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Nanotechnology-based Materials for Sustainable Pest and Disease Control in Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Nanotechnology is emerging as a transformative tool in agriculture, offering innovative approaches for sustainable pest and disease management. The incorporation of nanomaterials into agricultural practices has the potential to address the limitations of conventional pesticides and fertilizers, providing targeted, efficient, and eco-friendly alternatives. This review examines the current advancements in nanotechnology-based materials for sustainable pest and disease control, focusing on their mechanisms of action, environmental benefits, and challenges. Nanomaterials such as nanoscale pesticides, nano-formulated fertilizers, and smart delivery systems can significantly enhance the precision of agrochemical application, reducing chemical runoff and minimizing harm to non-target organisms. These materials offer controlled release properties, ensuring prolonged effectiveness and reducing the frequency of applications. Additionally, the use of nanoparticles can disrupt pest resistance mechanisms, providing a novel approach to resistance management, the promising benefits, the adoption of nanotechnology in agriculture is not without challenges. Key concerns include the potential environmental and health risks associated with the long-term use of nanomaterials, the cost of production, and the need for clear regulatory frameworks, biodegradable and environmentally friendly nanoparticles are being developed to mitigate some of these risks.

Keywords: Nanotechnology; agriculture; novel materials; sustainability; diseases control.

1. INTRODUCTION

Agriculture plays a fundamental role in global food production and economic stability, but it faces numerous challenges that threaten its sustainability. Among these challenges, pest and disease control are major concerns, as they can significantly reduce crop yields and quality, leading to economic losses and food insecurity (Rasool et al. 2020, Alagarasi 2011, Anjali et al. 2012). Traditional agricultural practices have relied heavily on synthetic pesticides, chemical fertilizers, and other agrochemicals to combat these issues. While effective in the short term, these conventional methods have been associated with several adverse effects, including environmental pollution, the development of pest resistance, soil degradation, and human health risks. The excessive use of chemical pesticides and fertilizers has led to the contamination of soil and water resources, as well as a decline in biodiversity. Additionally, the repeated application of these chemicals has accelerated the development of pest resistance, making pests harder to control and requiring even higher doses of chemicals, thus creating a vicious cycle. Furthermore, the residue of pesticides on food products poses health risks to consumers (Bhattacharyya et al. 2016, Rasool et al. 2022, Chauhan and Kumar 2016, Chen and Yada 2011). Therefore, there is an urgent need to develop more sustainable and eco-friendly solutions for pest and disease management in agriculture (Ditta 2012). In recent years, nanotechnology has emerged as a revolutionary approach that offers innovative solutions for sustainable agriculture. Nanotechnology involves the manipulation of materials at the nanoscale, typically between 1 and 100 nanometers, where unique physical, chemical, and biological properties become apparent. This allows for the creation of novel materials with enhanced capabilities, such as increased surface area, improved solubility, and controlled release properties. In agriculture, nanotechnology-based materials can be engineered to provide more precise and efficient pest and disease control, reducing the environmental impact and promoting sustainable farming practices.

Nanotechnology-based materials, including nanoscale pesticides, nano-formulated fertilizers, and smart delivery systems, offer several advantages over conventional agrochemicals. These materials are designed to deliver active ingredients directly to the target pest or pathogen, minimizing the risk of off-target effects and reducing the overall quantity of chemicals needed (Rasool et al. 2020, Alagarasi 2011, Anjali et al. 2012, Bhattacharyya et al. 2016, Rasool et al. 2022, Chauhan and Kumar 2016, Chen and Yada 2011, Ditta 2012, Gogos et al. 2012, Grillo et al. 2016, Rasool et al. 2024, Jabeen et al. 2022). For example, nanoscale pesticides can penetrate the protective barriers of pests more effectively than traditional pesticides, leading to faster and more efficient pest control. Similarly, nano-formulated fertilizers can improve nutrient uptake by plants, reducing nutrient runoff and minimizing the environmental impact of fertilizers (Hussain et al. 2019). Moreover, nanotechnology-based materials can be engineered for controlled or slow release, which ensures that the active ingredients are released gradually over time, providing prolonged protection against pests and diseases (Kah et al. 2013, Asma et al. 2023, Asma et al. 2023, Kumar and Dasgupta 2017). This not only reduces the need for frequent applications but also minimizes the risk of chemical residues in the environment and on food products. Furthermore, some nanomaterials have antimicrobial properties, which can be used to control plant pathogens and enhance plant health.

The potential of nanotechnology in agriculture extends beyond pest and disease control. It also offers opportunities for improving crop productivity, enhancing plant nutrition, and reducing post-harvest losses. For instance, nano-sensors can be used to monitor environmental conditions in real-time, allowing farmers to make more informed decisions about when and how to apply agrochemicals (George et al. 2023). This precision agriculture approach not only reduces the wastage of resources but also minimizes the environmental footprint of farming practices. Despite the promising benefits of nanotechnology in agriculture, there are several challenges and concerns that need to be addressed. One of the main concerns is the potential toxicity of nanomaterials to non-target organisms, including beneficial insects, soil microbes, and aquatic life. Additionally, the long-term environmental impact of nanomaterials is not yet fully understood, and more research is needed to assess their safety. There are also concerns about the cost of producing nanomaterials, which may limit their accessibility to small-scale farmers in developing countries, regulatory frameworks for the use of nanotechnology in agriculture are still in the early stages of development, and there is a need for clear guidelines to ensure the safe and responsible use of nanomaterials (Khot et al. 2012). And to explore the current status, mechanisms, and applications of nanotechnology in pest and disease control, highlighting its potential for contributing to sustainable agricultural systems. The recent advancements in nanotechnology-based materials, this article will provide insights into the mechanisms through which these materials enhance pest and disease control, their advantages over conventional methods, and the challenges that need to be overcome for their widespread adoption. Ultimately, nanotechnology offers a promising pathway towards achieving sustainable pest and disease management in agriculture, but careful consideration of its risks and benefits is essential for its responsible implementation.

2. NANOTECHNOLOGY IN AGRICULTURE: AN OVERVIEW

Nanotechnology refers to the manipulation and utilization of materials at the nanoscale, typically between 1 to 100 nanometers, where the properties of materials can differ significantly from their larger-scale counterparts. The ability to design and engineer materials at this scale has opened up new avenues for innovation in agriculture, offering solutions to several persistent challenges such as inefficient agrochemical use, pest resistance, and environmental degradation (Rajabov et al. 2024). Nanotechnology holds promise in transforming agricultural practices by enhancing the efficiency of inputs, minimizing waste, and reducing the environmental impacts associated with conventional farming.

The application of nanotechnology in agriculture is rapidly expanding, with the development of nanomaterials designed to improve crop protection, plant nutrition, and disease management (Reddy et al. 2024). These innovations aim to enhance the bioavailability of agrochemicals, increase precision in their application, and ensure the controlled release of active compounds. The integration of nanotechnology into agriculture has led to the creation of a range of advanced materials, including nanopesticides, nanofertilizers, and nano-sensors, each with its unique benefits and applications.

Nanopesticides: Nanopesticides represent one of the most promising applications of nanotechnology in agriculture. Traditional pesticides often suffer from issues such as low bioavailability, rapid degradation, and non-target effects, which contribute to environmental pollution and pest resistance. Nanopesticides are engineered to overcome these challenges by providing controlled and targeted delivery of active ingredients to pests. Encapsulated or nano-formulated pesticides can be released in a slow and controlled manner, ensuring that the active ingredient remains effective over an extended period (Safdar et al. 2024). Moreover, the small size of nanoparticles allows them to penetrate pest barriers more easily, improving efficacy while reducing the quantity of chemicals needed. This targeted approach minimizes off-target impacts, reduces chemical residues, and lowers the risk of pests developing resistance.

Nanofertilizers: Nanofertilizers are another breakthrough in the application of nanotechnology to agriculture. Conventional fertilizers often suffer from inefficiencies in nutrient delivery, with a significant portion of the applied fertilizer being lost through leaching, volatilization, or runoff, leading to environmental contamination and reduced nutrient use efficiency by plants. Nanofertilizers are designed to release nutrients in a controlled and sustained manner, ensuring that plants receive a steady supply of essential elements over time (Rasool et al. 2024). This not only enhances nutrient uptake and utilization by plants but also reduces the need for frequent fertilizer applications. Furthermore, nanofertilizers can be engineered to respond to environmental stimuli, such as soil moisture or temperature, to release nutrients when they are most needed by the plant, thereby optimizing their effectiveness and minimizing environmental harm.

Nano-sensors: Nano-sensors represent a cutting-edge application of nanotechnology for precision agriculture. Precision agriculture involves the use of data-driven technologies to optimize farming practices, improving crop yields while minimizing resource use. Nano-sensors are capable of monitoring environmental conditions such as soil moisture, temperature, nutrient levels, and the presence of pests or diseases in real-time (Pithiya et al. 2022). These sensors can be deployed in the field to provide continuous data, enabling farmers to make informed decisions about irrigation, fertilization, and pest control. For instance, nano-sensors can detect early signs of pest infestations or disease outbreaks, allowing farmers to take timely action before the problem escalates. This proactive approach not only reduces crop losses but also minimizes the need for excessive chemical applications, promoting more sustainable farming practices. In addition to these applications, nanotechnology holds potential for improving seed treatments, enhancing plant growth regulators, and developing innovative packaging materials to reduce post-harvest losses. The integration of nanotechnology in agriculture is still in its early stages, but its potential to revolutionize the sector is significant. As research continues to advance, we can expect to see even more sophisticated nanotechnology-based solutions that contribute to the sustainability, productivity, and resilience of agricultural systems.

3. TYPES OF NANOMATERIALS USED IN PEST AND DISEASE MANAGEMENT

The development of nanomaterials for agricultural use has led to the creation of highly specialized materials that offer enhanced capabilities for pest and disease control. These nanomaterials are designed to target pests and pathogens with greater precision and efficiency, while reducing the environmental impact of traditional agrochemicals (Safdar et al. 2023). Different types of nanomaterials, each with unique properties and applications, are being explored for their role in sustainable pest and disease management. Below are some of the most widely used nanomaterials in this field:

Metallic Nanoparticles: Metallic nanoparticles, including silver (Ag), copper (Cu), and zinc (Zn) nanoparticles, have gained significant attention due to their potent antimicrobial and pesticidal properties. Silver nanoparticles (AgNPs) are particularly renowned for their broad-spectrum antimicrobial activity, making them effective against a wide range of plant pathogens, including bacteria, fungi, and viruses. These nanoparticles work by disrupting the cellular membranes of pathogens, generating reactive oxygen species (ROS), and interfering with the genetic material of microorganisms (Ghosh and Ghosh 2022). Copper nanoparticles (CuNPs) have also demonstrated strong fungicidal and bactericidal activity, making them valuable for managing fungal infections in crops. Zinc nanoparticles (ZnNPs), on the other hand, are often used for their ability to inhibit the growth of harmful microorganisms while promoting plant growth. The use of metallic nanoparticles offers an environmentally friendly alternative to conventional chemical treatments by reducing the need for large quantities of pesticides, lowering the risk of pathogen resistance, and minimizing harmful residues in the environment.

Nanoemulsions: Nanoemulsions are a type of nanomaterial that has been extensively studied for pesticide delivery. These emulsions consist of tiny droplets of one liquid dispersed in another, stabilized by surfactants. Nanoemulsions are particularly effective for encapsulating hydrophobic pesticides, improving their solubility, stability, and bioavailability. The small size of the droplets in nanoemulsions enhances their penetration into pest cells, leading to improved efficacy compared to traditional formulations (Rathna Kumari 2022). Furthermore, nanoemulsions allow for the controlled release of pesticides, reducing the overall amount of active ingredients needed and lowering the risk of chemical residues on crops. This approach also enhances the environmental safety of pesticides by minimizing their leaching into soil and water bodies. Nanoemulsions are versatile and can be designed to deliver a wide range of active ingredients, including insecticides, fungicides, and herbicides, making them a valuable tool for integrated pest management (IPM) strategies.

Nanoclay composites: Nanoclay composites are materials that incorporate nanoclay particles into a polymer matrix, providing enhanced stability and controlled release properties for pesticides and fertilizers. These materials are highly effective in improving the slow-release behavior of agrochemicals, ensuring that active ingredients are released gradually over time, offering prolonged protection against pests and diseases (Osuntokun et al. 2024). Nanoclay composites also protect the active ingredients from environmental degradation caused by factors such as sunlight, heat, and moisture. This leads to a reduction in the frequency of pesticide applications, lowering labor costs and minimizing the environmental impact. In addition to pest control, nanoclay composites can be used to deliver fertilizers more efficiently, enhancing nutrient availability to plants while preventing nutrient losses due to leaching or runoff.

Biopolymer nanoparticles: Biopolymer nanoparticles are derived from natural, biodegradable sources such as chitosan, starch, cellulose, and alginate. These nanoparticles have gained popularity as environmentally friendly alternatives for pesticide and fertilizer delivery. Chitosan nanoparticles, for example, are well-known for their antimicrobial and pesticidal properties, making them effective in controlling plant pathogens while promoting plant growth. Since biopolymer nanoparticles are biodegradable and non-toxic, they pose minimal risks to the environment and human health. Additionally, their ability to deliver active ingredients in a controlled manner reduces the overall amount of chemicals needed for effective pest and disease control. Biopolymer nanoparticles are a promising alternative to synthetic pesticides and fertilizers, especially in organic and sustainable farming practices (Meena 2023). These nanomaterials represent a transformative approach to pest and disease management in agriculture. Their enhanced properties—such as controlled release, increased stability, and improved targeting—make them superior alternatives to conventional agrochemicals, providing more sustainable and environmentally friendly options for crop protection.

4. MECHANISMS OF ACTION

Nanomaterials enhance pest and disease control through several mechanisms:

Increased Surface Area: Nanoparticles have a larger surface area-to-volume ratio, allowing for more efficient interaction with pests and pathogens.

Targeted Delivery: Nano-formulations can be designed to deliver active ingredients precisely to the site of action, reducing off-target effects.

Controlled Release: Nanoparticles can be engineered for slow or stimuli-responsive release, prolonging the duration of effectiveness and reducing the frequency of applications.

Pathogen Resistance Suppression: Some nanomaterials disrupt pest and pathogen resistance mechanisms, making it harder for them to adapt.

4.1 Over Conventional Methods

Nanotechnology-based materials offer several distinct advantages over traditional pest and disease control approaches, particularly in terms of efficiency, safety, and environmental sustainability (Li and Zhang 2016). These advantages make them an appealing alternative for modern agricultural practices, where there is a growing emphasis on reducing chemical use and minimizing ecological damage.

Reduced chemical use: One of the most significant benefits of nanotechnology-based materials is their ability to reduce the overall quantity of active ingredients needed for effective pest and disease control. Traditional pesticides and fertilizers are often applied in large quantities to compensate for poor bioavailability or rapid degradation in the environment. In contrast, nano-formulations can deliver the active compounds in a more targeted manner, ensuring that they reach the intended pest or plant more efficiently (Pattoo 2023). This precision allows for smaller amounts of chemicals to be used, leading to reduced environmental contamination, such as pesticide runoff into water sources and chemical residues in the soil. Additionally, this reduction in chemical use also contributes to lower production costs for farmers, as fewer applications are needed to achieve the same results.

Increased efficiency: Nanotechnology enhances the effectiveness of pest control and plant health treatments by improving the delivery mechanisms of pesticides, fertilizers, and other agrochemicals. For instance, nano-encapsulation of pesticides ensures that the active ingredients are protected from environmental factors like UV radiation, temperature, or microbial degradation, allowing them to remain effective for longer periods (Liu et al. 2016). Controlled-release mechanisms embedded within nanomaterials enable the gradual and sustained release of nutrients or pest control agents, ensuring that crops receive continuous protection or nourishment. This increased efficiency in delivering active ingredients leads to more consistent pest control and better plant health, ultimately improving crop yields.

Environmental safety: Traditional agrochemicals often pose significant risks to non-target organisms, including beneficial insects, animals, and aquatic life. The indiscriminate use of broad-spectrum pesticides can lead to the decline of important pollinators such as bees or the contamination of water bodies, affecting aquatic ecosystems (Anushi et al. 2024). Many nanomaterials, particularly those made from biodegradable or biopolymer-based substances, present a safer alternative. These materials break down more readily in the environment and pose minimal risks to non-target organisms. For example, chitosan nanoparticles, derived from natural sources, have antimicrobial properties while being non-toxic to plants, animals, and humans. Furthermore, because nano-formulations require lower doses of active ingredients, they reduce the risk of harmful residues accumulating in the environment.

Resistance management: One of the growing concerns in agricultural pest management is the rapid development of pest resistance to conventional pesticides. Over time, pests can evolve mechanisms to survive repeated pesticide applications, rendering many chemical treatments ineffective. Nanotechnology-based pest control systems, with their novel modes of action, offer a solution to this problem. Nanopesticides can target pests in multiple ways, such as disrupting cellular membranes, interfering with reproduction, or delivering active ingredients directly into the pest's cells (Rohi and Teeli 2024). The diversity of these mechanisms reduces the likelihood of pests developing resistance compared to conventional pesticides, which typically rely on a single mode of action. Moreover, the slow and controlled release of active ingredients in nano-formulations ensures that pests are exposed to sub-lethal doses over a longer period, which further slows the development of resistance. In summary, nanotechnology-based materials provide a more sustainable and effective approach to pest and disease control. They offer improved precision, lower chemical use, and reduced environmental risks, positioning them as essential tools in the transition to more environmentally conscious and efficient agricultural practices.

5. POTENTIAL RISKS AND CHALLENGES

While nanotechnology-based materials offer significant promise for improving agricultural practices, several challenges must be addressed before they can be widely adopted. These challenges include concerns about their environmental impact, economic feasibility, and the need for updated regulatory frameworks to ensure their safe and responsible use.

Environmental impact: One of the major concerns surrounding the use of nanomaterials in agriculture is their long-term environmental impact. Although nanomaterials can reduce the amount of harmful chemicals released into the environment, their own fate and behavior in ecosystems are not yet fully understood. Once released into soil, water, or air, nanomaterials could interact with other chemicals or biological systems in unpredictable ways. For instance, metallic nanoparticles like silver or copper could accumulate in soil or water, potentially affecting soil microorganisms or aquatic life (Milad 2022, Bari et al. 2024). Additionally, the small size of nanoparticles means they could travel more easily through environmental pathways, possibly entering the food chain. To address these concerns, more research is needed on the biodegradability, bioaccumulation, and potential toxicity of different types of nanomaterials in agricultural settings. Without a clearer understanding of their environmental impacts, there could be unintended consequences that offset the benefits of nanotechnology.

Cost of production: Another significant challenge is the cost associated with producing nanomaterials on a large scale. Currently, the manufacturing processes for many nanomaterials are complex and expensive, making them less accessible to small-scale farmers, particularly in developing regions. The cost of nanotechnology-based agricultural products, such as nanopesticides or nanofertilizers, can be higher than that of conventional agrochemicals, potentially limiting their adoption. While the long-term benefits of reduced chemical use, enhanced efficiency, and improved yields may offset these initial costs, the upfront investment required could be a barrier for widespread adoption. Research into more cost-effective and scalable methods of producing nanomaterials is essential to make these technologies viable for all types of farming operations. Additionally, financial incentives, subsidies, or public-private partnerships could help bridge the gap and make nanotechnology more affordable for smallholder farmers.

Regulatory concerns: The rapid development of nanotechnology in agriculture has outpaced the establishment of comprehensive regulations to govern its use. Current agricultural regulations are often insufficient to address the unique properties and risks associated with nanomaterials. For example, traditional pesticide regulations are not designed to evaluate the safety of nanoparticles, which may behave differently from their bulk counterparts. Regulatory agencies need to develop updated guidelines and frameworks for assessing the risks and benefits of nanomaterials in agricultural applications (Safdar et al. 2023). These regulations should ensure that nanomaterials are safe for human health, animals, and the environment while encouraging innovation and sustainable practices. The lack of clear regulatory pathways could also slow the approval and commercialization of nanotechnology-based products, creating uncertainty for companies and farmers alike. Addressing these regulatory challenges will require collaboration between scientists, policymakers, and industry stakeholders to develop science-based guidelines that can ensure both safety and innovation. In conclusion, while nanotechnology holds significant potential for transforming pest and disease management in agriculture, its widespread adoption will depend on addressing key challenges. These include understanding the long-term environmental impacts of nanomaterials, reducing production costs to make them accessible to all farmers, and establishing clear regulatory frameworks to ensure their safe and responsible use (Safdar et al. 2024). Overcoming these hurdles is critical for ensuring that nanotechnology can fulfill its promise of contributing to a more sustainable and efficient agricultural system.

Table 1. Types of nanomaterials used in agriculture

Nanomaterial Type	Examples	Applications in Agriculture	Benefits
Metallic Nanoparticles	Silver, Copper, Zinc	Antimicrobial agents for controlling plant pathogens	Strong antimicrobial properties
Nanoemulsions	Oil-based nano-formulations	Pesticide delivery with enhanced penetration	Improved stability and efficacy
Nanoclay Composites	Layered nanoclays	Controlled release of agrochemicals	Prolonged protection, slow release
Biopolymer Nanoparticles	Chitosan, Alginate	Biodegradable pesticide delivery systems	Eco-friendly, low toxicity

Table 2. Advantages of nanotechnology over conventional methods

Category	Nanotechnology-Based Methods	Conventional Methods
Chemical Use	Reduced due to targeted delivery	High volume application
Efficiency	Enhanced bioavailability and precision	Lower efficiency and broad application
Environmental Impact	Lower due to reduced chemical runoff	High risk of soil and water contamination
Pest Resistance	Delayed resistance development	Rapid resistance development in pests
Non-target Effects	Minimal, especially with biopolymers	High risk of affecting non-target species

Table 3. Potential risks of nanomaterials in agriculture

Risk Category	Description	Mitigation Strategy
Environmental Impact	Unknown long-term effects on soil, water, and biodiversity	Conduct extensive ecotoxicological studies
Human Health Concerns	Potential toxicity of nanoparticles if ingested or inhaled	Ensure proper safety guidelines for nanoparticle handling
Cost of Production	High costs of synthesizing nanomaterials at large scale	Research into cost-effective production methods
Regulatory Challenges	Lack of clear regulations for nanomaterials in agriculture	Develop specific regulatory frameworks for nanopesticides

Table 4. Key applications of nanotechnology in pest and disease control

Application Area	Nanomaterial Type	Mechanism	Benefits
Targeted Pesticide Delivery	Nanoemulsions, Nanoparticles	Controlled release of pesticides to pest sites	Reduces chemical usage and residues
Precision Nutrient Supply	Nanofertilizers	Slow-release of nutrients to crops	Increases nutrient uptake, reduces runoff
Pathogen Detection	Nano-sensors	Early detection of plant pathogens in the field	Early intervention, reduced crop loss
Enhanced Antimicrobial Action	Metallic nanoparticles	Direct inhibition of microbial growth on crops	Effective against a wide range of pathogens

6. CASE STUDIES AND APPLICATIONS

Several case studies demonstrate the successful application of nanotechnology in pest and disease control:

Silver Nanoparticles in Fungal Control: Silver nanoparticles have been shown to effectively control fungal pathogens such as Alternaria and Botrytis, leading to improved crop yield and reduced pesticide use.

Copper Nanoparticles for Pest Management: Copper-based nanomaterials have demonstrated efficacy in managing bacterial and viral infections in crops like tomatoes and cucumbers.

Nanoencapsulated Insecticides: Encapsulation of insecticides in nanomaterials has resulted in more efficient pest control with fewer applications, reducing both costs and environmental impact (Lowry et al. 2012, Nazneen 2024, Singh and Shashikant 2024, Mattos et al. 2017, Arubalueze and Ilodibia 2024, Nair et al. 2010, Perez-de-Luque et al. 2013, Mydeenet al. 2023, Safdar et al. 2023, Servin and White 2016, Mirekar et al. 2024, Azra and Fatima 2024, Safdar et al. 2023, Sinha and Shukla 2015).

7. FUTURE PERSPECTIVES

The future of nanotechnology in agriculture looks promising, with ongoing research focused on improving the safety, efficacy, and affordability of nano-based products. Key areas for further exploration include:

Developing Biodegradable Nanomaterials: To minimize environmental impact, efforts should focus on creating sustainable and biodegradable nanomaterials.

Precision Agriculture Integration: Integrating nanotechnology with precision agriculture practices will enable more efficient use of resources and targeted pest control.

Regulatory Frameworks: Establishing clear guidelines for the use of nanomaterials in agriculture will be essential for ensuring their safe and responsible use.

8. CONCLUSION

Nanotechnology-based materials present a promising and innovative solution for sustainable pest and disease management in agriculture. Their ability to enhance the precision and efficiency of agrochemical delivery, reduce the overall use of harmful chemicals, and provide targeted treatments makes them an attractive alternative to traditional agricultural practices. These materials, such as nanopesticides and nanofertilizers, offer the potential to improve crop protection and productivity while minimizing the negative environmental and health impacts often associated with conventional methods. However, the successful integration of nanotechnology into mainstream agricultural systems requires addressing several key challenges. These include the need for more cost-effective production methods to make nanomaterials accessible to all farmers, particularly those in resource-limited regions, and ensuring a thorough understanding of their long-term environmental impacts. Additionally, updated regulatory frameworks must be developed to guarantee the safety and responsible use of nanomaterials in agriculture. Overall, with continued research and development, nanotechnology-based approaches have the potential to revolutionize agricultural pest and disease management, contributing to more sustainable, efficient, and environmentally friendly farming practices in the future.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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