for reducing chemical inputs in organic farming (Wang et al., 2022).

Nanofertilizers made from nanoparticles provide targeted nutrient delivery with less loss than conventional fertilizers. Their sustained-release properties enhance nutrient uptake and reduce water pollution from runoff and leaching (Jakhar et al., 2022; Mahapatra et al., 2022). This promotes organic practices by reducing dependency on synthetic fertilizers and assisting growers to satisfy certification criteria (Wang et al., 2022). Nanoparticle-based approaches also protect beneficial organisms and biodiversity. Unlike traditional chemical pesticides that harm non-target species such as pollinators and natural predators, nanopesticides target invasive pests specifically, sparing beneficial species (Mittal et al., 2020). Studies confirm nanoparticles' ability to distinguish pests from beneficial organisms, aiding ecological preservation alongside effective pest control (Wang et al., 2023). Nanoparticles enhance beneficial species' resilience by stimulating soil microbial activity and improving soil health. This supports microbial populations essential for nutrient cycling and disease suppression, fostering ecosystems sustained by biological processes rather than synthetic inputs (Ameen et al., 2021; Rajput et al., 2023). Nanotechnology also helps plants tolerate environmental stresses by conserving soil moisture and improving mineral nutrient absorption (Pokrajac et al., 2021). This strengthens crop resilience, benefiting both agricultural productivity and natural habitats. Thus, nanoparticle technologies align well with sustainable and organic farming goals by protecting beneficial organisms and preserving biodiversity (Besha et al., 2020). Overall, nanotechnology is transforming agricultural sustainability by enabling efficient nutrient management and advanced pest control that minimize environmental harm. Ongoing research highlights nanoparticles' pivotal role in developing sustainable systems to meet future food production challenges (Tovar-Lopez, 2023).

4. Regulatory and consumer acceptance challenges

Nanoparticles offer many benefits in agriculture. However, regulatory and safety challenges limit their adoption. The absence of standardized global guidelines specific to nanomaterials creates fragmented and inconsistent oversight frameworks. In regions such as the United States, regulatory control is divided between the Environmental Protection Agency (under the Federal Insecticide, Fungicide, and Rodenticide Act) and the Food and Drug Administration (under the Food, Drug, and Cosmetic Act), often resulting in case-by-case assessments with no nanoparticle-specific statutes (Stucki et al., 2022; Yadav et al., 2023). In Europe, frameworks such as REACH and the Biocidal Products Regulation (BPR) require nanoform documentation but often rely on protocols designed for conventional chemicals, leading to ambiguity in evaluating nanoscale risks (Machado et al., 2023; Hahn et al., 2021).

A fundamental regulatory barrier remains the lack of universally accepted definitions for nanoparticles. Definitions vary by authority, with criteria ranging from particle size (1–100 nm) to reactivity and surface characteristics, which impedes the establishment of consistent risk assessment protocols (Demirer et al., 2021; Machado et al., 2023). In countries like India, although efforts are underway to develop toxicity testing and environmental evaluation tools, dedicated regulations for nano-enabled agricultural products are still lacking (Wu et al., 2024).

To address these disparities, international collaboration is crucial. Initiatives such as the ISO/TS 80004–1 standard provide harmonized terminology to guide global regulatory alignment (Allan et al., 2021). Broader implementation of such frameworks is essential to govern the full lifecycle of nanomaterials from production to disposal and ensure environmental and human safety (Ramachandran et al., 2020).

Consumer trust also plays a vital role in the successful integration of nanoparticles in agriculture. Public apprehension often arises due to insufficient knowledge and transparency in safety evaluations (Cummings et al., 2021). Countries like Canada have mandated labeling of nanoparticle-containing products under the Food and Drugs Act to foster informed consumer choices. Research indicates that when consumers understand the benefits of enhanced crop yields and reduced pesticide usage, acceptance of nanotechnology will increase significantly (Kamarulzaman et al., 2020; Yang and Duncan, 2021; Wu et al., 2024). Regulatory agencies must develop comprehensive and transparent evaluation protocols that encompass long-term environmental and health effects. Creating clear, standardized regulations will not only enhance public confidence but also ensure that innovations in nanotechnology align with sustainability and safety goals (Singh et al., 2021, 2024a, 2024b; B.V. Singh et al., 2024; G. Singh et al., 2024; M. Singh et al., 2024; N.B. Singh et al., 2024).

5. Conclusion

The application of nanoparticles for the control of insect pathogens and plant diseases signifies a significant progression in agricultural technology, offering answers for global food security and promoting environmental sustainability. Nanoparticle formulations enhance the solubility and bioavailability of active substances, facilitating precise controlled delivery systems that augment pesticide efficacy and diminish environmental pollution by reducing chemical consumption by up to 50 percent. These nanoformulations enhance sustainable agriculture by enabling targeted pest management with reduced amounts of active chemicals, utilizing biodegradable nanocarriers sourced from renewable resources, and advancing circular economy concepts. Nanotechnology is notably compatible with organic farming via green synthesis processes and biogenic nanoparticles, which augment the efficacy of organic inputs while maintaining ecological equilibrium. Regulatory problems, safety evaluations, and consumer acceptability concerns necessitate updated rules, enhanced analytical methodologies, and open communication tactics. The future of nanoparticle-based agriculture is the incorporation of precision farming technology, including nanosensors and data-driven decision support systems, to enhance resource efficiency and reduce environmental impact. nanoparticle-enabled pest and disease control has transformational promise for sustainable, efficient, and economically viable agriculture, dependent on ongoing scientific discovery, regulatory advancement, and stakeholder engagement.

CRediT authorship contribution statement

Ramat Onyeneoyiza Raji: Investigation, Data curation. **Konjerimam Ishaku Chimbekujwo:** Writing – original draft, Investigation. **Rasheed Olakitan Oyewale:** Supervision. **Oluwafemi Adebayo Oyewole:** Writing – review & editing, Supervision, Conceptualization. **Olabisi Peter Abioye:** Supervision. **Abdulrazaq Izuafa:** Writing – original draft, Software.

Ethical approval

Not applicable.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT to develop the outlines, edit, and correct the grammar and sentence structures. All AI-assisted content was reviewed and finalized by the authors, who take full responsibility for the accuracy and originality of the work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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