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Nanotechnology for Improving Agrotechnical Practice – Actual Significance and Prospects

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Agriculture faces growing challenges, including soil degradation, climate change, and the need for increased food production while minimizing environmental harm. Nanotechnology, specifically the use of nanoparticles and metal nanoparticles, presents a promising way for sustainable agricultural practices. It holds the promise of making agriculture more resilient, efficient, and sustainable. Its precision-based approach enables optimized use of inputs and improved crop outcomes, making it a key technology for addressing global food security challenges. Nanoparticles have emerged as a revolutionary tool in agriculture, providing innovative solutions for improving crop yield, reducing environmental damage, and enhancing sustainable farming practices. Nanotechnology offers innovative solutions that transcend traditional limitations related to soil type and climatic variability. Its applications range from enhanced nutrient delivery systems to advanced pest control and environmental monitoring, making it an asset for global agricultural development. This review summarizes in short the benefits and risks associated with the application of nanoparticles in agriculture, focusing on nano-fertilizers, nano-pesticides, and nano-remediation technologies. Nano-fertilizers hold significant promise for advancing sustainable agriculture by enhancing nutrient efficiency and reducing environmental impacts. Nanopesticides represent a significant advancement in agricultural pest management, offering the potential for more effective and environmentally conscious solutions. Nano-remediation has substantial promise for enhancing environmental sustainability in agriculture by effectively addressing soil and water contamination. The discussion also highlights regulatory concerns and future directions in nano-enabled agriculture.

Keywords: nanoparticles, effect in agrobiodiversity, nano-fertilizers, nano-pesticides, nano-remediation

Introduction

Sustainability practices toward the environment have become an inevitable part of human responsibility in our interactions with nature and natural resources that can render the environment safe for present as well as for future generations (Arora et al., 2018). The controlled management of natural resources emphasises harmony between ecology and the environment and can sustain the ecological/natural balance within the universe (Barrington-Leight, 2016). Agriculture is a fundamental industry, essential for food security and economic stability. The rapid expansion

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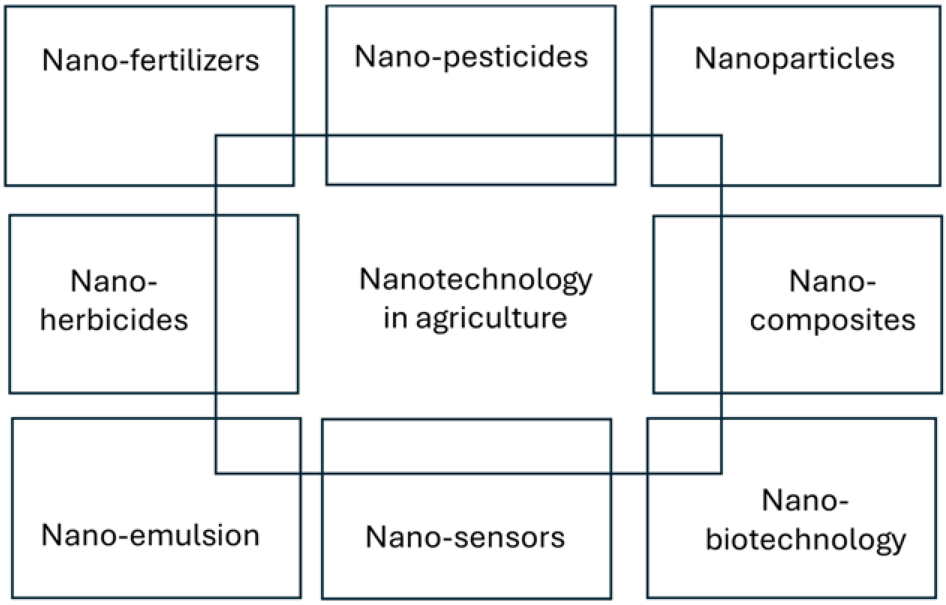

Figure 1 Nanotechnology applications in agriculture

of nanotechnology has introduced novel applications in agriculture, particularly in nutrient delivery, pest control, and soil remediation. Nanotechnology is used in different fields of interest in agriculture (Figure 1).

Especially metal nanoparticles have garnered significant attention in agriculture due to their unique properties, which can influence plant growth, soil health, and microbial communities. Their application offers promising possibilities for enhancing crop productivity and sustainability. The uniqueness of nanotechnologies lies in the possibility of their use in different regions, regardless of the soil and climatic conditions of a particular zone. However, understanding their holistic effects on agrobiodiversity is crucial to ensure environmental safety and ecological balance as well as concerns regarding toxicity, environmental accumulation, and potential health hazards necessitate a balanced evaluation of the benefits and risks of nanoparticles.

Applications of Nanoparticles and Metal Nanoparticles in Agriculture

Different types of nanoparticles are used in agricultural practice for a total of three main purposes.

Nano-fertilizers

Nano-fertilizers provide targeted nutrient delivery, that improves efficiency and reduction of nutrient loss through leaching (Mahesha et al., 2023). They represent an innovative advancement in agricultural practices, aiming to enhance nutrient efficiency and promote sustainable crop production. Promising technology in nano-fertilizers is the production of bio-based nanoparticles (Verma et al., 2024). By leveraging nanotechnology, these fertilizers potentially lead to increasing yields while minimizing environmental impacts. They are categorized based on their composition and function to nanoparticles as nutrient sources, nanomaterial-coated fertilizers and nanoscale additives.

Nanoparticles as nutrient sources (Table 1), that directly include supplementation by essential nutrients, such as nano-sized nitrogen, phosphorus, calcium, magnesium, sulfur, or potassium compounds (Yadav et al., 2023).

Nanomaterial-coated fertilizers where conventional fertilizers are coated or loaded with nanomaterials to control the release and improve the efficiency of nutrient uptake (Beig et al., 2022). They involve encapsulating macroscale fertilizers with a nanoscale coating or film, that potentially contains nanoscale pores that gradually release soluble nutrient (Mahaletchumi, 2021).

Nanoscale additives are materials added to fertilizers to enhance their properties, such as increasing solubility or reducing nutrient losses (Guha et al., 2022). They incorporate nanoscale particles or substances into larger-scale products or inputs. They do not serve as direct nutrients but they enhance the properties of the larger inputs.

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Table 1 Benefits of nano-fertilizers in selected crops

Nanoparticle	Species	Application	Effect
CuO	*Solanum lycopersicum*	foliar application	eliminated the spread of disease
Zn, Fe and NPK	*Cicer arietinum*	foliar application	significant increase in both biological and seed output
Al_2O_3 NPs	*Solanum lycopersicum*	foliar application	effectively counteract *Fusarium* as a biocontrol agent
N, P and NPK NPs	*Triticum aestivum*	foliar application	significant changes in plant growth parameters like shoot length, root length, and others
ZnO	*Coffea arabica*	foliar spray	acceleration of net photosynthesis and increased biomass production
TiO_2 and SiO_2	*Oryza sativa*	foliar application	better development and Cd translocation inhibition

Source: Nongbet et al., 2022

The efficacy of nano-fertilizers is attributed to several key mechanisms. Enhanced nutrient uptake is connected to the small size and large surface area of nanoparticles that facilitate easier penetration through plant cell walls and membranes, leading to improved nutrient absorption (Mahaletchumi, 2021). Controlled release of nanomaterial coatings can regulate the release rate of nutrients, ensuring a steady supply aligned with the plant's growth stages and reducing the frequency of fertilizer application (Madlala et a., 2024). Targeted delivery, where functionalization of nanoparticles allows for the precise delivery of nutrients to specific plant parts, optimizing nutrient use efficiency (Beig et al., 2022).

A positive correlation exists between the particle size and the ability of its nutrient uptake. In soybean, CuO nanoparticles of 25 nm were reported as exhibiting high nutrient uptake, and nanoparticles of 50 nm had lower nutrient uptake (Yusefi-Tanha et al., 2020).

Nano-pesticides

Nanopesticides have emerged as a promising innovation in sustainable agriculture. By manipulating materials at the nanoscale, these formulations aim to enhance the efficacy and environmental safety of pest control measures. Nano-pesticides are classified into two types: the first one are metal-based nano-pesticides (Cu, Ti, Ag), and the second one involves nanopesticides where AIs are encapsulated within nanocarriers, composed of materials such as clays, polymers, and zein NPs (Wang et al., 2022). Nano-pesticides offer increased efficiency and reduced environmental impact compared to traditional pesticides. However, long-term effects on soil microbiota remain a concern (Chaud et al., 2021.) Based on a specific nanoscale formulation of their active component, nano-pesticides activate delivery and effectiveness, which results in improvement in the dispersion stability, creates slow/controlled release formulations, and provides better control in the field applications (Grillo et al., 2021). Nano-pesticides were reported to have many benefits, such as improved durability and potency as well as reduced active components, which leads to reducing the environmental impact that chemical pesticides have on the ecosystem (Awad et al., 2022). They have high adsorption, reduced volatilization, or improved tissue permeation. However, studies are also highlighting the potential toxicity of nano-pesticides in the non-target organism and their environmental risk (Table 2) (Kannan et al., 2023).

Table 2 Pros and cons of nano-pesticides

Benefits of nano-pesticides	Environmental risks of nano-pesticides
Increased stability	impact on terrestrial organisms
Controlled release	impact on soil organisms
Superior efficacy	impact on aquatic organisms
Lower rate required	impact on plants
Suitable dispersion	interaction with environmental pollutants
Minimizing residues	toxicity

Source: Zainab et al., 2024

Nano-remediation

Pollution and environmental protection are important global concerns that must be resolved as soon as possible. Globally, there are an astounding amount of contaminated dumps, oil fields, military facilities, private estates, and manufacturing and industrial sites (Patil et al., 2016). Nanotechnology assists in soil and water remediation, aiding in the removal of toxic elements while improving soil quality (Kaningi et al., 2022). Nano-remediation offers creative solutions for the rapid and effective removal of pollutants from contaminated environments, enabling the resolution of the major problems of the twenty-first century, including the pollution crisis, contaminated land management, and environmental imbalance restoration (Das et al., 2019). In addition to lowering the total cost of cleaning up large-scale contamination, technologies that use nanostructures have the potential to shorten cleanup times, do away with the need to treat and dispose of contaminated materials, and lower contaminant concentrations to almost zero in situ (Corsi et al., 2018). Reactive nanomaterials like metal oxides, nanodots, bimetallic nanoparticles, carbon nanotubes, nanoclusters, and nanocomposites are used in nanoremediation technologies to break down and mineralise pollutants (Guerra et al., 2018; Garnie et al., 2021). Nanoremediation techniques can offer long-term solutions to environmental pollution issues and may lessen the cost of cleaning up contaminated sites when compared to a number of conventional remediation techniques, including chemical oxidation, solvent co-flushing, pump treatment methods, and thermal decomposition (Patil et al., 2016; Ganie et al., 2021).

Benefits of Nanoparticles and Metal Nanoparticles in Agriculture

A pest infestation, microbial attacks, natural catastrophes, poor soil quality, and reduced nutrient availability are the main causes of damage to approximately one-third of crops grown using conventional farming. To solve these problems, more inventive technologies are urgently needed. In this sense, nanotechnology has aided in the agrotechnological revolution, which holds promise for food security and the immediate overhaul of the robust agricultural system. As a result, nanoparticles are emerging as a cutting-edge substance that will revolutionise contemporary farming methods. For managing plant health and improving soil, a wide range of nanoparticle-based formulations have been studied, including nano-sized insecticides, herbicides, fungicides, fertilisers, and sensors. By increasing qualities like disease resistance, crop output, and nutrient utilisation, a thorough understanding of the interactions between plants and nanomaterials opens up new possibilities for bettering agricultural operations (Mittal et al., 2020).

In general, nanotechnology assists in soil and water remediation, aiding in the removal of toxic elements while increased efficiency of fertilizers and pesticides (Singh et al., 2021), enhance crop protection and disease resistance (Bhushan et al., 2024), improve soil health and nutrient retention (Hafez and Khalil, 2024) and reduction in environmental contamination (Kumar et al., 2019).

The application of nano-fertilizers was reported to have several advantages. Increased crop yield, where it have been demonstrated that nano-fertilizers can significantly boost crop productivity by enhancing nutrient use efficiency, leading to higher yields (Saurabh et al., 2024. Environmental sustainability as a secondary effect of improving nutrient uptake and reducing losses, nano-fertilizers minimize the runoff of chemicals into water bodies, thereby lessening environmental pollution (Nongbet et al., 2022). Economic efficiency in the case of the controlled release and targeted delivery nano-fertilizers reduce the total amount of fertilizer required, potentially lowering costs for farmers.

One of the primary benefits of nanopesticides is their potential to improve the solubility and bioavailability of active ingredients. Traditional pesticides often face challenges with water solubility, leading to inefficient application and environmental runoff. Nanopesticide formulations can increase water solubility and protect agrochemicals against environmental degradation, thereby enhancing their effectiveness and reducing the required application rates (Chaud et al., 2021). Moreover, the unique size and properties of nanoparticles facilitate controlled release and targeted delivery of active ingredients. This precision reduces the frequency of applications and minimizes non-target effects, contributing to more sustainable pest management practices (Ali et al., 2023).

Nano-remediation has emerged as a promising strategy to address soil and water contamination in agricultural settings. This approach leverages the unique properties of nanoparticles to degrade or immobilize pollutants, thereby enhancing soil health and crop productivity. Several nanomaterials have been explored for their efficacy in environmental remediation. *Nanoscale* zero-valent Iron (nZVI) is widely used for its strong reducing properties, nZVI effectively degrades a range of contaminants, including chlorinated solvents and pesticides. Its high reactivity stems from its large surface area, facilitating rapid pollutant breakdown (Alazaiza et al., 2021). Metal oxide nanoparticles such as titanium dioxide (TiO_2) and zinc oxide (ZnO) have demonstrated photocatalytic capabilities under light exposure, leading to the degradation of organic pollutants like dyes and pesticides. These materials are particularly useful in treating wastewater and contaminated soils (Guerra et al., 2018). Carbon-based nanomaterials like carbon nanotubes and graphene oxide exhibit high adsorption capacities, making them suitable for removing heavy metals and organic contaminants from soil and water. Their large surface area and functionalizable surfaces enhance their remediation potential (Alazaiza et al., 2021). Nanoremediation has gained attention as a potential tool for mitigating climate change through greenhouse gas sequestration, too. While traditionally used in soil and groundwater remediation, recent studies have explored its role in capturing and converting CO_2, CH_4, and N_2O into less harmful or utilizable forms. *Nanomaterials* such as metal–organic frameworks (MOFs), carbon nanotubes (CNTs), and graphene-based materials exhibit high surface area and tunable porosity, making them suitable for CO_2 capture. MOFs can be engineered for high selectivity and reversible adsorption, crucial for carbon capture and storage (CCS) applications (Younas et al., 2021). Photocatalytic nanomaterials such as TiO_2, ZnO, and doped nanocomposites can convert CO_2 into value-added chemicals (e.g., methanol) under light irradiation, mimicking natural photosynthesis (Islam et al., 2023).

Molecular Response of Plants to Nanoparticles and Metal Nanoparticles

Nanoparticles (NPs) have been increasingly recognized for their significant role in modulating gene expression in plants through various mechanisms. Their ability to interact with cellular components, including nucleic acids, has profound implications for plant physiology and development. Different mechanisms can be affected by nanoparticles such as cellular uptake and interaction, epigenetic modifications, signaling pathways, influence on hormone regulation or antioxidant pathways, and stress response (Verma et al., 2024).

Recent investigations have highlighted the intricate relationship between nanoparticle (NP) exposure and the expression of pathogen-responsive genes in plants. In a study examining the responses of *Arabidopsis thaliana* to various NPs, it was found that most genes activated during pathogen challenges, such as those involved in systemic acquired resistance (SAR), were significantly repressed following NP exposure. For instance, the gene FRK1, known for its role in the basal immune response upon bacterial flagellin perception, was notably downregulated when plants were exposed to nanoparticles like silver (Ag-NPs) and titanium dioxide (TiO_2-NPs) (García-Sánchez et al., 2015; Yan and Chen, 2019). This repression suggests that NP exposure can inhibit the plant's immune response, making plants more susceptible to pathogens.

Silver nanoparticles are widely recognized for their antimicrobial properties, but they also play a crucial role in modulating plant defense mechanisms. Research indicates that exposure to Ag-NPs can enhance the expression of pathogenesis-related (PR) genes such as PR-1, PR-2, and PR-12, particularly during viral infections like those caused by Tobacco mosaic virus (TMV) (Shivashakarappa et al., 2025). The ability of Ag-NPs to trigger SAR pathways suggests a dual effect where they not only provide direct antimicrobial benefits but also bolster the plant‘s innate immune responses, thereby improving resistance to viral infections.

Titanium dioxide nanoparticles exhibit complex regulatory effects on gene expression in plants. Studies have shown that TiO_2-NP exposure can lead to both upregulation and downregulation of genes involved in responses to biotic and abiotic stresses. Specifically, while some genes associated with oxidative stress and immune responses were upregulated, others, including those linked to root development and phosphate starvation, were downregulated (García-Sánchez et al., 2015; Aseel et al., 2024). This differential regulation indicates that the physiological responses of plants to TiO_2-NPs are context-dependent and may vary based on environmental conditions.

Comparative studies on the impact of various nanoparticles, including silver and zinc oxide (ZnO-NPs), on gene expression related to pathogen resistance, were realized. Their findings revealed a significant overlap in the genes that were responsive to both the NPs and bulk materials, emphasizing the need for further research into the shared mechanisms of action and potential crosstalk between NP exposure and plant defense signaling pathways (Carrilo-Lopez et al., 2024). The data highlighted that exposure to ZnO-NPs resulted in the upregulation of genes that facilitate functional responses to both abiotic and biotic stressors, further underscoring the multifaceted role of nanoparticles in plant physiology.

The impact of gold nanoparticles on plant receptor-ligand interactions and signalling cascades has been investigated (Konwarh and Sharma, 2020). Gold nanoparticles functionalised with auxin hormone analogues by activating signalling pathways and could modify plant growth and development. Gold nanoparticles‘ function in plant signalling was highlighted by the alterations in gene expression and physiological reactions they caused in plants (Ferrari et al., 2021).

The effect of silver nanoparticles on plant signalling has also been studied. Silver nanoparticles activate signalling cascades involved in stress tolerance and increase the expression of genes responsive to stress. According to this, plants may use silver nanoparticles as signalling inducers to initiate adaptive reactions to environmental stressors (Khan et al., 2023). Additionally, it has been demonstrated that metal nanoparticles alter signalling molecules and pathways associated with defence systems in plants.

Copper nanoparticles have been shown to increase plant synthesis of defense-related signalling chemicals including salicylic acid and jasmonic acid. The activation of plant defence mechanisms against pests and diseases is facilitated by this signalling pathway modification (Shang et al., 2020).

When examining how exposure to metal nanoparticles affects transcription and transcript processing in plants, these particles are essential. Their distinct physicochemical characteristics allow for accurate modification and study of RNA metabolism and gene expression regulation (Van Aken, 2015). To evaluate metal nanoparticles‘ uses in agriculture, environmental monitoring, and risk assessment, it is essential to comprehend how they affect these processes. The effect of zinc oxide nanoparticles on alternative splicing patterns in maize has been studied by Xun et al. (2017).

The ability of gold nanoparticles to affect RNA processing systems and contribute to transcriptome diversity in plants was demonstrated by notable changes in the splicing patterns of genes. Additionally, RNA stability and degradation mechanisms are impacted by metal nanoparticles (Tiwari et al., 2016). Aluminium oxide nanoparticles were studied to affect tobacco plant RNA decay, noting increased breakdown of RNA components and possible modifications to gene expression profiles. This implies that metal nanoparticles have a part in plant post-transcriptional control (Burklew et al., 2012). The impact of metal nanoparticles on transcription and transcript processing in plants can be influenced by several variables, including plant species, concentration, exposure time, and nanoparticle size.

Risks and Challenges of Nanoparticles and Metal Nanoparticles in Agriculture

Reported risks and challenges of nanoparticles are in the area of potential toxicity to humans and soil organisms (Dimkpa, 2014), uncertain environmental fate of nanoparticles (Mishra et al., 2017), and regulatory and ethical concerns (Poddar et al., 2017).

Despite the potential of nano-fertilizers, several challenges must be addressed, such as safety and toxicity in the long-term effects of nanoparticles on human health and the environment, as they are not yet fully understood. Comprehensive risk assessments are necessary to ensure safe application as well as regulatory framework of the development of standardized regulations governing the use of nano-fertilizers is essential to facilitate their adoption and ensure safety. Further, the cost of production, as the synthesis of nanoparticles can be expensive, which may limit the accessibility of nano-fertilizers to resource-constrained farmers needs to be studied.

Nanopesticides offer advantages, but their environmental impact requires to be carefully considered. Studies have shown that nanopesticides can outperform their non-nano counterparts by 32% in effectiveness against target organisms, including a 19% increase in efficacy against insects (Kannan et al., 2023). However, the long-term effects of nanoparticles on soil health, water quality, and non-target organisms are not yet fully understood. Therefore, comprehensive risk assessments and the development of regulatory frameworks are essential to ensure the safe integration of nanopesticides into agricultural practices. Nanopesticides are being explored for various applications, including the delivery of insecticides, herbicides, and fungicides. Their ability to provide controlled release and targeted action makes them suitable for managing a wide range of agricultural pests. As research progresses, the development of environmentally friendly nanopesticide formulations is anticipated to play a significant role in advancing sustainable agriculture (Deka et al., 2021).

While nano-remediation presents significant advantages, several challenges must be addressed. The environmental impact of the long-term effects of nanomaterials on soil microbiota and overall ecosystem health are not fully understood. There is a need for comprehensive studies to assess potential risks associated with nanoparticle accumulation in the environment (Alazaira et al., 2021). Economic viability, as the cost of synthesizing and deploying nanomaterials can be high. Research into cost-effective production methods and the use of sustainable, bio-derived nanomaterials is ongoing to make nano-remediation more accessible. The regulatory framework, as the application of nanotechnology in agriculture, requires robust regulatory guidelines to ensure safe usage. Establishing standardized protocols for the application and disposal of nanomaterials is crucial to prevent unintended environmental consequences (Mittal et al., 2020).

The use of nanoparticles in agriculture raises significant environmental and safety concerns, particularly regarding their interaction with terrestrial plants and subsequent impacts on ecosystems and human health. As NPs enter soil through agricultural practices, especially via biosolids from sewage treatment plants, their long-term accumulation poses risks to plant health and productivity. Nanoparticles can induce phytotoxic effects, adversely affecting plant growth and development. Studies indicate that different types of NPs, such as silver and copper oxide, lead to oxidative stress in plants, resulting in genotoxicity, chromosomal aberrations, and altered gene expression. exposure to silver nanoparticles has been linked to significant physiological changes in peanut plants, impacting their growth and food safety. Furthermore, the differential accumulation of NPs within plant tissues, influenced by factors such as particle size and charge, has been documented, revealing the complex interactions between plants and nanoparticles (Gao et al., 2023).

Considerations for Sustainable Application of Nanoparticles and Metal Nanoparticles in Agriculture

Nanoparticles offer innovative approaches for improving soil fertility, pest control, plant growth, and crop yield, with reduced dependency on chemical fertilizers and pesticides (Mgadi et al., 2024).

Nano-fertilizers provide essential nutrients in a controlled and efficient manner, reducing nutrient losses and improving soil health. Metal oxide nanoparticles such as zinc, copper, iron, and manganese have been shown to enhance plant nutrition, leading to improved growth and productivity (Kumari et al., 2019). The application of these nanoparticles reduces soil degradation while ensuring long-term agricultural sustainability. Recent studies have focused on the development of nanohybrid fertilizers, which combine nanoparticles with organic or inorganic materials to enhance nutrient delivery and sustainability. These fertilizers aim to integrate the benefits of nanotechnology with traditional fertilization methods to achieve precision and efficiency in nutrient management (Easwaran et al., 2024).

Nanopesticides and nanoherbicides have emerged as efficient alternatives to traditional chemicals. These formulations use nanoparticles as delivery vehicles, increasing the efficacy of pest control agents while minimizing environmental contamination. Metal-based nanoparticles, such as silver and copper, possess strong antimicrobial properties that help in plant disease prevention (Shende et al., 2022).

Certain nanoparticles have been found to improve plant stress tolerance against drought, salinity, and extreme temperatures. Their application enhances photosynthesis, seed germination, and biomass production, leading to better crop resilience (Zhao et al., 2020). Additionally, nanoparticles promote root and shoot development, boosting overall crop yield.

Nanotechnology also contributes to food security by extending shelf life and preventing spoilage. Metal nanoparticles like silver and titanium dioxide are being incorporated into food packaging materials to provide antimicrobial protection and improve food preservation (Maity et al., 2022).

The integration of nano-remediation techniques in agriculture offers multiple benefits. Soil decontamination where nanoparticles can immobilize heavy metals, reducing their bioavailability and toxicity to plants. This process not only cleanses the soil but also restores its fertility, promoting healthier crop growth (Dhanapal et al., 2024). Water purification by nanomaterials can be employed to treat irrigation water contaminated with organic pollutants and pathogens. For instance, ozone micro-nanobubbles have been used to disinfect water, effectively inactivating bacteria without harmful residues (Jkunkeaw et al., 2021). Enhanced fertilization, where nanotechnology has led to the development of nano-fertilizers, which offer controlled nutrient release and improved uptake efficiency. These fertilizers can reduce the environmental impact of traditional fertilization methods and enhance crop yields (Mirbakhsh, 2023).

While nanoparticles offer substantial benefits, concerns about their long-term environmental

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impact and bioaccumulation must be addressed. Studies emphasize the need for comprehensive risk assessments and regulatory policies to ensure the safe deployment of these materials in agriculture (Hafez and Khalil, 2024). Green synthesis methods, such as mycosynthesis and plant-based nanoparticle production, provide eco-friendly alternatives that minimize toxicity (Chhipa, 2018).

Further research is needed to develop biodegradable nanoparticles to reduce environmental risks; improve safety regulations,create standardized guidelines, and enhance public awareness and acceptance of nano-enabled agriculture.

Conclusions

Nanoparticles present both promising applications and notable risks in agriculture. While their efficiency in enhancing plant growth, reducing chemical inputs, and improving soil health is well-documented, their long-term environmental and health effects require deeper exploration. Continued research and regulatory advancements will play a crucial role in ensuring the responsible use of nanotechnology in agriculture. Nano-fertilizers hold significant promise for advancing sustainable agriculture by enhancing nutrient efficiency and reducing environmental impacts. Ongoing research and development, coupled with the establishment of regulatory frameworks and cost-effective production methods, are crucial for the widespread adoption of this technology in modern farming practices. Nanopesticides represent a significant advancement in agricultural pest management, offering the potential for more effective and environmentally conscious solutions. While promising, it is imperative to conduct thorough research to fully understand their environmental interactions and to establish appropriate regulatory measures. This approach will ensure that the benefits of nanopesticides are realized without compromising ecological integrity. Nano-remediation holds substantial promise for enhancing environmental sustainability in agriculture by effectively addressing soil and water contamination. Ongoing research and development are essential to overcome current challenges, ensuring that the integration of nanotechnology into agricultural practices is both safe and beneficial. Nanoparticles and metal nanoparticles present transformative opportunities for sustainable agriculture by improving crop productivity, reducing environmental impact, and enhancing food security. However, further research is needed to optimize their application, minimize risks, and establish regulatory guidelines for their widespread adoption. The future of nanotechnology in agriculture lies in responsible innovation that balances productivity with ecological sustainability.

Conflicts of Interest

The authors declare no conflict of interest.

Ethical Statement

This article doesn't contain any studies that would require an ethical statement.

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References

Alazaiza, M. Y. D., Albahnasawi, A., Ali, G. A. M., Bashir, M. J. K., Copty, N. K., Amr, S. S. A., Abushammala, M. F. M., Al Maskari, T., Alazaiza, C., Albahnasawi, M. Y. D., Ali, A., Bashir, G. A. M., Copty, M. J. K., Amr, N. K., Abushammala, S. S. A., Al Maskari, M. F. M., Sergi, G. S., & Huang, C. P. (2021). Recent Advances of Nanoremediation Technologies for Soil and Groundwater Remediation: A Review. *Water*, 13, 2186. https://doi.org/10.3390/W13162186

Ali, S., Ahmad, N., Dar, M.A., Manan, S., Rani, A., Alghanem, S. M. S., Khan, K. A., Sethupathy, S., Elboughdiri, N., Mostafa, Y. S., Alamri, S. A., Hashem, M., Shahid, M., & Zhu, D. (2023). Nano-agrochemicals as substitutes for pesticides: prospects and risks. *Plants*, 13(1), 109. https://doi.org/10.3390/PLANTS13010109

Arora, N. K., Fatima, T., Mishra, I., Verma, M., Mishra, J., & Mishra, V. (2018). Environmental sustainability: challenges and viable solutions. *Environmental Sustainability*, 1(4), 309–340. https://doi.org/10.1007/S42398-018-00038-W

Aseel, D. G., Ibrahim, O. M., & Abdelkhalek, A. (2024). Biosynthesized silver nanoparticles mediated by Ammi visnaga extract enhanced systemic resistance and triggered multiple defense-related genes, including SbWRKY transcription factors, against tobacco mosaic virus infection. *BMC Plant Biology*, 24(1), 1–16. https://doi.org/10.1186/S12870-024-05449-Y/FIGURES/7

Awad, M., Ibrahim, E.D.S., Osman, E.I., Elmenofy, W.H., Mahmoud, A.W.M., Atia, M.A.M., & Moustafa, M. A. M. (2022). Nano-insecticides against the black cutworm Agrotis ipsilon (Lepidoptera: Noctuidae): Toxicity, development, enzyme activity, and DNA mutagenicity. *Plos One*, 17(2), e0254285. https://doi.org/10.1371/JOURNAL.PONE.0254285

Barrington-Leigh, C. (2016). *Sustainability* and well-being: A happy synergy. *Development*, 59(3–4), 292–298. https://doi.org/10.1057/S41301-017-0113-X/METRICS

Beig, B., Niazi, M. B. K., Sher, F., Jahan, Z., Malik, U. S., Khan, M. D., Américo-Pinheiro, J. H. P., & Vo, D. V. N. (2022). Nanotechnology-based controlled release of sustainable fertilizers. A review. *Environmental Chemistry Letters*, 20(4), 2709–2726. https://doi.org/10.1007/s10311-022-01409-w

Bhushan, I., Mehta, M., Sharma, M., Chopra, C., Chandra, R., Mohd Noor, I. S., Azhan Yahya, M. Z., Tripathi, A., & Yadav, A. K. (2024). Role of nanomaterials in modern agriculture. *Zastita Materijala*. https://doi.org/10.62638/ZASMAT1098

Burklew, C. E., Ashlock, J., Winfrey, W. B., & Zhang, B. (2012). Effects of aluminum oxide nanoparticles on the growth, development, and microrna expression of tobacco (*Nicotiana tabacum*). *Plos One*, 7(5), e34783. https://doi.org/10.1371/JOURNAL.PONE.0034783

Carrillo-Lopez, L. M., Villanueva-Verduzco, C., Villanueva-Sánchez, E., Fajardo-Franco, M. L., Aguilar-Tlatelpa, M., Ventura-Aguilar, R. I., & Soto-Hernández, R. M. (2024). *Nanomaterials* for plant disease diagnosis and treatment: A review. *Plants*, 13 (18), 2634. https://doi.org/10.3390/PLANTS13182634

Chaud, M., Souto, E. B., Zielinska, A., Severino, P., Batain, F., Oliveira-Junior, J., & Alves, T. (2021). Nanopesticides in agriculture: benefits and challenge in agricultural productivity, toxicological risks to human health and environment. *Toxics*, 9(6). https://doi.org/10.3390/TOXICS9060131

Chhipa, H. (2018). Mycosynthesis of nanoparticles for smart agricultural practice: A green and eco-friendly approach. In Shukla, A.K., Iravani, S. (Eds.), *Green Synthesis, Characterization and Applications of Nanoparticles*, 87–109. Elsevier. https://doi.org/10.1016/B978-0-08-102579-6.00005-8

Corsi, I., Winther-Nielsen, M., Sethi, R., Punta, C., Della Torre, C., Libralato, G., Lofrano, G., Sabatini, L., Aiello, M., Fiordi, L., Cinuzzi, F., Caneschi, A., Pellegrini, D., & Buttino, I. (2018). Ecofriendly nanotechnologies and nanomaterials for environmental applications: Key issue and consensus recommendations for sustainable and ecosafe nanoremediation. *Ecotoxicology and Environmental Safety*, 154, 237–244. https://doi.org/10.1016/J.ECOENV.2018.02.037

Das, A., Kamle, M., Bharti, A., & Kumar, P. (2019). Nanotechnology and it's applications in environmental remediation: an overview. *Vegetos*, 32(3), 227–237. https://doi.org/10.1007/S42535-019-00040-5

Deka, B., Babu, A., Baruah, C., & Barthakur, M. (2021). Nanopesticides: A systematic review of their prospects with special reference to tea pest management. *Frontiers in Nutrition*, 8, 686131.

https://doi.org/10.3389/FNUT.2021.686131/PDF

Dhanapal, A. R., Thiruvengadam, M., Vairavanathan, J., Venkidasamy, B., Easwaran, M., & Ghorbanpour, M. (2024). Nanotechnology Approaches for the Remediation of Agricultural Polluted Soils. *ACS Omega*, 9(12), 13522. https://doi.org/10.1021/ACSOMEGA.3C09776

Dimkpa, C. O. (2014). Can nanotechnology deliver the promised benefits without negatively impacting soil microbial life? *Journal of Basic Microbiology*, 54(9), 889–904. https://doi.org/10.1002/JOBM.201400298

Easwaran, C., Christopher, S.R., Moorthy, G., Mohan, P., Marimuthu, R., Koothan, V., & Nallusamy, S. (2024). Nano hybrid fertilizers: A review on the state of the art in sustainable agriculture. *The Science of the Total Environment*, 929. https://doi.org/10.1016/J.SCITOTENV.2024.172533

Ferrari, E., Barbero, F., Busquets-Fité, M., Franz-Wachtel, M., Köhler, H. R., Puntes, V., & Kemmerling, B. (2021). Growth-promoting gold nanoparticles decrease stress responses in arabidopsis seedlings. *Nanomaterials*, 11(12), 3161. https://doi.org/10.3390/NANO11123161/S1

Ganie, A. S., Bano, S., Khan, N., Sultana, S., Rehman, Z., Rahman, M. M., Sabir, S., Coulon, F., & Khan, M. Z. (2021). Nanoremediation technologies for sustainable remediation of contaminated environments: Recent advances and challenges. *Chemosphere*, 275, 130065. https://doi.org/10.1016/J.CHEMOSPHERE.2021.130065

Gao, M., Chang, J., Wang, Z., Zhang, H., & Wang, T. (2023). Advances in transport and toxicity of nanoparticles in plants. *Journal of Nanobiotechnology*, 21(1), 1–16. https://doi.org/10.1186/S12951-023-01830-5

García-Sánchez, S., Bernales, I., & Cristobal, S. (2015). Early response to nanoparticles in the *Arabidopsis* transcriptome compromises plant defence and root-hair development through salicylic acid signalling. *BMC Genomics*, 16(1), 1–17.
https://doi.org/10.1186/S12864-015-1530-4/FIGURES/9

Grillo, R., Fraceto, L. F., Amorim, M. J. B., Scott-Fordsmand, J. J., Schoonjans, R., & Chaudhry, Q. (2021). Ecotoxicological and regulatory aspects of environmental sustainability of nanopesticides. *Journal of Hazardous Materials*, 404, 124148. https://doi.org/10.1016/J.JHAZMAT.2020.124148

Guerra, F.D., Attia, M.F., Whitehead, D.C., & Alexis, F. (2018). Nanotechnology for environmental remediation: Materials and applications. *Molecules*, 23(7), 1760. https://doi.org/10.3390/MOLECULES23071760

Guha, T., Gopal, G., Mukherjee, A., & Kundu, R. (2022). Fe3O4-urea nanocomposites as a novel nitrogen fertilizer for improving nutrient utilization efficiency and reducing environmental pollution. *Environmental Pollution*, 292. https://doi.org/10.1016/j.envpol.2021.118301

Hafez, M., & Khalil, H. F. (2024). Nanoparticles in sustainable agriculture: recent advances, challenges, and future prospects. *Communications in Soil Science and Plant Analysis*, 55(14), 2181–2196. https://doi.org/10.1080/00103624.2024.2339950

Islam, R., Akteruzzaman, M., & Mazumder, M. M. R. (2023). A Review on Photocatalytic CO_2 Reduction using Nanomaterial. *ChemRxiv*. https://doi.org/10.26434/CHEMRXIV-2023-LWKDD

Jhunkeaw, C., Khongcharoen, N., Rungrueng, N., Sangpo, P., Panphut, W., Thapinta, A., Senapin, S., St-Hilaire, S., & Dong, H. T. (2021). Ozone nanobubble treatment in freshwater effectively reduced pathogenic fish bacteria and is safe for *Nile tilapia* (*Oreochromis niloticus*). *Aquaculture*, 534, 736286. https://doi.org/10.1016/J.AQUACULTURE.2020.736286

Kaningini, A. G., Nelwamondo, A. M., Azizi, S., Maaza, M., & Mohale, K. C. (2022). Metal nanoparticles in agriculture: A review of possible use. *Coatings*, 12(10). https://doi.org/10.3390/COATINGS12101586

Kannan, M., Bojan, N., Swaminathan, J., Zicarelli, G., Hemalatha, D., Zhang, Y., Ramesh, M., & Faggio, C. (2023). Nanopesticides in agricultural pest management and their environmental risks: a review. *International Journal of Environmental Science and Technology*, 20(9), 10507–10532. https://doi.org/10.1007/S13762-023-04795-Y

Khan, I., Awan, S.A., Rizwan, M., Akram, M. A., Zia-ur-Rehman, M., Wang, X., Zhang, X., & Huang, L. (2023). Physiological and transcriptome analyses demonstrate the silver nanoparticles mediated alleviation of salt stress in pearl millet (*Pennisetum glaucum* L). *Environmental Pollution*, 318, 120863. https://doi.org/10.1016/J.ENVPOL.2022.120863

Konwarh, R., & Sharma, P. L. (2020). Nanosensor platforms for surveillance of plant pathogens and phytometabolites/analytes vis-à-vis plant health status. *Nanomaterials for Agriculture and Forestry Applications*, 357–385. https://doi.org/10.1016/B978-0-12-817852-2.00014-7

Kumar, A., Gupta, K., Dixit, S., Mishra, K., & Srivastava, S. (2019). A review on positive and negative impacts of nanotechnology in agriculture. *International Journal of Environmental Science and Technology*, 16(4), 2175–2184. https://doi.org/10.1007/S13762-018-2119-7

Kumari, S., Chauhan, S., & Sachin Kumari, C. (2019). A review on applications of metal oxide Nanopaticles in agriculturee. *International Journal of Chemical Studies*, 7(4), 2143–2146. https://doi.org/10.1021/la800951v

Mahaletchumi, S. (2021). Review on the use of nanotechnology in fertilizers. *Journal of Research Technology and Engineering*, 2(1), 60–72.

Mahesha K. N., Singh, N. K., Amarshettiwar, S. B., Singh, G., Gulaiya, S., Das, H., & Kumar, J. (2023). Entering a new agricultural era through the impact of nano-fertilizers on crop development: A review. *International Journal of Plant & Soil Science*, 35(20), 94–102. https://doi.org/10.9734/ijpss/2023/v35i203789

Maity, D., Gupta, U., & Saha, S. (2022). Biosynthesized metal oxide nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management. *Nanoscale*, 14(38), 13950–13989. https://doi.org/10.1039/D2NR03944C

Mgadi, K., Ndaba, B., Roopnarain, A., Rama, H., & Adeleke, R. (2024). Nanoparticle applications in agriculture: overview and response of plant-associated microorganisms. *Frontiers in Microbiology*, 15, 1354440. https://doi.org/10.3389/FMICB.2024.1354440/PDF

Mirbakhsh, M. (2023). Role of nano-fertilizer in plants nutrient use efficiency (NUE) – A mini-review. *Journal of Genetic Engineering and Biotechnology Research*, 5(1), 75–81. https://doi.org/10.33140/JGEBR

Mishra, S., Keswani, C., Abhilash, P. C., Fraceto, L. F., & Singh, H. B. (2017). Integrated approach of Agri-Nanotechnology: Challenges and future trends. *Frontiers in Plant Science*, 8. https://doi.org/10.3389/FPLS.2017.00471/PDF

Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: recent advances and future outlook. *Frontiers in Nanotechnology*, 2, 579954. https://doi.org/10.3389/FNANO.2020.579954/PDF

Nongbet, A., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Ray, M. K., Khan, M., Baek, K. H., & Chakrabartty, I. (2022). Nanofertilizers: A smart and sustainable attribute to modern agriculture. *Plants*, 11(19). https://doi.org/10.3390/plants11192587

Patil, S. S., Shedbalkar, U. U., Truskewycz, A., Chopade, B. A., & Ball, A. S. (2016). Nanoparticles for environmental clean-up: A review of potential risks and emerging solutions. *Environmental Technology & Innovation*, 5, 10–21. https://doi.org/10.1016/J.ETI.2015.11.001

Poddar, K., Vijayan, J., Ray, S., & Adak, T. (2017). Nanotechnology for sustainable agriculture. biotechnology for sustainable agriculture. Singh, R.L., Mondal, S. Emerging Approaches and Strategies, 281–303. *Woodhead Publishing*. https://doi.org/10.1016/B978-0-12-812160-3.00010-6

Saurabh, K., Prakash, V., Dubey, A. K., Ghosh, S., Kumari, A., Sundaram, P. K., Jeet, P., Sarkar, B., Upadhyaya, A., Das, A., Kumar, S., Makarana, G., Kumar, U., Kumar, A., & Singh, R. R. (2024). Enhancing sustainability in agriculture with nanofertilizers. *Discover Applied Sciences*, 6(11), 1–23. https://doi.org/10.1007/S42452-024-06267-5

Shang, H., Ma, C., Li, C., White, J. C., Polubesova, T., Chefetz, B., & Xing, B. (2020). Copper sulfide nanoparticles suppress *Gibberella fujikuroi* infection in rice (*Oryza sativa* L.) by multiple mechanisms: contact-mortality, nutritional modulation and phytohormone regulation. *Environmental Science: Nano*, 7(9), 2632–2643. https://doi.org/10.1039/D0EN00535E

Shende, S., Rajput, V. D., Gade, A., Minkina, T., Fedorov, Y., Sushkova, S., Mandzhieva, S., Burachevskaya, M., & Boldyreva, V. (2022). Metal-based green synthesized nanoparticles: Boon for sustainable agriculture and food security. *IEEE Transactions on NanoBioscience*, 21(1), 44–54. https://doi.org/10.1109/TNB.2021.3089773

Shivashakarappa, K., Marriboina, S., Dumenyo, K., Taheri, A., Yadegari, Z., Ghosh, I., Roy, A. K., & Kumar Kamaraj, S. (2025). Nanoparticle-mediated gene delivery techniques in plant systems. *Frontiers in Nanotechnology*, 7, 1516180. https://doi.org/10.3389/FNANO.2025.1516180

Singh, R. P., Handa, R., & Manchanda, G. (2021). Nanoparticles in sustainable agriculture: An emerging opportunity. *Journal of Controlled Release*, 329, 1234–1248. https://doi.org/10.1016/j.jconrel.2020.10.051

Tiwari, M., Krishnamurthy, S., Shukla, D., Kiiskila, J., Jain, A., Datta, R., Sharma, N., & Sahi, S. V. (2016). Comparative transcriptome and proteome analysis to reveal the biosynthesis of gold nanoparticles in *Arabidopsis*. *Scientific Reports*, 6(1), 1–13. https://doi.org/10.1038/srep21733

Van Aken, B. (2015). Gene expression changes in plants and microorganisms exposed to nanomaterials. *Current Opinion in Biotechnology*, 33, 206–219. https://doi.org/10.1016/J.COPBIO.2015.03.005

Verma, S. K., Kumar, P., Mishra, A., Khare, R., & Singh, D. (2024). Green nanotechnology: illuminating the effects of bio-based nanoparticles on plant physiology. *Biotechnology for Sustainable Materials*, 1(1). https://doi.org/10.1186/s44316-024-00001-2

Wang, D., Saleh, N. B., Byro, A., Zepp, R., Sahle-Demessie, E., Luxton, T. P., Ho, K. T., Burgess, R. M., Flury, M., White, J. C., & Su, C. (2022). Nano-enabled pesticides for sustainable agriculture and global food security. *Nature Nanotechnology*, 17(4), 347–360. https://doi.org/10.1038 /s41565-022-01082-8

Xun, H., Ma, X., Chen, J., Yang, Z., Liu, B., Gao, X., Li, G., Yu, J., Wang, L., & Pang, J. (2017). Zinc oxide nanoparticle exposure triggers different gene expression patterns in maize shoots and roots. *Environmental Pollution*, 229, 479–488. https://doi.org/10.1016/J.ENVPOL.2017. 05.066

Yadav, A., Yadav, K., & Abd-Elsalam, K. A. (2023). Nanofertilizers: Types, delivery and advantages in agricultural sustainability. *Agrochemicals*, 2(2), 296–336. https://doi.org/10.3390/AGROCHEMICALS2020019

Yan, A., & Chen, Z. (2019). Impacts of silver nanoparticles on plants: A focus on the phytotoxicity and underlying mechanism. *International Journal of Molecular Sciences*, 20(5), 1003. https://doi.org/10.3390/IJMS20051003

Younas, M., Ul Azam, S., Farukh, S., Ullah, N., Ihsan, H., Mukhtar, H., & Rezakazemi, M. (2021). Metal-organic frameworks for carbon dioxide capture. *ACS Symposium Series*, 1393, 203–238. https://doi.org/10.1021/BK-2021-1393.CH009

Zainab, R., Hasnain, M., Ali, F., Abideen, Z., Siddiqui, Z. S., Jamil, F., Hussain, M., & Park, Y. K. (2024). Prospects and challenges of nanopesticides in advancing pest management for sustainable agricultural and environmental service. *Environmental Research*, 261, 119722. https://doi.org/10.1016/J.ENVRES.2024.119722

Zhao, L., Lu, L., Wang, A., Zhang, H., Huang, M., Wu, H., Xing, B., Wang, Z., & Ji, R. (2020). Nanobiotechnology in Agriculture: Use of *Nanomaterials* to Promote Plant Growth and Stress Tolerance. *Journal of Agricultural and Food Chemistry*, 68(7), 1935–1947. https://doi.org/10.1021/ACS.JAFC.9B06615