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# Enhancing Agricultural Efficiency and Biodiversity Conservation through Nano Pesticides; A Focus on Food Research

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*The sole author designed, analyzed, interpreted and prepared the manuscript.*

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**Review Article**

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## ABSTRACT

Nanotechnology has emerged as a promising approach to addressing the challenges faced by modern agriculture, particularly in the field of crop protection. Nano-pesticides, which are pesticide formulations that incorporate nanomaterials or nanostructures, have garnered significant attention due to their potential to enhance the efficacy of active ingredients while minimizing adverse environmental and health impacts. This review provides a comprehensive overview of on the current state of research on nano-pesticides, focusing on their synthesis, characterization, mode of action, and efficacy in various agricultural applications. The unique physicochemical properties of nanomaterials, such as high surface area to volume ratio, enhanced solubility, and controlled release, are exploited in the development of nano-pesticide formulations. Different types of nano-pesticides, including nanoemulsions, nanoencapsulation, and nanocomposites, are discussed in detail, highlighting their advantages over conventional pesticide formulations. The review also examines the interactions of nano-pesticides with target pests and the environment, as well as their potential toxicity and ecotoxicological effects. The role of nano-pesticides in integrated pest management strategies and their compatibility with sustainable agricultural practices are explored. Furthermore, the review addresses the challenges associated with the commercialization and regulatory aspects of nano-pesticides, emphasizing the need for thorough risk assessment and standardized testing protocols. Future research directions and opportunities for the development of nano-pesticides are outlined, focusing on the optimization of formulations, targeted delivery, and precision agriculture. Overall, this review provides valuable insights into the potential of nano-pesticides as a tool for enhancing agricultural productivity and sustainability while minimizing the negative impacts on biodiversity and food safety.

*Keywords: Nanotechnology; nano-pesticides; crop protection; sustainable agriculture; biodiversity; food safety.*

## 1. INTRODUCTION

The global population is expected to reach 9.7 billion by 2050, placing an unprecedented demand on agricultural production to ensure food security [1]. However, the This has resulted in an increasing pressure to intensify crop production that has led to the overuse and misuse of synthetic pesticides, resulting in culminating into numerous adverse environmental and health consequences. Conventional pesticides often suffer from low efficacy, off-target effects, and the development of pest resistance, necessitating the application of higher doses and more frequent treatments [2]. Moreover, the indiscriminate use of pesticides has been linked to the decline of in beneficial insects, such as pollinators, and the contamination of soil and water resources [3].

Nanotechnology has emerged as a promising approach to addressing these challenges by enabling the development of novel pesticide formulations with enhanced efficacy and reduced environmental footprint. Nano-pesticides are pesticide formulations that incorporate nanomaterials or nanostructures, such as nanoparticles, nanoemulsions, or nano-encapsulation systems [4]. The unique physicochemical properties of nanomaterials, including high surface area to volume ratio, enhanced solubility, and controlled release, can be exploited to improve the performance of active ingredients and minimize their adverse impacts [5].

The application of nanotechnology in agriculture has gained significant attention in recent years, with numerous studies demonstrating the potential of nano-pesticides to revolutionize crop protection strategies. Nano-pesticides have been shown to enhance the efficacy of active ingredients, reduce the required dosage, and improve the targeting of pests while minimizing off-target effects [6]. Moreover, the encapsulation of active ingredients within nanocarriers can protect them from premature degradation, enable controlled release, and facilitate their penetration into plant tissues [7].

Despite the promising potential of nano-pesticides, there are also concerns regarding their potential risks and uncertainties. The behaviour and fate of nanomaterials in the environment, their interactions with non-target organisms, and their potential for bioaccumulation and toxicity are not yet fully understood [8]. Therefore, a comprehensive understanding of the benefits and risks associated with nano-pesticides is crucial for their responsible development and application in agriculture.

This review aims to provide a comprehensive overview of the current state of research on nano-pesticides, focusing on their synthesis, characterization, mode of action, and efficacy in various agricultural applications. The review will also discuss the potential environmental and health implications of nano-pesticides, as well as the challenges and opportunities for their commercialization and regulation. By synthesizing the available knowledge on nano-pesticides, this review seeks to inform future research directions and support the development of sustainable and effective crop protection strategies.

## 2. SYNTHESIS AND CHARACTERIZATION OF NANO-PESTICIDES

The synthesis and characterization of nano-pesticides are critical steps in the development of effective and safe formulations for agricultural applications. Various approaches have been employed to synthesize nano-pesticides, each with its unique advantages and limitations. The choice of synthesis method depends on the desired properties of the nano-pesticide, such as size, shape, composition, and functionality [9].

### 2.1 Nanoemulsions

Nanoemulsions are thermodynamically stable colloidal dispersions of two immiscible liquids, typically an oil phase and an aqueous phase, with droplet sizes ranging from 20 to 200 nm [10]. Nanoemulsions have been widely explored as delivery systems for pesticides due to their ability to enhance the solubility, stability, and bioavailability of active ingredients [11].

The small droplet size of nanoemulsions also facilitates their penetration into plant tissues and improves their coverage on leaf surfaces [12].

The preparation of nanoemulsions involves the dispersion of the oil phase, containing the active ingredient, in the aqueous phase under high shear or high-pressure conditions in the presence of surfactants or emulsifiers [13]. The selection of appropriate oil phase, surfactants, and process parameters is crucial to obtaining stable nanoemulsions with desired properties. Various oils, such as vegetable oils, essential oils, and biodegradable polymers, have been used as the oil phase in pesticide nanoemulsions [14]. Non-ionic surfactants, such as polysorbates and polyethylene glycol derivatives, are commonly employed to stabilize the nanoemulsions and prevent coalescence of the droplets [15].

The characterization of pesticide nanoemulsions involves the assessment of their physicochemical properties, such as droplet size, size distribution, zeta potential, and morphology. Dynamic light scattering (DLS) and transmission electron microscopy (TEM) are commonly used techniques to determine the size and size distribution of nanoemulsion droplets [16]. Zeta potential measurements provide insights into the surface charge and stability of the nanoemulsions, with higher absolute zeta potential values indicating better stability against aggregation and coalescence [17].

### 2.2 Nanoencapsulation

Nanoencapsulation is a technique that involves the encapsulation of active ingredients within a polymeric or lipid-based nanocarrier, providing protection against degradation, controlled release, and targeted delivery [18]. Various nanocarriers, such as polymeric nanoparticles, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), have been explored for the encapsulation of pesticides [19].

Polymeric nanoparticles are synthesized by the polymerization of monomers or the dispersion of preformed polymers in the presence of the active ingredient [20]. Biodegradable polymers, such as poly(lactic-co-glycolic acid) (PLGA), poly(ε-caprolactone) (PCL), and chitosan, are commonly used for the preparation of pesticide-loaded polymeric nanoparticles due to their biocompatibility and controlled release properties [21]. The encapsulation of pesticides within polymeric nanoparticles can be achieved through various techniques, such as emulsion-solvent evaporation, nanoprecipitation, and ionic gelation [22].

SLNs and NLCs are lipid-based nanocarriers that have gained increasing attention for the

**Table 1. Components and process parameters for the synthesis of pesticide nanoemulsions**

| Component/Parameter | Description |
|---|---|
| Oil phase | Vegetable oils, essential oils, biodegradable polymers |
| Aqueous phase | Water, buffer solutions |
| Surfactants | Non-ionic surfactants (e.g., polysorbates, polyethylene glycol derivatives) |
| Preparation methods | High shear mixing, high-pressure homogenization, ultrasonication |
| Process parameters | Temperature, pressure, mixing speed, duration |

**Table 2. Nanocarriers used for the encapsulation of pesticides**

| Nanocarrier | Composition | Preparation methods | Key characteristics |
|---|---|---|---|
| Polymeric nanoparticles | PLGA, PCL, chitosan | Emulsion-solvent evaporation, nanoprecipitation, ionic gelation | Controlled release, biodegradability, biocompatibility |
| Solid lipid nanoparticles (SLNs) | Solid lipids (e.g., triglycerides, fatty acids, waxes) | High-pressure homogenization, solvent emulsification-evaporation | Enhanced solubility and stability of lipophilic active ingredients, controlled release |
| Nanostructured lipid carriers (NLCs) | Solid and liquid lipids | High-pressure homogenization, solvent emulsification-evaporation | Improved drug loading capacity and release properties compared to SLNs |

encapsulation of pesticides due to their biocompatibility, biodegradability, and ability to enhance the solubility and stability of lipophilic active ingredients [23]. SLNs are prepared by dispersing the active ingredient in a molten lipid matrix, followed by solidification upon cooling, while NLCs are prepared by incorporating liquid lipids into the solid lipid matrix to create a partially crystalline structure with improved drug loading capacity and release properties [24].

The characterization of pesticide-loaded nanocarriers involves the assessment of their particle size, size distribution, zeta potential, encapsulation efficiency, and release kinetics. DLS and TEM are commonly used to determine the particle size and morphology, while high-performance liquid chromatography (HPLC) or UV-visible spectroscopy are employed to quantify the encapsulation efficiency and release kinetics of the active ingredient [25].

### 2.3 Nanocomposites

Nanocomposites are materials that consist of a matrix phase and a dispersed nanoscale phase, which can be inorganic or organic in nature [26]. In the context of pesticide delivery, nanocomposites have been explored as carriers for the controlled release and targeted delivery of active ingredients. Various inorganic nanomaterials, such as clay minerals, silica nanoparticles, and metal oxide nanoparticles, have been used as the dispersed phase in pesticide nanocomposites due to their unique physicochemical properties and ability to interact with the active ingredients [27].

The synthesis of pesticide nanocomposites typically involves the intercalation or adsorption of the active ingredient within the nanoscale phase, followed by the dispersion of the nanoscale phase in the matrix material [28]. The matrix material can be a polymer, such as chitosan, alginate, or starch, which provides mechanical stability and controlled release properties to the nanocomposite [29]. The interaction between the active ingredient and the nanoscale phase can be through various mechanisms, such as electrostatic interactions, hydrogen bonding, or van der Waals forces, depending on the nature of the materials involved [30].

The characterization of pesticide nanocomposites involves the assessment of their morphology, composition, and release kinetics. Scanning electron microscopy (SEM) and TEM are used to visualize the dispersed nanoscale phase within the matrix material, while X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) provide information on the crystallinity and chemical interactions

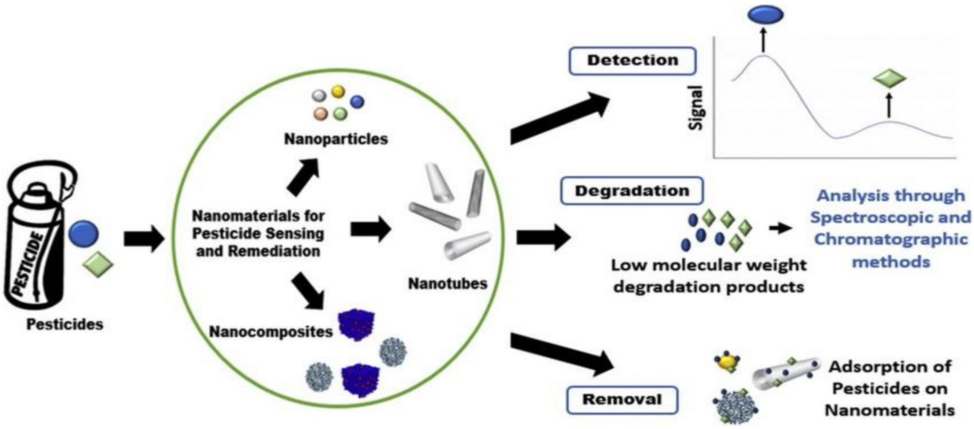


**Fig. 1. Schematic representation of a pesticide nanocomposite**

between the components [31]. The release kinetics of the active ingredient from the nanocomposite can be studied using HPLC or UV-visible spectroscopy, providing insights into the controlled release properties of the system [32].

## 3. MODE OF ACTION AND EFFICACY OF NANO-PESTICIDES

The mode of action and efficacy of nano-pesticides are crucial aspects that determine their potential for successful application in agriculture. Nano-pesticides exhibit unique mechanisms of action that differ from those of conventional pesticides, owing to their nanoscale size and enhanced physicochemical properties [33].

### 3.1 Enhanced Penetration and Translocation

One of the primary advantages of nano-pesticides is their ability to enhance the penetration and translocation of active ingredients into plant tissues. The small size of nanoparticles allows them to easily cross the barriers of plant cells and enter the vascular system, enabling systemic distribution of the pesticide throughout the plant [34]. This enhanced penetration and translocation can lead to improved efficacy against pests and diseases, as the active ingredient can reach its target site more effectively [35].

Several studies have demonstrated the enhanced penetration and translocation of nano-pesticides compared to their conventional counterparts. For example, Liu et al. [36] showed that chitosan-based nanoparticles loaded with the insecticide imidacloprid exhibited better penetration and translocation in rice plants compared to the conventional formulation. The nanoparticles were able to enter the leaf tissues and translocate to other parts of the plant, resulting in improved control of the brown planthopper (*Nilaparvata lugens*).

Similarly, Mattos et al. [37] investigated the penetration and translocation of chitosan-tripolyphosphate nanoparticles loaded with the fungicide tebuconazole in soybean plants. The nanoparticles were found to penetrate the leaf surface and translocate to distant parts of the plant, providing enhanced protection against the fungal pathogen *Phakopsora pachyrhizi*, the causal agent of Asian soybean rust.

### 3.2 Controlled Release and Targeted Delivery

Nano-pesticides offer the advantage of controlled release and targeted delivery of active ingredients, minimizing off-target effects and environmental contamination. The encapsulation of pesticides within nanocarriers, such as polymeric nanoparticles, SLNs, or NLCs, provides protection against premature degradation and allows for the sustained release of the active ingredient over an extended period [38]. The controlled release profile of nano-pesticides can be tailored by manipulating the composition and properties of the nanocarriers, such as the polymer type, lipid composition, and surface functionalization [39].

Targeted delivery of nano-pesticides can be achieved by functionalizing the surface of the nanocarriers with ligands or biomolecules that specifically bind to the target pest or pathogen [40]. This approach enables the selective

**Table 3. Advantages of nano-pesticides in terms of mode of action and delivery mechanisms**

| Advantage | Description |
|---|---|
| Enhanced penetration and translocation | Nanoparticles can easily cross plant cell barriers and enter the vascular system, enabling systemic distribution of the pesticide throughout the plant |
| Controlled release | Encapsulation of pesticides within nanocarriers provides protection against premature degradation and allows for sustained release of the active ingredient over an extended period |
| Targeted delivery | Surface functionalization of nanocarriers with ligands or biomolecules enables selective delivery of the active ingredient to the target pest or pathogen, reducing exposure of non-target organisms |

delivery of the active ingredient to the target site, reducing the exposure of non-target organisms and minimizing the environmental impact of the pesticide application.

For instance, Kumar et al. [41] developed a targeted delivery system for the insecticide chlorpyrifos using chitosan nanoparticles functionalized with a lectin that specifically binds to the midgut epithelial cells of the cotton bollworm (*Helicoverpa armigera*). The targeted delivery of chlorpyrifos resulted in enhanced insecticidal activity and reduced toxicity to non-target organisms compared to the conventional formulation.

### 3.3 Efficacy of Nano-Pesticides

The efficacy of nano-pesticides has been extensively studied against a wide range of pests and diseases in various crops. Numerous studies have demonstrated the superior performance of nano-pesticides compared to their conventional counterparts, highlighting their potential for effective pest and disease management in agriculture.

For example, Bhattacharyya et al. [42] investigated the efficacy of copper oxide nanoparticles against the fungal pathogen *Fusarium oxysporum* f. sp. *lycopersici*, which causes Fusarium wilt in tomato plants. The study found that the copper oxide nanoparticles exhibited strong antifungal activity and effectively controlled the disease, with a significantly higher efficacy compared to conventional copper-based fungicides.

In another study, Chhipa [43] evaluated the efficacy of nanoencapsulated deltamethrin against the cotton bollworm (*Helicoverpa armigera*) and the tobacco caterpillar (*Spodoptera litura).* The nanoencapsulated deltamethrin showed enhanced insecticidal activity and prolonged residual effect compared to the conventional formulation, resulting in better control of the insect pests.

Ashfaq et al. [44] explored the use of silver nanoparticles as a novel insecticide against the dengue vector mosquito, *Aedes aegypti*. The study demonstrated that silver nanoparticles exhibited high larvicidal and adulticidal activity, suggesting their potential as an effective alternative to conventional insecticides for mosquito control.

The efficacy of nano-pesticides can be attributed to various factors, including their enhanced penetration and translocation, controlled release, and targeted delivery properties. The nanoscale size of the active ingredients allows them to effectively reach and interact with the target pests or pathogens, while the encapsulation within nanocarriers provides protection against premature degradation and enables sustained release over time.

However, it is important to note that the efficacy of nano-pesticides may vary depending on the specific formulation, target pest or pathogen, crop species, and environmental conditions. Therefore, further research is needed to optimize the formulation and application strategies of nano-pesticides for different crop protection scenarios.

## 4. ENVIRONMENTAL FATE AND RISKS OF NANO-PESTICIDES

While nano-pesticides offer numerous benefits in terms of enhanced efficacy and targeted delivery, it is crucial to consider their potential environmental fate and risks. The unique properties of nanomaterials that make them advantageous for pesticide formulations may also raise concerns regarding their behaviour, persistence, and toxicity in the environment [45].

### 4.1 Fate and Behavior in the Environment

The fate and behaviour of nano-pesticides in the environment are governed by various factors, including their size, surface properties, composition, and the characteristics of the receiving environment [46]. Once released into the environment, nano-pesticides can undergo a range of processes, such as aggregation, dissolution, sorption, and transformation, which can influence their transport, bioavailability, and ultimate fate [47].

The small size and high surface area to volume ratio of nanoparticles can lead to enhanced reactivity and interactions with environmental components, such as soil particles, organic matter, and water [48]. These interactions can result in the adsorption of nano-pesticides onto soil or sediment surfaces, affecting their mobility and bioavailability. The aggregation of nanoparticles can also occur, leading to changes in their size and behaviuor in the environment [49].

The dissolution of nano-pesticides is another important process that can influence their fate and toxicity. The release of metal ions from metal-based nano-pesticides, such as copper oxide or silver nanoparticles, can contribute to their antimicrobial activity but also raise concerns about their potential ecotoxicity [50]. The rate and extent of dissolution depend on various factors, including the composition of the nanoparticles, pH, and the presence of organic matter or other ligands in the environment [51].

Transformation processes, such as photodegradation, biodegradation, and chemical reactions, can also affect the fate and behaviour of nano-pesticides in the environment. These processes can lead to the formation of new transformation products with potentially different properties and toxicity compared to the parent compounds [52].

### 4.2 Ecological Risks and Toxicity

The ecological risks and toxicity of nano-pesticides are of significant concern, as their unique properties may lead to unintended consequences for non-target organisms and ecosystems. The small size of nanoparticles allows them to easily penetrate biological barriers and interact with cellular components, potentially inducing toxic effects [53].

Several studies have investigated the toxicity of nano-pesticides to various non-target organisms, including beneficial insects, aquatic organisms, and soil microbes. For example, Pappas et al. [54] assessed the impact of copper oxide nanoparticles on the survival and reproduction of the beneficial insect *Chrysoperla carnea,* commonly known as the green lacewing. The study found that exposure to copper oxide nanoparticles resulted in reduced survival and reproductive output of *C. carnea*, highlighting the potential risks to beneficial insects.

The toxicity of nano-pesticides to aquatic organisms is also a major concern, as these organisms may be exposed to nanomaterials through surface runoff or leaching from treated fields. Bai et al. [55] investigated the toxicity of silver nanoparticles to the freshwater crustacean *Daphnia magna* and found that exposure to increasing concentrations of silver nanoparticles led to significant mortality and reproductive impairment.

**Table 4. Examples of studies demonstrating the efficacy of nano-pesticides**

| Nano-pesticide | Target pest/disease | Crop | Key findings | Reference |
|---|---|---|---|---|
| Copper oxide nanoparticles | *Fusarium oxysporum f. sp. Lycopersici* | Tomato | Strong antifungal activity, higher efficacy compared to conventional copper-based fungicides | Bhattacharyya et al. [42] |
| Nanoencapsulated deltamethrin | *Helicoverpa armigera, Spodoptera litura* | Cotton | Enhanced insecticidal activity, prolonged residual effect compared to conventional formulation | Chhipa [43] |
| Silver nanoparticles | *Aedes aegypti* | - | High larvicidal and adulticidal activity, potential alternative to | Ashfaq et al. [44] |

| Nano-pesticide | Target pest/disease | Crop | Key findings | Reference |
|---|---|---|---|---|
| | | | conventional insecticides | |
| Chitosan-based nanoparticles loaded with imidacloprid | *Nilaparvata lugens* | Rice | Better penetration and translocation, improved control of the pest compared to conventional formulation | Liu et al. [36] |

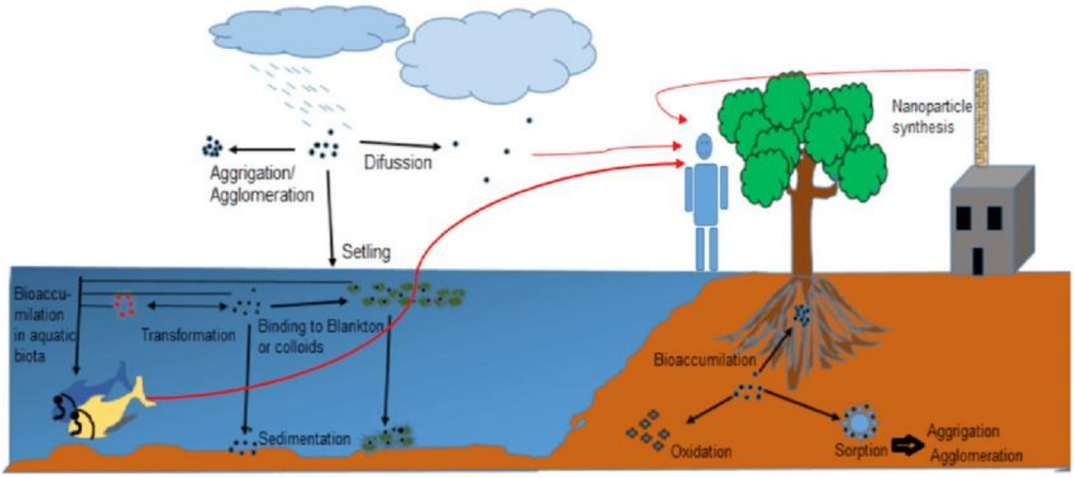


**Fig. 2. Illustrates the potential environmental fate and behavior of nano-pesticides**

Nano-pesticides can also pose risks to soil microbial communities, which play crucial roles in nutrient cycling, organic matter decomposition, and plant growth promotion. The interaction of nano-pesticides with soil microbes can lead to changes in microbial diversity, abundance, and activity, with potential consequences for soil health and ecosystem functioning [56].

Moreover, the bioaccumulation and trophic transfer of nano-pesticides in food chains is another area of concern. Nanomaterials can be taken up by plants and other organisms at the base of the food chain and subsequently transferred to higher trophic levels, potentially leading to biomagnification and long-term ecological consequences [57].

To assess the ecological risks of nano-pesticides, it is essential to conduct comprehensive ecotoxicological studies that consider the full life cycle of the nanomaterials, from their synthesis and application to their ultimate fate and effects in the environment. These studies should encompass a wide range of organisms, including beneficial insects, pollinators, aquatic organisms, and soil biota, to provide a holistic understanding of the potential impacts of nano-pesticides on ecosystems.

## 5. HUMAN HEALTH IMPLICATIONS OF NANO-PESTICIDES

In addition to the environmental risks, the potential human health implications of nano-pesticides are also a significant concern. The unique properties of nanomaterials that make them effective pesticides may also pose risks to human health, particularly through occupational exposure during the manufacturing, handling, and application of nano-pesticides [58].

### 5.1 Exposure Routes and Toxicity Mechanisms

Humans can be exposed to nano-pesticides through various routes, including inhalation, dermal contact, and ingestion. Inhalation is a major exposure route, particularly for workers involved in the manufacturing and application of nano-pesticides. The small size of nanoparticles allows them to easily penetrate deep into the respiratory tract and potentially translocate to other organs [59].

Dermal contact is another significant exposure route, as nano-pesticides can come into contact with the skin during handling and application. The ability of nanoparticles to penetrate the skin barrier and enter the systemic circulation is a concern, as it may lead to systemic toxicity [60].

Ingestion of nano-pesticides can occur through the consumption of contaminated food or water, as well as hand-to-mouth transfer during occupational exposure. Once ingested, nano-pesticides can interact with the gastrointestinal tract and potentially be absorbed into the bloodstream [61].

The toxicity mechanisms of nano-pesticides in the human body are complex and not yet fully understood. Nanomaterials can interact with cellular components, such as proteins, lipids, and nucleic acids, leading to oxidative stress, inflammation, and genotoxicity [62]. The generation of reactive oxygen species (ROS) is a common mechanism of nanoparticle toxicity, which can cause damage to cellular membranes, proteins, and DNA [63].

Moreover, the ability of nanoparticles to cross biological barriers, such as the blood-brain barrier and the placental barrier, raises concerns about their potential neurotoxicity and developmental toxicity [64].

### 5.2 Health Risk Assessment and Regulation

Given the potential human health risks associated with nano-pesticides, it is crucial to conduct thorough health risk assessments and establish appropriate regulatory frameworks to ensure their safe use and management.

Health risk assessment of nano-pesticides involves the identification and characterization of hazards, assessment of exposure, and characterization of risks [65]. This process requires a comprehensive understanding of the physicochemical properties of the nanomaterials, their toxicity mechanisms, and the potential exposure scenarios.

Toxicological studies, including in vitro and in vivo experiments, are essential for evaluating the potential health effects of nano-pesticides. These studies should assess a range of endpoints, such as acute and chronic toxicity, genotoxicity, neurotoxicity, and reproductive and developmental toxicity [66]. In addition to toxicological studies, exposure assessment is crucial for determining the likely levels and routes of human exposure to nano-pesticides. This involves considering occupational exposure during manufacturing and application, as well as potential consumer exposure through residues in food and water [67].

Based on the outcomes of health risk assessments, regulatory authorities need to establish appropriate guidelines and standards for the safe use and management of nano-pesticides. This may include setting occupational exposure limits, establishing safety protocols for handling and application, and developing guidelines for the assessment and registration of nano-pesticide products [68]. Furthermore, effective risk communication and public engagement are essential for promoting the responsible development and use of nano-pesticides. Transparent and accessible information about the potential benefits and risks of nano-pesticides should be provided to all stakeholders, including industry, regulators, farmers, and the general public [69].

## 6. CHALLENGES AND FUTURE PERSPECTIVES

While nano-pesticides offer promising opportunities for sustainable pest and disease management in agriculture, several challenges need to be addressed to realize their full potential and ensure their safe and responsible use.

### 6.1 Technological Challenges

One of the major technological challenges in the development of nano-pesticides is the scalability and reproducibility of synthesis methods. Many of the current synthesis approaches for nano-pesticides are based on small-scale laboratory experiments, and their translation to large-scale commercial production can be challenging [70]. Ensuring consistent quality, stability, and performance of nano-pesticides during scale-up processes is crucial for their successful commercialization.

Another challenge is the development of nano-pesticides with targeted delivery and controlled release properties. While significant progress has been made in this area, further research is needed to optimize the design and functionalization of nanocarriers for specific target pests and pathogens [71]. The development of multi-functional nano-pesticides that combine pesticide delivery with other agronomic benefits, such as nutrient delivery or drought tolerance, is also an area of interest [72].

### 6.2 Environmental and Health Safety Concerns

As discussed earlier, the environmental fate and risks of nano-pesticides are significant concerns that need to be thoroughly addressed. The development of standardized protocols for the assessment of the environmental impact of nano-pesticides is necessary to ensure their safe use and minimize potential ecological risks [73].

Similarly, the human health implications of nano-pesticides require extensive research and risk assessment. Long-term toxicological studies are needed to evaluate the chronic health effects of nano-pesticide exposure, particularly for occupational settings [74]. The establishment of appropriate regulatory frameworks and guidelines for the safe handling, use, and disposal of nano-pesticides is essential to protect human health and the environment.

### 6.3 Regulatory and Policy Considerations

The development and commercialization of nano-pesticides are subject to various regulatory and policy considerations. The unique properties of nanomaterials may require adaptations to existing pesticide registration and approval processes [75]. Regulatory authorities need to establish clear guidelines and criteria for the assessment and registration of nano-pesticide products, taking into account their specific characteristics and potential risks.

Moreover, the international harmonization of regulations and standards for nano-pesticides is important to facilitate their global trade and ensure consistent safety standards across different countries [76].

### 6.4 Public Perception and Acceptance

The public perception and acceptance of nano-pesticides are crucial factors that can influence their successful adoption and commercialization. Concerns about the potential risks and uncertainties associated with the use of nanomaterials in agriculture may lead to public skepticism and resistance [77].

Effective communication and engagement with the public are essential to address these concerns and promote informed decision-making. Transparency about the benefits, risks, and uncertainties of nano-pesticides, as well as clear labeling and information provision, can help build public trust and acceptance [78,79].

### 6.5 Future Research Directions

To address the challenges and realize the full potential of nano-pesticides, future research should focus on several key areas:

1. Development of advanced synthesis methods for nano-pesticides with improved stability, targeted delivery, and controlled release properties.
2. Comprehensive environmental fate and risk assessment studies to understand the long-term impact of nano-pesticides on ecosystems and biodiversity.
3. Long-term toxicological studies to evaluate the chronic health effects of nano-pesticide exposure, particularly in occupational settings.
4. Optimization of nano-pesticide formulations and application strategies for different crop protection scenarios and agricultural systems.
5. Integration of nano-pesticides with other sustainable pest management approaches, such as biological control and cultural practices, to develop holistic and resilient crop protection strategies.
6. Socio-economic and life cycle assessment studies to evaluate the cost-effectiveness and sustainability of nano-pesticides in comparison to conventional pesticides and other alternative approaches.
7. By addressing these research priorities and engaging in collaborative and interdisciplinary efforts, the development of nano-pesticides can be advanced in a responsible and sustainable manner, contributing to the broader goals of food security, environmental protection, and human health.
8. The use of nano-encapsulation techniques can improve the stability and controlled release of active ingredients in pesticide formulations [80].
9. Nano-pesticides can reduce the environmental impact of pesticides by minimizing off-target effects and reducing the required application rates [81].
10. Silver nanoparticles have demonstrated strong antimicrobial activity against a wide range of plant pathogens [82].
11. Nano-fertilizers can improve nutrient uptake efficiency and reduce nutrient losses, leading to higher crop yields [83].
12. Nano-sensors can be used for early detection and monitoring of pests and diseases in crops, enabling timely and targeted interventions [84].

13. Nano-based smart delivery systems can enhance the bioavailability and efficacy of biopesticides and botanical pesticides [85].
14. Nano-pesticides can be designed to target specific pests or pathogens, reducing the impact on beneficial organisms and biodiversity [86].
15. The use of biodegradable polymers in nano-pesticide formulations can minimize the persistence of pesticide residues in the environment [87].
16. Nano-pesticides can improve the penetration and translocation of active ingredients within plant tissues, enhancing their effectiveness [88].
17. The incorporation of nanomaterials in seed coatings can provide protection against seed-borne pathogens and improve seed germination [89].
18. Nano-based controlled release formulations can reduce the frequency of pesticide applications, saving time and resources for farmers [90].
19. Nano-pesticides can be used in combination with other pest management strategies, such as biological control agents, to develop integrated pest management (IPM) programs [91].
20. The use of nano-encapsulated essential oils as pesticides can provide a safer and more sustainable alternative to synthetic pesticides [92].
21. Nano-based fungicides have shown potential in controlling post-harvest diseases in fruits and vegetables, extending their shelf life [93].
22. Nano-pesticides can be designed to respond to specific environmental stimuli, such as pH or temperature, enabling targeted release of active ingredients [94].
23. The application of nano-pesticides through smart irrigation systems can optimize pesticide delivery and reduce water consumption [95].
24. Nano-based insect repellents can provide longer-lasting protection against insect pests compared to conventional repellents [96].
25. The incorporation of nanomaterials in pesticide formulations can enhance their adhesion and retention on plant surfaces, reducing the need for frequent reapplication [97].
26. Nano-pesticides can be used to control invasive species and protect native biodiversity in ecosystems [98].
27. The use of nano-based slow-release formulations can reduce the risk of pesticide leaching and groundwater contamination [99].
28. Nano-pesticides can be engineered to target specific insect stages, such as larvae or eggs, for more effective pest control [100].
29. The application of nano-pesticides through drone technology can enable precise and targeted pesticide delivery, reducing labor costs and environmental impact [101].
30. Nano-based herbicides can provide effective weed control while minimizing the impact on non-target plant species [102].
31. The use of nano-encapsulated pheromones can disrupt insect mating and reduce pest populations without the need for chemical pesticides [103].
32. Nano-based diagnostic tools can enable rapid and on-site detection of pesticide residues in food products, ensuring food safety [104].
33. The incorporation of nanomaterials in pesticide formulations can improve their stability under harsh environmental conditions, such as high temperatures or UV radiation [105].
34. Nano-pesticides can be designed to target specific plant pathogens, such as fungi or bacteria, reducing the development of pesticide resistance [106].

The use of nano-based controlled release formulations can minimize pesticide drift and off-target exposure to humans and wildlife [107]. Nano-pesticides can be integrated with precision farming techniques, such as remote sensing and data analytics, to optimize pesticide application and reduce environmental impact [108].

## 7. CONCLUSION

Nano-pesticides represent a promising approach to enhancing the efficacy and sustainability of pest and disease management in agriculture. By leveraging the unique properties of nanomaterials, nano-pesticides offer the potential for targeted delivery, controlled release, and reduced environmental impact compared to conventional pesticides.

This review has provided a comprehensive overview of the current state of knowledge on nano-pesticides, including their synthesis, characterization, mode of action, and efficacy against various pests and diseases. The environmental fate and risks of nano-pesticides, as well as their potential human health implications, have also been discussed, highlighting the need for thorough risk assessment and appropriate regulatory frameworks.

While nano-pesticides offer significant benefits, several challenges need to be addressed to ensure their safe and responsible use. These challenges include technological barriers, environmental and health safety concerns, regulatory and policy considerations, and public perception and acceptance.

Future research should focus on developing advanced synthesis methods, conducting comprehensive environmental and health risk assessments, optimizing formulations and application strategies, and integrating nano-pesticides with other sustainable pest management approaches. By addressing these research priorities and engaging in collaborative and interdisciplinary efforts, the development of nano-pesticides can contribute to sustainable agriculture, food security, and environmental protection.

As the field of nano-pesticides continues to evolve, it is essential to maintain a balance between the potential benefits and the need for responsible development and use. Ongoing research, risk assessment, and stakeholder engagement will be critical to realizing the full potential of nano-pesticides while minimizing potential risks to human health and the environment.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

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