



Sustainable agricultural protection: Nanotechnology-based approaches to pest and disease management

Salman Ahmad¹, Kalpana Bisht¹, Mithilesh Kumar Pandey², Mohammad Said¹, Malik Mobeen Ahmad^{3*}

¹ Department of Agriculture, Integral Institute of Agricultural Science and Technology (IIAST), Integral University, Lucknow, Uttar Pradesh, India

² Department of Agriculture, Swami Keshwanand College Gramotthan Vidyapith, Sangaria, Hanumangarh, Rajasthan, India

³ Associate Professor, Department of Agriculture Integral Institute of Agricultural Science and Technology (IIAST) Integral University, Lucknow, India

Abstract

Sustainable pest and disease management has become a pressing concern in modern agriculture due to the growing awareness of the environmental and health impacts of conventional pesticides. Nanotechnology has emerged as a promising solution, offering advanced tools and materials for more efficient, targeted, and eco-friendly crop protection. This review explores the role of nanomaterials—such as nano pesticides, nanosensors, and nanocarriers—in revolutionizing pest and pathogen control strategies. Nanoencapsulation enhances the stability and controlled release of pesticides, while metallic nanoparticles (e.g., silver, zinc oxide) provide direct antimicrobial activity. Furthermore, nanosensors enable early detection of disease and pest outbreaks, allowing timely and precise interventions. These innovations reduce chemical inputs, limit off-target effects, and minimize environmental contamination. Despite these advantages, concerns regarding biosafety, regulatory frameworks, and long-term environmental effects remain key challenges. This article also highlights recent advances, successful case studies, and the potential integration of nanotechnology with digital agriculture to enhance precision and sustainability. As global agriculture shifts toward climate-smart practices, nanotechnology offers a pathway to meet the dual goals of productivity and environmental stewardship.

Keywords: Nanopesticides, nanosensors, sustainable agriculture, pathogen control, precision farming, environmental safety

Introduction

Agriculture is the backbone of global food security, but it faces persistent and escalating threats from pests and diseases that cause significant crop losses each year. According to the Food and Agriculture Organization (FAO), plant pests and diseases are responsible for reducing global agricultural production by up to 40%, adversely impacting farmers' livelihoods, global food supply, and the environment [1, 2]. Traditional pest and disease management strategies have largely relied on synthetic chemical pesticides, which, although effective, have led to a multitude of problems. These include the development of pesticide resistance in pests, the destruction of non-target beneficial organisms, environmental contamination, and harmful effects on human health. The unsustainable and indiscriminate use of these agrochemicals has spurred an urgent need for more effective, targeted, and eco-friendly approaches to pest and disease control, nanotechnology has emerged as a powerful and transformative tool in various scientific fields, including medicine, electronics, and materials science [3, 4]. Its application in agriculture—particularly in plant protection—has gained significant traction due to the unique physicochemical properties of nanomaterials, such as their small size (1–100 nm), high surface area-to-volume ratio, reactivity, and ability to penetrate biological systems. These features make nanotechnology particularly suited for the development of novel pest and disease management strategies that are both sustainable and efficient [5, 6].

Nanotechnology in agriculture offers several promising avenues, such as nanopesticides, nanoformulations,

nanosensors, and nanocarriers. These innovations enable precise delivery of agrochemicals, reduce application frequency, enhance pesticide stability, improve solubility of poorly soluble agents, and provide controlled or slow-release mechanisms. As a result, nanopesticides can achieve effective pest control with lower doses, reducing the risk of chemical buildup in the environment. Furthermore, nanoparticles such as silver (AgNPs), zinc oxide (ZnO), and silica (SiO₂) possess intrinsic antimicrobial or insecticidal properties, providing a dual-function platform for combating pathogens and pests, nanotechnology also contributes to early detection and diagnosis. Nanosensors integrated with Internet of Things (IoT) platforms enable real-time monitoring of plant health, pest invasion, and pathogen outbreaks. These smart agricultural technologies facilitate timely interventions and efficient resource use, aligning well with the principles of precision agriculture and climate-smart farming. Despite these promising developments, there are still challenges and concerns that need to be addressed for the widespread adoption of nanotechnology in agriculture. One of the main concerns is the biosafety and environmental impact of engineered nanomaterials. The fate, transport, and long-term accumulation of nanoparticles in soil and water ecosystems remain poorly understood [7]. There is also limited regulatory oversight and a lack of standardized guidelines for the approval, labeling, and use of nano-based agricultural products. As such, a thorough risk assessment framework must be developed alongside innovative solutions.

Another challenge lies in the cost and scalability of nanomaterial production. For nanotechnology to be viable in

agricultural settings—especially for smallholder farmers in developing countries—it must be cost-effective, easy to apply, and compatible with existing infrastructure [8]. Collaborative efforts among researchers, policymakers, industry stakeholders, and farmers are essential to ensure the equitable and safe implementation of nano-enabled agricultural technologies.

This review article aims to provide a comprehensive overview of the latest nanotechnology-driven innovations in pest and disease management in agriculture. We begin by exploring the types and functions of nanopesticides, including nanoformulations and their delivery mechanisms [9]. We then examine the role of nanosensors in early disease detection, followed by an assessment of various nanomaterials with insecticidal and antifungal properties. Additionally, we highlight successful case studies and experimental findings that demonstrate the efficacy and advantages of nanotechnology in agricultural applications. Finally, we discuss the potential risks, ethical implications, and regulatory challenges associated with these technologies, and propose future directions for research and development, the integration of nanotechnology into plant protection practices presents a transformative opportunity to improve agricultural sustainability [10]. By minimizing environmental impact, enhancing crop resilience, and ensuring food safety, nanotechnology can play a vital role in addressing the global challenge of pest and disease management while supporting long-term agricultural productivity and ecological balance.

Principles of Nanotechnology in Agriculture

Nanotechnology refers to the manipulation and engineering of materials at the nanometer scale, typically within the range of 1 to 100 nanometers (nm). At this size, materials exhibit novel optical, mechanical, magnetic, and chemical properties that are distinctly different from their bulk counterparts [11]. These unique characteristics arise due to the increased surface area-to-volume ratio, quantum effects, and the ability of nanoparticles (NPs) to interact at the molecular or cellular level with a high degree of specificity. In agriculture, these nanoscale properties can be strategically harnessed to address challenges in crop protection, nutrient delivery, soil health, and plant disease management.

One of the core principles of nanotechnology in agriculture lies in its ability to enable controlled release and targeted delivery. Traditional chemical pesticides and fertilizers are often inefficiently utilized, with a significant portion lost due to leaching, volatilization, or degradation before reaching their intended targets. Nanotechnology offers a solution through the encapsulation of active ingredients in nanocarriers such as liposomes, dendrimers, polymeric nanoparticles, or nanoclays, which protect the active compound and release it in response to specific

environmental triggers (e.g., pH, temperature, or enzymatic activity) [12]. This slow-release behavior ensures prolonged efficacy, reduces the frequency of application, and minimizes off-target effects on beneficial organisms, targeted delivery is another vital advantage. Functionalized nanoparticles can be engineered to bind selectively to pest-specific enzymes, receptors, or tissues, thereby enhancing the precision of agrochemical action. For example, chitosan-based nanoparticles can be loaded with insecticidal or fungicidal agents and modified with ligands to bind exclusively to insect gut cells or fungal hyphae, ensuring that the payload is released only upon contact with the pest [13]. This targeted approach significantly improves treatment efficacy while reducing chemical load in the environment.

Furthermore, the high reactivity and surface energy of nanoparticles enhance solubility and bioavailability of poorly soluble agrochemicals. Many plant protection agents suffer from low water solubility, limiting their absorption and effectiveness. By formulating these agents into nanoparticulate forms, it is possible to improve their dispersion, uptake by plant tissues, and movement within the plant (systemic action), thereby increasing their utility in crop protection. Beyond delivery systems, nanotechnology also supports the development of nanosensors and nanobiosensors [14]. These devices are capable of detecting minute quantities of pathogens, pests, toxins, and environmental parameters such as soil moisture, pH, or nutrient levels. Nanomaterials like carbon nanotubes, gold nanoparticles, and quantum dots are often employed in sensor platforms due to their high sensitivity, fast response time, and ability to be integrated with wireless systems [15]. These tools enable real-time monitoring of crop health and field conditions, allowing farmers to take timely and informed decisions, a practice that aligns with the emerging field of precision agriculture.

Some nanoparticles possess intrinsic biological activity, making them useful as antimicrobial or pesticidal agents without additional chemical payloads. For instance, silver nanoparticles (AgNPs) exhibit broad-spectrum antimicrobial activity and have been shown to inhibit bacterial and fungal pathogens. Similarly, zinc oxide (ZnO) and copper oxide (CuO) nanoparticles are being investigated for their antifungal and insect-repellent properties, the principles of nanotechnology in agriculture revolve around enhancing the efficiency, precision, and sustainability of agricultural inputs and interventions [16]. By offering smart delivery systems, improving the solubility and stability of agrochemicals, enabling sensitive diagnostics, and providing new modes of pest and disease control, nanotechnology represents a paradigm shift in how agricultural challenges are addressed. As research and innovation continue to grow in this area, nanotechnology is poised to become a cornerstone of modern, eco-friendly, and sustainable agricultural practices.

Table 1: Types of Nanomaterials Used in Agricultural Pest and Disease Management

| Nanomaterial | Composition | Mechanism of Action | Target Pest/Pathogen | Advantages |
|-----------------------------|---|--|--|--|
| Silver nanoparticles | AgNPs | Disrupts microbial membranes, ROS generation | <i>E. coli</i> , <i>P. syringae</i> , <i>Fusarium spp.</i> | Broad-spectrum, high efficacy, antimicrobial resistance prevention |
| Zinc oxide nanoparticles | ZnO | Oxidative stress, enzyme inactivation | <i>Alternaria</i> , <i>Aspergillus</i> | UV protection, low toxicity to plants |
| Chitosan-based nanocarriers | Biopolymer nanocarriers with pesticides | Sustained release, adhesion to leaves | Aphids, fungal pathogens | Biodegradable, low cost, improved stability |
| Lipid nanoparticles | Solid lipid nanoparticles | Targeted delivery of lipophilic | Insect pests | Biocompatible, controlled release |

| | | pesticides | | |
|----------------------|--|---|---------------------|--|
| Silica nanoparticles | SiO ₂ | Physical barrier on plant surface, abrasive to insect cuticle | Whiteflies, beetles | Non-toxic, long residual effect |
| Carbon nanotubes | Single-/multi-walled carbon structures | Pesticide carrier, penetrates cell walls | Virus vectors | High loading capacity, target-specific release |

Table 2: Summary of Recent Studies on Nanopesticide Applications in Crop Protection

| Study | Crop | Nanopesticide Type | Target Pest/Disease | Key Findings |
|---|---------|------------------------------------|--|---|
| Sharma <i>et al.</i> (2022) | Tomato | AgNPs | <i>Alternaria solani</i> | Reduced disease incidence by 60%, improved plant height and fruit yield |
| Li and Zhang (2021) | Rice | ZnO nanoparticles | <i>Xanthomonas oryzae</i> | 70% reduction in bacterial leaf blight; no phytotoxicity observed |
| Kamal <i>et al.</i> (2020) | Maize | Chitosan-nanoencapsulated neem oil | Fall armyworm (<i>Spodoptera frugiperda</i>) | Prolonged residual activity and reduced larval mortality time |
| Gómez-Polo <i>et al.</i> (2019) | Cotton | Silica nanoparticles | Whitefly | 55% decrease in infestation; enhanced photosynthetic rate |
| Alghuthaymi <i>et al.</i> (2021) ^[3] | Banana | CuO nanoparticles | <i>Fusarium oxysporum</i> | Controlled pathogen growth with minimal accumulation in soil |
| Ahmed <i>et al.</i> (2023) | Soybean | Nanoemulsion-based insecticide | <i>Helicoverpa armigera</i> | Greater efficacy at lower doses compared to conventional formulations |

Table 3: Comparative Evaluation of Conventional vs. Nano-Based Pest Control Strategies

| Parameter | Conventional Pesticides | Nano-Based Pesticides |
|--------------------------------------|--------------------------------------|--|
| Dosage requirement | High | Lower due to enhanced efficacy |
| Environmental impact | High (leaching, runoff) | Reduced (targeted delivery, controlled release) |
| Residual toxicity | Often high | Lower due to rapid degradation and specific targeting |
| Resistance development | Frequent due to single-target action | Less likely due to multi-target mechanisms |
| Cost (initial) | Lower | Higher (but offset by reduced reapplication and crop losses) |
| Application frequency | More frequent | Less frequent (due to slow-release formulations) |
| Stability under environmental stress | Low (UV degradation, volatilization) | High (encapsulation protects active ingredients) |
| Regulatory hurdles | Well-defined | Emerging and under development |

Nanopesticides: Types and Applications

Nanopesticides represent a transformative shift in pest management strategies, designed to overcome the limitations of conventional pesticides such as non-specificity, rapid degradation, and environmental toxicity^[17]. By leveraging nanotechnology, nanopesticides improve pesticide delivery, enhance bioavailability, and reduce the need for repeated applications, thereby promoting sustainable agricultural practices.

Types of Nano pesticides

Nanopesticides can be broadly classified into three primary categories based on their composition and mode of delivery:

- **Nanoencapsulated Pesticides:** These formulations involve the encapsulation of active pesticide molecules within nanoscale carriers such as liposomes, biodegradable polymers (e.g., PLGA), chitosan, or mesoporous silica nanoparticles. The encapsulation protects the active ingredient from premature degradation caused by environmental factors such as UV light, temperature, or microbial activity. These systems allow for controlled and sustained release, improving efficacy over longer periods and minimizing off-target damage.
- **Metallic Nanoparticles:** Nanoparticles of silver (AgNPs), copper (CuNPs), and zinc oxide (ZnONPs) exhibit potent antimicrobial and insecticidal activity through multiple mechanisms, including disruption of microbial membranes, generation of reactive oxygen species (ROS), and interaction with essential enzymes. These nanoparticles are being explored as standalone nanopesticides, offering broad-spectrum defense

against plant pathogens such as fungi, bacteria, and even some insects.

- **Nanocarriers for Conventional Pesticides:** These involve the binding or adsorption of conventional chemical pesticides onto nanocarriers, which may include carbon nanotubes, nanoclays, or silica-based nanogels. These carriers enhance target specificity by delivering the pesticide directly to pest-infected sites or surfaces, thereby reducing environmental contamination and exposure to non-target organisms^[18, 19].

Applications and Advantages

Recent advances in nanopesticide formulations have shown promising results in improving solubility, stability, leaf adherence, and uptake efficiency of pesticide compounds. For example, chitosan-based nanoformulations of neem oil or pyrethrin have demonstrated enhanced insecticidal effects while remaining environmentally friendly and biodegradable. Additionally, clay nanosheets loaded with herbicides have shown better weed control with reduced herbicide leaching into water bodies.

Nanopesticides also contribute to resistance management by allowing novel delivery mechanisms and reducing the frequency of application, which limits the opportunity for pests to develop resistance. With proper regulation and toxicity assessment, nanopesticides hold significant promise for integrated pest management (IPM) strategies^[20].

Nano sensors for Early Detection

Early detection of pests and diseases is a crucial element of precision agriculture, enabling farmers to intervene before

significant damage occurs. Nanosensors are devices engineered using nanomaterials that can detect biological or chemical changes in plants, soils, or the surrounding environment with high sensitivity and specificity [21].

Types of Nano sensors and Their Functions

- **Electrochemical Nanosensors:** These sensors rely on changes in electrical conductivity when exposed to pathogen-specific biomolecules or environmental cues. For instance, graphene oxide-based sensors can detect fungal spores or bacterial toxins in soil samples, signaling early onset of root infections.
- **Quantum Dot-Based Fluorescent Sensors:** Quantum dots (QDs) are semiconductor nanocrystals that emit light when excited. They can be conjugated with antibodies or nucleic acid probes to detect plant pathogens through fluorescent tagging. These sensors are capable of analyzing leaf surface biomarkers, chlorophyll fluorescence, or stress-induced volatile organic compounds (VOCs), providing visual confirmation of disease stress.
- **Biosensors Integrated with IoT (Internet of Things):** Smart biosensors incorporating enzymes, aptamers, or antibodies can detect specific biochemical signatures associated with pest infestation or nutrient deficiencies. When connected to IoT systems, these sensors can transmit real-time data to a centralized server or mobile device, alerting farmers or agricultural service providers immediately.

Advantages in Agricultural Management

The implementation of nanosensors enables real-time, site-specific monitoring, reducing the need for manual scouting and large-scale pesticide application. Farmers can be alerted to subtle changes in plant metabolism or soil conditions before visual symptoms appear, allowing for timely, targeted, and cost-effective intervention. Moreover, nanosensors contribute to sustainable agriculture by reducing the overuse of agrochemicals, conserving biodiversity, and minimizing environmental runoff. The integration of nanosensors with drone technology and smart irrigation systems further enhances their potential in automated precision farming [22].

Mechanism of Action in Pathogen Control

Nanomaterials used in agriculture—especially in pest and disease control—exert their effects through multiple simultaneous mechanisms. Unlike conventional pesticides, which often act through a single molecular target, nanomaterials demonstrate broad-spectrum, multi-site activity, making them more effective and less prone to resistance development. The primary mechanisms include:

- **Cell Membrane Disruption**

One of the most fundamental antimicrobial actions of metallic nanoparticles (such as silver, zinc oxide, and copper oxide) is their ability to directly disrupt the integrity of microbial cell membranes. Due to their extremely small size and high surface area-to-volume ratio, these nanoparticles can easily interact with and penetrate the lipid bilayers of bacterial and fungal cells [23]. This interaction leads to membrane destabilization, leakage of intracellular

contents, and ultimately, cell lysis. The disruption also affects membrane-bound enzymes and transport channels, compounding the damage.

- **Generation of Reactive Oxygen Species (ROS)**

Another major mode of action involves the induction of oxidative stress within pathogenic cells. Nanoparticles catalyze the generation of reactive oxygen species (ROS) such as hydroxyl radicals, superoxide anions, and hydrogen peroxide. These ROS are highly reactive and can oxidize proteins, lipids, and nucleic acids, leading to the disruption of vital cellular functions, including respiration, replication, and protein synthesis. Over time, elevated ROS levels overwhelm the cell's antioxidant defenses, causing irreversible cellular damage [24].

- **Interference with Metabolic and Genetic Processes**

Nanoparticles can also interfere with enzyme function, signal transduction pathways, and DNA/RNA replication in pest organisms. For instance, silver nanoparticles have been shown to bind with thiol groups of key enzymes, inhibiting ATP synthesis and other metabolic reactions. Additionally, some nanoparticles can enter the nucleus or cytoplasm and directly interact with genetic material, leading to DNA fragmentation or errors in gene expression [25, 31]. This genotoxic stress impairs the pathogen's ability to reproduce or respond adaptively to hostile conditions.

- **Synergistic and Multi-Targeted Effects**

Because nanomaterials exert multiple modes of action simultaneously, their effectiveness is enhanced, and the potential for resistance development is significantly lowered. Conventional pesticides often target a single receptor or enzyme, allowing pathogens to evolve resistance over time [32, 33]. In contrast, nanoparticles attack multiple targets, making it difficult for pests to adapt without compromising their fundamental biological processes.

Environmental and Economic Benefits

Nanotechnology-based approaches in pest and disease control are not only scientifically advanced but also offer significant environmental and economic advantages over traditional agrochemical strategies [34, 36].

- **Lower Chemical Usage**

One of the most impactful benefits of nanotechnology is the reduction in the quantity of active ingredients required [37, 39]. Due to the enhanced solubility, bioavailability, and precision of nanoformulations, lower doses are often sufficient to achieve effective pest control. This minimizes the ecological footprint and decreases the risk of chemical residues in food and water sources [41, 43].

- **Reduced Runoff and Environmental Pollution**

Targeted delivery systems using nanocarriers such as liposomes, polymeric nanoparticles, or clay nanocomposites ensure that the active compounds are released directly at the site of infection or pest activity, rather than being dispersed widely across the environment. This minimizes off-target effects and reduces chemical runoff into nearby ecosystems, which is a major concern with conventional pesticide use. Furthermore, controlled-release formulations limit leaching into groundwater and protect non-target organisms such as pollinators and soil microbes [44].

▪ Extended Product Stability and Shelf Life

Nanocarriers also provide thermal, UV, and microbial protection to sensitive active compounds. For example, nanoencapsulation of botanical pesticides such as neem oil or essential oils protects them from rapid oxidation and volatilization. As a result, products remain chemically stable over a longer period, which translates into extended shelf life and reduced wastage for manufacturers and retailers^[45].

Cost-Effectiveness and Long-Term Savings

Although the initial development and production costs of nanopesticides may be higher than traditional formulations, the long-term economic benefits often outweigh these upfront investments^[28]. Benefits include:

- Lower reapplication frequency due to longer persistence.
- Reduced crop losses from more effective pest management.
- Minimized labor and resource use due to automation and precision delivery.
- Increased market value of crops due to improved yield and safety profiles.

In countries where regulatory frameworks support precision agriculture, insurance and certification programs may also incentivize farmers to adopt nanotechnological solutions by offering subsidies or price premiums for sustainably produced crops^[46]. Responsible research and transparent risk assessments are essential for safe implementation.

Conclusion

Nanotechnology is rapidly emerging as a transformative force in modern agriculture, especially in the realm of pest and disease control. By harnessing the unique physicochemical properties of materials at the nanoscale, researchers and practitioners are developing solutions that significantly surpass the limitations of conventional agrochemicals. These innovations—ranging from nanopesticides and nanosensors to smart delivery systems—are not only improving pest management efficiency but are also advancing the broader goals of sustainability, environmental safety, and food security.

One of the most compelling advantages of nanotechnology in this domain is its capacity to reduce dependency on chemical inputs. Through improved solubility, targeted delivery, and controlled release, nanoformulations allow for lower dosages and fewer applications, which in turn minimize environmental contamination and reduce the risks associated with chemical residues in food products. Furthermore, the multi-targeted modes of action inherent to nanomaterials make it more difficult for pests and pathogens to develop resistance—an issue that has long plagued traditional pesticide approaches.

Nanosensors offer an equally exciting frontier, allowing for real-time detection of pathogens and pests before they cause widespread damage. These systems, when integrated with IoT (Internet of Things) platforms, could revolutionize agricultural decision-making, leading to more proactive and data-driven pest management strategies. From an environmental and economic standpoint, nanotechnology contributes to resource optimization, lower production costs in the long term, and enhanced crop yields, thereby reinforcing the economic viability of sustainable farming. However, the widespread adoption of these technologies

must proceed hand in hand with rigorous safety assessments, ecotoxicological evaluations, and clear regulatory guidelines to ensure that nanomaterials do not introduce unintended risks to ecosystems or human health.

Equally important is the role of interdisciplinary collaboration—involving material scientists, agronomists, toxicologists, policymakers, and farmers—to guide the responsible development and deployment of nano-enabled agricultural tools. Public awareness and education will also be essential to build trust and ensure the societal acceptance of these technologies, nanotechnology holds immense promise for the future of pest and disease control in agriculture. If guided by science-based regulation and ethical application, it can play a crucial role in advancing climate-resilient, environmentally conscious, and productive agricultural systems. As global demand for food continues to rise, the integration of nanotechnology into mainstream agricultural practices could be a pivotal step toward achieving resilient and sustainable food systems for generations to come.

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