

Review

Nanoparticles for Sustainable Agriculture: Assessment of Benefits and Risks

Mohammed Bouhadi ¹, Qaiser Javed ¹, Monika Jakubus ², M'hammed Elkouali ³, Hassan Fougrach ⁴, Ayesha Ansar ⁵, Smiljana Goreta Ban ¹, Dean Ban ¹, David Heath ⁶ and Marko Černe ^{1,*}

¹ Institute of Agriculture and Tourism, Karla Huguesa 8, 52440 Poreč, Croatia; mohammed@iptpo.hr (M.B.); qaiser@iptpo.hr (Q.J.); smilja@iptpo.hr (S.G.B.); dean@iptpo.hr (D.B.)

² Department of Soil Science and Microbiology, Poznan University of Life Sciences, ul. Szydlowska 50, 60-656 Poznań, Poland; monika.jakubus@up.poznan.pl

³ Laboratory of Analytical and Molecular Chemistry, Faculty of Sciences Ben M'sick, Hassan II University of Casablanca, BP 7955, Casablanca 20660, Morocco; m.elkouali.fsbm@gmail.com

⁴ Laboratory of Ecology and Environment, Faculty of Sciences Ben M'sick, Hassan II University of Casablanca, BP 7955, Casablanca 20660, Morocco; hafougrach@gmail.com

⁵ School of Management, Jiangsu University, Zhenjiang 212013, China; ayeshaansar888@gmail.com

⁶ Jožef Stefan Institute, Jamova Cesta 39, 1000 Ljubljana, Slovenia; david.heath@ijs.si

* Correspondence: marko@iptpo.hr; Tel.: +385-52-408-332; Fax: +385-52-431-659

Abstract: Nanotechnology is rapidly emerging as a transformative force in agriculture, offering innovative solutions to support sustainable crop production. This review examines the interactions between nanoparticles (NPs) and plants, elucidating the underlying mechanisms that govern NP uptake, translocation, and interactions at the cellular level. We explore how NPs influence key physiological processes and modulate plant defense responses to both biotic and abiotic stresses, highlighting their potential for enhancing stress resistance. The diverse applications of NPs in agriculture are also comprehensively surveyed, encompassing targeted delivery of nutrients, enhanced biocontrol of phytopathogens, and engineering improved tolerance to environmental extremes. We also address the broader environmental and socioeconomic implications of the widespread use of NPs in agriculture, critically evaluating their ecotoxicity, impacts on biodiversity, and the associated economic costs and benefits. Finally, we offer a perspective on future directions for research, including emerging trends in NPs synthesis and characterization, challenges to sustainable implementation, and the prospects for large-scale deployment of nanotechnology-enabled agricultural solutions. This review provides a rigorous and balanced assessment of the potential of nanotechnology to revolutionize agricultural practices while acknowledging the need for responsible innovation and risk mitigation.

Keywords: environmental impact; nanoparticles; plant growth; stress tolerance; sustainable agriculture



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1. Introduction

Abiotic stresses, including drought, low temperatures, salinity and excess water (Excess runoff), alongside biotic stresses such as bacteria, viruses, fungi, parasites, insect pests and weeds, represent major constraints on agricultural productivity worldwide. These environmental stresses induce physiological responses in plants that can alter their growth and development. Abiotic stresses are responsible for an estimated 20–50% loss in agricultural yield each year worldwide [1]. Drought alone can reduce cereal yields by 50% or more [2]. When stressed, plants implement elaborate defense mechanisms

that often involve the production of signaling molecules, such as abscisic acid (ABA) [3]. Plants can also modulate their metabolic pathways and gene expression, synthesizing protective compounds that enhance stress tolerance. These modifications can have long-term consequences for both the plant and the ecosystem. In the case of abiotic stresses, this can result in reduced growth, altered photosynthesis, hormonal disruption, increased susceptibility to pathogens, and loss of product quality [4]. Several strategies have been explored to address these challenges, including varietal selection, biotechnology (genetic engineering, genome editing), biostimulants, nanotechnology, and precision agronomy [5].

Among these emerging approaches, nanotechnology, especially nanoparticles, holds significant promise due to its versatility, scalability, and potential to enhance plant performance under stress conditions.

As the global population rises, demand for food increases, and with it, there is an urgency to ensure food safety and sustainable production. In this context, the use of nanoparticles in agricultural systems seems increasingly justified. As one of the most important sectors of a country's economy, agriculture faces many challenges, including the need to produce biomass for food, feed and fiber while maintaining soil health and following sustainable agriculture principles. Attaining this balance is especially challenging with climate change, intensive land use, and continual degradation of the environment, all of which lead to reductions in soil productivity and long-term ecosystem stability.

Nanotechnology offers many solutions for enhancing crop resilience to abiotic and biotic stresses and ensuring long-term food security [5,6]. Nanotechnology involves manipulating, studying, and applying matter on an atomic, molecular, and supramolecular scale, typically at dimensions between 1 and 100 nanometers [7]. At this scale, materials like nanoparticles have unique physicochemical properties that distinguish them from macroscopic materials. This nanometric dimension increases their specific surface area, increasing their reactivity and environmental interactions [8]. In addition, quantum size effects, such as electronic energy quantization and surface plasmon resonance, give nanoparticles unique optical, electrical, and magnetic properties, opening up unprecedented prospects in agriculture [9]. Usually, metallic nanoparticles exhibit vibrant optical properties primarily due to surface plasmon resonance (SPR), a phenomenon where incident light causes collective oscillations of their surface electrons [10]. This resonance leads to strong absorption and scattering of specific wavelengths of light, highly dependent on the nanoparticle's size, shape, material, and surrounding environment [11]. This extreme sensitivity to their surroundings makes SPR invaluable for developing nanosensors that can detect minute changes in agricultural environments, such as the presence of pathogens or changes in nutrient levels [12]. Furthermore, the enhanced electromagnetic fields associated with SPR can be utilized for targeted delivery of agrochemicals and for advanced imaging techniques to monitor plant health at a cellular level [13].

Nanoparticle synthesis is the subject of intensive research. Synthesis methods vary, and the choice of method depends on the type of nanoparticle and its final application. They can be produced from solid materials using physical techniques, including mechanical grinding and laser ablation [14], although chemical methods, such as precipitation, chemical reduction or sol-gel, offer greater control over their composition and morphology [15]. In addition, biological methods involving bacteria or fungi can be used to produce nanoparticles more ecologically and with specific properties such as controlled size, specific surface functionalization, enhanced biocompatibility, and targeted catalytic or biological activities [16].

The interest in the agricultural application of nanoparticles is driven by their potential to improve crop productivity and quality by interacting with plants and soil at a molecular level.

Nanoparticles can address many of the current agricultural challenges, such as improving plant growth, yield, and resilience to pathogens by acting as fertilizers or targeted nutrient delivery systems [17,18]. Their unique physicochemical properties, such as high surface area and reactivity, facilitate enhanced biomass production, improved nutritional quality, and increased disease resistance. Recent studies have highlighted their ability to optimize nutrient use efficiency, enable the controlled release of agrochemicals, and support the precise application of bioactive compounds, thereby minimizing over-fertilization and pesticide use through their high surface area, small size, and tunable properties that enable targeted delivery, controlled release, and enhanced interaction with plants and their environment [19,20]. They can also contribute to soil restoration and sustainability by decontaminating polluted soils, refining key physicochemical properties, enhancing soil structure, improving water retention and nutrient availability, and supporting beneficial microbial communities [21,22].

Within plants, the introduction of nanoparticles can lead to interactions with fundamental biomolecules, including proteins, nucleic acids (DNA and RNA), and lipids, which may result in altered biological activities [23]. Notably, these interactions can extend to the regulation of gene expression. By engaging with DNA or RNA, nanoparticles can influence genes associated with critical pathways governing growth, development, and responses to environmental stresses [24]. Furthermore, Zou et al.'s [25] transcriptomic analysis demonstrated that low silver nanoparticle (AgNP) concentrations likely enhance stress resistance and induce stress memory in rose seedlings by activating ROS signaling pathways, which in turn leads to the upregulation of genes within crucial metabolic pathways (riboflavin, peroxisome, glutathione, cysteine/methionine metabolism) and key transcription factor families (WRKY, TIFY, bHLH). In addition, Omar et al. [26] showed that titanium dioxide nanoparticles (nTiO₂) can mitigate the negative impacts of salinity stress in broad bean plants by enhancing growth, reducing oxidative damage and genetic instability, and upregulating protective antioxidant and heat shock protein genes. On the other hand, Mokhtarabadi et al. [27] revealed that, while low concentrations of nanoscale red elemental selenium (nSe) enhanced the fresh weight of chicory seedlings, high concentrations proved toxic. Their biosafety assessment further indicated distinct epigenetic responses to nSe compared to selenate, identifying DNA hypomethylation as a key mechanism, with the DREB1A gene's activity increasing alongside nSe levels. Additionally, the researchers found that nSe upregulated genes involved in phenylpropanoid synthesis (PAL, HQT, HCT), increased proline content, and stimulated the accumulation of beneficial phenylpropanoids such as caffeic, chlorogenic, and cichoric acids, as well as antioxidants like ascorbate and glutathione. Their large surface area also boosts nutrient uptake by adsorbing and delivering nutrients to plant roots, improving assimilation [28]. Moreover, nanoparticles can also be used to create diagnostic tools for early disease detection and plant growth monitoring [29] and to strengthen plant defenses by activating resistance mechanisms against pathogens, abiotic stresses, and disease [5,30].

While the potential of nanoparticles to revolutionize agriculture is evident, their widespread adoption necessitates a thorough understanding of the intricate interplay between their mechanisms of action in plants, diverse agricultural applications, and the potential environmental and socioeconomic ramifications, particularly concerning toxicity, regulation, and cost. Moving beyond a descriptive overview of these areas, this comprehensive review, synthesizing findings from over 200 scientific publications, critically examines the current evidence to identify key knowledge gaps and conflicting findings that hinder the development of sustainable and responsible nano-agricultural practices. By highlighting these critical junctures, we aim to propose a future research agenda that prioritizes interdisciplinary approaches and addresses the most pressing uncertainties,

ultimately paving the way for the translation of promising nanotechnologies into viable and safe agricultural solutions.

2. Mechanisms of Nanoparticle Action on Plants

2.1. Nanoparticles: Cellular Interactions and Physiological Effects in Plants

Due to their small size, nanoparticles can be taken up by plants through roots, leaves, or other pathways and subsequently translocated via the vascular systems [31,32]. Their effects vary depending on many factors, such as the nature of the nanoparticle, dose, duration of exposure and environmental conditions [33]. For example, they can stimulate growth by increasing nutrient availability or inhibit growth by causing cell damage [34]. In addition, they can cause oxidative stress, interact with biomolecules, and disrupt cellular signals [35,36]. However, a key challenge in nanoparticle research is separating the effects attributed to their nanoscale size from those caused by the material. For instance, metal and metal oxide NP dissolution, influenced by the specific metal's properties, significantly impacts their biological activity, both positive and negative [37–40] (Figure 1).

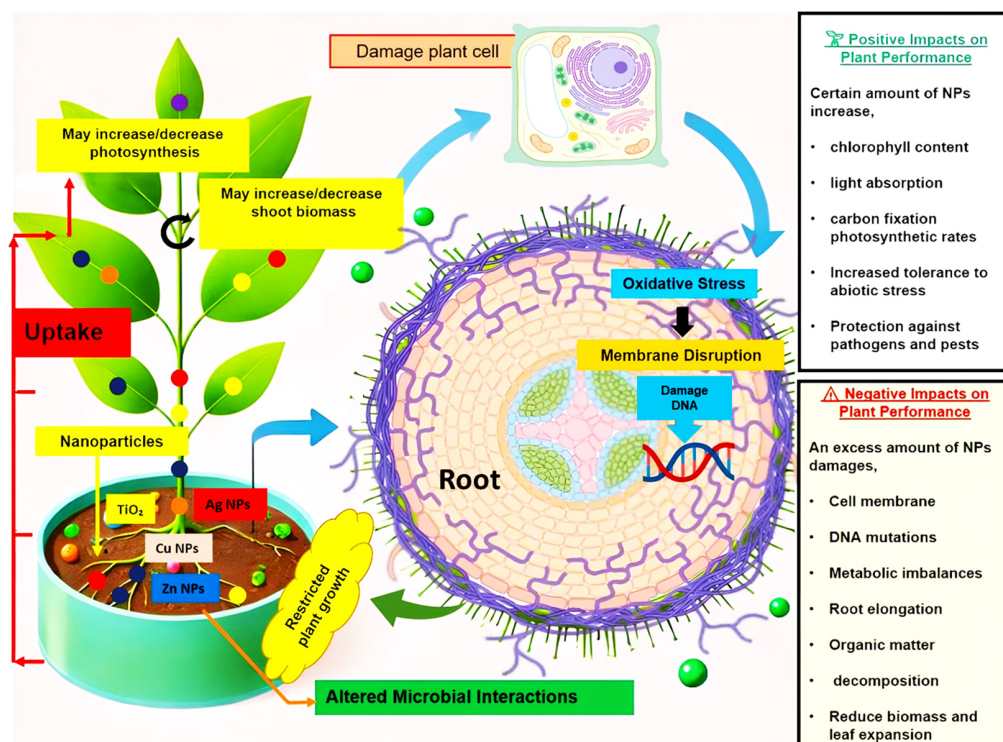


Figure 1. Nanoparticle-plant interactions: uptake, translocation, oxidative stress, cellular and physiological responses of plants to nanoparticles exposure: positive and negative impacts.

Nanoparticles enter plant cells through various mechanisms, including endocytosis and passive diffusion [41]. For instance, highly charged nanoparticles can passively penetrate plant cell membranes and chloroplast envelopes, potentially via disruption of the lipid bilayer, though the cell wall and nanoparticle coatings add complexity to this process [42]. Once inside, they can interact with cellular components such as membranes, organelles (mitochondria, chloroplasts), and DNA [43]. Extensively studied nanoparticles, including Ag NPs, Au NPs, TiO_2 NPs, ZnO NPs, SiO_2 NPs, CuO NPs, and CaCO_3 NPs, can trigger rapid molecular interactions in plants, leading to a dual response involving both ROS protection and induction of oxidative stress that subsequently activates the plant's antioxidant defense system. This ultimately enables plants to more effectively adjust to stressful environmental conditions and enhance overall productivity by mitigating abiotic stress and influencing a

range of their morphological, anatomical, physiological, biochemical, and molecular characteristics [44]. Mahakham et al. [45] demonstrated how soaking rice seeds in 10 or 20 mg/L of silver nanoparticles (Ag NPs) for 24 h significantly enhanced germination and seedling growth. This effect was attributed to increased water uptake, the upregulation of aquaporin genes (PIP1;1 and PIP2;1), and elevated amylase, dehydrogenase, and catalase activity.

In addition, Manickavasagam et al. [46] observed that treating rice (*Oryza sativa*) callus grown with 1-Ag NPs at 5 and 10 mg/L significantly enhanced callus regeneration. This positive effect was correlated with a reduction in oxidative stress markers, including hydrogen peroxide (H₂O₂), malondialdehyde (MDA), and proline levels. Furthermore, the researchers reported a down-regulation of genes involved in the plant's hormonal responses, specifically those related to ethylene, abscisic acid, auxins, cytokinins, and gibberellic acid [39].

Likewise, Rostami et al. [47] reported that foliar application of zinc oxide nanoparticles (ZnO NP) at concentrations of 2–9 g/L increased saffron flower yield, chlorophyll content, water retention, protein levels, and antioxidant enzyme activity (POX and CAT). Similarly, Shabbir et al. [48] demonstrated that foliar application of TiO₂ nanoparticles on *Vetiveria zizanioides* significantly enhanced biomass growth, essential oil and khusimol production, chlorophyll content, photosystem II efficiency, and the activity of nitrate reductase and carbonic anhydrase. In addition, Hassanpouraghdam et al. [49] revealed that the foliar treatment with CeO₂:SA-nanoparticles alleviated the side effects of salinity by improving the physiological responses and growth-related traits of purslane plants (*Portulaca oleracea* L.). Furthermore, foliar treatment with silver, copper, and copper–silver nanoparticles at various concentrations enhanced the growth and productivity of chili plant, leading to increased plant height and number of fruits compared to the untreated control groups [50].

In contrast, high concentrations of TiO₂, ZnO, and Ag NPs can generate oxidative stress, disrupt cellular metabolism, and even damage DNA [51–53]. Studies have shown that copper oxide NPs (CuO-NPs) cause oxidative DNA lesions and growth suppression in various agricultural and grassland plants (radish, perennial ryegrass, and annual ryegrass) [54]. Similarly, high concentrations of ZnO-NPs also act as genotoxic agents, leading to DNA damage. Such damage occurs as membrane integrity loss, increased chromosome aberrations, and DNA strand breaks in onion root cells (*Allium cepa*) [55]. Furthermore, ZnO-NPs have been shown to induce reactive oxygen species (ROS) production in broad bean (*Vicia faba*) and tobacco (*Nicotiana tabacum*), which in turn also contribute to DNA damage and strand breaks [56–58].

Nanoparticle interactions can trigger a range of physiological effects. For instance, Yoon et al. [59] demonstrated that 500 mg/kg of 54 nm Fe-NPs in *Arabidopsis thaliana* soil increased plant biomass, carbohydrate, and phosphorus levels by enhancing photosynthesis due to increased stomatal opening and improved phosphorus availability via reduced rhizosphere pH. In addition, ref. [60] demonstrated that soaking rice seeds (cv. Gobindabhog) in 20 mg/L of Fe-NPs for three days significantly enhanced seedling growth. According to the same study, this result was achieved by improving water content, increasing the activity of hydrolytic and antioxidant enzymes, improving cell membrane integrity and viability, and raising chlorophyll and iron levels. Moreover, Raliya et al. [61] demonstrated that foliar application of 10 mg/L of zinc oxide nanoparticles (ZnO NPs) on mung bean plants significantly enhanced growth (longer stems, larger root volume), nutrient uptake (increased phosphorus accumulation via stimulated phosphatase and phytase activity), photosynthetic capacity (higher chlorophyll and protein levels), and beneficial rhizospheric microbial populations. In addition, applying iron nanoparticles (Fe NPs) at 25 mg/kg significantly enhanced wheat growth in both normal and salt-affected soils, increasing the

dry weights of roots, shoots, and grains more substantially in the salt-affected soil than in the normal soil, and outperformed other iron sources like FeSO₄ and Fe-EDTA [62]. Moreover, Fe nanoparticles can boost the response to oxidative stress through biochemical pathways and improve plant growth by promoting seed germination and root growth [63]. Feigl [64] show that CuO NPs can positively influence plant growth and development by enhancing photosynthesis, nutrient uptake, and root growth at appropriate levels; however, high concentrations can have detrimental effects, causing oxidative stress and cell damage that lead to reduced growth and yield.

In contrast, high concentrations of NPs can be harmful to plants. While both silver (Ag) and titanium dioxide nanoparticles (TiO₂ NPs) induce increased reactive oxygen species (ROS), a common marker of toxicity, AgNPs have paradoxically been observed to stimulate growth in certain plant species [65]. TiO₂ NPs caused oxidative stress and DNA oxidative damage in BEAS-2B cells, as demonstrated by [51]. Oxidative stress, mediated by reactive oxygen species (ROS) production, is a key factor in cellular damage [66–68]. These highly reactive molecules target and damage vital cellular constituents such as lipids, proteins, and DNA, impairing essential cellular functions [69–72]. Moreover, silver nanoparticles (AgNPs) can bind to proteins and enzymes essential for cellular respiration, reducing metabolic efficiency [73].

2.2. Modulation of Plant Defense Responses by Nanoparticles

Nanoparticle interactions with plants can significantly enhance their defense mechanisms by stimulating the production of defense-related molecules (Table 1), such as phenolic compounds and defense proteins, thereby increasing tolerance and resistance to pathogens and insect herbivores [27,74]. Specifically, Silica nanoparticles (SiNPs) enhance plant disease resistance through multiple mechanisms. Firstly, they strengthen cell walls, providing a physical barrier against pathogen invasion [75]. Secondly, SiNPs activate plant signaling pathways, initiating a cascade of defense responses [76]. Furthermore, nanoparticle-mediated priming is observed. For instance, ZnONPs can induce a state of heightened preparedness in plants, pre-activating defense mechanisms against future pathogen attacks [77]. In addition, the study by Mohammadi et al. [78] revealed that Fe-0 nanoparticles (35–45 nm, 8–14 m²/g) alleviate hexavalent chromium (Cr (VI)) stress in sunflower plants through a dual mechanism: immobilization of Cr within the soil and upregulation of antioxidant enzyme activity (superoxide dismutase, peroxidase, catalase, and ascorbate peroxidase). Furthermore, seed priming with 25 ppm of zinc oxide nanoparticles ZnO NPs effectively alleviates drought stress in rice plants by reducing oxidative damage, enhancing antioxidant enzyme activity and proline levels [79]. Additionally, priming tomato seeds with 75 ppm selenium nanoparticles (SeNPs) enhances drought tolerance by lowering oxidative stress, boosting antioxidant defense mechanisms and the ascorbate–glutathione cycle, and increasing the accumulation of beneficial bioactive compounds [80]. Similarly, under drought stress, canola seed nano-priming with 75 ppm CaONPs significantly enhanced plant performance by improving germination (30%), seedling fresh weight (34%), leaf number (16%), total chlorophyll (28.9%), pod and seed production (up to 73%), 100 seed weight (35.13%), and overall yield (35.18%), likely due to improved antioxidant enzyme activity and reduced stress indicators [81].

However, under different conditions, such as high concentrations or prolonged exposure, NPs may impair these defenses, and excessive ROS production induced by NPs can disrupt signaling pathways or damage cellular components, potentially leading to cell death and growth inhibition [82].

Furthermore, engineered nanomaterials (ENMs) have attracted considerable attention in the field of agriculture, especially nanopesticides and nanofertilizers aimed at boosting

agricultural sustainability and productivity [83,84]. Similarly, Li et al. [85] demonstrated that exposing wheat plants to molybdenum (Mo) engineered nanomaterials (ENMs) leads to significant Mo uptake by the roots and its subsequent translocation to the leaves. While copper-based ENMs offer protection against fungi and other pests, they can elicit stress responses and metabolic adaptations, particularly in the early stages of exposure. In addition, Fatemi et al. [86] demonstrated that foliar application of 1.5 mM ENM silicon nanoparticles (SiNPs) to *Coriandrum sativum* under salt stress mitigated the negative effects by enhancing the antioxidant defense system (increased SOD, CAT, POD activity), and reducing oxidative stress markers like MDA and H₂O₂. Similarly, Umair Hassan et al. [87] noted that priming *Sorghum bicolor* seeds with ZnNPs under salt stress improved shoot and root length, significantly decreased the Na⁺/K⁺ ratio (indicating better ion homeostasis), and mitigated oxidative stress, leading to enhanced growth and stress tolerance. Fouda et al. [88] showed that foliar application of CuNPs (20 mg/L) on *Trigonella foenum-graecum* L. under salt stress improved plant growth and biomass, promoted the production of plant pigments, osmolytes, anthocyanin, shikimic acid, and phenols, and upregulated antioxidant enzyme activity, suggesting a positive role in mitigating salt stress and enhancing bioactive compound production.

Table 1. Potential effects of NPs on the modulation of plant defense responses.

Plant	NPs Nature	Potential Effects	Reference
Saffron (<i>Crocus sativus</i>)	ZnO NPs	Increasing POX (peroxidase) and CAT (catalase) activity	[47]
Wheat (<i>Triticum aestivum</i>)	ZnO NPs	lowering oxidative stress (higher activity of SOD (superoxide dismutase) and POD (peroxidase))	[89]
Soybean (<i>Glycine max</i>)	ZnO NPs	Higher activities of SOD, CAT, POD, and APX enzymes.	[90]
Rice (<i>Oryza sativa</i>) callus	Ag NPs	Decreasing levels of H ₂ O ₂	[46]
Spinach (<i>Spinacia oleracea</i>)	TiO ₂ NPs	Increasing activity of SOD, CAT, APX, and guaiacol peroxidase. Decreased level of superoxide radicals, H ₂ O ₂	[91]
Maize (<i>Zea mays</i> L.)	TiO ₂ NPs	Activation of SOD (superoxide dismutase) and glutathione S-transferase (GST)	[92]
Rice (<i>Oryza sativa</i>)	TiO ₂ , Si NPs	Lowering oxidative stress (increasing activity of CAT, POD, and APX)	[93]
(<i>Oryza sativa</i> cv. Gobindabhog L.)	Fe-0 NPs	Increasing the activity of SOD, CAT and glutathione peroxidase,	[60]
Evening primrose (<i>Oenothera biennis</i>)	Fe ₂ O ₃ NPs	Increasing the activity of CAT, SOD, and POD	[94]
<i>Brassica napus</i> L.	γ-Fe ₂ O ₃ NP	Decreasing the level of H ₂ O ₂	[95]
Sunflower (<i>Helianthus annuus</i>)	Fe ⁰ NPs	Increasing the activity of antioxidant enzymes superoxide dismutase, peroxidase, catalase and ascorbate peroxidase	[78]
Wheat (<i>Triticum aestivum</i>)			[96]
Maize (<i>Zea mays</i>)			[97]
<i>Arabidopsis thaliana</i> L.	CeO ₂ NPs	Scavenging of hydroxyl radicals, superoxide anions, and H ₂ O ₂ in chloroplasts	[98]

3. Applications of Nanoparticles in Agriculture

Nanoparticles offer many potential agricultural uses, including crop growth, production, processing, storage, packaging, and transportation [99]. A key challenge in plant production is maintaining abundant available nutrients and effective plant protection against pests and diseases, typically achieved using fertilizers and pesticides, such as herbicides, insecticides, and fungicides. This approach, although widely used by farmers, unfortunately, when used intensively, often leads to environmental degradation, soil and water pollution and diminishing soil quality due to inefficient nutrient uptake by plants, leading to nutrient loss [100]. Nanofertilizers and nanopesticides can enhance plant nutrient and pesticide delivery [101,102]. Moreover, nanosensors facilitate the early detection of plant diseases and pests, enabling timely intervention and yield protection [103]. Furthermore, nanoparticles can improve soil health by enhancing water retention and nutrient availability [104].

3.1. Improving Growth, Development of Plant Nutrition

The unique role of NPs in agriculture is emphasized in crop protection and fertilization, improving precision farming and stress tolerance. Mai et al. [105] found that irrigating red oak, chestnut oak, and red maple seedlings with $\text{Mn}(\text{OH})_2$ NPs increased seedling size and nitrogen/phosphorus uptake over a period of 12 weeks.

In addition, NPs are considered a good transport tool that can ultimately be used for fertilizers, pesticides, synthetic hormones or genetic material. [21]. They can also promote plant productivity by increasing tolerance to adverse conditions such as abiotic stress and unfavorable environmental conditions (e.g., salinity, heavy metals, Figure 2, Table 2).

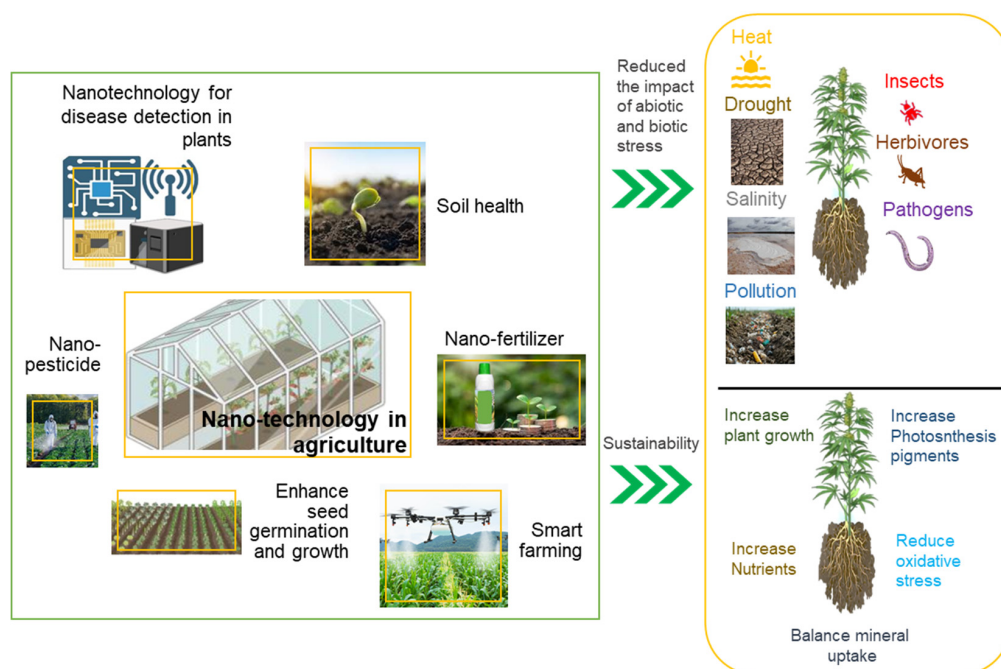


Figure 2. Schematic representation of nanotechnology in agriculture: enhancing plant growth, mitigating abiotic (drought) and biotic (pests, pathogens) stressors, and promoting sustainability through nano-enabled solutions (nano-fertilizers, nano-pesticides, nanosensors).

Nanofertilizers, as described by Yadav et al. [106], include metal or metal oxide nanoparticles (e.g., FeO , ZnO) and organic compounds such as chitosan and humic acid. The authors outline the various production methods and delivery systems for commercial nanofertilizers, including encapsulation, coating, and blending with organic, inorganic, or

polymeric materials. Extending this concept of targeted nutrient delivery, the application of titanium, potentially in nano-formulations, has also demonstrated significant improvements in plant physiological parameters [46]. Studies have shown that titanium fertilization enhances nitrate reductase enzymatic activity, chlorophyll and carotenoid concentrations, photosynthetic rate, symbiotic nitrogen fixation, and the uptake of essential elements like iron and magnesium [107,108]. Incorporating titanium into nanofertilizer delivery systems could offer a promising avenue for optimizing plant nutrition and enhancing productivity. In addition, Dinler et al. [109] study reveals that priming *Carthamus tinctorius* L. (safflower) seeds with 200 ppm ENM TiO₂ nanoparticles positively impacts radicle length and plumula fresh weight by boosting the conversion of inorganic nitrogen into protein and chlorophyll structures, likely through the regulation of nitrate reductase, glutamine synthase, glutamate dehydrogenase, and glutamic-pyruvic transaminase enzymatic activity. Under salinity stress, Gohari et al. [110] research indicates that irrigating *Dracocephalum moldavica* with 100 mg/L titanium nanoparticles (Ti NPs) increased plant height, enhanced nutrient uptake, and boosted antioxidant enzyme activities.

Silica nanoparticles have been shown to exhibit pesticidal properties, while mesoporous Si-NPs can serve as nanocarriers for the controlled release of commercial pesticides and fertilizers [111]. Additionally, Si-NPs and nano-zeolites can enhance the soil's water-holding capacity by improving porosity and moisture retention.

In Garg et al.'s [99] opinion, smart nano-sensors can enhance productivity by improving fertilization management, reducing input costs, and protecting the environment when combined with precision farming. Thanks to nanosensors, the detection of plant pathogens and nutrient deficiency in soil will be possible. Moreover, precision farming based on nanosensors allows the sustainable use of natural resources without damaging them, while meeting the principles of safe food production.

Based on their functionality, nanofertilizers can be classified into three types: nanocomposite fertilizers, controlled-release fertilizers, and hybrid nano-devices designed to deliver both macro- and micronutrients [112]. Rehmanullah et al. [113] also categorize nanoparticles (NPs) used in fertilizers as derived from macronutrients, micronutrients, and NPs that enhance fertilizer performance. Irrespective of their classification, nanofertilizers outperform conventional fertilizers due to their reduced toxicity and enhanced efficiency in nutrient delivery [114].

Jiang et al. [112] also list the many benefits of using nanofertilizers, such as a slow release mechanism, reduction in transportation and application cost, low salt accumulation compared to conventional fertilizers, and improved nutrient bioavailability to meet crop demands efficiently. They also offer advantages over conventional fertilizers, including enhanced nutrient uptake, nutrient use efficiency, improved crop nutritional quality, root biomass development, microbial regulation of the rhizosphere, and higher yields [115]. Their properties allow for more precise delivery and controlled release, reducing the overall application rate and increasing cost and time savings [22]. They also help reduce eutrophication by minimizing nutrient runoff [21]. Additionally, nanoparticles are beneficial in promoting seed germination and early plant development [115].

When addressing nutrient uptake, another factor to consider is mitigating nutrient competition, specifically through weed control. Here, nanoparticles can contribute by enhancing herbicide efficacy via NP-mediated transport and delivery. Kusumavathi et al. [116] show how nano-herbicides can control weeds using inorganic, organic, and hybrid compounds. According to the authors cited, nanoherbicides offer more precise and less environmentally harmful solutions for agricultural weed control. The affinity for the target can be increased by providing a larger specific surface area, potentially lowering the required dosages and minimizing adverse effects on non-target organisms and soil

health. Encapsulation of nano-herbicides also increases the uniformity of application, avoiding adverse effects on crop plants such as phytotoxicity, yield reduction, environmental contamination, and harm to beneficial organisms [112].

Table 2. Potential beneficial effects of NPs on plant growth, physiology, and nutrition.

Plant	NPs Nature	Potential Effects	Reference
Rice (<i>Oryza sativa</i>)	Ag NPs	Increasing water uptake into the seeds. Up-regulation of aquaporin genes	[45]
<i>Arabidopsis thaliana</i>		Increasing the rate of evapotranspiration	[117]
Common bean (<i>Phaseolus vulgaris</i>)		Increasing the concentration of indole-3acetic acid (IAA), gibberellin GA3 and total cytokinins	[118]
Two orchids (<i>Lilium</i> cv. Mona Lisa and cv. Little John)		Increasing the chlorophyll and carotenoid content, potassium, calcium, and sulfur content	[119]
Wheat (<i>Triticum aestivum</i> , variety Galaxy-2013)	TiO ₂ NPs	Stimulating activity of microorganisms in rhizosphere, increased phosphorus content in shoots	[120]
Tobacco (<i>Nicotiana benthamiana</i>)		Significant increases in plant biomass	[121]
Rice (<i>Oryza sativa</i>)		higher levels of chlorophyll and carotenoids, higher transpiration rate	[122]
Maize (<i>Zea mays</i> L.)		Increasing glycine, serine and threonine accumulation and promoted energy metabolism (citrate and galactose cycle)	[123]
<i>Vetiveria zizanioides</i>		Increasing chlorophyll content and photochemical efficiency of photosystem II, increased activity of nitrate reductase and carbonic anhydrase	[48]
Sorghum (<i>Sorghum bicolor</i> var. 251)	ZnO NPs	Increasing uptake of zinc, boron and copper into plants, increased chlorophyll content	[124]
Saffron (<i>Crocus sativus</i>)		Increasing content of chlorophyll, relative water content, soluble protein content,	[47]
Lemon balm (<i>Melissa officinalis</i>) seedlings		Increasing accumulation of potassium, iron and zinc, increased activity of nitrate reductase.	[125]
Foxtail millet (<i>Setaria italica</i>)		Increasing oil and nitrogen content in grains	[126]
Wheat (<i>Triticum aestivum</i>)		increasing zinc content in grains,	[127]
<i>Arabidopsis thaliana</i>	Fe NPs	Increasing photosynthesis rate, assimilation rate, intracellular CO ₂ concentration, transpiration rate, and stomatal conductance) as consequence of increased stomatal opening. Decreased pH in rhizosphere resulting increased P availability	[59]
Wheat (<i>Triticum aestivum</i>)		Increasing root length, plant height, biomass growth and chlorophyll content	[128]
Muskmelon (<i>Cucumis melo</i>)		NPs served as a source of Fe supporting chlorophyll synthesis	[129]
Rice (<i>Oryza sativa</i>)		Higher water content, higher activity of hydrolytic enzymes amylase and protease	[60]

Table 2. Cont.

Plant	NPs Nature	Potential Effects	Reference
Lettuce (<i>Lactuca sativa</i>)	TiO ₂ and Fe ₃ O ₄	Increasing P uptake	[130]
Soybean (<i>Glycine max</i>)	CeO ₂ NPs	Increasing stomatal conductance, enhanced photosynthesis rate, increased Rubisco activity, increased NADPH regeneration rate and synthesis of ribulose-1,5-bisphosphate	[131]
Jalapeño pepper (<i>Capsicum annuum</i>)	Mn NPs	Source of manganese as micronutrient	[132]

3.2. Protecting Plants Against Pathogens

The use of silica, zinc oxide, iron oxide, titanium dioxide, silver, and copper nanoparticles presents a promising strategy for enhancing crop yield and addressing global food security. SiO₂ NPs have been investigated for their potential to provide controlled nano-delivery of Si and other beneficial compounds to plants. Moradi et al. [133] demonstrated that low concentrations of SiO₂ NPs effectively protect the model plant *Arabidopsis* against *Pseudomonas* infection. This protective effect is achieved by activating salicylic acid (SA)-dependent plant immunity. The mechanism involves a dual approach: the gradual release of Si (OH)₄ from the NPs within the plant tissue, following stomatal uptake and distribution through the spongy mesophyll, and potentially, direct NP-induced SA responses. Furthermore, nanoparticle carriers can minimize environmental contamination by delivering smaller amounts of active molecules. Moreover, AgNPs and CuNPs exhibit inherent antimicrobial properties, disrupting pathogen cell walls or membranes and producing ROS with toxic effects. In addition, ref. [74] found that Cu-NPs, with EC₅₀ values ranging from 162 to 310 µg/mL, were the most effective in inhibiting fungal growth compared to ZnO-NPs (EC₅₀ 235–848 µg/mL), silver, and CuO-NPs, demonstrating higher potency than bulk metal counterparts and a standard copper hydroxide fungicide, especially against spores, and silver nanoparticles completely inhibited gray mold symptoms on plum fruit, suggesting their potential as protective antifungal agents. A wide range of NPs, including metal oxides (e.g., ZnO, TiO₂, NiO, MgO, Fe₃O₄, CuO, CeO₂, Ag₂O, Au₂O₃, Al₂O₃), metalloids (e.g., B, Si), non-metals (e.g., fullerenes, graphene oxide), and other nanomaterials (e.g., quantum dots, liposomes), have been explored for their potential in plant pathology [134,135]. As previously mentioned, TiO₂ NPs can trigger a plant immune system, producing defense-related enzymes and proteins [136]. Nanoparticles can also act as carriers for fungicides, bactericides, and other antimicrobial agents, delivering them directly to the site of infection [137,138].

3.3. Increasing Plant Tolerance to Abiotic Stresses

Nanoparticles (NPs) offer a promising approach to enhancing plant tolerance against various abiotic stresses, including salinity, drought, and heavy metals toxicity [34]. Under saline conditions, NPs like Ag, Cu, ZnO, CeO, and Fe₃O₄ have positively affected various plant species. Furthermore, Ag NPs improved germination and seedling growth in *Lathyrus sativus* and basil [139,140], enhanced salt tolerance in wheat (through altered antioxidant enzyme activity) [141], *S. hortensis* [142], and cumin, and reduced salt-stress effects [143]. In addition, Cu NPs reduced oxidative stress and increased yield in wheat [144]. Likewise, ZnO NPs increased sunflower dry weight [145], while CeO NPs enhanced physiological responses in *B. napus* and boosted biomass in canola [146]. Moreover, ref. [147] demonstrated that soaking lupine (*Lupinus termis*) seeds in ZnO NPs at 20, 40, and 60 mg/L

for 12 h enhanced seedling growth under normal conditions and effectively mitigated the negative impacts of 150 mM NaCl salt stress.

Specifically, ZnO NP treatment, compared to salt-stressed controls, resulted in increased levels of photosynthetic pigments, organic solutes, total phenols, ascorbic acid, and zinc, along with elevated activities of antioxidant enzymes (SOD, CAT, POD, APX), and decreased levels of malondialdehyde and sodium. For drought stress, NPs like analcite, ZnO, Cu, Zn, SiO₂, TiO₂, and Si have demonstrated beneficial effects. Analcite NPs promoted germination and growth in wheat, while ZnO NPs increased soybean germination [148,149]. Additionally, Cu and Zn NPs enhanced wheat's antioxidant enzyme activity and relative moisture content [150]. Moreover, SiO₂ NPs increased shoot length and relative water content in barley, while TiO₂ NPs mitigated yield reduction in wheat [150,151].

Silicon NPs, although reported to reduce photosynthesis and stomatal conductivity in hawthorn [152], have also been shown to ameliorate drought stress effects in bananas [153], coriander [154], chickpeas [155], and rice (especially when combined with Se-NPs) [156]. Furthermore, they can reduce the negative impact of drought-enhanced Cd stress in wheat when used with ZnO NPs [157]. In addition, Mohasseli et al. [158] found that irrigating lemon balm (*Melissa officinalis*) with 40 nm iron oxide nanoparticles (Fe₂O₃ NPs) at concentrations of 5, 10, 20, 30, and 40 µM alleviated oxidative stress induced by drought by increased essential oil content, restored chlorophyll levels, and decreased proline, malondialdehyde (MDA), and hydrogen peroxide (H₂O₂) levels in drought-stressed plants. Similarly, ref. [95] demonstrated that irrigating *Brassica napus* with γ-Fe₂O₃ NP at concentrations of 0.5, 0.8, 1, or 2 mg/mL effectively alleviated drought stress, leading to increased chlorophyll content, enhanced plant growth, and a reduction in H₂O₂ levels.

Regarding heavy metal stress, NPs can reduce heavy metal concentration in soil, regulate the transfer of genes, increase antioxidant activity, and stimulate the production of protective substances. Si NPs reduced As stress effects in maize [159], while TiO₂ NPs mitigated Cd toxicity in *Zea mays* [92]. Similarly, SiO₂ NPs increased antioxidant enzyme activity in pea seedlings under Cr stress, reduced Cr toxicity by reducing Cr accumulation and oxidative stress, and upregulated the antioxidant defense system and nutrient elements [160]. Konate et al. [96] showed that Fe₃O₄ NPs significantly improved wheat (*Triticum aestivum*) seedling growth under heavy metal stress. A 2000 mg/L aqueous suspension of the NPs reduced heavy metal uptake (cadmium, zinc, lead, copper), enhanced antioxidant enzyme activity (peroxidase, SOD), and limited oxidative damage (decreased MDA). In addition, Se NPs alleviated Cd stress in Chinese cabbage [161], and Si NPs reduced Cd stress in rice [162]. Previous studies showed that combined applications of ZnO NPs with biochar and Fe NPs with biochar proved effective against Cd stress. It has also been shown that iron oxide NPs reduce Cd content and improve antioxidant enzyme activity in wheat [34]. Similarly, the foliar application of Fe NPs, particularly Fe₃O₄, reduced Cd accumulation and toxicity in tomato plants [163]. In addition, data from Ullah et al. [164] showed that the application of ZnO, Fe₂O₃, TiO₂, and CeO₂ NPs to rice (*Oryza sativa* L.) effectively reduced cold stress damage by improving plant defense mechanisms, in particular by regulating antioxidant enzyme activity, as well as significantly enhancing plant development and chlorophyll production. Similarly, Song et al. [165] found that spraying ZnO nanoparticles on the leaves of rice seedlings significantly reduced the negative effects of cold stress. This was evident in taller plants, longer roots, and increased overall dry weight. Additionally, the ZnO nanoparticles helped the plants maintain their chlorophyll levels and lessened the oxidative damage caused by the cold, as shown by lower amounts of harmful substances (H₂O₂, MDA, proline) and increased activity of protective enzymes (SOD, CAT, POD) [165]. The study of Djanaguiraman et al. [166] demonstrated that foliar application of Se-NPs enhanced the antioxidant defense system of sorghum

[*Sorghum bicolor* (L.) Moench], improved pollen germination, and significantly increased seed yield under high-temperature conditions.

4. Environmental Aspects of Nanoparticles

4.1. Environmental Toxicity of Nanoparticles (NPs)

The environmental toxicity of NPs is a concern, primarily due to their persistence, bioaccumulation potential, and interaction with biological systems at the cellular level [167–169]. Nanoparticles in pesticides, fertilizers, and soil amendments are directly applied to ecosystems (Figure 3), leading to contamination [170,171]. Soil parameters are also important factors. For example, soil pH plays a critical role in the availability and toxicity of Al and Mn. In acidic soils ($\text{pH} < 5$), Al (Al^{3+}) becomes soluble and poses a significant threat to plant health [172,173]. Al toxicity primarily inhibits root cell division, leading to stunted, swollen, and damaged roots with impaired water uptake [174]. While Al toxicity is well documented, studies indicate the potential stimulatory effects of Al_2O_3 NPs on plant growth. Similarly, Mn availability is also highly dependent on soil conditions. Manganese deficiency is prevalent in dry, well-aerated, and calcareous soils and those rich in organic matter. Conversely, Mn toxicity is more common in poorly drained and acidic soils [175].

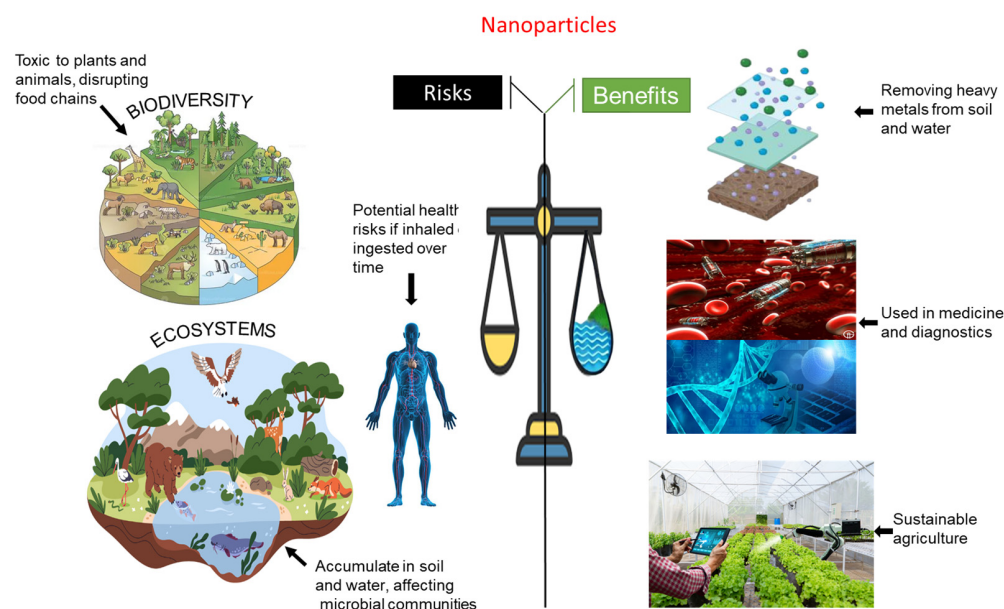


Figure 3. A comparative overview of nanoparticle risks (ecosystem disruption, human health) and benefits (heavy metal removal, medicine, sustainable agriculture).

Metal oxide nanoparticles (e.g., TiO_2 , ZnO , AgNPs) have been shown to disrupt essential soil microbial communities [176–178]. Soil microorganisms play a crucial role in vital processes such as nitrogen fixation [179], organic matter decomposition [180], and carbon cycling [181], all of which are fundamental for maintaining soil fertility and healthy ecosystems. NPs accumulation in soil can disrupt critical ecological functions [182], impaired nutrient cycling [183], and consequently, diminished soil fertility and carbon sequestration capacity [184,185]. In turn, this may contribute indirectly to climate change by altering carbon storage processes in the soil [186]. Additionally, the high reactivity of nanoparticles can lead to phytotoxicity [187].

Excessive NPs accumulation in the soil can also cause adverse effects on plant growth (Table 3), including stunted root and shoot development, reduced seed germination rates, and chlorosis (yellowing of leaves) [188]. These symptoms indicate the stress plants

experience due to nanoparticle exposure, which can interfere with essential metabolic processes such as photosynthesis [189,190]. The disruption of plant growth not only impairs agricultural productivity but also poses significant challenges to the sustainability of agricultural systems, especially in regions where soil health is already compromised by factors like erosion, salinization, or nutrient depletion [191].

Airborne nanoparticles, including carbon-based materials and metal oxides, reduce air quality and settle onto vegetation and water bodies, introducing contaminants into terrestrial and aquatic systems [192]. This deposition exacerbates environmental pollution and ecological imbalances. By altering beneficial plant microbial communities' structure, composition, and diversity, nanoparticles can negatively impact the plant–soil–microbe system, contrasting with the enhanced microbial activity and nutrient cycling fostered by a healthy soil structure [193,194].

However, the widespread use of nanoparticles necessitates implementing strategies to mitigate their adverse environmental impacts [195,196]. Also, biological and eco-friendly nanoparticle synthesis methods can significantly reduce their environmental footprint [197], while developing biodegradable nanoparticles that break down into non-toxic components offers a promising solution to prevent their long-term persistence in the environment [198]. Within the past decade, substantial research efforts have focused on the synthesis of nanoparticles utilizing a spectrum of biological sources, including plant extracts [199,200], actinomycetes [201], bacteria [201], fungi [202], and basidiomycetes [202]. These biogenically synthesized nanoparticles exhibit distinctive characteristics, rendering them suitable for a broad array of applications encompassing catalysis, biosensing, bio-labeling, tissue engineering, electronics, agriculture [203], optical devices, and environmental remediation [204–206].

Table 3. Certain potential adverse effects of NPs on plant growth and physiology.

Plant	NPs Type	Effects	Reference
Wheat (<i>Triticum aestivum</i> L.) Sorghum (<i>Sorghum bicolor</i> L. Moench) Garden cress (<i>Lepidium sativum</i> L.) Mustard (<i>Sinapis alba</i> L.)	AgNPs	Germination inhibition Inhibition of root and shoot growth Disintegration of cell membranes	[207]
Wheat (<i>Triticum aestivum</i> L.)	Ag NPs	Growth suppression and changes in cell division and structure	[208]
<i>Camelina sativa</i> L	Ag NPs	Affecting the seedling growth and photosynthetic pigments.	[209]
Cucumber (<i>Cucumis sativus</i> L.).	SiO ₂ /ZnO NPs	Upregulated or downregulated the contents of sugars, amino acids, glycosides and organic acids, and secondary metabolites	[210]
<i>Glycine max</i>	ZnO/TiO ₂ NPs	Alteration of primary and secondary metabolites levels regulate the stress level in plant	[211]
<i>A. thaliana</i> seedlings	Yttrium oxide (Y ₂ O ₃) NPs	Reduced the lignin synthesis-related gene expression, and increased abscisic acid and ethylene signaling pathway	[212]
Duckweed (<i>Lemna minor</i> L.)	CeO ₂ NPs	Hindered the root elongation	[213]
Bean crop (<i>Phaseolus vulgaris</i> L.)	CeO ₂ NPs	Chromosome abnormality and malformations in pollen grains and defects in pollen walls	[214]

Table 3. Cont.

Plant	NPs Type	Effects	Reference
Rice (<i>Oryza sativa</i> L.)	CuO NPs	Damaging the enzymes by the accumulation of excess Cu and ROS induced oxidative damage	[215]
Pepper (<i>Capsicum annuum</i> L.)	Cu NPs	Enhanced lipid peroxidation level and H ₂ O ₂ content, thus implying oxidative stress and potentially causing impairment in plasma membrane integrity	[216]
		Reduced the expression of the Mevalonate kinase (MVK) gene involved in terpenoid metabolism, which limits photosynthesis and decreases energy production efficiency, thereby leading to reduced transcription	

4.2. Potential Impact of Nanoparticles on Biodiversity

Nanoparticles can positively or negatively impact plant biodiversity and are directly linked to agricultural practices. Their potential to improve stress tolerance, nutrient supply and pest control could increase crop yields and reduce chemical inputs, indirectly promoting biodiversity by reducing the need for extensive land use. However, the risks of nanoparticle toxicity, soil disturbance, and bioaccumulation pose a direct threat to plant biodiversity, which could compromise the long-term sustainability of agriculture. NPs can harm ecosystems by impacting microorganisms and higher-order species [217]. NPs such as Ag, TiO₂, and ZnO possess antimicrobial properties, which can disrupt the balance of microbial communities in both soil and aquatic environments [218].

Furthermore, NPs can alter the structure and function of microbial biofilms, which are essential for maintaining ecological balance in aquatic systems [219]. High concentrations of NPs, such as CeO₂ and CuO, can impair plant growth by inhibiting seed germination, reducing root elongation, and decreasing photosynthetic efficiency [219]. These effects reverberate throughout the food web, influencing herbivores and other species dependent on plants [220]. Soil-dwelling organisms, including earthworms and nematodes, are also sensitive to NPs [221]. Exposure to these particles can alter their population dynamics and behavior, affecting processes like soil aeration, organic matter turnover, and overall plant productivity [222].

Previous studies indicate that nanoparticle exposure can significantly impact plant development. Vannini et al. [223] demonstrated that silver nanoparticles reduce shoot and root length, decrease biomass, and alter metabolic and defense protein expression in wheat. Similarly, [224] observed that Ag NPs lead to reduced root elongation, shoot and root fresh weights, decreased chlorophyll and carotenoid content, and increased rice's ROS production. Mccracken et al. [225] reported that zinc (Zn) and copper nanoparticles negatively affect wheat, resulting in reduced root and shoot length, decreased biomass and chlorophyll, and increased antioxidant enzyme activity. Furthermore, Rif et al. [226] found that TiO₂ nanoparticles in maize cause delayed seed germination, reduced root length, decreased mitotic index, and increased chromosomal aberrations. Considering the fundamental role of plant health in maintaining biodiversity and ensuring sustainable agricultural practices, these nanoparticle-induced disruptions pose a significant concern. Reduced plant vigor and reproductive success, as evidenced by decreased biomass, chlorophyll content, and increased cellular stress, can negatively impact crop yields and the overall resilience of agricultural ecosystems.

Terrestrial animals may also be exposed to NPs through contaminated water, soil, or food [227]. Once ingested, these particles can cross biological barriers, accumulate in tissues, and lead to oxidative stress, inflammation, and toxicity, affecting animal health [228]. Thus, NPs present a multi-level environmental threat, impacting aquatic and terrestrial ecosystems through bioaccumulation and disruption of biological functions [229].

Nanoparticles have been shown to disrupt endocrine systems, leading to reproductive challenges and developmental anomalies [230]. In particular, pollinators, such as bees, exposed to ZnO NPs through contaminated pollen or water have exhibited altered foraging behavior, reduced navigation abilities, and impaired learning [231]. The application of NPs also affects ecosystem engineers, such as corals and keystone species, leading to habitat degradation and the loss of biodiversity [232]. The persistent exposure to NPs can push sensitive species toward extinction, reducing biodiversity and ecological resilience [233]. This decline in biodiversity alters critical ecosystem functions, such as nutrient cycling, water filtration, and primary production, ultimately reducing the ecosystem services supporting wildlife and human populations (Figure 3).

In summary, nanoparticles present both opportunities and challenges for biodiversity. While they have revolutionary applications, their release into the environment poses significant risks to various life and ecological systems. A balanced approach integrating innovation with environmental stewardship is critical to minimizing their adverse impacts and preserving global biodiversity.

4.3. Economic Costs and Benefits of Nanoparticle Use

The economic implications of nanoparticles (NPs) in agriculture are multifaceted, with significant costs and substantial benefits [234]. Understanding the balance between these factors is crucial for assessing the long-term viability and sustainability of NPs. As reported above, in agriculture, nanoparticles such as nano-fertilizers and nano-pesticides improve nutrient delivery and pest control, which can reduce the overall quantity of inputs required and increase crop yields [235]. This leads to cost savings for farmers and boosts productivity. For instance, applying nanoparticles enhances nutrient absorption in plants, thereby offering a strategy to reduce the over-application of chemical fertilizers and mitigate associated environmental pollution [236].

The development and large-scale manufacturing of nanoparticles (NPs) involves significant costs, particularly in research and development (R&D) [237]. The R&D phase requires substantial financial investment, specialized equipment, skilled personnel, and lengthy testing procedures, all contributing to the high upfront costs [238]. These investments are necessary to produce nanoparticles with the required precision, quality, and safety standards [239]. Manufacturing NPs on a large scale presents its own set of challenges. The need for sophisticated technology, strict quality control measures, and consistent production processes means that scaling up nanoparticle production is costly [237]. Additionally, ensuring the safety and efficacy of nanoparticles at a large scale requires constant testing, which adds to the operational costs [237]. These high production costs, combined with scalability limitations, can hinder the adoption of nanoparticles in industries where cost sensitivity is crucial [238].

The potential environmental toxicity and health risks NPs pose further increase the manufacturers' economic burden. As the release of NPs into the environment could have harmful effects, industries must invest in rigorous testing procedures and comply with stringent safety regulations [239,240]. This regulatory compliance adds to production costs and increases the time required for approval and commercialization of NP-based products [241]. Without adequate oversight, the release of nanoparticles into ecosystems could

result in pollution clean-up costs [238], biodiversity loss [242], public health concerns [243], and additional financial liabilities for companies [244].

While the economic benefits of nanoparticles (NPs) are substantial, particularly in enhancing efficiency, productivity, and sustainability, the associated costs pose significant challenges that must be addressed. Insurance and liability costs for businesses working with nanoparticles can be substantial [245]. Given the potential risks of nanoparticle exposure and environmental contamination, companies must often carry specialized insurance to cover potential damages [246]. This is especially true in industries where nanoparticles' long-term environmental and health effects are not fully understood, leading to more significant uncertainty for investors. This uncertainty can make it difficult for companies to secure funding, potentially slowing market growth.

Additionally, adopting nanoparticles across various industries often requires a considerable investment in new infrastructure, including specialized production facilities, storage systems, and waste disposal measures, particularly relevant in industries like agriculture, where production and disposal must adhere to strict regulatory standards [247]. Developing streamlined regulatory frameworks that ensure safety without imposing excessive financial burdens is crucial, thus encouraging broader adoption. Furthermore, increasing public understanding of the benefits and risks of nanoparticles can help mitigate resistance to their use, fostering a supportive market environment.

5. Future Trends in Nanoparticle Research in Agriculture

Biosynthesis of nanoparticles offers enormous potential to alleviate biotic and abiotic stress, boost plant growth and improve agricultural production. Most studies indicate numerous benefits resulting from the use of nanoparticles. However, it should be emphasized that the studies are not yet advanced and present only preliminary results derived under controlled conditions, often confirmed for selected plants and chosen soil and climatic conditions [21,22]. Moreover, there remain limitations and gaps in knowledge concerning using NPs in agriculture and their long-term impact on the environment (soil, plant, water, air, humans, and animals).

Specifically, we lack comprehensive knowledge regarding the long-term fate of NPs in soil, water, and air, including their transformation, degradation, and accumulation. More research is also needed on their ecotoxicological effects on non-target organisms (beneficial insects and soil microbes), their potential bioaccumulation and biomagnification, the mechanisms of plant uptake and translocation and subsequent effects on plant growth, metabolism, and nutritional value, as well as the potential for transfer to humans through the food chain. Notably, the potential human health risks associated with exposure to NPs, including ingestion, inhalation, dermal contact, and interactions with human biological systems, also require further study.

The best application method of NPs, foliar or soil, should also be studied. In this respect, there is little data on the long-term impact of the NPs on plants in crop rotation and soil properties. Studies are also lacking regarding the interaction of NPs with basic soil properties, such as soil reaction, clay minerals or organic matter, which can effectively change the effectiveness of the introduced substances. Similarly, more information related to environmental and public health issues from the agricultural use of NPs is needed. For instance, the dispersion of NPs into the atmosphere during application may lead to respiratory disorders, allergic reactions, and accumulation in bodily organs.

Regarding policy, gaps remain concerning appropriate guidelines for the production and law regarding NPs usage and the public's perception of these substances. A separate issue is the introduction of uniform safety rules and standards for the production and prospective agricultural use of NPs. Currently, no such regulations indicate the need

for process control or further monitoring of the fate and transformation of NPs in the environment. Moreover, the general public is unaware of the presence of NPs and the possibilities associated with their use. In this context, public participation cannot be ignored, and the public should be informed about the presence of NPs in the environment and the pros and cons associated with NPs in the context of food and feed production.

Nanotechnology is a promising interdisciplinary research area that various fields, including agriculture, have adopted. The development of agrochemicals in the nanoscale will continue to develop and be observed, but the direction must be carefully indicated so that the use of NPs is smart and safe without any adverse effects on the environment, plants, animals, and humans. This approach sets future trends in research related to the appropriate application and dosage of NPs. It is necessary to track the transport paths of NPs to plants and in plants and the transformation of NPs in the soil, depending on their properties. This effort requires the development of suitable standards that should be developed in the scope of the use and production of NPs without detriment. Many experts believe that NPs in the form of nanofertilizers and nanopesticides can increase the nutrient efficiency of plants and lead to reduced losses resulting from leaching, volatilization, precipitation or immobilization. While nanoparticles offer an excellent opportunity for advancing precision farming and their development should be encouraged, their potential for rapid entry into the food chain necessitates careful monitoring of environmental safety to protect animal and human health.

Future trends in nanoparticle research in agriculture include precision agriculture with nanosensors for real-time monitoring [248] and targeted delivery of agrochemicals, enhanced crop production via nanofertilizers and nanopesticides, improved plant health through nanomaterials for disease management, environmental sustainability with nanoremediation and efficient water management, advancements in food safety and quality using nanotechnology in packaging and for nutritional enhancement, exploration of novel bio-based and multifunctional nanoparticles, and a growing focus on risk assessment and regulatory development to ensure safe and responsible application [249].

6. Conclusions and Perspectives

Despite the recognized challenges, the trajectory of nanotechnology in agriculture points towards a fundamental shift in how we approach crop production, moving beyond incremental improvements to potentially transformative changes in sustainability and efficiency. Years of research now allow us to envision a future where nano-enabled agriculture facilitates truly precision-based farming, optimizing resource allocation at the individual plant level and fostering resilient agroecosystems. This necessitates a move beyond simply applying nanoscale versions of existing inputs. Instead, the focus should shift towards designing smart nanomaterials that dynamically interact with plants and their environment, responding in real-time to changing conditions and minimizing unintended consequences.

Furthermore, the convergence of nanotechnology with other advanced fields like biotechnology and artificial intelligence holds immense promise. Imagine nanosensors providing real-time data that inform AI-driven robotic systems for targeted interventions, creating a closed-loop system for optimized crop management. This integrated approach could unlock unprecedented levels of resource efficiency and significantly reduce agriculture's environmental footprint. However, realizing this vision demands a parallel evolution in our understanding of the long-term ecological and health implications of nanomaterials. Future research must prioritize the development of inherently safer and more sustainable nanomaterials, drawing inspiration from biological systems and focusing on biodegradability and minimal off-target effects. Moreover, proactive and globally harmonized regulatory

frameworks are essential, not as a barrier to innovation, but as a crucial element in building public trust and ensuring the responsible adoption of these powerful technologies.

Ultimately, the future of nano-enabled agriculture lies not just in the application of tiny particles, but in harnessing their unique properties to create intelligent, responsive, and sustainable agricultural systems that can meet the growing global demand for food while safeguarding our planet. This requires a bold, interdisciplinary approach that fosters innovation while prioritizing safety and long-term sustainability.

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