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NANOPARTICLE-BASED PREPARATIONS AS EFFECTIVE TOOLS TO IMPROVE THE SUSTAINABILITY OF CROP PRODUCTION

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SUMMARY

Nanoparticles (NPs) are multifunctional materials, and their utilization in sustainable agriculture is very promising. The NPs authenticate targeted delivery with their controlled release of agrochemicals that promote their gradual entry into the arable soil. The NPs contribute to reduced environmental impact, and their efficient use enhances absorption of essential macromolecules necessary for plant protection, growth, and physiological responses. Moreover, nanoparticles are highly reactive substances and could have risks associated with their toxic kinetic and toxic dynamic properties. The following review analyzed the potential of NPs in improving cropping systems sustainability and their effect on yield and adaptive traits, including those subjected to abiotic stress conditions, which highlights the advantages of nano-fertilizers and nano-pesticides. In addition, the conduct of an analysis determined the risks of their use. However, the NPs' utilization can improve crop efficiency and their production. The information presented in this review will be useful in the fields of general agriculture and plant growing.

Keywords: Nanoparticles, antimicrobial properties, nano-fertilizers, nano-pesticides, nano-safety

Key findings: The unique properties of nanoparticles open up entirely new opportunities for improving cropping systems sustainability, including improving seed quality. However, further advanced research is necessary to optimize protocols for obtaining their specified characteristics and long-term use.

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INTRODUCTION

Currently, nanotechnology has permeated all aspects of daily human life. In the field of agriculture, nanotechnology has demonstrated significant potential for enhancing the sustainability of cropping systems (Ahmed *et al.*, 2022). The primary objective of agriculture is to supply sufficient food for the increasing global population. At present, agriculture faces considerable challenges related to climate change, salinization, desertification, water scarcity, and drought stress conditions, which further enhance the risks of global food security and hunger worldwide (Adrees *et al.*, 2021).

Numerous studies revealed rapid population growth, coupled with declining soil fertility, further exacerbates these challenging issues. The environment's negative impacts, including the use of synthetic pesticides, are interrelated and represent significant risks to the sustainability of global agriculture and food security (Hano and Abbasi, 2022). In the field of crop production, nanoparticles have proven effective as nano-fertilizers, nano-pesticides, and nano-biosensors, including the detection of environmental stress factors and their better effective management (Hussain *et al.*, 2019; Yadav *et al.*, 2023). This is important because a significant proportion of arable land is under threat from climate change and increased levels of soil and groundwater contamination, posing risks to food security. (Faizan *et al.*, 2023).

Plant protection is one of the most pressing challenges in agriculture, and its resolution has close linkages with the application of metal nanoparticles. Diseases and pests pose a significant threat to crop yield and quality. The drawbacks associated with conventional pesticides include low efficacy and substantial environmental damage. The small size and high reactivity of nanoparticles contribute to their remarkable biocidal activity. The unique characteristics of nanoparticle transport within plants facilitate the optimization of their delivery and targeted release, thereby enhancing their effectiveness and minimizing adverse effects on ecosystems.

Consequently, research on the use of nanoparticles for plant protection has considerable practical significance. Various studies have demonstrated that nanoparticles (NPs) influence the growth, yield, and nutritional quality of fruits derived from agricultural plants. The results vary based on factors such as the type of nanoparticle, concentration, particle size, treatment method, duration of exposure to NPs, and the specific plant species involved (Wang *et al.*, 2023).

Therefore, the presented review aimed to analyze the potential applications of nanoparticles in crop production, as well as study their important economic and environmental roles in protecting different crop plants against phytopathogens, stress factors, and pesticides.

MATERIALS AND METHODS

Carrying out the review data search continued in the databases, such as Google Scholar, the American Chemical Society website (pubs.acs.org), and the website owned by Elsevier Publishing House (www.sciencedirect.com) for the last 10 years. This research work complied with the principles of academic integrity, properly quoting the used past research materials.

RESULTS AND DISCUSSION

The role of NPs in the agricultural sector

Currently, global agriculture faces several considerable challenges, including significant climate change, declining soil fertility, salinization, soil pollution, limited access to quality water resources, and the low efficiency of chemical pesticides and fertilizers. In addressing these issues, a significant scope for the right application of nanotechnology became a basis. This innovative technology has emerged as a valuable tool in agriculture to enhance the sustainability of crop plants and overall precision farming (Ernst *et al.*, 2023; Faizan *et al.*, 2023).

Agriculture is one of the primary sectors where nanotechnology's active employment is favorable, particularly because of its considerable potential for environmentally friendly application of pesticides and herbicides through various mechanisms such as delayed release, nanofertilizers, and nanosensors (Rizwan *et al.*, 2017; Yadav *et al.*, 2023). However, studies mentioned that despite its extensive application and growing popularity in agriculture, nanotechnology remains at its early stages of development (Yadav *et al.*, 2023). Although, in crop production, the promising potential of nanoparticles showed a link to addressing nutritional challenges and protecting plants from phytopathogens (Grillo *et al.*, 2021; Salam *et al.*, 2026). Therefore, the development of nanofertilizers able to enhance crop yields while remaining environmentally friendly is a specialized area of research (Yadav *et al.*, 2023).

According to Yadav *et al.* (2023), existing nanofertilizers can comprise several categories of three main groups. These are a) nanoscale fertilizers, which include synthesized nanoparticles, such as metal and metal oxide nanoparticles; b) nanoscale additives, including bulk products containing nanoscale additives; and c) nano coatings, referring to products coated with nano polymers. The agriculture sector is of paramount importance to humanity, as it is responsible for producing food and raw materials for various food industries. Agricultural sustainability primarily pertains to the adoption of environmentally friendly practices that enhance crop yields, reduce land degradation, promote efficient irrigation methods, and minimize the use of synthetic pesticides (Kah *et al.*, 2019; Bibi *et al.*, 2023).

In crop production, the promising potential of nanoparticles correlates with addressing nutritional challenges and protecting plants from phytopathogens (Zaki *et al.*, 2021). The NPs' specialized area of research is the development of nanofertilizers that could enhance crop yields while remaining environmentally friendly. Root growth and development reached stimulations, eventually improving the yield and its quality (Disfani *et al.*, 2017; Kah *et al.*, 2019). The use of nanoparticles to enhance plant physiological responses and improve plant productivity is now widespread (Tables 1 to 3).

Silicon nanoparticles (SiNPs) stimulate plant growth and development and mitigate damages caused by abiotic and biotic stresses in crop plants (Manzoor *et al.*, 2021). Ahmed *et al.'s* (2022) findings revealed the differences in the effects of various concentrations of metal NPs and metal oxides on seed germination and seedling growth of different plant species. Similarly, Rizwan *et al.* (2017) reported varied inhibitory effects of nickel (II) oxide (NiO), titanium dioxide (TiO_2), copper oxide (CuO), cobalt (II, III) oxide or tricobalt tetroxide (Co_3O_4), and iron (III) oxide (Fe_2O_3) nanoforms on seed germination of radish, cucumber, and lettuce. They considerably depend on the crop genotype and seed characteristics. Therefore, the positive effects of exogenous application of nanoparticles on the development of cultivated plants under abiotic stress are fascinating to the global community. Past studies also reported the positive effects of nanoparticles on the mitigation of water stress conditions in different crop plants (Al-Selwey *et al.*, 2023).

The exogenous application of zinc oxide (ZnO) and silicon dioxide (SiO_2) NPs significantly improved potato growth performance under water-deficit conditions (Al-Selwey *et al.*, 2023). Potato foliar feeding with ZnO-NPs and SiO_2-NPs under water deficit conditions resulted in combating the oxidative stress in potato plants through significant activation of antioxidant enzymes such as catalase, superoxide dismutase, ascorbate peroxidase, and polyphenol oxidase. As a result of this, the enhanced number of branches, plant height, biomass, and leaf area were remarkable, with the total flavonoid and phenolic compounds also increased. Therefore, the application of ZnO-NPs and SiO_2-NPs improved the plant's biochemical characteristics, resulting in increased plant tolerance and growth and development, productivity, and quality parameters of potatoes under water stress conditions (Al-Selwey *et al.*, 2023).

Table 1. Different types and dosages of nanoparticles and their effects on different plant species (cereal–legume crops).

Types of plants	Types of NPs	Concentrations of NPs	Effects on plants	Recommendations
Wheat (*Triticum aestivum*)	Si	0, 300, 600, 900, 1200 mg kg^{-1}	Increased plant biomass and yield	Hussain *et al.*, 2019
	ZnO	100 mg kg^{-1}	Improved plant biomass and photosynthesis efficiency	Adrees *et al.*, 2021
	FeO	100 mg kg^{-1}	Increased growth, nutrient content, antioxidant enzymes	Manzoor *et al.*, 2021
	Cu	100 mg kg^{-1}	Increased plant growth and nutrient content	Noman *et al.*, 2020
	Si	0–1200 mg kg^{-1}	Increased wheat growth	Ali *et al.*, 2019
	ZnO; Fe; Si	ZnO 25 mg/L; Fe 5 mg/L; Si 300 mg/L	Significant increase in chlorophyll content and yield	Hussain *et al.*, 2021
Corn (*Zea mays*)	Fe/SiO_2	15 and 5 mg kg^{-1}	Increased plant height and root length	Disfani *et al.*, 2017
Maize (*Zea mays* L.)	ZnO	0, 20, 50 mg kg^{-1}	Increased biomass and root formation	García-Gómez and Fernández, 2019
Maize (*Zea mays* L.)	TiO_2	100–250 mg/L	Increased plant height and biomass	Lian *et al.*, 2020
Rice (*Oryza sativa*)	MgO	50–200 mg/L	Improved growth of rice plants	Ahmed *et al.*, 2021
Soybean (*Glycine max L.*)	Fe_2O_3	15, 30, 60 mg/L	Increased chlorophyll content, biomass, and root development	Yang *et al.*, 2020
Vicia faba (*Vicia faba L.*)	Ag	10 mg kg^{-1}	Increased root and shoot growth; stimulated photosynthetic processes	Alhammad *et al.*, 2023
Beans (*Phaseolus vulgaris* L.)	$ZnSO_4$	250 mg/L	Increased plant height and biomass	Salehi *et al.*, 2021

Table 2. Different types and dosages of nanoparticles and their effects on different plant species (Solanaceae, oilseed crops).

Types of plants	Types of NPs	Concentrations of NPs	Effects on plants	Recommendations
Chinese pepper (*Capsicum chinense*)	ZnO	1000 and 2000 mg/L	Stimulation of growth and yield	Garcia-Lopez *et al.*, 2019
Tomato (*Solanum lycopersicum*)	FeO	100 mg/L	Significant increase in chlorophyll and carotenoids	Brasili *et al.*, 2020
Tomato (*Solanum lycopersicum*)	TiO_2; ZnO	100–250 mg kg^{-1}	Increased plant height, root length, biomass, and yield	Raliya *et al.*, 2015
Tomato (*Solanum lycopersicum*)	ZnO	50–500 mg/L	Increased productivity and product quality	Lopez-Vargas *et al.*, 2018
Potato (*Solanum tuberosum*)	ZnO; SiO_2	ZnO 100 mg/L, SiO_2 50 mg/L	Increased number of branches, plant height, biomass, and leaf area	Al-Selwey *et al.*, 2023
Sunflower (*Helianthus annuus* L.)	ZnO; Au; SiO_2	ZnO 15.99 mg/L; Au 0.1 mg/L; SiO_2 10 mg/L	Increased productivity and quality	Ernst *et al.*, 2023
Sunflower (*Helianthus annuus* L.)	ZnO; TiO_2	2.6 mg/L	Increased plant height; earlier maturation; increased oil content	Kolenčík *et al.*, 2019

Table 3. Different types and dosages of nanoparticles and their effects on different plant species (essential oil and woody crops).

Types of plants	Types of NPs	Concentrations of NPs	Effects on plants	Recommendations
Cochin grass (*Cymbopogon flexuosus*)	Si	150 mg/L	Increased plant height, leaf area, and yield	Mukarram *et al.*, 2021; Brasili *et al.*, 2021
Coriander (*Coriandrum sativum* L.)	Cu	1.5 mM	Improved plant biomass and reduced oxidative stress	Fatemi *et al.*, 2021
Vetiver grass (*Vetiveria zizanioides* L.)	SiO_2; TiO_2; ZnO	50 mg/L	Increased growth rate, physiological traits and essential oil biosynthesis	Ahmed *et al.*, 2022
Wheel wingnut (*Cyclocarya paliurus*)	SiO_2; MnO_2	SiO_2 500 mg/L; MnO_2 50 mg/L	Increased height and biomass; increased photosynthesis	Zhang *et al.*, 2024
Mulberry (*Morus alba* L.)	Fe_2O_3	10 mg kg^{-1}	Increased germination, leaf count, biomass, and root development	Haydar *et al.*, 2021
Wheel wingnut (*Cyclocarya paliurus*)	SiO_2; MnO_2	SiO_2 500 mg/L; MnO_2 50 mg/L	Increased height and biomass; increased photosynthesis	Zhang *et al.*, 2024

The highest specific surface area combined with different types of intermolecular interactions is one of the most crucial advantages of nanomaterials, opening new opportunities for NPs utilization in various adsorption systems (Yadav *et al*., 2023). For soil remediation and groundwater purification, we greatly hope to use nanoparticles. Soil is the basis of agriculture and, therefore, food, and approximately 90% of humanity's food succeeded in their production in soils. According to previous studies, improvement in plant growth and development with nanoparticles precisely occurs because of the reduced toxicity of HMs (Yadav *et al.,* 2023). Recently, notable advances have progressed in using nanotechnology for managing plant pathogens' strategies (Bibi *et al.,* 2023). There has been much interest in the use of nanoparticles to improve the efficacy of common pesticides by increasing the duration of pesticide release.

Several studies have confirmed the effectiveness of metal nanoparticles as substitutes for synthetic pesticides for controlling phytopathogenic microorganisms (Bibi *et al.* 2023; Yadav *et al.,* 2023). Moreover, NPs seed treatment and foliar application of plant pathogens are the most common strategy for suppressing pathogens more effectively than chemical pesticides (Yadav *et al.* 2023). Zaki *et al.'s* (2021) investigations revealed the use of ZnONPs in addition to two chemical fungicides (Maxim XL and Moncut) considerably increased the fungicidal activity of the preparations against common soil pathogens such as *Fusarium* sp., *Macrophomina phaseolina,* and *Rhizoctonia solani*.

Nanoparticles have greater potential in controlling plant diseases and suppressing pathogens due to pronounced antimicrobial properties; however, they can also serve as fungicide carriers (Khan *et al.*, 2019). Their studies exhibited that, compared with conventional pesticides, nanoparticles emerged as highly effective in controlling plant pathogens at a much lower dose. The NPs can also act as carriers of hormones, pesticides, pheromones, and host defense substances that inhibit the development of plant pathogens, such as phytopathogenic fungi, bacteria, nematodes, and viruses. El-Shetehy *et al.'s* (2021) findings enunciated that SiO_2 NPs can serve as a low-cost, highly effective, safe, and sustainable alternative for protecting plants against various diseases. Bibi *et al.* (2023) reported the effectiveness of AgNPs in suppressing harmful *Erwinia carotovora* subsp. *atroseptica* and *Ralstonia solanacearum* bacteria on potato and tomato plants. Fouda *et al.'s* (2020) findings showed the antimicrobial activity of Ag-NP against four phytopathogenic fungi (*Alternaria alternata, Fusarium oxysporum, Pythium ultimum,* and *Aspergillus niger*). Hossain *et al*.'s (2019) investigations also revealed the efficacy of AgNPs against *Dickeya dadantii*, a bacterium causing stem and root rot in sweet potato. Yadav *et al.* (2023) reported that magnesium oxide (MgO) and manganese dioxide (MnO_2) nanoparticles derived from chamomile flower extracts proved effective against *A. oryzae*, a bacterium that causes brown streaks in rice.

These current inventions could also benefit the agri-food sector as a new way to achieve greater precision and sustainability (Kah *et al.,* 2019). For example, the novel nanotechnology-based formulations can provide precise tools for controlled release of active ingredients (AIs) from pesticides and fertilizers, nanoscale material for seed treatment, and nanosensors for monitoring pathogens, diseases, and environmental conditions in the field (Bibi *et al.*, 2023). However, the term 'nanopesticide,' becoming widely used, often referred to controlled-release systems that take the form of nanoscale encapsulated active ingredients in nanocarriers (Grillo *et al.*, 2021).

Nanopesticides and nanofertilizers helped solve various agro-production problems to overcome abiotic factors that negatively affect soil and water environments and achieve greater sustainability (Adrees *et al.*, 2021; Zhang *et al.*, 2024). Grillo *et al.* (2021) concluded nanoscale formulations enhance the efficacy of agrochemicals, such as pesticides, which decreases their use worldwide. Kah *et al.* (2019) studied the efficiency of different pesticides concerning the efficiency of nano-pesticides and reported the efficiency of nano-pesticides was 20%–30% greater than the same ingredients prepared conventionally. The advantages of nanoparticle action over conventional formulations have been evident for various herbicides, fungicides, nematicides, insecticides, acaricides, and bactericides (Grillo *et al.*, 2021).

The NPs' application is not only for in vivo conditions; several studies reported positive results for the NPs' application in the fight against microbial contaminants of plant cultures in vitro. They have also demonstrated the positive role of NPs in the induction of organogenesis, callusogenesis, somatic embryogenesis, genetic transformation, and production of secondary metabolites (Kim *et al.*, 2017). The positive influence of NPs on crop production has led to increasing research interest and investment in this area worldwide. A growing number of patents revealed greater potential for growth in this field in the near future. However, previous studies mentioned that more in-depth research is essential to identify potential risks (Rajput *et al.*, 2020).

Possible risks

In the agriculture and food industries, nanoparticles have raised greater interest about public safety concerns. The large surface area of nanopesticides and their small particle size may cause unintended ecotoxicological effects because of their interaction with the target and non-target species and existing environments (Grillo *et al.*, 2021). Agricultural land is a major source of nanoparticles used in the cultivation of crop plants (Rajput *et al.*, 2020). Once the application of nanoparticle agents seeped into arable fields, the NPs interacted with various environmental components and induced dynamic transformation processes, revealing themselves to be interconnected with multiple environmental aspects (Ahmed *et al.*, 2022). Moreover, soil organisms appeared non-confrontational with primary nanoparticles used for cultivation; rather, with their successors, the transformed nanoparticles materialized after their interaction with the environment (Hano and Abbasi, 2022). In this context, the toxicity assessment of nanoparticles to aquatic and terrestrial organisms should proceed, including the processes of their transformation in the natural environment.

The knowledge about the interaction of nanoparticles with soil particles is vital for understanding their fate in the soil microenvironment and identifying strategies for their utilization (Rajput *et al.*, 2020). Past studies enunciated that metal nanoparticles are typical to have toxic effects on plant growth and development (Adrees *et al.*, 2021). Toxicity determination can be from several intrinsic factors, such as shape, size, reactivity, effective doses, and surface characteristics, as well as environmental factors, form of application, age, and plant species (Gao *et al.*, 2023). Additionally, important concerns exist about the future fate of nanoparticles (Salehi *et al.*, 2021).

Application of metal nanoparticles to crop plants contributes to an increase in the concentration of nanoparticles in different parts of various crop plants, including fruits, which could enter human food and harm health (Rizwan *et al.*, 2017). The existing problems associated with the use of nanoparticles require analysis of their potential toxicity in agriculture, including their accumulation in foodstuffs and feed, which may cause them to enter the food chain. Therefore, it is particularly essential to investigate the conditions under which their ability to produce free radicals increases, causing possible oxidative stress in living organisms.

In the global community, a greater concern prevails about the NPs toxicological effects. The NPs are highly reactive substances that easily cross membrane barriers and capillaries, leading to the development of toxicokinetic and toxicodynamic properties. Furthermore, some NPs can bind to proteins and enzymes and stimulate ROS formation and oxidative stress. ROS accumulation can also lead to mitochondrial degeneration and apoptosis (Gao *et al.*, 2023). Thus, nanoparticles released into the environment inevitably have some degree of toxicological effects on different organisms at the molecular and physiological levels (Rajput *et al.*, 2020).

The toxicokinetic risks caused by nanoparticles mainly exhibit a relationship with their persistence and insolubility. Over time, the configuration, chemical, and physical characteristics of nanoparticles undergo transformation, resulting in different bioavailability and routes of action (Hano and Abbasi, 2022). Therefore, the risk assessment also requires additional research on the safety of specific nanoparticle dosages concerning hazardous risks (Rajput *et al.*, 2020). Rizwan *et al.* (2017) reported that metal and metal oxide nanoparticles cause oxidative stress and genotoxicity in crops. According to this past research, the intensity of the negative impact directly depends on the plant species, growth stage, growth conditions, method, dose, and duration of exposure to NPs.

By studying the factors and mechanisms involved in nanoparticle phytotoxicity, the timely research identified the potential detoxification strategies that can be beneficial to minimize the nanoparticle toxicity in different crop plants. Among these are the application of phytohormones, antioxidants, surface modifications, and ohmic approaches. These rely on the analysis of various biochemical, morphophysiological, and metabolic responses of plants. Toxicological testing is critical because the crop products must undergo evaluation for safety before they can succeed in marketing as food products. The effects of metal nanoparticles on living objects have shown that exposure has a pronounced dose-dependent effect, and the level of exposure also depends on the type and size of the nanoparticles and the organism species (Rizwan *et al.*, 2017).

CONCLUSIONS

In agriculture, nanotechnology has demonstrated greater potential in promoting the sustainability of farming systems. However, numerous studies have confirmed that NPs have several negative effects on living organisms, such as DNA damage, membrane integrity disruption, and cell uptake disruption. In this regard, to reduce the risks of phytotoxicity of nanoparticles, it is critical to use detoxification strategies that can be effective to minimize or reduce the toxicity of nanoparticles to plants. These will rely on the use of phytohormones, antioxidants, surface modification, and ohmic approaches. The latter will depend on the analysis of various biochemical, morphophysiological, and metabolic reactions. In improving the effectiveness of safety strategies, proposing analysis based on molecular methods, such as transcriptomics, next-generation sequencing (NGS), molecular markers, and ecotoxicity bioassays, is crucial. This will identify biomarkers as new reference parameters for assessing the impact of nanoparticles on the life of organisms. In ensuring nanosafety for humans and the environment, humanity faces important challenges in updating international toxicity assessment standards and nanotechnology regulatory frameworks.

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