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Review IJA

Revolutionizing Agriculture with Nanotechnology: Enhancing Efficiency and Sustainability in Crop Protection and Pest Management

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Abstract

This brief review highlights the potential of nanotechnology in addressing critical challenges in modern agriculture driven by population growth, climate change, and the intensification of farming practices. The extensive use of chemical fertilizers and pesticides has increased productivity and caused environmental issues, such as soil salinization, eutrophication, and health risks due to chemical residues in food. Nanomaterials have emerged as promising solutions, offering benefits like enhanced specificity in agrochemical delivery and reduced environmental impact. Recent studies underscore the efficacy of nanoparticles (NPs), including silicon dioxide (nnSiO_2), zinc oxide (ZnO), and silver (AgNPs) in controlling pests and diseases in crops, such as soybean, tomato and Brassicaceae. These materials have demonstrated potential for improving pest management and promoting plant growth with controlled release of active agents and lower environmental toxicity. Moreover, NP-based formulations, such as chitosan and titanium dioxide (TiO_2), have effectively mitigated biotic and abiotic stresses. For example, curcumin and glycyrrhizic acid nanoparticles reduced mite populations in water-stressed soybean plants, while sustainably synthesized silver nanoparticles effectively controlled phytopathogens. Despite significant progress, barriers, such as environmental safety concerns, cost, and regulatory challenges, still limit large-scale applications. Future studies are essential to evaluate the long-term impacts and refine nanomaterial applications in agriculture. With responsible development, nanotechnology can revolutionize agriculture, promoting more sustainable and productive practices. This concise overview stimulates further discussion and exploration of nanotechnology's role in creating a more resilient agricultural future.

Keywords: Nanotechnology, sustainable agriculture, nanotoxicology, agrochemicals, environmental impact, agricultural innovation

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INTRODUCTION

Population growth continues to rise alongside the increasing demand for food production [1]. Simultaneously, climate change, coupled with unsustainable production and consumption practices, exacerbates the depletion of natural resources and deteriorates the quality of life for the global population [2]. In this context, ensuring agricultural productivity at proportional levels becomes critical, driving the widespread use of chemical fertilizers and pesticides. Although these inputs enhance productivity, plants often do not fully absorb the inorganic nutrients in fertilizers, leading to soil mineralization, eutrophication, and salinization [3]. Over time, these processes reduce soil fertility and negatively impact agricultural sustainability. Moreover, chemical residues in crops pose significant risks to human health, raising concerns about food safety [4, 5].

Adopting innovative methods that reduce environmental impacts is imperative to mitigate these adverse effects while maintaining productivity. In this regard, nanotechnology has emerged as a promising alternative for advancing pest management and crop cultivation. Nanomaterials offer unique advantages, such as enhanced specificity in agrochemical delivery, reduced environmental toxicity, and the ability to protect plants from biotic stressors. They also contribute to improved plant growth and increased resilience against pests and diseases [6].

The use of nanomaterials is particularly relevant for economically significant crops like soybeans, tomatoes, and members of the Brassicaceae family, all of which play vital roles in global food security. Beyond pest control, nanotechnology supports sustainable agricultural practices by decreasing reliance on traditional chemical inputs and alleviating their environmental consequences [7, 8].

This brief review explores recent advancements in applying nanomaterials in agriculture, focusing on their contributions to improving efficiency and sustainability. By analyzing studies on nanomaterial use in pest management for Brassicaceae crops and their application in soybean and tomato cultivation, this work aims to provide insights into how nanotechnology can revolutionize agricultural practices, addressing current challenges and future demands.

MATERIALS AND METHODS (FIGURE 1)

The research was conducted comprehensively in recognized databases, including Scopus, Web of Science, PubMed and Google Scholar, using the keywords “nanotechnology”, “soybean”, “cultivation”, “tomato cultivation”, “insect pest control”, “nanomaterials”, “insecticides”, “Brassicaceae” and “Brassicae”. The identified studies were evaluated for their relevance, prioritizing those that explored the use of nanomaterials in agricultural systems, such as soybean and tomato cultivation, and strategies for pest control in plants from the Brassicaceae family.

The selected articles needed to describe experiments involving nanomaterials, presenting detailed information on characteristics, such as size, shape and concentrations, used *in vitro*, *in vivo*, *in situ* or plant-based tests. During the screening process, duplicate studies or those outside the main scope were excluded.

Initially, the titles and abstracts of the articles were analyzed to ensure compliance with the established selection criteria. Subsequently, a detailed review of the complete texts was conducted, focusing on the methodologies employed and the results obtained. The studies were categorized based on the type of nanomaterial investigated, the synthesis method used and their practical applications in soybean and tomato cultivation, pest management, and the protection of plants from the Brassicae genus.

The information was then systematized and discussed, highlighting the leading advancements in applying nanotechnology to develop sustainable pest control and agricultural crop management solutions.

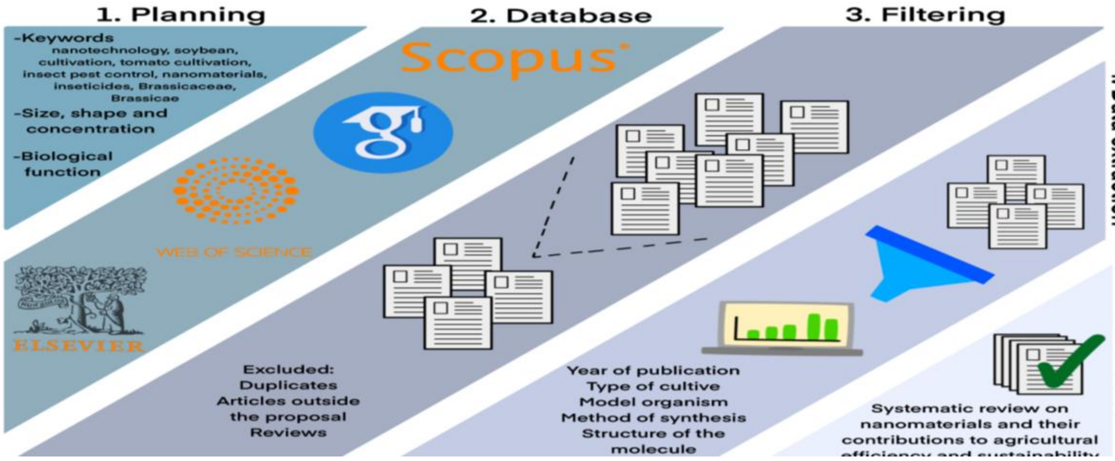

Figure 1. Research methodology.

Steps of the systematic study for analyzing nanomaterials applied in agriculture. It includes planning, searching recognized databases (Scopus, Web of Science, PubMed and Google Scholar), filtering studies by relevance and data extraction, resulting in a systematic review of the application of nanomaterials for agricultural efficiency and sustainability.

The Utilization of Nanomaterials in Pest Control and Crop Cultivation

This section analyzes the application of nanomaterials in pest control and crop cultivation. Collectively, these data illustrate the potential of nanomaterials to enhance agricultural productivity, protect crops from pests and minimize environmental impacts. A word cloud generated from the primary terms associated with this research (Figure 2) underscores critical concepts, such as "nanotechnology", "sustainable practices", "biocontrol agents", "crop protection", and "yield improvement". These terms highlight the growing trend of integrating nanotechnology into agriculture to provide precise and efficient solutions for pest management and soil health, thereby contributing to developing more resilient and sustainable agricultural systems.

Despite the significant advancements in the characterization and production of various nanomaterials and nanoparticles, a vast and largely unexplored field of their agricultural applications remains. This underlines the immense potential for further research to understand better the effective utilization of these innovative technologies in agriculture. Continued exploration could unlock novel approaches to achieving higher productivity and sustainable practices, reinforcing the critical role of nanotechnology in transforming modern agriculture.

Figure 2. Word Cloud related to the research. Key terms associated with the application of nanomaterials in agriculture, highlighting keywords, such as "nanotechnology", "cultivation", "pest control", "insecticides", and "nanomaterials". These terms reflect the focus on sustainable practices for agricultural management, emphasizing pest control and productivity improvement.

Figure 3 illustrates the distribution of scientific publications on nanomaterials (NMs) in agricultural practices for countries over the past two decades. Egypt leads with eight publications, followed by India with seven and China with four. This uneven distribution reflects variations in research investments, priorities, and regional challenges.

Countries, like Egypt, India, and China, emphasize the development of innovative agricultural technologies to address pressing issues related to food security and sustainability in areas with high demand. In contrast, regions, such as the United States, Mexico, and Chile, with fewer publications, may prioritize alternative strategies or allocate less focus to NMs research in agriculture. These findings suggest that the application of nanomaterials in agricultural practices is more concentrated in regions facing critical productivity challenges or actively seeking sustainable solutions for pest control and crop growth.

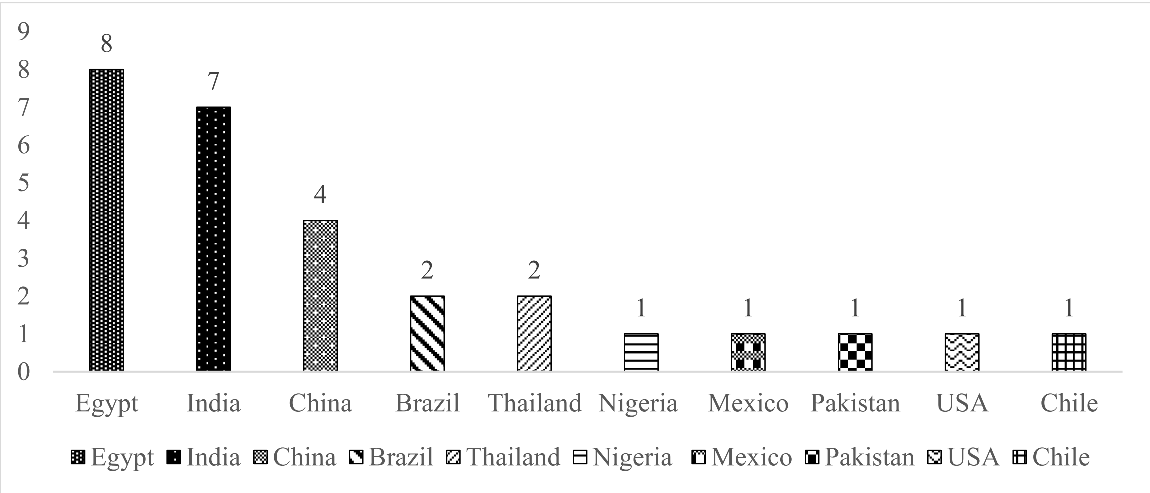

Figure 3. Geographical distribution of the analyzed scientific articles.

The world map and bar graph show the number of publications by country, with Egypt leading (eight) and India (seven). The intensity of the colors on the map represents the number of publications, highlighting the regions with the highest scientific contributions.

Applications for Nanomaterials in Pest Control and Sustainable Vegetable Cultivation

Among the notable findings, silicon dioxide nanoparticles ($nSiO_2$) have effectively reduced nematode populations and enhanced plant health, as shown by Charehgani et al. (2021) [9]. Foliar application of $nSiO_2$ at 300 mg/pot provided optimal results for tomato crops. Similarly, Xu et al. (2023) [10] reported that mesoporous silica nanoparticles (MSNs) loaded with rotenone achieved an 83.47% pest mortality rate, significantly improving rotenone's stability and controlled release.

Zinc oxide (ZnO) nanoparticles have emerged as highly versatile agents with dual functionalities. Sangeeta et al. (2024) [11] highlighted their insecticidal efficacy against *Hypena scabra* (Fabricius, 1798) (Lepidoptera: Erebidae), achieving an 83.33% mortality rate without adverse effects on seed germination. In parallel, Gutiérrez-Ramírez et al. (2021) [12] demonstrated the effectiveness of ZnO and TiO_2 nanoparticles against *Bactericera cockerelli* (Sulc.) (Hemiptera: Triozidae), with nanoparticle sizes around 23.44 nm and concentrations ranging from 40 to 3000 ppm.

Silver nanoparticles (AgNPs) synthesized via green methods also stood out as potent antimicrobial and insecticidal agents. When combined with graphene oxide (GO) and chlorophyllin derivatives (e.g., Mg-Chl/GO, Cu-Chl/Ag), these nanocomposites exhibited exceptional efficacy against *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelichiidae), with concentrations ranging from 1 to 100 mL/L [13]. However, their ecological persistence necessitates careful management to minimize potential toxicity.

Graphene oxide (GO) nanomaterials demonstrated innovative pest control capabilities, mainly via sustained pheromone release systems. Kaur et al. (2021) [14] reported superior GO efficiency against *T. absoluta* at a concentration of 3 mg, showcasing its potential for practical applications in integrated pest management systems.

Chitosan-silver nanoparticles (Chitosan-AgNPs) have proven effective against nematodes of the genus *Meloidogyne* spp., as Hamed et al. (2020) [15] reported. Furthermore, selenium nanoparticles (SeNPs) have shown promising multi-functional applications, such as enhancing soybean growth and pest resistance [16].

Table 1. Overview of nanomaterials used for pest control in vegetable cultivation, highlighting their properties, biological functions, and target organisms**.**

Nanoparticle	Size	Concentration	Biological Function	Organism Studied	REF
CeO_2	—	0, 10, 50 e 100 mg kg $^{-1}$	Insecticide	*Helicoverpa armigera*	[17]
Ag GO, Mg-Chl Cu-Chl Mg-Chl/GO, Cu-Chl/GO, Mg-Chl/Ag, Cu-Chl/Ag.	Ag: 10 nm Mg-Chl/Ag: 30 nm. Cu-Chl/Ag: 35 nm	100 mL/L; 10 mL/L; 1 mL/L	Insecticide	*Tuta absoluta*	[13]
Chitosan-Ag	81,08 − 216,22 nm	—	Insecticide	*Meloidogyne* spp	[15]
ZnO TiO_2	23.44 nm	ZnO: In the laboratory: 0, 100, 300, 500, 1000, 2000, 3000 ppm. In the oven: 0, 300, 1000, 3000 ppm. TiO_2: 40, 60, 80, 100, 300, 500 ppm. In the oven: 40, 100, 500 ppm. Combination of both: In the laboratory: 20, 30, 40, 50, 150, 250 ppm. In the oven: 20, 50, 250 ppm.	Insecticide	*Bactericera cockerelli*	[12]
Ag	12 to 46 nm	5, 10, 20, 40, 60, 80, 100,120, and 140 μg/ml	Insecticide	*Fusarium oxysporum*	[18]
Mesoporous Silica Nanoparticles (MSNs)	253 ± 73 nm	20 μg	Insecticide	Phytopathogens	[19]
	140~300 nm	0,2 mg/mL	*Insecticide*	*Pieris rapae*	[10]
GO	4−5 nm	3 mg	*Insecticide*	*Tuta absoluta*	[14]
Silicon	20−100 nm	0, 0.08 0.2 mg mL^{-1}	*Insecticide*	*Helicoverpa armigera*	[18]
	20−30 nm	1000 ppm 2000 ppm 3000 ppm	*Insecticide*	*Helicoverpa armigera*	[20]
	45 nm	50, 100, 150, 200, 250, 300 e 350 ppm	*Pesticide*	*Meloidogyne incognita*	[21]

Cerium dioxide nanoparticles (CeO_2-NPs) were also highlighted for their insecticidal activity against Helicoverpa armigera (Hubner) (lepidoptera: Noctuidae). Xiao et al. (2021) [17] demonstrated significant pest mortality at 10, 50, and 100 mg/kg concentrations. These findings underscore the biocompatibility, tunable properties, and environmental safety of Ceo_2-NPs, making them ideal candidates for sustainable pest control.

Silica-based nanoparticles (SiNPs) exhibited outstanding versatility, with spherical and amorphous forms tested against pests, such as *H. armigera* [20, 22], and *Meloidogyne incognita* [21]. Innovations, like porous hollow silica nanoparticles (PHSNs) and mesoporous silica nanoparticles (MSNs), achieved excellent insecticidal effects at low concentrations [10, 19] further demonstrating their practical potential.

Table 1 presents a comprehensive overview of various nanomaterials investigated for pest control in vegetable crops, focusing on their types, mechanisms of action, and targeted pests. These nanomaterials, including silicon dioxide ($nSiO_2$), titanium dioxide (TiO_2), silver nanoparticles (AgNPs), graphene oxide (GO), and selenium nanoparticles (SeNPs), represent significant innovations in agricultural pest management, offering targeted, efficient, and sustainable alternatives to conventional pesticides.

MSNs, AgNPs, and ZnO NPs stand out due to their stability, controlled release, and reduced non-target toxicity. CeO_2-NMs and silica-based nanoparticles, with their biocompatibility and environmental safety, are particularly promising for sustainable pest control. However, while AgNP-based composites, like Mg-Chl/Ag and Cu-Chl/Ag, demonstrate exceptional efficacy, their ecological persistence warrants further investigation to ensure long-term safety.

These findings highlight the transformative potential of nanotechnology in revolutionizing agricultural pest management. By integrating advanced nanomaterials into pest control systems, agriculture can achieve enhanced crop productivity, reduced reliance on chemical pesticides, and improved environmental sustainability. Future research should prioritize optimizing the synthesis and application of these nanomaterials, developing biodegradable or naturally derived alternatives, and scaling up production for real-world applications.

Additionally, understanding the long-term ecological effects of these materials is crucial to ensure their sustainable deployment. Adopting these innovations and other sustainable agricultural practices will significantly contribute to global food security in the face of increasing population demands and climate change challenges.

Advances and Limitations of Nanoparticles in Pest Management for Soybean and Corn Cultivation

Corn and soybean, two of the worlds' most important crops, are central to global food security and industrial products. Given their increasing production, particularly in countries, like Brazil, innovative agricultural technologies are necessary to enhance sustainability. Among these innovations, nanoparticles (NPs) have shown potential in pest management, offering targeted action with minimal environmental impact.

Recent studies have highlighted the effectiveness of various NPs for controlling pests in corn and soybean crops. Silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnO-NPs), and silica nanoparticles (SiNPs) stand out for their strong insecticidal properties. For instance, AgNPs effectively controlled pests like *Trichoplusia ni* (Hubner, 1803) (Lepidoptera: Noctuidae) and *Spodoptera frugiperda* (J. E. Smith, 1797) (Lepidoptera: Noctuidae), with varying concentrations yielding dose-dependent results [23]. ZnO-NPs also showed broad-spectrum antimicrobial activity, controlling pests like *H. scabra* and *S. frugiperda* [11, 23]. Moreover, SiNPs effectively reduced pest populations while attracting natural predators, providing an eco-friendly alternative to chemical pesticides [24].

Natural-based NPs, like curcumin and glycyrrhizic acid nanoparticles (GA-NPs), have shown promise in pest control with acaricidal effects against the two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae) in water-stressed soybean plants [25]. These findings suggest that natural compounds in nanoparticle form offer a sustainable, cost-effective alternative to traditional chemical acaricides. Additionally, selenium nanoparticles (SeNPs) tested against *Spodoptera littoralis* (Boisd., 1833) (Lepidoptera: Noctuidae) further reinforce the potential of eco-friendly options in pest control [16].

Graphene oxide (GO) and metal oxide nanoparticles, such as SiO_2 and CeO_2, have also been investigated for their potential in pest control and plant growth enhancement. GO, with its high surface area, exhibited insecticidal activity against *Ostrinia furnacalis* (Guenée, 1854) (Lepidoptera: Crambidae) [26], while SiO_2 and CeO_2 were found to enhance the absorption of environmental pollutants like pyrene. However, they raised concerns regarding plant metabolic disruptions [27]. This highlights the importance of studying the ecological impacts of NPs and their interactions with plants and pollutants.

In the context of crop growth, ZnO nanoparticles have shown benefits beyond pest control. Studies indicate that ZnO-NPs improve germination, chlorophyll content, and yield parameters in crops like maize by facilitating zinc absorption and enhancing metabolic processes [22]. This effect is particularly noticeable when nanoparticle concentrations are carefully managed, as excessive amounts can harm plants.

While the benefits of NPs in pest management and plant growth are evident, challenges remain. The co-exposure of nanoparticles with environmental contaminants and the variation in efficacy based on nanoparticle types and plant genetics emphasizes the need for continued research. Future studies should focus on optimizing nanoparticle formulations for field applications, evaluating their long-term environmental impacts, and establishing guidelines for their safe use.

Overall, nanoparticles represent a promising tool for sustainable agricultural practices, offering new avenues for pest control and plant growth enhancement. Silver and zinc oxide nanoparticles are among the most effective, with natural NPs like SeNPs and curcumin-based nanoparticles providing eco-friendly alternatives. Tailored pest control strategies, considering the properties of nanoparticles and the specific pest challenges, will be key to maximizing their effectiveness and sustainability in agriculture.

Table 2 summarizes various nanoparticles (NPs) tested for pest control in soybean and maize crops, highlighting their types, sizes, concentrations, and biological functions. These studies emphasize the diversity and potential of nanoparticles in pest management. Further research is needed to optimize the use of nanoparticles in agricultural settings, particularly in field applications.

Considerations, such as nanoparticle size, concentration, and interaction with different plant species, are key to maximizing their potential. Additionally, nanoparticles' long-term environmental impact and safety, particularly their interactions with soil and non-target organisms, must be thoroughly evaluated (Table 2). Despite these challenges, the growing body of research highlights the transformative potential of nanoparticles in enhancing the sustainability of corn and soybean farming, providing an effective alternative to conventional pest management methods.

Table 2. Summary of nanoparticles tested for pest control in soybean and maize, including their types, sizes, concentrations, and effectiveness.

Nanoparticle	Size	Concentration	Biological Function	Organism Studied	REF
Curcumin GA	Cu: 6 mM GA: 3 mM	16–30 nm 5–9 nm	Acaricide	Tetranychus urticae	[25]
ZnO	25–50 nm	100–500 ppm	Insecticide	Spodoptera frugiperda	[23]
	22–34 nm;	10 mg/100 mL	Insecticide	Hypena scabra	[11]
Ag	85 nm	20, 10, 5, 2,5, 1,25 and 0,63 mg/mL	Insecticide	Trichoplusia ni and Agrotis ipsilon	[21]
Cu, KI, Ag, Bd, and Gv	Cu: 8–74 nm Ki 13–65 nm Ag: 23–87 nm Bd: 15–63 nm Gv: 22–79 nm	1000 ppm 10000 ppm 100000 ppm	Insecticide	S. frugiperda larvae	[23]
Silica	29 nm	75, 150, 225, 300, 375	Insecticide	Aphis craccivora,	[24]

		and 425 mg/L		Liriomyza trifolii, Spodotera littoealis	
GO	712–955 nm	6,67 mg (Insecticide) 3,33 md (GO) in 100 mL of solvent	Insecticide	Ostrinia furnacalis	[26]
Se	30 nm	5 to 50 mg/mL	Insecticide	Spodoptera littoralis	[16]
Zein and Curcumin	Control 111 ± 5 nm NPs Cur.Carv. 100 ± 12 nm	0,033 mg/mL; 1,250 mg/mL.	Insecticide Acaricide	Tetranychus urticae; S. Cosmioides S. eridania	[18]
	—	0,5; 1,0; 5,0 and 10 mg/ml	Insecticide	Chrysodeixis includens	[12]

Figure 4 illustrates the dual functionalities of various nanomaterials in agricultural applications, explicitly highlighting their roles in pest control and plant growth enhancement. The two overlapping categories emphasize the multifunctional nature of specific nanomaterials.

In the Pest Control section (left circle), nanomaterials, such as curcumin, polyhydroxybutyrate (PHS), magnesium-chlorophyll/graphene oxide (Mg-Chl/GO), copper (Cu), iron oxide (FeO), selenium (Se), zein, and potassium (K), are listed. These materials demonstrate specific pesticide properties, aiding in reducing pest populations that negatively impact crop yields. The diagram indicates that some nanomaterials, like Cu and Mg-Chl/Ag, serve dual roles, as shown by their inclusion in the overlapping area.

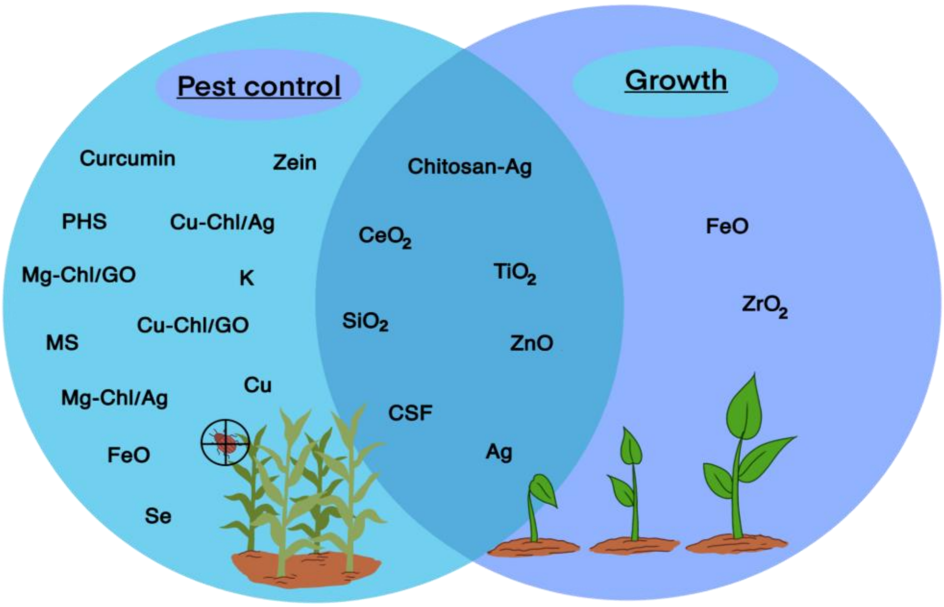

Figure 4. Applications of nanoparticles in agriculture: pest control and plant growth stimulation.

Nanoparticles: Silicon dioxide (SiO_2); nano chelated silicon fertilizer (CSF); Cerium dioxide (CeO_2); Selenium (Se); Graphene oxide combined with magnesium chlorophyllin (Mg-Chl/GO); Graphene oxide combined with copper chlorophyllin (Cu-Chl/GO); Silver combined with magnesium chlorophyllin (Mg-Chl/Ag); Silver combined with copper chlorophyllin (Cu-Chl/Ag); Silver with chitosan (Chitosan-Ag); Titanium dioxide (TiO_2); Zinc oxide (ZnO); Mesoporous silica nanoparticles (MS); Porous hollow silica nanoparticles (PHS); Curcumin (Curcumin); Copper (Cu); potassium (K); Silver (Ag); Zein (Zein); Iron oxide (Feo); Zirconium oxide (ZrO_2).

In the Growth Enhancement section (right circle), nanomaterials, such as zirconium oxide (ZrO_2), FeO, titanium dioxide (TiO_2), zinc oxide (ZnO), silver (Ag) and cerium oxide (CeO_2), are noted for their contributions to improving plant health, nutrient absorption and overall growth performance.

The overlap between the two categories highlights nanomaterials with pest control and growth-promoting capabilities. Examples include chitosan-silver (Chitosan-Ag), cerium oxide (CeO_2), titanium dioxide (TiO_2), zinc oxide (ZnO), silica (SiO_2) and carbon-sulfur frameworks (CSF). These nanomaterials demonstrate multifunctionality, making them valuable tools for sustainable agriculture by reducing reliance on chemical pesticides and fertilizers.

Therefore, the transformative potential of nanotechnology is in addressing key challenges in agriculture, offering a sustainable approach to promote healthier crops while mitigating pest damage. By leveraging multifunctional nanomaterials, future perspectives include the development of more efficient, eco-friendly alternatives to traditional pesticides and fertilizers. These advancements promise to improve agricultural productivity, reduce environmental impact and contribute to global food security in the face of growing population demands and climate change challenges.

CONCLUSIONS AND PERSPECTIVES

In conclusion, nanotechnology presents transformative opportunities to address the multifaceted challenges faced by modern agriculture, including the need for increased productivity, environmental sustainability and resilience to climate variability. Applying nanomaterials, such as silicon dioxide, zinc oxide, and silver nanoparticles, has shown promising results in pest control, plant growth enhancement, and stress mitigation. These advancements underscore the potential for nanotechnology to reduce dependency on conventional agrochemicals, minimize environmental harm and improve crop health. Additionally, innovative formulations, including chitosan-based nanoparticles and sustainably synthesized alternatives, further highlight these nanomaterials' versatility and eco-friendly potential.

Despite these advancements, significant hurdles remain. Concerns about the environmental safety of nanomaterials, their potential bioaccumulation and the lack of comprehensive regulatory frameworks pose challenges to widespread adoption. Moreover, the high cost of nanoparticle production and the need for scalable synthesis methods hinder practical implementation in resource-constrained settings.

Future research should prioritize long-term ecological assessments, the development of cost-effective and biodegradable nanomaterials and the establishment of standardized guidelines for their safe use in agriculture. Interdisciplinary collaborations will be vital to bridge the gap between laboratory findings and field applications. By addressing these challenges responsibly, nanotechnology has the potential to revolutionize agriculture, fostering more sustainable, productive and resilient farming practices to meet the demands of a growing global population.

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Data Availability Statement

Not applicable.

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Conflicts of Interest

The authors declare no conflict of interest.

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