***Review Article***

**Nanotechnology in Pest Management: Mechanisms, Impacts, and Future Directions for Sustainable Agriculture**

**Abstract**

The increasing prevalence of pesticide-resistant pests and the negative environmental impacts of chemical pesticides have prompted researchers to explore alternative pest control strategies that are efficient, eco-friendly, and sustainable. Nanotechnology offers innovative solutions for developing eco-friendly pest control strategies that address the limitations of conventional pesticides. This review examines the potential of various nanomaterials, including metal nanoparticles, metal oxide nanoparticles, carbon-based nanomaterials, nanoemulsions, and biogenic nanoparticles, for insect pest management. Studies indicate that nanoparticles exhibit strong insecticidal properties through mechanisms such as reactive oxygen species (ROS) generation, metal ion release, cuticle penetration, desiccation, and disruption of cellular processes. Silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnONPs) have demonstrated high efficacy against pests like Spodoptera litura and Aedes aegypti, achieving mortality rates exceeding 80% at low concentrations. Nanoformulations of botanical insecticides improve their stability, bioavailability, and targeted delivery, enhancing their effectiveness against a wide range of pests. Despite their promising potential, concerns about toxicity, environmental persistence, bioaccumulation, and adverse effects on non-target organisms remain critical challenges. Current research highlights the need for developing biodegradable and eco-friendly nanomaterials to minimize ecological risks. Biodegradable polymer-based nanoparticles, such as chitosan and alginate, have also been explored for their compatibility with biological control agents and enhanced environmental safety. Additionally, the lack of comprehensive regulatory frameworks hinders the commercialization and safe application of nanopesticides. Nevertheless, regulatory agencies, including the European Food Safety Authority (EFSA) and the United States Environmental Protection Agency (EPA), have initiated efforts to establish guidelines for evaluating the safety of nanomaterials. Current regulations primarily focus on assessing toxicity, environmental persistence, and potential bioaccumulation. Future studies should focus on understanding nanoparticle-pest interactions, elucidating molecular mechanisms of toxicity, and conducting long-term environmental assessments. Establishing standardized safety guidelines and integrating nanotechnology into existing pest management policies will be essential for promoting responsible use. Moreover, enhancing consumer awareness and market acceptance will play a crucial role in advancing the commercialization of nanopesticides. Studies demonstrate that nanoparticles such as silver, zinc oxide, and titanium dioxide exhibit strong insecticidal properties through mechanisms like ROS generation, metal ion release, and cuticle penetration. Overall, nanotechnology holds significant potential for achieving sustainable pest management by improving pesticide efficacy, reducing environmental contamination, and minimizing adverse effects on non-target organisms.

**Keywords**: *Nanotechnology, Nanoparticles, Pest management, Nanoformulations, Biopesticides, Environmental safety, Sustainable agriculture.*

**I. Introduction**

**A. Rationale**

Pest management in agriculture presents numerous challenges due to the widespread damage caused by insect pests (Banwo *et al.,* 2003). Approximately 20–40% of global crop production is lost annually to pests, resulting in economic losses exceeding USD 220 billion. The reliance on synthetic chemical pesticides remains the primary approach to managing agricultural pests, with nearly 2.5 million tons of pesticides applied worldwide each year. Despite their effectiveness, conventional pesticides pose several issues, including the development of resistance, environmental contamination, bioaccumulation, and detrimental effects on non-target organisms. Contact with the active chemical components of pesticides, such as organophosphates and carbamates, can cause cardiovascular and respiratory diseases, skin cancer, hearing loss, and amputations (Paragas & Viloria, 2023). Over 600 insect species have developed resistance to chemical pesticides, significantly reducing their efficacy and necessitating the use of higher doses or more toxic alternatives. Furthermore, approximately 90% of applied pesticides fail to reach their intended targets, contaminating soil, water, and air, thereby threatening ecological balance and human health. Adverse health effects associated with pesticide exposure include neurological disorders, cancer, and reproductive issues, raising concerns about their long-term safety. The excessive use of synthetic pesticides has also contributed to soil degradation, water pollution, and loss of biodiversity, particularly affecting beneficial insects such as pollinators and natural predators. The increasing prevalence of pesticide-resistant pests and the negative environmental impacts of chemical pesticides have prompted researchers to explore alternative pest control strategies that are efficient, eco-friendly, and sustainable. Integrated Pest Management (IPM) has emerged as a viable approach combining biological, cultural, mechanical, and chemical control methods. However, IPM practices often face limitations related to efficacy, high costs, and implementation challenges. Nanotechnology has recently emerged as a promising approach for developing innovative pest control strategies that enhance efficacy while minimizing environmental impacts (Vurro *et al.,* 2019). This is because nano-encapsulated biopesticides can improve stability, reduce degradation, and enhance targeted delivery (Verma et al., 2023). The application of nanotechnology in agriculture aims to improve pesticide delivery, reduce non-target effects, and achieve higher efficiency through controlled release mechanisms. This emerging field offers unique opportunities for developing eco-friendly pest control solutions that address the shortcomings of conventional pesticides.

**B. Concept of Nanotechnology**

Nanotechnology refers to the manipulation, synthesis, and application of materials at the nanoscale, typically ranging from 1 to 100 nanometers. Materials at this scale exhibit unique physicochemical properties, such as high surface area, increased reactivity, enhanced solubility, and improved stability, making them suitable for various agricultural applications. The potential of nanotechnology extends beyond conventional pest control by enabling precise targeting, controlled release of active ingredients, and enhanced efficacy at lower dosages. Nanoparticles (NPs) are the most commonly studied nanomaterials in agricultural entomology due to their distinctive properties (Jafir *et al.,* 2023). High surface area-to-volume ratios enhance their interaction with biological targets, improving efficacy even at lower concentrations. Enhanced solubility and dispersibility allow nanoparticles to increase the bioavailability and effectiveness of poorly soluble active ingredients. Controlled release systems, achieved through nanoformulations, enable the slow and sustained release of active compounds, reducing the frequency of application and minimizing environmental contamination. Functionalization of nanoparticles allows for selective targeting of pests, enhancing insecticidal activity while reducing adverse effects on non-target organisms. Metal nanoparticles, such as silver (Ag), zinc oxide (ZnO), and titanium dioxide (TiO₂), have demonstrated significant insecticidal and antimicrobial properties against various agricultural pests, including mosquitoes, beetles, and aphids. Carbon-based nanomaterials, including graphene and carbon nanotubes, also show potential in pest control due to their mechanical disruption capabilities and high adsorption capacity. Nanoemulsions and nanosuspensions are other nanotechnology-based tools being explored for pest control (Balestra *et al.,* 2021). Moreover, plant-derived iron oxide nanoparticles (Fe3O4 NPs) have even greater potential for use in water treatment and biomedical fields due to their enhanced biocompatibility and lower cytotoxicity (Chelike et al., 2024). These formulations enhance the stability and efficacy of pesticides by improving their solubility, dispersibility, and bioavailability. Biogenic nanoparticles synthesized using plant extracts and microbial systems offer an eco-friendly alternative to chemically synthesized nanoparticles, further expanding the scope of nanotechnology in agricultural pest management.

**C. Objectives of the Review**

This review aims to evaluate the potential of nanotechnology in developing eco-friendly pest control strategies by examining various nanomaterials and their applications in insect pest management. The primary objective is to provide a comprehensive assessment of the mechanisms by which nanoparticles exert insecticidal effects, including physical, chemical, and biological interactions. Understanding these mechanisms can guide the development of effective and sustainable nanoparticle-based pest control systems. The review also aims to identify knowledge gaps related to the environmental implications and safety concerns associated with nanomaterials in agricultural pest management. Addressing these concerns is essential for ensuring the safe and responsible use of nanotechnology in agriculture. Additionally, the review seeks to highlight the future prospects of nanotechnology in agricultural entomology and provide recommendations for research priorities and policy development (Mishra *et al.,* 2017).

**D. Structure of the Review**

The structure of this review is organized as follows:  
The first section provides an overview of the nanomaterials used in pest control, including metal nanoparticles, metal oxide nanoparticles, carbon-based nanomaterials, and nanoemulsions. The second section discusses the mechanisms of action by which nanoparticles exert their effects on pests, focusing on physical, chemical, and biological mechanisms. The third section examines the applications of nanotechnology in pest management, including nanoformulations of pesticides, nanocarriers for biopesticides, and the integration of nanotechnology into Integrated Pest Management (IPM) frameworks. The fourth section addresses environmental implications and safety concerns, including toxicity, regulatory aspects, and strategies for minimizing environmental risks. The final section identifies research gaps and future prospects, emphasizing the need for long-term studies, comprehensive risk assessments, and the development of eco-friendly nanomaterials.

**II. Nanomaterials Used in Pest Control**

**A. Types of Nanomaterials**

**1. Metal Nanoparticles (e.g., Silver, Gold, Zinc Oxide)**

Metal nanoparticles are extensively studied for their pesticidal and antimicrobial properties due to their unique physicochemical characteristics (Joudeh *et al.,* 2022). Silver nanoparticles (AgNPs) are the most widely investigated metal nanoparticles due to their broad-spectrum antimicrobial activity against bacteria, fungi, and insect pests. Their effectiveness is attributed to their ability to generate reactive oxygen species (ROS) and interact with cellular components such as proteins and DNA, leading to cellular damage and death. Studies have demonstrated that AgNPs exhibit high toxicity against agricultural pests such as *Spodoptera litura* (cotton leafworm) and *Sitophilus oryzae* (rice weevil). Laboratory experiments have shown that AgNPs cause significant mortality rates exceeding 80% at concentrations as low as 10 ppm. Zinc oxide nanoparticles (ZnONPs) are also gaining attention due to their low cost, environmental compatibility, and strong insecticidal properties. Research indicates that ZnONPs exhibit effective control against pests like *Helicoverpa armigera* and *Aedes aegypti*, with mortality rates ranging from 70% to 95% depending on concentration and exposure duration.

Gold nanoparticles (AuNPs) are less commonly used due to their high cost but are considered effective carriers for biopesticides and gene delivery. Studies suggest that AuNPs can enhance the efficacy of biological control agents by improving their stability and bioavailability.

**2. Metal Oxide Nanoparticles (e.g., Titanium Dioxide, Copper Oxide)**

Metal oxide nanoparticles, such as titanium dioxide (TiO₂) and copper oxide (CuO), have demonstrated promising insecticidal and antimicrobial activities (Rekha *et al.,* 2019). TiO₂ nanoparticles are widely used due to their photocatalytic properties, which produce reactive oxygen species under light exposure, effectively damaging pest tissues and disrupting physiological functions. Research has shown that TiO₂ nanoparticles can significantly reduce the population of pests like *Bemisia tabaci* (whitefly) and *Tetranychus urticae* (two-spotted spider mite) through direct contact and ingestion.

Copper oxide nanoparticles (CuONPs) possess strong antimicrobial properties and have been tested against pests such as *Callosobruchus maculatus* (cowpea weevil) and *Plutella xylostella* (diamondback moth). Laboratory studies have reported mortality rates exceeding 85% when exposed to CuONPs at concentrations between 50 and 100 ppm. Despite their effectiveness, concerns about the toxicity of metal oxide nanoparticles to non-target organisms and the environment remain a significant research priority.

**3. Carbon-Based Nanomaterials (e.g., Graphene, Carbon Nanotubes)**

Carbon-based nanomaterials, including graphene and carbon nanotubes (CNTs), are emerging as potential tools for pest control due to their unique structural properties (Hussain *et al.,* 2022). Graphene oxide (GO) exhibits strong antimicrobial activity by disrupting cell membranes and interfering with metabolic processes. Studies have demonstrated that GO nanosheets can effectively control pests such as *Drosophila melanogaster* (fruit fly) and *Tribolium castaneum* (red flour beetle). Carbon nanotubes possess high surface area and mechanical strength, making them effective carriers for pesticide delivery and gene transfer. Their ability to penetrate insect cuticles and cellular membranes enhances the efficiency of active ingredients. Studies have reported that CNT-based formulations exhibit enhanced insecticidal activity against pests like *Spodoptera litura* and *Helicoverpa armigera* when compared to conventional pesticides.

**4. Nanoemulsions and Nanopesticides**

Nanoemulsions are colloidal systems composed of oil, water, and surfactants, with droplet sizes typically below 200 nm. These systems offer improved solubility, stability, and bioavailability of active ingredients, making them effective for pest control applications. Research has shown that nanoemulsions enhance the delivery and efficacy of botanical insecticides, such as neem oil and essential oils, against pests like *Aphis gossypii* (cotton aphid) and *Tetranychus urticae* (spider mite). Nanopesticides are formulations of conventional pesticides at the nanoscale, offering benefits such as controlled release, reduced environmental contamination, and enhanced toxicity to target pests (Chaud *et al.,* 2021). Studies indicate that the nanoencapsulation of insecticides can enhance their stability and prolong their efficacy, thereby reducing the need for repeated applications.

**5. Biogenic Nanoparticles (Plant-Mediated and Microbial Synthesis)**

Biogenic nanoparticles synthesized using plant extracts and microorganisms offer a green approach to nanoparticle production, minimizing the use of hazardous chemicals. Studies have demonstrated that nanoparticles synthesized using *Azadirachta indica* (neem) and *Cymbopogon citratus* (lemongrass) extracts exhibit potent insecticidal activity against pests like *Anopheles stephensi* (malaria vector) and *Aedes aegypti* (dengue vector). Microbial synthesis involving bacteria, fungi, and algae also produces nanoparticles with significant pesticidal properties. Research shows that biogenic silver nanoparticles synthesized by *Bacillus thuringiensis* exhibit over 90% mortality against *Spodoptera litura* and *Helicoverpa armigera* within 48 hours of exposure.

**B. Synthesis Methods**

Nanoparticles are synthesized using various methods categorized into physical, chemical, and biological approaches (Iravani *et al.,* 2014). Physical methods such as laser ablation and ball milling produce nanoparticles through mechanical processes without involving chemical reagents. Chemical methods include sol-gel processes, precipitation, and hydrothermal techniques, which are commonly employed due to their efficiency and scalability.

Biological synthesis, also known as green synthesis, utilizes plant extracts, bacteria, fungi, and algae to produce nanoparticles under environmentally benign conditions. This approach offers advantages such as cost-effectiveness, eco-friendliness, and reduced toxicity, making it highly suitable for agricultural applications.

**C. Characterization of Nanomaterials**

Characterization of nanomaterials involves determining their size, shape, surface area, surface charge, stability, structural composition, and crystallinity (Sayes *et al.,* 2009). Techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), dynamic light scattering (DLS), and X-ray diffraction (XRD) are commonly used for characterization. Proper characterization is essential for understanding the physicochemical properties of nanoparticles and their potential interactions with biological systems.

**III. Mechanisms of Action of Nanomaterials Against Pests**

**A. Physical Mechanisms**

**1. Cuticle Penetration and Disruption**

One of the primary mechanisms by which nanoparticles exert their insecticidal effects is through direct physical interaction with the insect cuticle. The insect cuticle serves as a protective barrier composed of chitin, proteins, and lipids, which provide structural integrity and prevent desiccation. Nanoparticles, particularly metal nanoparticles and metal oxide nanoparticles, possess the ability to adhere to the insect cuticle and penetrate through micro-abrasions or pores. The high surface area and small size of nanoparticles enhance their ability to interact with the cuticular surface, leading to mechanical damage and disruption.

Studies have demonstrated that silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnONPs) can effectively penetrate the cuticle of various insect pests, including *Spodoptera litura* (cotton leafworm) and *Aedes aegypti* (mosquito) (Shabir *et al.,* 2023). Exposure to AgNPs at concentrations as low as 10 ppm resulted in over 80% mortality in *Spodoptera litura* due to cuticle penetration and subsequent cellular damage. The small size of these nanoparticles allows them to infiltrate the lipid-rich layers of the cuticle, causing structural damage that compromises the insect’s protective barrier.

Titanium dioxide nanoparticles (TiO₂NPs) also exhibit significant cuticle penetration abilities, especially under ultraviolet (UV) light exposure. The photocatalytic activation of TiO₂NPs generates reactive oxygen species (ROS) that degrade the cuticular components, causing irreparable damage. This mechanism has been demonstrated in pests such as *Tetranychus urticae* (two-spotted spider mite) and *Bemisia tabaci* (whitefly), where TiO₂NPs cause severe cuticular degradation, resulting in mortality rates exceeding 85%.

**2. Desiccation and Dehydration**

Desiccation is another critical physical mechanism by which nanoparticles exert insecticidal effects. Certain nanoparticles, particularly silica nanoparticles (SiO₂NPs), have strong desiccating properties due to their high surface area and porous structure (Singh *et al.,* 2014). When applied to insect pests, SiO₂NPs absorb lipids from the insect cuticle, resulting in moisture loss and dehydration.

Studies have shown that silica nanoparticles cause significant mortality in pests such as *Tribolium castaneum* (red flour beetle) and *Sitophilus oryzae* (rice weevil). Laboratory experiments indicate that SiO₂NPs can cause mortality rates exceeding 90% within 48 hours of exposure at concentrations as low as 5 mg/m². Desiccation-induced mortality is particularly effective against soft-bodied insects and immature stages of pests, which are more susceptible to water loss.

The application of SiO₂NPs as insecticides offers advantages such as low toxicity to non-target organisms and environmental compatibility. Unlike chemical insecticides, silica nanoparticles do not interfere with the metabolic pathways of pests, making them suitable for integration into environmentally friendly pest management strategies.

**B. Chemical Mechanisms**

**1. Generation of Reactive Oxygen Species (ROS)**

The generation of reactive oxygen species (ROS) is one of the most significant chemical mechanisms by which nanoparticles induce toxicity in pests. ROS include highly reactive molecules such as hydroxyl radicals (•OH), superoxide anions (O₂⁻), and hydrogen peroxide (H₂O₂), which can cause oxidative stress and cellular damage.

Metal nanoparticles, particularly silver (Ag), zinc oxide (ZnO), and titanium dioxide (TiO₂), are known to generate ROS upon interaction with biological systems or under specific conditions such as light exposure (Ziental *et al.,* 2020). The oxidative stress induced by ROS leads to damage to cellular membranes, proteins, lipids, and nucleic acids, ultimately resulting in cell death.

Studies have shown that AgNPs induce ROS generation in *Aedes aegypti* larvae, causing mitochondrial dysfunction and apoptosis at concentrations as low as 10 ppm. Similarly, TiO₂NPs under UV light exposure generate ROS that disrupts cellular processes in pests such as *Tetranychus urticae* and *Bemisia tabaci*.

**2. Release of Metal Ions and Their Toxic Effects**

Another important chemical mechanism involves the release of metal ions from nanoparticles upon interaction with the insect’s physiological environment. The dissolution of metal nanoparticles such as Ag, CuO, and ZnO releases ions that interfere with essential biological processes, including enzyme activity, membrane integrity, and genetic material.

Research indicates that silver ions (Ag⁺) released from AgNPs can bind to thiol groups in proteins, disrupting cellular functions and inhibiting enzyme activity (Jiang *et al.,* 2019). This mechanism has been demonstrated in pests like *Spodoptera litura* and *Anopheles stephensi*, where AgNPs exhibit over 80% mortality due to metal ion toxicity.

Zinc ions (Zn²⁺) released from ZnONPs also exhibit toxic effects by disrupting cellular metabolism and inducing oxidative stress. Studies have shown that ZnONPs cause significant mortality in *Helicoverpa armigera* and *Aedes aegypti* due to the combined effects of ion release and ROS generation.

**3. Interaction with Cellular Components (e.g., DNA, Proteins)**

Nanoparticles interact with various cellular components, leading to structural and functional damage (Engin *et al.,* 2017). Metal nanoparticles, due to their small size and high reactivity, can cross cellular membranes and bind to proteins, DNA, and other biomolecules, interfering with cellular functions.

Studies have demonstrated that AgNPs bind to DNA molecules, causing structural damage and inhibiting transcriptional and translational processes. Such interactions have been observed in pests like *Drosophila melanogaster* and *Spodoptera litura*, where exposure to AgNPs results in disrupted cellular metabolism and eventual mortality.

**C. Biological Mechanisms**

**1. Targeted Delivery of Biopesticides**

Nanotechnology offers innovative approaches for delivering biopesticides through encapsulation and controlled release mechanisms. Nanocarriers such as liposomes, dendrimers, and polymer nanoparticles enhance the stability and bioavailability of natural insecticides, improving their efficacy against various pests.

**2. Enhanced Efficacy of Natural Insecticides**

Nanoparticle formulations enhance the effectiveness of botanical insecticides such as neem oil and essential oils. Studies have shown that nanoemulsions of neem oil exhibit higher toxicity against *Aphis gossypii* and *Tetranychus urticae* than conventional formulations (Abdelaal *et al.,* 2021).

**3. Synergistic Effects with Existing Pest Control Agents**

The combination of nanomaterials with existing chemical and biological control agents can produce synergistic effects, enhancing overall efficacy. For example, silver nanoparticles combined with *Bacillus thuringiensis* have demonstrated improved insecticidal activity against *Helicoverpa armigera*.

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**IV. Applications of Nanotechnology in Pest Management**

**A. Nanoformulations of Pesticides**

**1. Nanoemulsions and Nanosuspensions**

Nanoemulsions and nanosuspensions have emerged as promising tools for enhancing the effectiveness of pesticides through improved solubility, stability, and bioavailability. Nanoemulsions are colloidal dispersions consisting of oil and water stabilized by surfactants, with droplet sizes typically below 200 nm. These formulations improve the dispersion of hydrophobic active ingredients, enhancing their penetration through insect cuticles and cellular membranes.

Studies have demonstrated that neem oil-based nanoemulsions exhibit higher insecticidal activity than conventional formulations against pests such as *Aphis gossypii* (cotton aphid) and *Tetranychus urticae* (spider mite) (Subramanya *et al.,* 2022). Research indicates that nanoemulsions containing 0.5% neem oil achieve 85% mortality in *Aphis gossypii* within 24 hours of application, compared to 55% mortality achieved by conventional neem oil formulations.

Nanosuspensions, which are dispersions of insoluble active ingredients stabilized by surfactants, offer enhanced stability and prolonged efficacy. These formulations have been successfully applied against pests like *Spodoptera litura* and *Plutella xylostella* (diamondback moth), resulting in higher mortality rates and reduced development of resistance.

**2. Controlled Release Systems**

Controlled release systems are designed to improve the efficiency and persistence of active ingredients by providing sustained release over extended periods. Nanocarriers such as polymeric nanoparticles, liposomes, and dendrimers have been developed to encapsulate insecticides and release them gradually, thereby reducing the frequency of application and minimizing environmental contamination.

Research has shown that polymeric nanoparticles loaded with botanical insecticides such as azadirachtin and pyrethrin exhibit enhanced efficacy against *Helicoverpa armigera* (cotton bollworm) and *Spodoptera litura* (cotton leafworm). Studies report that controlled-release formulations reduce the degradation of active ingredients by 30–40% and improve insecticidal activity by 50–60% compared to conventional formulations (Li *et al.,* 2021).

The use of controlled release systems also reduces the risk of pest resistance development by ensuring prolonged exposure to sub-lethal doses of active ingredients, thereby disrupting pest physiology and reproduction over time.

**3. Enhanced Stability and Efficacy of Active Ingredients**

Nanotechnology improves the stability of insecticides by preventing their degradation due to environmental factors such as heat, moisture, and ultraviolet radiation. Research has shown that the nanoencapsulation of botanical extracts significantly enhances their stability, extending their shelf life by up to 50% compared to non-encapsulated formulations.

The increased surface area of nanoparticles allows for better adhesion to pest surfaces, enhancing the efficacy of active ingredients. Studies have demonstrated that silver nanoparticles combined with essential oils exhibit 90% mortality against *Aedes aegypti* larvae, highlighting the synergistic effects achieved through nanotechnology (Lobato *et al.,* 2020).

**B. Nanocarriers for Biopesticides**

**1. Encapsulation of Botanical Extracts**

Nanocarriers offer an effective method for encapsulating botanical extracts, enhancing their stability, bioavailability, and insecticidal activity. Natural insecticides derived from plants such as neem (*Azadirachta indica*), garlic (*Allium sativum*), and citronella (*Cymbopogon nardus*) have demonstrated potential for pest control when formulated as nanoparticles.

Studies have shown that nanoencapsulated neem oil exhibits higher efficacy against *Plutella xylostella* (diamondback moth) and *Helicoverpa armigera*, achieving 80–90% mortality within 48 hours of exposure. The encapsulation process protects the active ingredients from degradation and enhances their solubility, improving their ability to penetrate insect cuticles and tissues.

**2. Improved Bioavailability and Sustained Release**

Nanocarriers improve the bioavailability of biopesticides by facilitating their absorption and distribution within the insect body (Christiaenes *et al.,* 2020). Lipid-based nanoparticles and polymeric nanoparticles are particularly effective in delivering botanical insecticides due to their biocompatibility and sustained-release properties.

Research indicates that nanoformulations of garlic extract achieve 70% higher efficacy against *Aphis gossypii* compared to conventional formulations, primarily due to enhanced bioavailability and prolonged release. The use of nanocarriers also reduces the frequency of application, making pest control strategies more cost-effective and environmentally sustainable.

**3. Enhanced Insecticidal Activity**

The combination of nanotechnology and biopesticides often results in synergistic effects that enhance insecticidal activity. Studies have demonstrated that silver nanoparticles loaded with essential oils exhibit significant larvicidal activity against *Anopheles stephensi* (malaria vector) and *Culex quinquefasciatus* (filariasis vector), achieving 95% mortality at concentrations as low as 20 ppm.

**C. Nanoparticles as Direct Insecticides**

**1. Metal and Metal Oxide Nanoparticles**

Metal nanoparticles such as silver, gold, and zinc oxide exhibit potent insecticidal properties due to their ability to generate reactive oxygen species (ROS), release metal ions, and disrupt cellular processes (Jameel *et al.,* 2020). Studies have shown that silver nanoparticles cause 85% mortality in *Spodoptera litura* within 24 hours of exposure at concentrations below 10 ppm.

Metal oxide nanoparticles such as titanium dioxide and copper oxide have demonstrated significant insecticidal activity against pests like *Bemisia tabaci* and *Helicoverpa armigera*, with mortality rates exceeding 80%.

**D. Nanotechnology for Pest Detection and Monitoring**

**1. Nanosensors for Pest Detection**

Nanosensors are highly sensitive devices capable of detecting pest populations at early stages (Dubey *et al.,* 2016). These sensors utilize nanomaterials such as graphene, gold nanoparticles, and quantum dots to detect specific biochemical markers released by pests.

Studies have demonstrated that nanosensors can detect *Spodoptera frugiperda* (fall armyworm) infestations within hours of exposure, facilitating timely interventions and reducing crop losses by 40%.

**E. Integrated Pest Management (IPM) Approaches**

Combining nanotechnology with biological control methods enhances pest management strategies by providing synergistic effects. Nanoparticles can be integrated with entomopathogenic fungi and bacteria to improve their efficiency against target pests.

Nanotechnology-based IPM approaches can significantly reduce pesticide usage while enhancing the efficacy of natural control agents. Research indicates that nanoformulations of *Bacillus thuringiensis* exhibit 30–40% higher efficacy against *Helicoverpa armigera* compared to conventional formulations.

**V. Environmental Implications and Safety Concerns**

**A. Toxicity of Nanomaterials**

**1. Environmental Persistence and Bioaccumulation**

The environmental persistence and bioaccumulation of nanomaterials are major concerns associated with their application in pest management (Jafir *et al.,* 2023). Metal nanoparticles, including silver (AgNPs), zinc oxide (ZnONPs), and copper oxide (CuONPs), exhibit high stability and low degradation rates, potentially leading to their accumulation in soil, water, and living organisms.

Studies have shown that silver nanoparticles can persist in soil for extended periods due to their resistance to chemical and biological degradation. Research indicates that AgNPs exhibit a half-life of approximately 150–200 days in soil, depending on environmental conditions. Their persistence increases the likelihood of bioaccumulation in terrestrial and aquatic food chains, posing risks to non-target organisms.

Bioaccumulation of nanoparticles has been documented in various species, including earthworms, fish, and aquatic invertebrates. Studies have demonstrated that earthworms (*Eisenia fetida*) exposed to AgNPs exhibit accumulation in their tissues, with concentrations reaching 0.7 mg/kg after 28 days of exposure. This bioaccumulation not only affects the health of non-target organisms but also disrupts ecological functions such as soil nutrient cycling and decomposition (Akhter *et al.,* 2024).

Metal oxide nanoparticles like ZnONPs and CuONPs are also known to accumulate in aquatic environments, where they exert toxic effects on fish, algae, and plankton. Research indicates that ZnONPs at concentrations of 100 mg/L cause significant mortality in *Daphnia magna* (water flea), reducing population growth rates by over 80% within 96 hours of exposure. Such findings raise concerns about the ecological impacts of nanomaterials released into natural ecosystems.

**2. Impact on Non-Target Organisms**

The potential toxicity of nanoparticles to non-target organisms is a critical issue that requires thorough investigation. While nanomaterials are designed to target specific pests, their non-specific mode of action often results in unintended effects on beneficial insects, pollinators, soil microorganisms, and aquatic organisms (Jaison *et al.,* 2024).

Pollinators, particularly bees, are highly vulnerable to nanoparticle exposure. Studies have shown that AgNPs can negatively affect bee behavior, immune function, and survival rates. Laboratory experiments indicate that honey bees (*Apis mellifera*) exposed to AgNPs at concentrations above 10 ppm exhibit reduced foraging activity and increased mortality rates by 40–50% within 48 hours.

The impact of nanoparticles on soil microorganisms is also concerning, as microbial communities play essential roles in nutrient cycling, soil fertility, and ecosystem resilience. Research has demonstrated that ZnONPs and CuONPs disrupt soil microbial activity by interfering with enzymatic processes and reducing microbial biomass by 20–30%. Such disruptions can have long-term implications for soil health and agricultural productivity.

Aquatic organisms, including fish and amphibians, are particularly sensitive to nanoparticle exposure. Studies have reported that AgNPs cause oxidative stress, DNA damage, and apoptosis in fish species such as *Oncorhynchus mykiss* (rainbow trout) and *Danio rerio* (zebrafish) (Kokturk *et al.,* 2022). Toxicity levels are often dose-dependent, with lethal concentrations (LC50) ranging from 1 to 10 mg/L depending on the species and exposure duration.

**3. Cytotoxicity and Genotoxicity Concerns**

Cytotoxicity and genotoxicity are significant concerns related to the use of nanoparticles in pest management. Nanomaterials can interact with cellular components such as DNA, proteins, and lipids, leading to oxidative stress, inflammation, and cell death.

Research indicates that metal nanoparticles, particularly AgNPs and ZnONPs, induce genotoxicity by generating reactive oxygen species (ROS) that cause DNA strand breaks and chromosomal aberrations. Studies have shown that AgNPs at concentrations of 20 ppm cause significant DNA damage in *Drosophila melanogaster* and *Spodoptera litura*, with damage rates exceeding 70% within 24 hours of exposure.

In vitro studies involving mammalian cell lines have demonstrated that AgNPs and ZnONPs induce cytotoxic effects by disrupting mitochondrial function, inducing apoptosis, and interfering with cellular signaling pathways. Such findings raise concerns about the potential health risks associated with nanomaterial exposure in agricultural environments (Jain *et al.,* 2018).

**B. Regulatory Aspects**

**1. Current Guidelines and Regulations**

The lack of comprehensive regulatory frameworks for nanomaterials used in pest management presents significant challenges. While traditional pesticides are subject to strict safety evaluations, nanopesticides often fall outside conventional regulatory guidelines due to their novel physicochemical properties.

Regulatory agencies, including the European Food Safety Authority (EFSA) and the United States Environmental Protection Agency (EPA), have initiated efforts to establish guidelines for evaluating the safety of nanomaterials. Current regulations primarily focus on assessing toxicity, environmental persistence, and potential bioaccumulation. However, standardized methodologies for evaluating nanopesticides remain limited (Kookana *et al.,* 2014).

**2. Risk Assessment Frameworks**

Effective risk assessment frameworks are essential for ensuring the safe and responsible use of nanomaterials. Studies emphasize the need for developing protocols that account for nanoparticle size, shape, surface charge, solubility, and chemical composition when evaluating their toxicity.

Risk assessments must consider the potential impacts of nanoparticles on non-target organisms, environmental compartments, and human health. The establishment of standardized testing protocols for evaluating acute and chronic toxicity is essential for accurate risk characterization.

**3. Need for Standardization and Labeling**

The absence of standardization and labeling requirements for nanomaterials poses challenges for their regulation and commercialization. Developing consistent guidelines for characterizing, labeling, and monitoring nanoparticles is crucial for ensuring their safe application in agriculture (Wahab *et al.,* 2024).

**C. Sustainable Use of Nanomaterials**

**1. Strategies to Minimize Environmental Risks**

Developing eco-friendly nanomaterials through green synthesis methods offers a promising approach for reducing environmental risks. Biogenic nanoparticles synthesized using plant extracts and microbial systems exhibit lower toxicity and higher biodegradability than chemically synthesized nanoparticles.

**2. Development of Eco-Friendly Nanomaterials**

Research focused on developing biodegradable and biocompatible nanomaterials is essential for minimizing ecological impacts. The use of natural polymers such as chitosan and alginate for nanoparticle synthesis has demonstrated reduced toxicity and enhanced environmental compatibility.

**3. Recommendations for Safe and Responsible Use**

Promoting the sustainable use of nanomaterials requires the implementation of regulatory frameworks, risk assessment protocols, and labeling standards (Subhan *et al.,* 2022). Collaboration between researchers, policymakers, and industry stakeholders is essential for developing guidelines that ensure the safety and efficacy of nanotechnology in pest management.

**VI. Research Gaps and Future Prospects**

**A. Improvement of Nanopesticide Formulations**

**1. Development of Biodegradable and Eco-Friendly Nanomaterials**

The development of biodegradable and eco-friendly nanomaterials remains a critical research priority aimed at minimizing environmental risks associated with conventional nanoparticles. Current nanopesticide formulations often include metal and metal oxide nanoparticles such as silver (AgNPs), zinc oxide (ZnONPs), and titanium dioxide (TiO₂NPs), which are effective but may persist in the environment, leading to bioaccumulation and potential toxicity.

Researchers are increasingly focusing on green synthesis methods involving plant extracts, bacteria, fungi, and algae to produce biogenic nanoparticles with reduced environmental impact. Studies have demonstrated that biogenic silver nanoparticles synthesized using *Azadirachta indica* (neem) extract exhibit insecticidal activity against *Anopheles stephensi* (malaria vector) with over 90% mortality at concentrations of 20 ppm.

Biodegradable polymer-based nanoparticles, such as chitosan and alginate, have also been explored for their compatibility with biological control agents and enhanced environmental safety (Pavithran *et al.,* 2024). Chitosan nanoparticles, for instance, have shown potential as carriers for botanical insecticides, improving their stability and bioavailability while exhibiting low toxicity to non-target organisms.

Developing eco-friendly nanopesticides that degrade into non-toxic byproducts is essential for achieving sustainable pest management. Such formulations would offer significant advantages over conventional pesticides by minimizing soil and water contamination, reducing harm to beneficial organisms, and improving crop productivity.

**2. Enhanced Delivery Systems for Pest Control Agents**

Optimizing the delivery of pest control agents using nanotechnology remains a key area of research. Traditional pesticide formulations often suffer from limited stability, low solubility, and inefficient targeting of pests, leading to excessive application rates and environmental contamination (Singh *et al.,* 2020).

Nanocarriers such as liposomes, polymeric nanoparticles, dendrimers, and nanoemulsions offer improved delivery of active ingredients by enhancing their solubility, protecting them from degradation, and facilitating targeted release. Studies have demonstrated that nanoencapsulation of azadirachtin, a botanical insecticide derived from neem, improves its stability by 40–50% and enhances insecticidal activity against *Helicoverpa armigera* (cotton bollworm) by 60–70% compared to conventional formulations.

The development of smart nanocarriers capable of responding to environmental triggers such as pH, temperature, and light represents an exciting area of innovation (Shishir *et al.,* 2021). Such systems can provide controlled release of active ingredients, improving their efficacy and reducing their environmental impact.

**B. Understanding Mechanisms of Action**

**1. Detailed Investigation of Nanoparticle-Pest Interactions**

Understanding the precise interactions between nanoparticles and pest organisms is essential for developing effective and targeted pest control strategies (Khandelwal *et al.,* 2016). While numerous studies have demonstrated the insecticidal properties of nanoparticles, the underlying mechanisms remain poorly understood.

Research has primarily focused on the physical and chemical interactions between nanoparticles and pests, such as cuticle penetration, desiccation, ROS generation, and metal ion release. However, the extent to which nanoparticles interact with specific biological pathways and physiological processes requires further investigation.

Emerging techniques such as transcriptomics, proteomics, and metabolomics can provide valuable insights into the molecular mechanisms underlying nanoparticle-induced toxicity. Studies have demonstrated that silver nanoparticles cause significant changes in gene expression related to oxidative stress, immune response, and cellular metabolism in insects like *Drosophila melanogaster* and *Spodoptera litura* (Wang *et al.,* 2023).

**2. Molecular Mechanisms Underlying Insecticidal Activity**

The molecular basis of nanoparticle-induced toxicity remains a critical area of research. Current studies suggest that nanoparticles can interfere with essential cellular functions, including DNA replication, protein synthesis, mitochondrial activity, and enzymatic processes.

Research indicates that silver nanoparticles induce DNA damage in insect cells by generating reactive oxygen species (ROS) and disrupting mitochondrial function. Studies have shown that exposure to AgNPs at concentrations of 20 ppm results in DNA fragmentation rates exceeding 70% in *Spodoptera litura* within 24 hours of exposure.

Further research is needed to elucidate the specific molecular pathways targeted by nanoparticles and determine their relevance to pest mortality. A comprehensive understanding of these mechanisms will facilitate the development of more effective and selective nanopesticides (Li *et al.,* 2023).

**C. Long-Term Environmental Impact Studies**

**1. Comprehensive Assessment of Toxicity**

Most studies evaluating the toxicity of nanoparticles focus on acute exposure scenarios, often overlooking long-term environmental impacts. While nanoparticles have demonstrated significant efficacy against pests, their potential for chronic toxicity, bioaccumulation, and ecological disruption remains underexplored. Assessing the long-term toxicity of nanoparticles requires standardized protocols for evaluating their persistence, degradation, and interaction with non-target organisms (Hennig *et al.,* 2023). Studies have shown that silver nanoparticles can persist in soil environments for months, raising concerns about their potential to disrupt microbial communities and soil health.

**2. Monitoring of Nanomaterial Residues in Ecosystems**

The development of reliable techniques for monitoring nanomaterial residues in soil, water, and living organisms is essential for ensuring their safe application. Current analytical methods, including transmission electron microscopy (TEM), scanning electron microscopy (SEM), and inductively coupled plasma mass spectrometry (ICP-MS), offer valuable tools for detecting and quantifying nanoparticles in various environmental matrices. Establishing guidelines for acceptable residue levels and evaluating their potential impacts on ecosystem health should be prioritized in future research.

**D. Regulatory and Policy Frameworks**

**1. Establishment of Standardized Safety Guidelines**

The absence of standardized safety guidelines for nanopesticides remains a significant barrier to their commercialization and widespread adoption (Cummings *et al.,* 2021). Regulatory agencies must establish clear protocols for evaluating the safety, efficacy, and environmental impact of nanoparticle-based pest control products.

**2. Integration of Nanotechnology in Pest Management Policies**

Incorporating nanotechnology into existing pest management policies requires collaboration between researchers, policymakers, and industry stakeholders. Effective regulatory frameworks that address risk assessment, labeling, and public perception are essential for promoting responsible use.

**E. Commercialization and Market Potential**

**1. Challenges in Scaling Up Nanopesticide Production**

The high cost of nanoparticle production and the complexity of scaling up laboratory-scale processes to commercial levels remain significant challenges. Developing cost-effective synthesis methods and improving manufacturing efficiency are critical for achieving market viability (Sharma *et al.,* 2011).

**2. Market Trends and Consumer Acceptance**

Public perception of nanopesticides and consumer acceptance of nanoparticle-based agricultural products require thorough investigation. Awareness campaigns emphasizing the safety, efficacy, and environmental benefits of nanotechnology are necessary to promote market adoption.

**Conclusion**

Nanotechnology presents significant potential for developing eco-friendly pest control strategies by enhancing pesticide efficacy, improving delivery systems, and reducing environmental contamination. Studies demonstrate that nanoparticles such as silver, zinc oxide, and titanium dioxide exhibit strong insecticidal properties through mechanisms like ROS generation, metal ion release, and cuticle penetration. Nanoformulations of biopesticides also show promise in enhancing bioavailability and providing sustained release, improving overall effectiveness. Despite these benefits, concerns about toxicity, environmental persistence, and impacts on non-target organisms remain unresolved. Regulatory frameworks for evaluating nanopesticides are still inadequate, necessitating the establishment of standardized safety guidelines. Future research should focus on developing biodegradable nanomaterials, understanding molecular mechanisms of action, and conducting comprehensive long-term environmental assessments. Promoting responsible use through improved regulations and public awareness will be essential for achieving sustainable pest management.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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