This is a repository copy of *Potential effects of metal oxide nanoparticles on leguminous plants: Practical implications and future perspectives*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/211201/

Version: Accepted Version

Article:

Kaur, S., Garg, T., Joshi, A. et al. (3 more authors) (2024) Potential effects of metal oxide nanoparticles on leguminous plants: Practical implications and future perspectives. Scientia Horticulturae, 331. 113146. ISSN 0304-4238

https://doi.org/10.1016/j.scienta.2024.113146

: © 2024, Elsevier. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/. This is an author produced version of an article published in Scientia Horticulturae. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Potential effects of Metal Oxide Nanoparticles on Leguminous Plants: Practical Implications and Future Perspectives

Simranjeet Kaur[1*], Tashima Garg[1], Anjali Joshi[2], Amit Awasthi[3], Vajinder Kumar[4*], Avneesh Kumar[5*]

[1]Department of Botany, Akal University, Talwandi Sabo, Bathinda, Punjab
[2]Centre for Nanoscience and Nanotechnology (UIEAST), Panjab University, Chandigarh

[3]Department of Applied Sciences, University of Petroleum and Energy Studies, Dehradun, Uttarakhand, India.

[4]School of Chemistry and Astbury Centre for Structural Molecular Biology, University of Leeds, Leeds, UK
[5]Department of Botany, SRM University, Sikkim Campus, Tadong, Sikkim
*** Corresponding authors: avnishenator@gmail.com, simranbotany@gmail.com vkvkumar17@gmail.com**

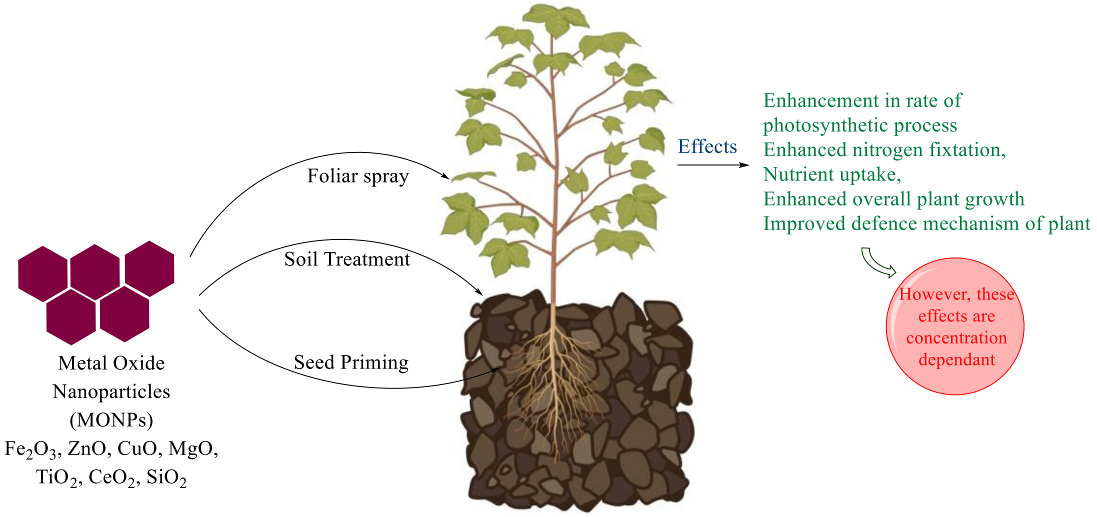
Abstract

The use of nanoparticles in agriculture is increasing due to their ability to readily enter plants. Among these nanoparticles, metal oxide nanoparticles (MONPs) have garnered significant attention owing to their unique attributes such as stability and catalytic activity. Extensive studies have demonstrated the positive effects of various MONPs, including iron oxide (Fe_2O_3 or Fe_3O_4), copper oxide (CuO), zinc oxide (ZnO), titanium dioxide (TiO_2), cerium oxide (CeO_2), silicon dioxide (SiO_2), and magnesium oxide (MgO) on the growth and productivity of legume plants in normal and abiotic stress conditions. These nanoparticles enhance symbiotic interactions with bacteria, photosynthesis, nutrient uptake, and nitrogen fixation. However, excessive utilization of MONPs can have detrimental consequences, including reduced photosynthesis, nitrogen fixation, and altered gene expression, leading to diminished crop yield. To ensure the safe and effective application of MONPs, it is imperative to consider factors such as MONP type, concentration, and exposure method. The main objective of this review is to provide a comprehensive overview of

the current research landscape concerning the role of MONPs and their effects on leguminous plants. Furthermore, it aims to identify potential avenues for future research in this domain. By addressing these aspects, this review endeavors to enhance our understanding of the implications and potential risks associated with the agricultural use of MONPs, facilitating informed decision-making and promoting sustainable practices.

Keywords: MONPs, abiotic stress, legumes, crop yield

Graphical Abstract



Introduction

Nanotechnology has gained significant attention in the field of agriculture due to its potential for improving crop productivity. Researchers have extensively studied the ability of nanoparticles to penetrate plants due to their nano size (Agrawal et al., 2022; Faizan et al., 2020). However, among the nanoparticles armamentaria, metal oxide nanoparticles are commonly utilized due to their unique features such as shape, size, concentration, composition, and physiochemical properties that play a crucial role in influencing the effects of MONPs on different plant species (Palacio-Márquez et al., 2021a; Xie et al., 2018). In agriculture, commonly employed in MONPs are ZnO, Fe_2O_3 or Fe_3O_4, SiO_2, TiO_2, CuO, CeO_2, and MgO (Amde et al., 2017; Gebre and Sendeku, 2019a). Traditional physical and chemical methods have been used for nanoparticle synthesis; however, these methods have drawbacks such as high pressure, temperature risks, and environmental pollution (Panakkal et al., 2021). In contrast, biological methods offer advantages such as biocompatibility and eco-friendliness (Vithanage et al., 2023).

MONPs can be applied directly to soil or plants, affecting plant metabolism through symplastic and apoplastic pathways. However, the interaction between plants and MONPs is not yet fully understood and requires further investigation at the molecular level. MONPs have the potential to be used as pesticides and fertilizers to enhance agricultural productivity while reducing inputs and nutrient losses(Gilbertson et al., 2020). Different studies have shown the positive effects of MONPs on plant growth and development. For instance, the application of Fe_2O_3 NPs to broad beans (*Vicia faba* L.) increased root node numbers, and ZnO nanoparticles improved yield in lentil (*Lens culinaris* Medik.) crops(S. M. Alwan et al., 2022; Kolenčík et al., 2022a). Additionally, these MONPs impart tolerance from various abiotic stress such as drought, salt, cold, temperature, and heavy metal by improving photosynthetic activity, antioxidant enzymes, and ultimately plant growth(Sarraf et al., 2022) such as TiO_2 nanoparticles enhanced germination and photosynthesis in the same plant species(Khan et al., 2019). However, increasing the dosage of nanoparticles can have detrimental effects, for instance, SiO_2 and TiO_2 nanoparticles reduced germination, plant length, and chromosomal structure in broad beans (*Vicia faba* L.)(Thabet et al., 2019) and CeO_2 nanoparticles decreased nitrogen fixation and photosynthetic pigments in mungbeans (*Vigna radiata* L.)(Kamali-Andani et al., 2022). Similarly, ZnO nanoparticles were found to decrease nodulation in alfalfa (*Medicago sativa* L.) plants(Sun et al., 2022). Leguminous plants, known for their high protein content and soil fertility enhancement through nitrogen fixation, are particularly affected by MONPs. The impact of MONPs such as Fe_3O_4, ZnO, and CeO_2, on the symbiotic relationships between legumes and bacteria is crucial to understand. These nanoparticles can also have adverse effects on soil microorganisms, reducing their growth and enzymatic activity, which can vary depending on the morphology, composition, and concentration of the nanoparticles and the plant species(Burke et al., 2015; Prakash et al., 2021a; Sun et al., 2022). Moreover, MONPs like CeO_2, ZnO, and TiO_2 have been found to reduce the count of soil microorganisms, including *Azotobacter*, fungal and actinomycetes colonies, and inhibit their enzymatic activity, as well as negatively impacting phosphorus and potassium-solubilizing bacterial growth(Chai et al., 2015; Verma et al., 2020).

The increasing use of MONPs in various industries raises concerns about their impact on the environment and human health. These nanoparticles can enter the food chain through plants, potentially causing adverse effects(Panakkal et al., 2021). Their release into water bodies can further affect aquatic ecosystems and the food chain. Therefore, it is imperative to identify the detailed impact of MONPs on symbiotic bacteria and plant nodulation. Soil polluted with MONPs may pose a threat to agricultural output and sustainability by disrupting the symbiotic association between *Rhizobium* and legume plants. To address these issues, a potential strategy is the controlled release of nutrients through metal oxide nano-fertilizers. This approach aims to optimize the benefits of MONPs while minimizing potential risks. This review aims to provide an evaluation of the current research concerning Metal Oxide Nanoparticles (MONPs) and their effects on leguminous plants. It will address the existing research gaps to shed light on the consequences and potential dangers of using MONPs in agriculture.

Synthesis methods for metal oxide nanoparticles

Recent advancements in nanotechnology have led to the development of new techniques for synthesizing nanoparticles with specific characteristics such as shape, size, and properties. Generally, two approaches (top-down and bottom-up) were followed for synthesizing nanoparticles. The top-down approach involves reducing the size of bulk materials to the nanoscale using mechanical forces. In contrast, the bottom-up approach involves synthesizing nanoparticles from smaller molecules using physical, chemical, or biological techniques (**Figure 1**). In the top-down approach, mechanical methods such as plasma synthesis, ball milling, laser ablation, and physical vapor deposition are used to compress bulk materials down to the nanoscale(Chavali and Nikolova, 2019; Koul et al., 2021; Saebnoori et al., 2022). A number of MONPs created through these techniques such as Fe_3O_4 by plasma synthesis, CuO by electrospinning, ZnO by laser ablation, and TiO_2 by ball milling(Jaber et al., 2021; Lee et al., 2018; Lyu et al., 2019; Sun et al., 2023). On the other hand, the bottom-up approach involves chemical reactions to synthesize MONPs using techniques such as sol-gel, wet-chemical reduction, pyrolysis, photoreduction, and hydrothermal methods (Dadkhah and Tulliani, 2022). Chemical processes such as sol gel, pyrolysis and wet chemical methods have been utilized to produce MONPs like TiO_2, ZnO, and Fe_3O_4 (Malek et al., 2018; Mathumba et al., 2017; Taziwa et al., 2017).

While physical and chemical approaches have shown potential in various applications, there are challenges associated with them including stability, toxicity, low yield, high cost, and the need for skilled operators (Purohit et al., 2019; J. Singh et al., 2018). These techniques often involve the use of hazardous substances, which can generate toxic fumes, contribute to environmental pollution, and pose risks to living organisms. Additionally, the nanostructures produced by these methods may not be suitable for agricultural use due to potential health hazards for humans (Gebre and Sendeku, 2019b). To overcome these limitations, researchers have turned to green synthesis techniques as a solution **(Figure 1).** Green synthesis, a bottom-up approach, involves the use of plant extracts and microorganisms to create MONPs. These methods are biocompatible and environmentally sustainable due to the lower toxicity of the compounds used and mild conditions. Plant extracts from various sources such as Indian mulberry (*Morinda citrifolia* L.), cassava (*Manihot esculenta* Crantz), yam (*Dioscorea* spp. L.), lemon peel (*Citrus limon* (L.) Osbeck), pomegranate peel (*Punica granatum* L.), and cumin (*Cuminum cyminum* L.) seeds have been employed for the fabrication of MONPs (Dubey and Singh, 2019; Herrera-Barros et al., 2018; Mathew et al., 2021; Sundrarajan et al., 2017). Aqueous solutions of cabbage (*Brassica oleracea* L.) and leaf extracts from guava (*Psidium guajava* L.), bay laurel (*Laurus nobilis* L.), mesquite (*Prosopis juliflora* L.), Jwarancusa lemongrass (*Cymbopogon jwarancusa* L.) and common olive (*Olea europaea* L.) have also been used (Fakhari et al., 2019; Irum et al., 2020; Issam et al., 2021; Osuntokun et al., 2019; Saha et al., 2018). Besides plants, yeast, algae, and fungi, and bacteria have been investigated as biological sources for synthesizing MONPs (Hassan et al., 2021; Majeed et al., 2021; Peiris et al., 2018; Salem et al., 2019). Plant materials are often preferred over microorganisms due to their ease of use, cost-effectiveness, and scalability (Gebre and Sendeku, 2019a). These green synthesis techniques provide stable and non-toxic plant metabolites that can act as stabilizing and reducing agents. Additionally, advanced methods like microwave irradiation, which utilizes dielectric heating, have been proposed for plant extract preparation (Ganguly and Sengupta, 2023). Consequently, there is a growing demand for environmentally friendly materials and methods as an alternative for the production of nanostructures. To characterize and study these nanostructures, various spectroscopic methods such as UV-Visible absorption spectroscopy, FTIR, XRD, DLS, TEM, SEM, and EDAX are commonly used. These techniques provide valuable information about their size, shape, structure, elemental composition, concentration, and other physical and chemical properties. Each method offers unique insights that cannot be obtained through a single technique alone (Nair et al., 2022). The distinctive physical and chemical properties of these nanoparticles such as their unique edges and corners and increased density, make them highly useful in various industries, including agriculture, medicine, and environmental preservation.

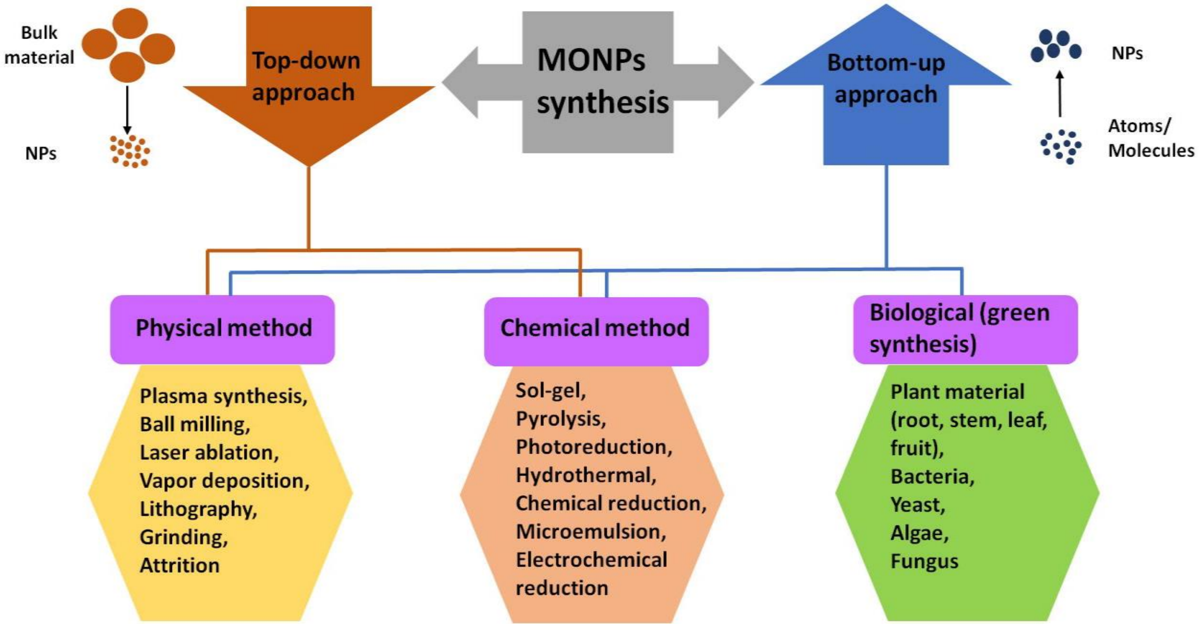


Figure 1. Different methods for synthesizing metal oxide nanoparticles (MONPs).

Uptake and accumulation of metal oxide nanoparticles in leguminous plants

MONPs can be applied to plants through foliar application, which involves spraying them on the leaves, or soil fertilization, which involves adding them to the soil. Understanding the pathways through which plants absorb MONPs is crucial, with the cuticle and stomatal pathways being the two main routes (Avellan et al., 2019). The cuticle, which is the outermost layer of leaves, acts as a barrier against nanoparticle penetration **(Figure 2).** However, nanoparticles with diameters ranging from 0.6 to 4.8 nm can pass through the cuticle efficiently via the stomatal and cuticular pathways (Lv et al., 2019). Some studies even suggest that nanoparticles as small as 5 nm can penetrate the cuticle (Rastogi et al., 2017). Nevertheless, the exact route taken by these nanoparticles is still not fully understood, as it can vary depending on factors such as the plant species, nanoparticle characteristics, experimental conditions, and the plant's growth stage, environmental conditions, and presence of pests or diseases (Huang et al., 2021; Rani et al., 2022). In addition to the cuticular pathway, nanoparticles can also enter and migrate through stomatal pores in plants (Khan et al., 2022). The entry of nanoparticles through stomata is influenced by factors such as stomatal density, size, aperture opening, leaf structure, and the activity of specific pumps within plant cells (Wang et al., 2023). Numerous studies have reported the penetration of nanoparticles, including CeO_2, TiO_2, Fe_2O_3, and ZnO through stomata. Furthermore, these nanoparticles can interact with various cellular components, affecting their toxicity, genotoxicity, and metabolic processes (A Ebrahimi et al., 2016; Khan et al., 2021; Mahdieh et al., 2018; Salehi et al., 2018a). Techniques such as fluorescence, confocal microscopy, SEM, and TEM have been employed to investigate the entry of different MONPs through stomata and their accumulation in deeper plant tissues, particularly in leguminous species like common beans (*Phaseolus vulgaris* L.) (Dina M Salama et al., 2019; Salehi et al., 2021a; Zhang et al., 2019; Zhu et al., 2020). Even plant species can influence the absorption of nanoparticles through leaves (Su et al., 2019).

Once MONPs enter the substomatal cavity, they can travel through plant tissues via apoplastic and symplastic pathways (Liu et al., 2020) **(Figure 2).** When applied to leaves, MONPs are typically transported to the roots through the phloem, whereas seed or soil treatments lead to their movement from roots to shoots. It is worth noting that chemicals transported downward through the phloem are not circulated upward through the xylem (Lv et al., 2019). Several studies have shown that MONPs can enter plants through stomata and eventually reach the root system. For instance, Xiong et al. found that foliarly sprayed CuO NPs with a size of about 40-200 nm reached the roots through the phloem in lettuce (*Lactuca sativa* L.) plants (Xiong et al., 2021). TEM analysis revealed the presence of Fe_3O_4 NPs ranging from 10 to 40 nm in pumpkin (*Cucurbita pepo* L.) phloem sap, indicating their entry into the plant through the apoplastic pathway. However, no transfer from roots to shoots was observed (Tombuloglu et al., 2020). Similarly, TEM examination of wheat (*Triticum aestivum* L.) plant root sections detected Fe_3O_4 NPs, suggesting their entry via the

apoplastic pathway. Fe_3O_4 NPs caused an increase in iron levels in the root tissues, as evidenced by a hysteresis loop in the M-H curve, demonstrating their presence in different regions of the wheat plant. However, the aerial samples exhibited weak ferromagnetic behavior, suggesting that Fe_3O_4 NPs did not move from the roots to the above ground parts (Iannone et al., 2016).
The movement of nanoparticles in the root cells of wheat plants was investigated using techniques such as TEM. The results demonstrated the transport of nanoparticles from the leaves to roots via phloem pathway ("Annual report 2013-2014," 2014). Similarly, X-ray fluorescence microscopy (XRF), Laser confocal scanning microscopy, and SEM was used to observe the movement of Zn NPs and polystyrene NPs from roots to shoots in common bean (*Phaseolus vulgaris* L.) and wheat (*Triticum aestivum* L.) plants (da Cruz et al., 2019; Lian et al., 2020).

Seed priming was also identified as an effective technique for facilitating the uptake and accumulation of MONPs in plants. During seed priming, seed pretreatment with metal oxide nanoparticles (MONPs) was observed to enhance essential aspects of plant growth, including germination, seedling growth, and overall plant performance ((Mazhar et al., 2023b, 2023a). The uptake and accumulation of nanoparticles through seed priming occur primarily through the seed coat and embryo **(Figure 2)**. The inserted nanoparticles could influence various physiological and biochemical processes, enhancing plant growth and development. Multiple studies demonstrated that seed priming with MONPs such as ZnO (Mazhar et al., 2023a), Fe_2O_3 (V. Pawar et al., 2019), CuO (Sarkar et al., 2021), TiO_2 (Mathew et al., 2021), MgO (P Sharma et al., 2022)could improve seed germination rates, seedling vigor, and plant biomass.

Additionally, nanoparticles absorbed through seed priming could affect plant morphology, nutrient uptake, and stress tolerance (Ghorbani et al., 2021). The uptake of nanoparticles by seeds and their subsequent distribution within plant tissues were displayed with advanced microscopic techniques such as SEM and TEM (Kashyap and Siddiqui, 2021). These techniques have revealed the presence of nanoparticles in various plant organs, including roots, stems, leaves, and fruits, indicating their systemic movement within the plant.

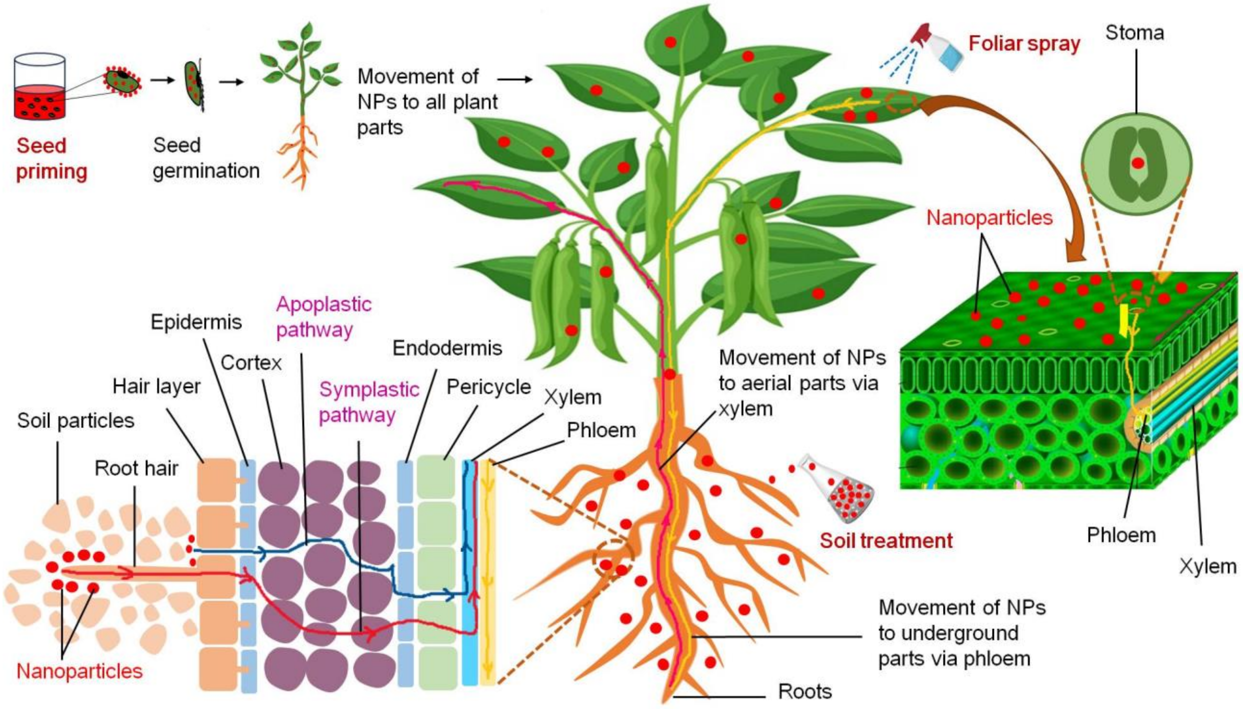


Figure 2. Uptake mechanism of MONPs in plants through the soil and foliar application.

Role of metal oxide NPs in leguminous plant

The agricultural sector faces numerous challenges such as food security, seed germination, plant growth improvement, targeted pesticide delivery, diagnostic devices, food quality enhancement, storage, and pest management, but nanotechnology holds great potential for addressing various challenges in agriculture (Vijayakumar et al., 2022). Nanomaterials, at the nanoscale, exhibit exceptional properties such as quantum size effects, increased surface area, and unique magnetic properties, which often result in higher activity compared to their bulk counterparts (Singh et al., 2022). MONPs have shown promising effects on plant growth, particularly in leguminous crops. Their application as fertilizers can reduce reliance on chemical inputs, enhance nutrient bioavailability, optimize water-nutrient ratios, and ultimately increase plant production (Salehi et al., 2020). MONPs have demonstrated positive effects on plant morphology, including improvements in germination percentage, shoot and root length, and total biomass of seedlings. Numerous studies have reported the beneficial effects of MONPs on different leguminous plants such as soybeans (*Glycine max* (L.) Merr.) (Stowers et al., 2018), yellow medick (*Medicago falcata* L.) (Kokina et al., 2020), and peas (*Pisum sativum* L.) (Kashyap and Siddiqui, 2021) in enhancing various physiological parameters related to plant growth. However, the widespread use of MONPs in industry and agriculture has raised concerns about their potential toxicity and environmental impact. Upon entry into the environment, these nanoparticles interact with plants, affecting their physiological, biochemical, and genetic makeup, and potentially leading to negative effects on human health and the ecosystem (Kamali et al., 2019; Rastogi et al., 2017). This discussion highlights both the positive and negative effects of various MONPs on different crops.

IRON OXIDE

Iron oxide nanoparticles have gained significant attention for their positive impact in plants (Yang et al., 2020). Iron is an essential nutrient element for plants and plays a crucial role in various metabolic processes, including photosynthesis, nitrogen metabolism, respiration, stomatal closure, and nucleic acid synthesis. Iron acts as a cofactor for several enzymes involved in redox reactions, electron transport chain, peroxide activation, and decomposition (Rai et al., 2021). While iron is traditionally used in its ionic form, the use of iron oxide nanoparticles has shown promising effects due to their efficient absorption and ability to form complexes with other molecules, facilitating the delivery of iron to different plant parts (Poddar et al., 2020). The higher surface area of Fe_2O_3 or Fe_3O_4 NPs allows them to bind with carrier proteins or ion transporters, facilitating their absorption through the plasma membrane of plant cells (Deng et al., 2022). Various studies have found that Fe_2O_3 NPs are transported via xylem vessels, and the transfer and accumulation depend on particle size, concentration, exposure time, and plant species (Saleem and Khan, 2023; Yang et al., 2023). Upon interacting with the soil, Fe_2O_3 NPs actively boost the presence of soluble iron. This is facilitated by the release of soluble iron ions from the nanoparticles, utilizing their significant surface area and small size. As a result, plants can absorb these ions, providing an essential nutrient for their growth (Zia-ur-Rehman et al., 2018).

Plants respond to iron oxide nanoparticles by altering the various physiological processes for instance, increase in the photosynthetic pigments and upregulation of gene expression. Iron oxide nanoparticles (Fe_2O_3) have roles in water purification and can be used as catalysts, adsorbents, and iron fertilizers (Algarni and Al-Mohaimeed, 2022; Gillispie et al., 2019). Iron oxide nanoparticles interact with plants when the pH is mildly acidic and help convert to Fe^{+3} ions into Fe^{+2} ions that can be utilized by plants The introduction of iron oxide nanoparticles improves the growth of plants by enhancing their biomass and length. The roots absorb these nanoparticles which are then transported to parts of the plant through shoots (Khan et al., 2023). However, the reactivity of iron poses a dual nature, as low concentrations of iron have beneficial effects including increased height, root length, biomass, and chlorophyll levels, while higher concentrations caused a phototoxic effect on plants due to their involvement in the Fenton (Fe) reaction, generating hydroxyl radicals (OH) within the plant. The availability of iron in plants is regulated by various enzymes, transporters, scavengers, and chaperones (Distéfano et al., 2021). Researchers investigated the role of iron oxide nanoparticles, specifically Fe_2O_3, in improving seed germination, root growth, pod number, root nodules, and chlorophyll content in legume crops such as chickpeas (*Cicer arietinum* L.), green peas(Palchoudhury et al., 2018) (*Pisum sativum* L.), broad beans(Abdel-Salam, 2018; S. Alwan et al., 2022; Palchoudhury et al., 2018; Rani et al., 2022) (*Vigna radiata* L.), and yellow medick(Kokina et al., 2020) (*Medicago falcata* L.) **(Table 1).** In peanut (*Arachis hypogea* L.) seeds, Fe_2O_3 NPs boosted glycoprotein production and enhanced root length, plant height, chlorophyll content, plant biomass, root development, and SPAD (soil plant analysis development) values (Rui et al., 2016; S Suresh et al., 2016a). Nevertheless, the research is only focused on hydroponic conditions, raising concerns about potential nanomaterial toxicity. Comparative analyses with traditional iron fertilizers are needed for a thorough understanding.

Legume seeds such as green gram (*Vigna radiata* L.), green peas (*Pisum sativum* L.), chickpeas (*Cicer arietinum* L.) when soaked with Fe-enriching hematite (α-Fe_2O_3 NPs) resulted in improved root length, and seedling growth in chickpea plants (Boutchuen et al., 2019; Palchoudhury et al., 2018; V. A. Pawar et al., 2019). These studies suggested that using lower nanoparticle concentrations in seed pre-soaking solutions can reduce fertilizer usage, minimizing environmental impact. The comparative analysis and investigation of varied pH conditions provide valuable insights for the sustainable and efficient use of nano fertilizers in promoting food production. Furthermore, foliar application of Fe_2O_3 NPs and fulvic acid-coated Fe_2O_3 NPs in soybean (*Glycine max* (L.) Merr.) plants has demonstrated increased chlorophyll content, biomass, root developmental indices, and biological nitrogen fixation. The mildly acidic pH in the hydroponic environment facilitates the conversion of Fe^{+3} ions to Fe^{+2} ions, readily absorbed by plants. Consequently, the exposure to iron nanoparticles has led to enhanced biomass and root length, fostering positive contributions to soybean (*Glycine max* (L.) Merr.) plant growth (Yang et al., 2020). In meantime, Cao and colleagues conducted a pivotal study focusing on the foliar application of differently sized γ-Fe_2O_3 nanomaterials (NPs) to assess their impact on soybean (*Glycine max* (L.) Merr.) growth and physiology (Cao et al., 2022). The investigation revealed size- and concentration-dependent effects, with small-sized NPs (S-Fe_2O_3, 4-15 nm) at 30 mg/L exhibiting superior growth promotion compared to a commercial iron fertilizer (EDTA-Fe). Other studies have shown the positive effects of Fe_2O_3 NPs on chlorophyll fluorescence, root length, and miRNA expression in yellow medick (*Medicago falcata* L.) as well as the role of Fe_3O_4 NPs and *Rhizobium* in enhancing iron content, nodule leghemoglobin, nitrogenase activity, nodule number, plant length, and dry weight in common beans (*Phaseolus vulgaris* L. cv. Red Guama) (De Souza-Torres et al., 2021a; Kokina et al., 2020). However, these reported studies did not provide an explanation of the underlying mechanisms, through which Fe_3O_4 nanoparticles affected root length, chlorophyll fluorescence nitrogen fixation and miRNA expression in yellow medick (*Medicago falcata* L.) and common beans (*Phaseolus vulgaris* L.). and common beans. The seed soaking with polyethylene glycol-coated Fe_3O_4 nanoparticles ($Fe_3O_4^-$PEG; at a concentration of 1,000 mg Fe/L) had a beneficial effect on the germination and seedling growth of bean plants (*Phaseolus vulgaris* L.) (Duran et al., 2017). Moreover, recent research has indicated that foliar application of Fe_2O_3 NPs improved nitrate reductase activity, chlorophyll content, iron level, biomass, and plant yield in green beans (*Phaseolus vulgaris* L. cv. 'Strike') (GUTIÉRREZ-RUELAS et al., 2021) **(Table 1).** This study highlighted the enhanced assimilation of nitrogen, emphasizing the potential of nano-fertilizers in improving crop yield and nutrient absorption. Irum and his co-workers found that iron oxide NPs made from *Cymbopogon jwarancusa* leaf extract effectively stimulate in-vitro callus, support shoot regeneration, and improve root induction in chickpea (*Cicer arietinum* L.) plants (Irum et al., 2020). The Punjab-Noor 09 chickpea variety stands out with high callogenesis (96%) and shoot regeneration (88%), along with increased iron content (4.88 mg/g) in the regenerated plants. This environmentally friendly method highlights the promise of iron oxide NPs in advancing tissue culture for vital legume crops like chickpeas. Further, Saleem and Khan found that the application of Fe_2O_3 NPs, either alone or in combination with *Rhizobium pusense*, enhances seed germination, protein and pigment content, plant length, and dry biomass in green grams, making them a potential nano-fertilizer for legume plants (Saleem and Khan, 2023). Conversely, Pawar et al. revealed adverse effects of iron oxide nanoparticles (Fe_2O_3 NPs) on chickpea (*Cicer arietinum* L.) seedling growth, particularly at higher concentrations (16mg/L). These negative impacts include reduced seedling length, decreased fresh and dry weights, altered root-to-shoot ratio, and indications of phytotoxicity through stress indices (V. A. Pawar et al., 2019) **(Table 1).** This study showed the significance of choosing nanoparticle concentrations carefully to avoid adverse effects on plant growth. So, further research is required to determine the optimal concentration and application method for different plant species and growth stages. Moreover, it is necessary to assess the long-term effects of repeated exposure to iron oxide nanoparticles, their potential accumulation in soil and plant tissues, their impact on soil microorganisms and non-target organisms in the ecosystem, considering their corrosive nature, larger surface area, and small size. Such investigations would provide insights into the safety and sustainability of using these nanoparticles in agricultural practice.

334 **Table 1: Effects of various concentration of iron oxide nanoparticles on legume plants**

Type of MONPs	**Effective MONPs Concentrations**	**Plant used**	**Experimental Type**	**Mode of Treatment**	**Effects**	**Reference**
Positive Effects						
Fe_2O_3	2, 10, 50, 250, and 1000 mg/kg	*Arachis hypogea* L.	Pot experiment	Soil application	Improved root length, plant biomass, plant height, antioxidant enzyme activity, and the SPAD value	(Rui et al., 2016)
	500 and 4000 mg/L	*Arachis hypogea* L.	Pot experiment	Seed priming	Increased glycoprotein content	(S. Suresh et al., 2016)
	0.00554 mg/L	*Pisum sativum* L., *Vigna radiata* L., *Cicer arietinum* L., and *Phaseolus vulgaris* L.	Growth vials solution	Seed priming	Increased root length in chick peas (88%), green peas (160%), and green grams (366%)	(Palchoudhury et al., 2018)

	22 and 1100 mg/L	*Cicer arientinum* L., *Phaseolus vulgaris* L., *Vigna radiate* L., and *Phaseolus vulgaris* L.	Petriplate	Seed priming	Growth boosts (230-830%) across four legume species, enhanced survival, accelerated fruit production, and yields healthier second-generation plant	(Boutchuen et al., 2019)
	4, 8, and 12 mg/L	*Cicer arietinum* L. variety Digvijay	Pot experiment	Seed priming	Enhanced seedling growth	(V. Pawar et al., 2019)
	1, 5, 10, 15, 20 mg/L	*Cicer arietinum* L.	Growth vials solution	In growth medium	Enhanced chickpea growth, induce callus, promoted shoot regeneration, and improved root development	(Irum et al., 2020)
	15, 30, and 60 mg/pot	*Glycine max* (L.) Merr.	Pot experiment	Direct soil application and foliar spray	Increased nodulation number, root surface area, root volume, shoot	(Yang et al., 2020)

					and root fresh weight and dry weight	
	25, 50, and100 mg/L	*Phaseolus vulgaris* L. cv. ‘Strike’	Pot experiment	Foliar spray	Biomass, nitrate reductase activity, Fe content, and yield were increased	(GUTIÉRREZ-RUELAS et al., 2021)
	30 mg/L	*Glycine max* (L.) Merr.	Pot experiment	Foliar spray	Increased the shoot and nodule biomass, improved soybean yield (13.7%) and promoted the nutritional quality (e.g., free amino acid content) of the seeds.	(Cao et al., 2022)
	100, 250, and 500 mg/kg	*Vigna radiata* L.	Pot experiment	Soil application	Plant length, biomass, seeds per plant, and protein	(Saleem and Khan, 2023)

					content were enhanced	
Fe_3O_4	1, 2, and 4 mg/L	*Medicago falcata* L.	Hydroponic experiment	In hydroponic solution	Improvement in root length, chlorophyll fluorescence, and miRNA expression	(Kokina et al., 2020)
	2000 mg/L	*Phaseolus vulgaris* L. cv. Red Guama	Polythene culture	Soil application	Increased iron level, nitrogenase activity, leghaemoglobin content, nodule number, plant length, and dry weight were observed	(De Souza-Torres et al., 2021b)
	1,000 mg/L	*Phaseolus vulgaris* L. cv. Sintonia	Petriplate	Seed priming	Increased radicle elongation	(Duran et al., 2018)
Negative effects						
Fe_2O_3	0.016 mg/L	*Cicer arietinum* L. variety Digvijay	Pot experiment	Seed priming	Decreased seedling growth	(V. Pawar et al., 2019)

335

ZINC OXIDE

Zinc (Zn) is an essential micronutrient that acts as a co-factor in the biosynthesis of proteins and enzymes in plants such as alcohol dehydrogenase, alkaline phosphatase, carbonic anhydrase, RNA polymerase, phospholipase, and Cu-Zn SOD. It plays a crucial role in lipid metabolism, nitrogen fixation, and gene expression by participating in DNA replication and transcription processes (Kaur and Garg, 2021; A. Singh et al., 2018).

Zinc oxide nanoparticles (ZnO NPs) are receiving attention in plant applications due to their high bioavailability, smaller size, and enhanced absorption properties (Siddiqui et al., 2018). However, high concentrations of zinc can have detrimental effects on plants, including seed germination inhibition, chlorosis, nutrient imbalances, and growth inhibition. These negative effects are attributed to increased lipid peroxidation, protein degradation, and other underlying mechanisms. It is important to note that the response to zinc varies among different plant species. Several studies have investigated the positive as well as negative effects of ZnO NPs on legume plants **(Table 2).** For instance, Mukherjee et al. studied the effects ZnO NPs on peas (*Pisum sativum* L.) at low and high concentrations (250 and 1000 mg/kg). The soil application of ZnO NPs (1000 mg/kg) led to an increase in chlorophyll and carotenoid content, as well as higher zinc content in various plant tissues compared to untreated pea plants (Mukherjee et al., 2016). In kidney beans (*Phaseolus vulgaris* L.), the effects of soil treatment with ZnO NPs (125 mg/kg) was investigated by Medina-Velo et al. (Medina-Velo et al., 2017). They found the increased levels of zinc in leaves (136%), stems (139%), and nodules (203%) of kidney beans, along with elevated manganese (74%) and boron (122%) levels in the stem. These findings demonstrated the potential of ZnO NPs to influence nutrient uptake and accumulation in legume plants. Further the effects of seed priming and foliar application of different zinc forms was compared in pinto beans (*Phaseolus vulgaris* L.) (Mahdieh et al., 2018). They reported that foliar treatment with ZnO NPs had a more significant impact on the growth and yield of pinto bean plants compared to seed priming. Additionally, zinc oxide nanoparticles (ZnO NPs) positively impacted *Phaseolus vulgaris* L. growth, with significant improvements in yield at a low concentration of 300 mg/kg. Higher doses (600 and 1000 mg/kg) showed phytotoxic effects, while ZnO NPs enhanced zinc uptake, bioaccumulation, and antioxidant enzyme activities in plant tissues (Akanbi-gada et al., 2019).

Foliar treatments of zinc oxide nanoparticles (ZnO NPs) have shown positive effects in various plant species. Kolenčík et al. reported increased pod number, seed weight, and overall plant yield in field-grown lentil (*Lens culinaris* Medik.) plants with ZnO NPs foliar treatment (1 mg/L) (Kolenčík et al., 2022b). Similarly, Salama et al. observed enhanced branch, leaf, and overall production in common bean (*Phaseolus vulgaris* L.) plants with foliar treatment of ZnO NPs (30 mg/L) (Dina M Salama et al., 2019). This positive impact was linked to the upregulation of specific genes encoding enzymes and proteins, although higher concentrations induced genotoxic effects. Palacio-Marquez et al. found that foliar application of ZnO NPs at 25 mg/L significantly improved biomass accumulation and production in green beans (*Phaseolus vulgaris* L.) (Palacio-Márquez et al., 2021b).

Various studies have investigated the impact of zinc oxide nanoparticles (ZnO NPs) on different plant species depending on factors such as particle size and concentration. Yusefi-Tanha et al. investigated the size and concentration-dependent effects of ZnO NPs on soybean (*Glycine max* (L.) Merr.) plants (Yusefi-Tanha et al., 2022a). ZnO NPs with a size of 38 nm, at concentrations up to 160 mg Zn/kg, enhanced seed yield. In contrast, a higher concentration of 400 mg/kg resulted in increased oxidative stress indicators and altered antioxidant enzymatic activity in soybeans. Skiba et al. reported that ZnO NPs influenced the uptake and translocation of manganese, iron, and copper in green peas (*Pisum sativum* L.) grown under hydroponic conditions (Skiba et al., 2020). This study revealed how ZnO NPs impact the uptake and translocation of essential elements in plants, providing insights into their influence in overall plant growth. Salehi et al. found that lower concentrations of ZnO NPs positively affected zinc content, plant height, and peroxidase and catalase activity in bean (*Phaseolus vulgaris* L.) plants. However, higher concentrations resulted in damaging effects on photosynthetic activity, protein levels, increased lipid peroxidation, and decreased antioxidant activity (Salehi et al., 2021b). Yusefi-Tanha et al. and Salehi et al. reported their toxic effects at higher concentrations were evident in soybean (*Glycine max* (L.) Merr.) and common bean (*Phaseolus vulgaris* L.) crops (Salehi et al., 2021c; Yusefi-Tanha et al., 2022b). Conversely, Sun et al. (2022) and Verma et al. (2023) highlighted both detrimental and beneficial impacts on alfalfa (*Medicago sativa* L.) and field pea (*Pisum sativum* L.) crops, respectively (Sun et al., 2022; Verma et al., 2023). In a subsequent investigation, the exposure of peas (*Pisum sativum* L.) to zinc oxide nanoparticles (ZnO NPs) resulted in a growth impact that depended on the size of the nanoparticles. The more toxic ZnO NPs (50 nm) at a concentration of 1000 mg/L resulted in a 20–30% slowdown in root elongation. Metabolically, there was a significant increase in sucrose and GABA levels in both roots and shoots. Additionally, pea (*Pisum sativum* L.) seedlings exhibited enhanced content of metabolites related to the aspartate–glutamate pathway and the TCA cycle, such as citrate and malate. This suggests that ZnO NPs influence various metabolic processes in peas, indicating a potential role in altering plant growth and metabolic pathways (Stałanowska et al., 2023)(Stałanowska et al., 2023). Despite the positive and detrimental effects of ZnO NPs on plants at different concentrations, the underlying mechanisms explaining these effects remain largely unknown. Further studies are needed to explore how ZnO NPs behave, interact, move, and get absorbed by plants and soil. Understanding their physical and chemical characteristics over time is crucial for a more detailed assessment.

Table 2: Effects of various concentration of zinc oxide nanoparticles on legume plants

Type of MONPs	Effective MONPs Concentrations	Plant used	Experimental Type	Mode of Treatment	Effects	Reference
Positive Effects						
ZnO	1000 mg/kg	*Pisum sativum* L.	Pot culture	Mixed in soil	Improved Chl a and carotenoid content as well as increased Zn accumulation, were observed in the root, shoot, and leaf tissues	(Mukherjee et al., 2016)
	125 mg/kg	*Phaseolus vulgaris* L. var. red hawk kidney	Pot culture	Mixed in soil	The Zn level was enhanced in nodules, stems, and leaves, while concentrations of Mn and B also showed improvement	(Medina-Velo et al., 2017)
	50, 100 and 150 mg/L	*Phaseolus vulgaris* L.	Pot culture	Seed priming and foliar spray	Foliar application resulted in enhanced vegetative characteristics, yield, and crop quality	(Mahdieh et al., 2018)

	1 mg/L	*Lens culinaris* Medik.	Field experiment	Foliar spray	Seed weight, number of pods, and overall plant yield was increased	(Kolenčík et al., 2022b)
	10, 20, 30, and 40 mg/L	*Phaseolus vulgaris* L.	Field experiment	Foliar spray (spray after 20 days)	The number, fresh weight, and dry weight of leaves and branches were also enhanced along with improved seed production	(Dina M. Salama et al., 2019)
	40, 80, and 160 mg/kg	*Glycine max* (L.) Merr. cv. Kowsar	Polythene bags	Soil application	Improved seed yield	(Yusefi-Tanha et al., 2020a)
	250 mg/L	*Phaseolus vulgaris* L.	Pot culture	Foliar and soil application	Foliar application showed positive effects on peroxidase and catalase activity as well as increased Zn content in leaves, and plant height	(Salehi et al., 2021b)
	200 mg/kg	*Glycine max* (L.) Merr.	Pot culture	Soil application	Root architecture and Zn accumulation were improved leading to better nutrient and water uptake	(Yusefi-Tanha et al., 2022b)

	1.5 mg/L	*Phaseolus vulgaris* L., *Vigna radiata* L., and *Vigna unguiculata* L.	Hogland solution	Roots dipped in Hogland solution for 24 hours	Increased nitrogenase activity	(Kumar et al., 2015)
	25 mg/L	*Phaseolus Vulgaris* L. cv. Strike	Plastic pot culture	Foliar application	Improved biomass accumulation and production	(Palacio-Márquez et al., 2021a)
	300, 600, and 1000 mg/kg	*Phaseolus Vulgaris* L.	Pot culture	Mixed in soil	Increased plant productivity at lower concentration, but Zn level, SOD, APX, and CAT activity	(Akanbi-gada et al., 2019)
	20 mg/L	*Vigna radiata* L.	Pot culture	Foliar application	Improved Zn and protein content, leaf area index, 1000-seed weight, seed yield, root biomass, and active nodule content	(Sahoo et al., 2021)
	10, 20, and 50 mg/L	*Pisum sativum* L.	Pot culture	Foliar application	Improved plant height and yield	(Verma et al., 2023)

Negative effects						
ZnO	400 mg/kg	*Glycine max* (L.) Merr. cv. Kowsar	Polythene bags	Soil application	Increased oxidative stress	(Yusefi-Tanha et al., 2020b)
	2000 mg/L	*Phaseolus vulgaris* L.	Pot culture	Foliar and soil application	Decreased photosynthetic efficiency and compromised antioxidant defense system as well as increased protein degradation and lipid peroxidation	(Salehi et al., 2021c)
	2000 mg/L	*Phaseolus vulgaris* L.	Pot culture	Foliar application	Tapetum abnormalities, cell apoptosis, and reduced seed development, seed dry weight, and yield were observed	(Salehi et al., 2022)
	250 and 750 mg/L	*Medicago sativa* L.	Pot culture	Soil application	Decreased nodule number and root nodule area, and nitrogen fixation	(Sun et al., 2022)

	500 mg/kg	*Glycine max* (L.) Merr.	Pot culture	Soil application	Reduction in root architecture and Zn accumulation, nutrient, and water uptake	(Yusefi-Tanha et al., 2022a)
	1000 mg/L	*Pisum sativum* L.	Petriplate	Added in petriplate	Decreased root elongation by 20-30%	(Stałanowska et al., 2023)
	600 and 1000 mg/kg	*Phaseolus Vulgaris* L.	Pot culture	Mixed in soil	Decreased yield parameters and increased the duration of flowering and fruit emergence	(Akanbi-gada et al., 2019)
	1.5 and 10 mg/L	*Cyamopsis tetragonoloba*, *Vigna aconitifolia* Jacq., *Vigna radiata* L., and *Vigna unguiculata* L.	Hogland solution	Roots dipped in Hogland solution containing ZnO NPs for 24 hours	Decreased nitrogenase activity in cluster bean, green gram, and cowpea at 1.5 µg/mL but in moth bean nitrogenase activity reduced at both concentration	(Kumar et al., 2015)

	100 (priming), 250, 500, and 750 mg/L (chronic effects)	*Pisum sativum* L.	1% water agar in large Petri dishes for priming and 150 mL of FP medium with ZnO NPs for chronic effects	Seed priming	Reducing the count of first and second-order lateral roots, stem length, leaf surface area, and transpiration, affecting bacterial surface, root nodulation, nitrogen fixation, and triggered early senescence of nodules	(Huang et al., 2014)

COPPER OXIDE

Copper (Cu) is a vital redox metal that serves as a cofactor for various proteins, including Cu/Zn-superoxide dismutase, cytochrome C oxidase, plastocyanin, and ethylene receptors. It's role in vital biological processes such as iron oxidation, carbohydrate metabolism, and chlorophyll synthesis are well established in plants (Mir et al., 2021). Insufficient copper levels can disrupt critical physiological functions such as nitrogen metabolism and respiration, resulting in oxidative stress and the accumulation of detrimental free radicals. While the effects of bulk CuO on plants have been extensively studied, the implications of CuONPs on legume crops are still under investigation.

Recent investigations provided insights into the influence of CuONPs on legumes **(Table 3).** For instance, priming peanuts (*Arachis hypogea* L.) with CuONPs resulted in enhanced protein content without compromising overall plant growth (S Suresh et al., 2016b). Similar positive effects on shoot length, root length, leaf number, and elemental composition were observed in peas (*Pisum sativum* L.) treated with CuONPs. In comparison to untreated plants, the presence of nickel in the pods decreased when conventional copper oxide was replaced with CuONPs (Ochoa et al., 2017a). Another study demonstrated that the addition of CuONPs (100 mg/kg) with indole-3-acetic acid (IAA; 100 μM) led to increased iron and aluminum content in pea seeds, thereby augmenting their nutritional value (Ochoa et al., 2018). This enhanced iron level could be attributed to the activity of iron and copper-linked reductases in cell membranes. Copper oxide nanoparticles (CuONPs) revealed concentration-dependent effects on plant physiology. Gautam et al. reported significant changes in soybean at 200 mg/L, while toxicity was observed at higher concentrations (Gautam et al., 2016). Singh et al. highlighted toxic effects on *Vigna radiata* L. germination and seedling growth, with both adverse and potentially favorable outcomes at different concentrations (Singh et al., 2017). Moreover, low concentrations of CuONPs (1 and 10 mg/L) positively influenced germination and root growth in common bean (*Phaseolus vulgaris* L.) plants, whereas high concentrations (100 and 1000 mg/L) exhibited adverse effects (Duran et al., 2017). Liu et al. demonstrated concentration-dependent effects of copper oxide nanoparticles resulting in increased copper content, oxidative stress and gene expression in soybean (*Glycine max* (L.) Merr.) roots (Liu et al., 2021). Karmous et al. found positive impacts at lower concentrations (10 mg/L) in mungbeans (*Vigna radiata* L.) but detrimental effects at higher levels (100–2000 mg/L) of copper oxide nanoparticles (Karmous et al., 2022). CuONPs and CuO coated with 3-aminopropyl triethoxysilane nanoparticles applied to mungbean seeds were found to enhance water absorption and germination rates, indicating improved metabolic processes (Sarkar et al., 2021). However, the utilization of smaller CuONPs (25 nm) resulted in increased copper uptake and nutritional value but led to reduced seed yield and antioxidant activity in soybean (*Glycine max* (L.) Merr.) seeds, yielding contradictory outcomes (Yusefi-Tanha et al., 2020c). This disparity was attributed to the higher accumulation of nano-Cu ions within the soybean plant system (Yusefi-Tanha et al., 2020d). Adverse effects of CuONPs on green pea (*Pisum sativum* L.) (1 mg/L) and slender sesbania plants (*Sesbania grandiflora* L.) (100, 200, 300, and 400 mg/L) were observed, including decreased seed germination, stunted seedlings, and slowed root development. These consequences were associated with diminished photosynthetic activity and metabolic processes (Ghosh et al., 2017; Santos et al., 2021). Similarly, Kavitha et al. demonstrated that higher concentrations of CuONPs (500 mg/L) adversely affected seed germination and cyto-physiological activities in mungbean (*Vigna radiata* L.) plants by inducing alterations in chromosomal structure and mitotic index (Kavitha et al., 2022). More recently, a study on common beans (*Phaseolus vulgaris* L.) revealed detrimental effects of CuONPs, such as chromosomal breakage, genetic material damage, and cell distortion at various stages of cell division (metaphase, anaphase, and telophase) in root cells (Tasar, 2022). It is crucial to prioritize research into the molecular and physiological mechanisms governing the impact of CuO NPs on plant growth, development, and metabolic processes. These insights will guide the development of customized strategies, ensuring the safe and effective use of CuO NPs in agriculture.

479 **Table 3: Effects of various concentration of copper oxide nanoparticles on legume plants**

Type of MONPs	**Effective MONPs Concentrations**	**Plant used**	**Experimental Type**	**Mode of Treatment**	**Effects**	**Reference**
Positive Effects						
CuO	500 mg/L	*Arachis hypogea* L.	Pot culture	Seed priming	Influenced protein content positively in leaves	(S Suresh et al., 2016b)
	50 mg/kg	*Pisum sativum* L.	Pot culture	Mixed in soil	Improved plant growth and increased Fe and Ni content in pods	(Ochoa et al., 2017b)
	100 mg/kg	*Pisum sativum* L.	Pot culture	Mixed in soil	Increased Fe, B, and Al content	(Ochoa et al., 2018)
	1 and 10 mg/L	*Phaseolus vulgaris* L.	Petriplate	Seed priming	Stimulated root growth and seed germination	(Duran et al., 2017)
	16, 48, and 80 mg/L	*Vigna radiata* L.	Petriplate	Seed priming	Enhanced seed imbibition and germination rate	(Sarkar et al., 2021)
	50, 100, 200, and 500 mg/kg	*Glycine max* (L.) Merr.	Polythene pot culture	Mixed in soil	Increased Cu^{2+} uptake in leaves, shoots, roots, and seeds	(Yusefi-Tanha et al., 2020c)
	10 mg/L	*Vigna radiata* L.	Petriplate	Impregnated in filter paper	Improved essential minerals, free amino acids, total soluble sugars,	(Karmous et al., 2022)

					antioxidant polyphenols and flavonoids content	
	200 mg/L	*Glycine max* (L.) Merr.	Murashige and Skoog	Mixed in solution	Increased plant germination, shoot and root length, vigor index and total chlorophyll content	(Gautam et al., 2016)
Negative effects						
CuO	100 and 1000 mg/L	*Phaseolus vulgaris* L.	Petriplate	Seed priming	Decreased seed germination rate and inhibited root growth	(Duran et al., 2017)
	0.25, 0.50, and 1.00 mg/L	*Lathyrus sativus* L.	Petriplate	Impregnated in filter paper	Inhibited seed germination and resulted in reduced seedling growth	(Ghosh et al., 2017)
	50, 100, 200, and 500 mg/kg	*Glycine max* (L.) Merr. cv. Kowsar	Polythene pot culture	Mixed in soil	Led to decreased seed yield and reduced antioxidant enzyme activity	(Yusefi-Tanha et al., 2020d)
	100, 200, 300, and 400 mg/L	*Sesbania virgata* (Cav.) Poir.	Petriplate	Seed priming	Resulted in reduced root length	(Santos et al., 2021)
	500 mg/L	*Vigna radiata* L.	Petriplate	Impregnated in filter paper	Decreased seed germination and negatively affected cyto-physiological activity	(Kavitha et al., 2022)
	50, 150, and 300 mg/L	*Phaseolus vulgaris* L.	Petriplate	Impregnated in filter paper	Induced increased chromosomal damage and cell distortion at	(Tasar, 2022)

					different phases of cell division in the roots	
	2, 5 and 10 mg/L	*Glycine max* (L.) Merr.	Plastic pot culture	Root treatment	Increased ROS, MDA, relative electrical conductivity, inhibit root growth, destruction in pro-meristem, primary meristem, meristematic zone, and decreased mitotic index	(Liu et al., 2021)
	400, 600, and 800 mg/L	*Glycine max* (L.) Merr.	Murashige and Skoog medium	Mixed in solution	Reduced plant germination, shoot and root length, vigor index and total chlorophyll content	(Gautam et al., 2016)
	1, 10, 100, 500, and 1000 mg/L	*Vigna radiata* L.	Petriplate	Seed priming	Inhibited germination, seedling growth, and decreased sugar and protein content	(Singh et al., 2017)
	100, 1000, and 2000 mg/L	*Vigna radiata* L.	Petriplate	Impregnated in filter paper	Altered quality of phenolic compounds, macronutrients (Na, Mg, and Ca) and micronutrients (Cu, Fe, Mn, Zn, and K).	(Karmous et al., 2022)

TITANIUM DIOXIDE

Titanium is a beneficial element that plays a significant role in nitrogen fixation, nutrient absorption, and stimulation of enzymatic activities, and exhibits a hormesis effect in legume roots (Lyu et al., 2019). Recently, there has been growing interest in utilizing manufactured TiO_2 NPs in agriculture to enhance crop yield. Current studies have generally reported more beneficial effects of TiO_2 NPs on leguminous plants compared to detrimental outcomes **(Table 4).** For example, AL-oubaidi and Kasid observed enhanced fresh and dry weight and the generation of secondary metabolites in chickpea (*Cicer arietinum* L.) callus embryos treated with TiO_2 NPs (AL-oubaidi and Kasid, 2015). Foliar application of TiO_2 NPs to common beans (*Phaseolus vulgaris* L.) at concentrations ranging from 10, 20, 30, and 50 mg/L increased chlorophyll content, antioxidant enzyme activity, 8-deoxy-2-hydroxyguanosine, seed protein, grain weight, and crop yield (A Ebrahimi et al., 2016; Ahmad Ebrahimi et al., 2016). Similarly, Khan et al. found that the response of lentil (*Lens culinaris* Medik.) plants to TiO_2 NPs was concentration-dependent, with lower concentrations positively influencing parameters such as vigor index, seed germination, photosynthetic pigments, and biomass, while higher concentrations had adverse impacts, including increased lipid peroxidation, DNA damage, and reactive oxygen species generation (Khan et al., 2019). Priya et al. demonstrated that applying TiO_2 NPs at a concentration of 10 mg/L improved various seedling traits in mungbean (*Vigna radiata* L.) plants, including germination rate, root and shoot length, fresh and dry weight, and vigor index (Priya et al., 2020).

Furthermore, Verma et al. showed that common bean plants responded favorably to lower doses of TiO_2 NPs (30 and 60 mg/L), which increased shoot and root growth, leaf number, chlorophyll content, and seed weight (Verma et al., 2020). However, higher doses (240 mg/L) negatively impacted these parameters. In kidney bean (*Phaseolus vulgaris* L.) seedlings, seed priming with TiO_2 NPs at various doses (ranging from 0.10% to 2.50%) increased root and shoot length and antioxidant activity (Paul et al., 2020a). Similarly, Mathew et al. found that applying TiO_2 NPs to mungbean (*Vigna radiata* L.) plants at various concentrations (25 to 250 mg/L) enhanced seed germination and growth rate compared to the control (Mathew et al., 2021). Further, it was found that pea (*Pisum sativum* L.) defense mechanisms restricting water uptake were overcome by TiO_2 photocatalytic activity, stimulating photosynthesis. The impact of TiO_2 nanoparticles on photosynthesis process in green pea was investigated through hydroponic cultivations at three Ti levels (10, 50, and 100 mg/L). The nanoparticles penetrated plant tissues, altering CO_2 assimilation and gas exchange parameters. The most significant effects were observed at 50 mg/L TiO_2 nanoparticles, enhancing photosynthesis efficiency and related parameters. Changes in element concentrations, particularly Cu, Zn, Mn, and Fe, were noted, emphasizing their involvement in photosynthesis (Skiba et al., 2024). Evaluating nanosized titanium dioxide ($nTiO_2$) interaction with *Vigna radiata* L. demonstrated improved plant performance, increased seed germination, root and shoot length, and elevated chlorophyll, flavonoid, and phenolic contents. Despite mild oxidative stress, antioxidant enzyme activity countered lipid peroxidation (Thakur et al., 2021).

Kushwah et al. discovered that concentrations of TiO_2 NPs between 15 and 240 mg/L enhanced root growth in green pea (*Pisum sativum* L.) plants but decreased the number and weight of germinated seeds (Kushwah et al., 2022a). Higher concentrations of nanoparticles further reduced seed germination, seed weight, survival rate, and overall plant growth compared to the control. Kushwah and Patel reported that faba beans (*Vicia faba* L.) exposed to higher concentrations of TiO_2 NPs exhibited aberrant chromosomal structure and meiotic activity (Kushwah and Patel, 2020). TiO_2 NPs exposure during seed germination in pea seeds (50 mg/L) was assessed over five days. There were adverse effects on germination rate, mean daily germination, tissue dry weights, water supply, solute leakage, oxidative stress, and antioxidant enzyme activities. Oxidative and metabolic disturbances were identified as significant factors influencing pea (*Pisum sativum* L.) seed germination. These studies suggested TiO_2 nanoparticles could affect plant growth and physiological processes, but the outcomes depend on concentration, exposure duration, and plant species (Basahi, 2021). So, it is essential to identify the appropriate concentration range of TiO_2 NPs that maximizes benefits while minimizing potential risks for different leguminous crops. Further research is necessary to fully understand the precise mechanisms by which TiO_2 NPs affect plant growth, development, and biochemical activity. This knowledge will be crucial for maximizing the potential use of TiO_2 NPs in agriculture. Additionally, long-term studies are needed to assess the ecological risks and feasibility of utilizing TiO_2 NPs in agricultural practices.

537 **Table 4: Effects of various concentration of titanium dioxide nanoparticles on legume plants**

Type of MONPs	**Effective MONPs Concentrations**	**Plant used**	**Experimental Type**	**Mode of Treatment**	**Effects**	**Reference**
Positive Effects						
TiO_2	4.5 and 6 mg/L	*Cicer arietinum* L.	Culture vessels	Added in culture medium	Increased callus fresh weight, dry weight, and secondary metabolite production	(AL-oubaidi and Kasid, 2015)
	10, 20, 30, and 50 mg/L	*Phaseolus vulgaris* L.	Factorial experiment	Spraying at different plant growth stages	Enhanced chlorophyll a content, seed protein levels, grain weight, crop yield, antioxidant activity, and the 8-deoxy-2-hydroxyguanosine content	(A Ebrahimi et al., 2016; Ahmad Ebrahimi et al., 2016)
	10 mg/L	*Vigna radiata* L.	Glass plate	Seed priming	Improved seed germination rates, root-shoot length, total fresh and dry weight, and vigor index	(Priya et al., 2020)
	100, 250, 500, 750, 1000, 1500, 2000, and 2500 mg/L	*Phaseolus vulgaris* L.	Germination paper	Seed priming	Increased shoot-root length, lateral root formation, and antioxidant enzyme activities	(Paul et al., 2020b)
	25, 50, 200, 150, 200, and 250 mg/L	*Vigna radiata* L.	Petriplate experiment	Seed priming	Increased germination indices	(Mathew et al., 2021)

	15, 30, 60, 120, and 240 mg/L	*Pisum sativum* L.	Pot experiment	Seed priming	Increased root growth but decreased shoot growth, seed germination, and weight	(Kushwah et al., 2022b)
	10, 50, and 100 mg/L	*Pisum sativum* L.	Hydroponic culture	Mixed in solution	Increased photosynthesis efficiency, transpiration, stomatal conductance, rubisco and ETC activity, micro and macronutrients	(Skiba et al., 2024)
	10 and 100 mg/L	*Vigna radiata* L.	Hydroponic culture	Mixed in solution	Increased seed germination, root and shoot length, fresh and dry weight, chlorophyll, flavonoid, phenolic content	(Thakur et al., 2021)
Negative Effects						
TiO_2	25, 50, 75, 100, and 200 mg/L	*Lens culinaris* Medik.	Petriplate and pot culture	Seed priming	Increased DNA damage, lipid peroxidation, and reactive oxygen species (ROS) accompanied by a decrease in the vigor index, seed germination, fresh weight, dry weight, and photosynthetic pigments	(Khan et al., 2019)
	15, 30, 60, 120, and 240 mg/L	*Vicia faba* L.	Pot experiment	Seed priming	Reduction in seed germination, seed weight, rate of survival, plant growth, and an increase in chromosomal abnormalities	(Kushwah and Patel, 2020)
	15, 30, 60, 120, and 240 mg/L	*Phaseolus vulgaris* L.	Plastic pot experiment	Exogenous treatment	Decreased the root and shoot growth rate of seedlings, plant height, leaf number, seed weight, and chlorophyll content	(Verma et al., 2020)

	50 mg/L	*Pisum sativum* L. cv. Merveille de Kelvedon	Petriplate	Moistened filter paper	Decreased germination rate, mean daily germination, embryo, coat, and cotyledon dry weights, water supply, solute leakage, and elevated oxidative stress and antioxidant enzyme activities	(Basahi, 2021)

CERIUM OXIDE

CeO_2 NPs have attracted interest recently due to their potential to increase crop yield (Prakash et al., 2021b). Applying cerium to soil positively impacts overall plant growth by enhancing nitrogen assimilation and photosystem II activity (Awad et al., 2023). However, the effects of cerium on plants depend on several factors, like concentration, exposure time, and plant species **(Table 5).** Higher concentrations of CeO_2 NPs were observed to reduce Mg, K, Ca, Cu, Mn, and Fe in roots and shoots in peas (*Pisum sativum* L.) (Skiba et al., 2021). According to Cao et al., CeO_2 NPs in soybeans at 100 mg/kg increased the activity of the enzyme rubisco carboxylase, the rate of photosynthetic reaction, and plant development (Cao et al., 2017). In comparison, higher concentrations had the opposite effects. With 100 and 500 mg/kg concentrations, CeO_2 NPs accelerated photosynthetic rate and nodule formation in soybean (*Glycine max* (L.) Merr.) plants (Stowers et al., 2018). Similar improvements in shoot elongation, biomass, stress-related enzyme activity, and antioxidants were seen in common beans (*Phaseolus vulgaris* L.) when CeO_2 NPs were applied at 50 and 100 mg/L (Salehi et al., 2020). When applied foliarly to mungbeans, CeO_2 NPs at dosages of 250 and 500 mg/L increased dry matter and antioxidant activity, but at 1000 mg/L, they had the opposite effect (Kamali-Andani et al., 2022).

In contrast, a study on common bean plants found that foliar treatment with CeO_2 NPs (250, 500, 1000, and 2000 mg/L) resulted in altered proteomics and metabolomics, electrolyte leakage, stomatal length, increased osmolytes and phytosiderophores concentration, lipid degradation, and changes in the electron transport chain machinery and photosynthesis rate (Salehi et al., 2018b). Common beans were subjected to a foliar application of CeO_2 NPs (250–2000 mg/L), resulting in modifications to the proteome, metabolomics, electrolyte leakage, stomatal length, osmolyte concentration, lipid breakdown, and photosynthesis rate (Salehi et al., 2018b). Moreover, the application of CeO_2 NPs at 2000 mg/L resulted in adverse effects such as chromosomal abnormalities, pollen abortion, and lower yield (Salehi et al., 2021a). The levels of Cu, Fe, Zn, and Mn in pea (*Pisum sativum* L.) plants were also decreased by CeO_2 NPs (Skiba and Wolf, 2019). Further, Viezcas found CeO_2 NPs adversely affected soybean (*Glycine max* (L.) Merr.) plant growth and nitrogen fixation. However, in Mesquite (*Prosopis juliflora* (Sw.) DC.) plants, the exposure of CeO_2 NPs showed increased cerium uptake in roots. His study pointed out the necessity of assessing nanoparticle transfer into the food chain, particularly in plants' reproductive/edible parts, highlighting potential concerns for plant health and food safety

(Hernandez Viezcas, 2013). Research on nutrient uptake, photosynthesis, and plant metabolism must be done in-depth to understand how CeO_2 NPs interact with plants. Standardized techniques and comparative studies under controlled conditions will improve the validity and comparability of findings across legume species, helping establish guidelines for the safe and efficient use of CeO_2 NPs in agriculture.

575 **Table 5: Effects of various concentration of cerium oxide nanoparticles on legume plants**

Type of MONPs	**Effective MONPs Concentrations**	**Plant used**	**Experimental Type**	**Mode of Treatment**	**Effects**	**Reference**
Positive Effects						
CeO_2	100 mg/kg	*Glycine max* (L.) Merr. var. 'Tohya'	Pot culture	Mixed in soil	Improved photosynthetic rate, rubisco activity, and plant growth were observed	(Cao et al., 2017)
	100 and 500 mg/kg	*Glycine max* (L.) Merr.	Pot culture	Added in soil	Increased net photosynthetic rate and the number of nodules	(Stowers et al., 2018)
	50 and 100 mg/L	*Phaseolus vulgaris* L. var. khomain	Agar medium	Mixed with agar medium	Proline content, shoot elongation, root, and shoot fresh weight, JAs, and antioxidant content were enhanced	(Salehi et al., 2020)
	250 and 500 mg/L	*Vigna radiata* L.	Pot culture	Foliar application	Dry matter and antioxidant enzymatic activity showed improvement	(Kamali-Andani et al., 2022)
Negative Effects						
CeO_2	500 mg/kg	*Glycine max* (L.) Merr. var. 'Tohya'	Pot culture	Mixed in soil	Decreased in the photosynthetic rate, rubisco activity, and plant growth	(Cao et al., 2017)

	250, 500, 1000, and 2000 mg/L	*Phaseolus vulgaris* L.	Pot culture	Foliar and soil application	Increased electrolyte leakage, stomatal length, osmolytes, phytosiderophores concentration, and lipid degradation	(Salehi et al., 2018b)
	200 mg/L	*Pisum sativum* L.	Hydroponic	Mixed with Hoagland nutrient solution	Zinc concentration, root length, metal concentration, and solution-root transfer were restricted	(Skiba and Wolf, 2019)
	50, 100, and 500 mg/kg	*Glycine max* (L.) Merr.	Pot culture	Added in soil	Diminished plant growth and nitrogen fixation	(Hernandez Viezcas, 2013)
	2000 mg/L	*Phaseolus vulgaris* L.	Pot culture	Foliar spray	Pollen showed increased structural and chromosomal damage, resulting in decreased seed yield	(Salehi et al., 2021a)
	1000 mg/L	*Vigna radiata* L.	Pot culture	Foliar application	Starch granules, ROS, and chloroplast swelling increased, while photosynthetic pigments, nitrogen fixation, and plant growth were reduced	(Kamali-Andani et al., 2022)

SILICON DIOXIDE

Silicon (Si) positively affects crop productivity and stress tolerance when applied in bulk form (Shivaraj et al., 2022). In the case of rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) plants grown in soils contaminated with As, Cd, and Cr, using SiO_2 NPs has shown promising results (Manzoor et al., 2022; Wang et al., 2021). Based on existing research conducted on leguminous plants, the effects of SiO_2 NPs have been observed to be predominantly detrimental rather than advantageous **(Table 6).** Ross et al. observed reduced growth in mungbean (*Vigna radiata* L.) plants treated with SiO_2 NPs compared to the control group (Ross et al., 2016). This could be attributed to the fact that silicon nanoparticles possess the potential to influence nutrient absorption, cellular activities, and hormonal balance in mungbean physiology, consequently hindering growth processes.

Similarly, Thabet et al. reported detrimental effects on germination, shoot length, and chromosomal structure in broad bean (*Vicia faba* L.) seeds treated with SiO_2 NPs at 25, 50, and 75 mg/L 14 concentrations. On the other hand, Kashyap and Siddiqui discovered that pea (*Pisum sativum* L.) plants exhibited enhanced growth, chlorophyll and carotenoid content, proline content, plant length, total fresh weight, dry weight, and nodule number when treated topically with SiO_2 NPs at low concentration (100 mg/L) (Kashyap and Siddiqui, 2021). They suggested that pea plants' interaction with SiO_2 NPs at a lower concentration could promote nutrient absorption, physiological activities, and symbiotic interactions with nitrogen-fixing bacteria. Given the distinctive biological characteristics of leguminous plants and their symbiotic relationships with nitrogen-fixing bacteria, it is imperative to conduct further investigation to fully understand the precise interactions and potential differential effects of SiO_2 NPs in these plants.

Table 6: Effects of various concentration of silicon dioxide nanoparticles on legume plants

Type of MONPs	Effective MONPs Concentrations	Plant used	Experimental Type	Mode of Treatment	Effects	Reference
Positive Effects						
SiO_2	100 mg/L	*Pisum sativum* L.	Pot culture	Foliar and soil application	Increased levels of proline, chlorophyll, and carotenoids, along with higher fresh and dry weight, increased plant length, and number of nodules	(Kashyap and Siddiqui, 2021)
Negative Effects						
SiO_2	20 mg/L	*Vigna radiata* L.	Petriplate	Nanopore solution	Reduced growth of seedlings	(Ross et al., 2016)
	25, 50, and 75 mg/L	*Vicia faba* L.	Petriplate	Seed priming	Decreased germination percentage, shorter shoot length, and increased occurrence of chromosomal aberrations	(Thabet et al., 2019)

MAGNESIUM OXIDE

Magnesium (Mg), an essential macronutrient and a pivotal component of the chlorophyll molecule, is critical in regulating photosynthetic enzymes, plant development, and physiological processes. It is also indispensable for synthesizing and functioning nucleic acids and adenosine triphosphate (ATP) (Leher, 2022). Several studies have explored the impacts of MgO NPs on legume plants **(Table 7).** For instance, Elakkiya et al. conducted a study on long beans (*Vigna unguiculata* L. ssp. sesquipedalis), elucidating that the application of MgO NPs at a concentration of 5 mg/L led to an increase in chlorophyll content (Elakkiya V. et al., 2020). Improved chlorophyll content could enhance photosynthetic efficiency, increasing plant growth energy production. Similarly, Kocak et al. observed that MgO NPs, at varying concentrations (185, 370, and 555 mg/L), enhanced shoot formation, with the highest efficacy observed at 555 mg/L. Additionally, applying MgO NPs at 370 mg/L resulted in an augmentation of shoot number, shoot length, root number, root formation, and root length in cowpeas (*Vigna unguiculata* L.) (Koçak et al., 2021). Thus, it could be inferred that MgO nanoparticles positively impacted metabolic processes, enhancing nutrient uptake and utilization, ultimately resulting in improved plant growth, shoot formation, and root development. In the case of mungbean plants (*Vigna radiata* L.), Abdallah et al. reported that MgO NPs, at a concentration of 100 mg/L, positively influenced shoot-root fresh weight, dry weight, as well as the number and length of root nodules (Abdallah et al., 2022). This may be attributed to improved nutrient availability, creating a conducive environment for symbiotic interactions with nitrogen-fixing bacteria. Similarly, Sharma et al. documented that treatment with MgO NPs enhanced chlorophyll, carbohydrate, protein, phenol, and flavonoid levels (Priya Sharma et al., 2022a, 2022b, 2022c). Furthermore, it stimulated root and shoot elongation, along with augmenting the activity of antioxidant enzymes such as catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase (APX) in horse gram and black chickpea (*Cicer arietinum* L.) plants. Additionally, MgO NPs, sized 35–40 nm, positively impacted cowpea plantlets *in vitro*. Higher concentrations (555 mg/L) increased callus formation by 25%, while 370 mg/L enhanced shoot multiplication, indicating potential efficiency improvements in cowpea (*Vigna unguiculata* L.) tissue culture (Koçak et al., 2023). Recently, Abdelfattah et al. innovatively synthesized MgO NPs using *Saccharomyces cerevisiae* extract, with notable impacts on cowpea *in vitro* parameters (Abdelfattah et al., 2023). At 200 mg/L concentration, the MgO NPs demonstrated significant enhancements in shoot length, shoot dry-weight, and root dry-weight by 27.35%, 45.09%, and

31.91%, respectively. Moreover, MgO NPs increased photosynthetic pigments and biochemical constituents, showcasing insecticidal efficacy against cowpea pests and dose-dependent effects on rats' biochemical and histopathological profiles. Nevertheless, it is noteworthy that certain studies have reported adverse effects of MgO NPs **(Table 7).** Sharma et al. found that exposure to MgO NPs resulted in increased toxicity, leading to alterations in root length, chlorophyll content, plant biomass, antioxidant activity, non-enzymatic antioxidants, carbohydrate, and protein accumulation in black gram (*Cicer arietinum* L.), mungbean (*Vigna radiata* L.), and lentil (*Lens culinaris* Medik.) plants. Consequently, further research endeavors are necessary to elucidate the factors contributing to the variability in the response of legume plants to MgO NPs, including disparities in nanoparticle characteristics, plant species, experimental conditions, and exposure duration (P Sharma et al., 2022; Priya Sharma et al., 2022a, 2022c; Sharma et al., 2021).

Table 7: Effects of various concentration of magnesium oxide nanoparticles on legume plants

Type of MONPs	**Effective MONPs Concentrations**	**Plant used**	**Experimental Type**	**Mode of Treatment**	**Effects**	**Reference**
Positive Effects						
MgO	5000 mg/L	*Vigna unguiculata* L. ssp. sesquipedalis	Petriplate	MS medium	Increased chlorophyll concentration	(Elakkiya V. et al., 2020)
	370 and 555 mg/L	*Vigna Unguiculata* L.	Petriplate	MS medium	Improved number of shoots, roots, root length, shoot length, and callus formation	(Koçak et al., 2021)
	100 mg/L	*Vigna radiata* L.	Plastic cups	Added in soil	Enhanced shoot and root fresh weight, dry weight, root and shoot length, and root nodule number	(Abdallah et al., 2022)
	10, 50, 100, and 150 mg/L	*Macrotyloma uniflorum* (Lam.) Verdc. and *Cicer arientinum* L.	Petriplate	Seed priming	Increased shoot length, biomass, chlorophyll content, accumulation of carbohydrates, proteins, phenols, flavonoids, and antioxidants	(Priya Sharma et al., 2022b, 2022a)
	370 and 555 mg/L	*Vigna unguiculata* L.	Petriplate	MS medium	Improved shoot, root, and callus formation, shoot and root length, and plantlets' growth	(Koçak et al., 2023)

	150 and 200 mg/L	*Vigna unguiculata* L.	Pot culture	Foliar spray	Enhanced shoot length, shoot and root dry-weight, photosynthetic pigments, soluble proteins, and carbohydrates	(Abdelfattah et al., 2023)
Negative Effects						
MgO	10, 50, 100, and 150 mg/L	*Vigna mungo* L.	Petriplate	Seed priming	Decreased shoot and root length, chlorophyll content, biomass, phenol and flavonoid content, and antioxidant levels	(Sharma et al., 2021)
	10, 50, 100, and 150 mg/L	*Vigna radiata* L.	Petriplate	Seed priming	Reduced plant growth, fresh biomass, chlorophyll and protein content, enzymatic and non-enzymatic levels	(P Sharma et al., 2022)
	10, 50, 100, and 150 mg/L	*Lens culinaris* Medik.	Petriplate	Seed priming	Decreased shoot and root length, carbohydrate, chlorophyll, flavonoid, and protein content, as well as antioxidant levels	(Priya Sharma et al., 2022a)

Effect on the nitrogen fixation

Nitrogen fixation is a vital metabolic process that enhances the productivity of leguminous crops by converting atmospheric nitrogen into ammonium with the help of diazotrophic microorganisms, such as *Rhizobium*. These microorganisms form a symbiotic relationship with legume plants within root nodules and utilize the nitrogenase enzyme for this conversion (Rapson et al., 2020). Improving the symbiotic interaction between plants and bacteria is crucial for enhancing legume production, and various nanoparticles, including metal oxide nanoparticles (MONPs), have been investigated for this purpose. For instance, Muñoz-Márquez et al. (Muñoz-Márquez et al., 2022) applied nano-Mo in green beans (*Phaseolus vulgaris* L.), Osman et al. (Osman et al., 2020) used MoO_3 NPs in dry beans (*Phaseolus vulgaris* L.), and Alwan et al. (S. Alwan et al., 2022) employed Fe_2O_3 NPs in broad beans (*Vicia faba* L.) for improving and understanding the symbiotic interaction between plants and bacteria. However, the effects of MONPs on plants depend on their type and concentration, exhibiting beneficial effects at lower levels but detrimental effects at higher levels. For instance, Kumar et al. **(Table 2)** demonstrated that ZnO NPs (1.5 mg/L) improved the activity of the nitrogenase enzyme in nodulated roots of green gram (*Vigna radiata* L.), cluster bean (*Cyamopsis tetragonoloba* (L.) Taub.), and cowpea (*Vigna unguiculata* L.) plants, while higher concentrations (10mg/L) of ZnO NPs reduced the activity (Kumar et al., 2015). Similarly, applying Fe_2O_3 or Fe_3O_4 NPs enhanced nitrogen fixation and nitrogenase activity in soybeans (*Glycine max* (L.) Merr.) and green beans (*Phaseolus vulgaris* L.) (De Souza-Torres et al., 2021b; GUTIÉRREZ-RUELAS et al., 2021; Huang et al., 2014; Yang et al., 2020). Nevertheless, conducting a comparative study evaluating different MONPs and their varying concentrations under controlled conditions would be beneficial for identifying the optimal and safest formulations to enhance the symbiotic interaction between bean plants and diazotrophic bacteria.

On the contrary, several studies have observed undesirable effects when exposing garden pea plants (*Rhizobium leguminosarum* bv. viciae 3841) to TiO_2 and ZnO NPs. These effects include a decrease in the number of secondary lateral roots, impairment of the nodulation process and nodule development, and inhibition of nitrogen fixation. Furthermore, the application of ZnO NPs was found to disrupt the symbiotic relationship between Rhizobium and legume plants, resulting in reduced nodulation and impaired nitrogen fixation in lentil (*Lens culinaris* Medik.) and alfalfa (*Medicago sativa* L.) plants. These findings indicate the potential toxic effects of nanoparticles on the nitrogen fixation process (Kamali-Andani et al., 2022; Siddiqui et al., 2018; Sun et al., 2022). To optimize the use of MONPs and minimize any potential negative effects, a comprehensive understanding of how MONPs interact with legume plants and diazotrophic bacteria, affecting nodulation, nodule formation, nitrogenase activity, and overall nitrogen fixation efficiency, is essential. Additionally, it is critical to investigate the persistence, mobility, and accumulation of MONPs in soil and their impact on microbial populations, soil health, and ecosystem dynamics.

Effect of metal oxide nanoparticles under abiotic stress conditions

Reducing agricultural land area due to abiotic stresses such as salinity, drought, cold, water scarcity, temperature fluctuations, and heavy metal contamination poses a significant challenge, especially given the increasing global population. Nowadays, scientists are investigating the use of metal and metal oxide nanoparticles to address the impact of these abiotic stresses on leguminous plants (Sarraf et al., 2022; Ulhassan et al., 2022). As a result, various scientific studies have been conducted to determine the possible benefits of MONPs on leguminous crops **(Table 8).** In a study conducted by Gaafar et al., found that the application of zinc oxide nanoparticles (ZnO NPs) mitigated salt stress in soybean (*Glycine max* (L.) Merr.) plants (Gaafar et al., 2020). The most favorable outcomes were observed with a 50 mg/L concentration of ZnO NPs, resulting in enhanced growth and decreased oxidative stress.

Similarly, the application of nano-ZnO demonstrated positive effects in alleviating salinity stress in cowpeas (*Vigna unguiculata* L.), suggesting a potential role in increasing crop productivity (Mohammad Alabdallah and Saeed Alzahrani, 2020). Biosynthesized ZnO nanoparticles positively impacted faba bean (*Vicia faba* L.), indicating a potential role in improving tolerance to salinity (Mogazy and Hanafy, 2022). Furthermore, foliar-applied Zn nanoparticles and nano-loaded *Moringa* extract showcased positive effects on *Vicia faba* L. under saline conditions (Ragab et al., 2022). Meanwhile, titanium dioxide nanoparticles ($nTiO_2$) also displayed concentration-dependent effects, with lower concentrations positively influencing *Vicia faba* L. growth under salty conditions (Abdel Latef et al., 2017). Lately, $nTiO_2$ has demonstrated a protective effect against salinity-induced stress in *Vicia faba* L., resulting in improved growth, reduced DNA damage, and upregulation of antioxidant genes (Omar et al., 2023). These findings demonstrate the efficacy of MONPs, especially ZnO NPs and $nTiO_2$, alleviating salt stress in leguminous crops and offering valuable perspectives for sustainable agriculture.

Further studies discussed the role of nanoparticle, particularly zinc oxide (ZnO), iron oxide (FeO), titanium dioxide (TiO_2), and silicon dioxide (SiO_2), in mitigating the adverse effects of drought stress on various crops, including *Glycine max* (L.) Merr. (soybean), *Vigna radiata* L. (mungbean), *Pisum sativum* L. (pea), *Cicer arietinum* L. (chickpea), *Lathyrus sativus* L. (grass pea), and *Vigna unguiculata* L. (cowpea) **(Table 8).** These nanoparticles positively impacted seed germination, plant growth, physiological processes, antioxidant defense mechanisms, and yield parameters under water-deficient conditions. Notably, ZnO nanoparticles improved *Glycine max* (L.) Merr. (soybean) growth and countered oxidative stress induced by salt stress (Gaafar et al., 2020). The underlying mechanism likely involves ZnO NPs influencing the plant's biochemical processes, such as enhancing antioxidant activity, thus mitigating the negative impact of salt-induced stress. Similarly, seed priming with ZnO nanoparticles enhanced *Vigna radiata* L. (mungbean) performance, including growth, antioxidant defense, and yield, under water stress (Mazhar et al., 2023a). It is attributed to the nanoparticles' ability to enhance osmolyte accumulation, such as proline and soluble sugars, thereby enhancing the plant's resilience to drought. Iron oxide nanoparticles also proved effective in improving the activity of *Pisum sativum* L. (pea) plants under drought, as seen in increased root length, antioxidant enzyme activity, and yield (Mazhar et al., 2023b). TiO_2 nanoparticles positively affected *Cicer arietinum* L. (chickpea), improving chlorophyll index and osmotic potential, and reducing cellular inflammation under drought stress (Ghorbani et al., 2021). The mechanisms potentially involve the nanoparticles' influence on plant physiological processes, resulting in enhanced water use efficiency and diminished cellular inflammation during water scarcity. Furthermore, nano-iron foliar spray enhanced *Glycine max* (L.) Merr. (soybean)'s drought tolerance, yield, and seed quality, offering the potential for reducing losses caused by drought stress (Dola et al., 2022). Silicon dioxide nanoparticles also showed promising results in mitigating drought stress in *Vigna unguiculata* L. (cowpea) by improving plant growth, biochemical attributes, and fatty acid profiles (Zadegan et al., 2023).

Aghdam et al. demonstrated that applying TiO_2 NPs to plants, such as lentils (*Lens culinaris* Medik.), could reduce oxidative stress caused by drought (Aghdam et al., 2016). TiO_2 NPs increased chlorophyll and carotenoid levels while decreasing the accumulation of hydrogen peroxide (H_2O_2) and malondialdehyde (MDA), indicators of oxidative damage. Similarly, Singh and Lee discovered that a different type of metal oxide nanoparticle (MONP) reduced the negative impacts of cadmium on soybeans (*Glycine max* (L.) Merr.) by increasing photosynthetic efficiency and overall growth (Singh and Lee, 2016). Hasanpour et al. revealed that TiO_2 NPs alleviate cold stress in chickpeas (*Cicer arietinum* L.) by restoring rubisco activity and decreasing H_2O_2 levels (Hasanpour et al., 2015). TiO_2 NPs possibly act as mediators in enhancing the plant's antioxidant defense system, thus reducing oxidative stress induced by cold conditions. This restoration of rubisco activity contributes to efficiently utilizing carbon dioxide during photosynthesis, mitigating the negative impacts of cold stress on chickpea plants. Mustafa et al. demonstrated that aluminum oxide (Al_2O_3) nanoparticles could improve soybean (*Glycine max* (L.) Merr.) growth under flood conditions by controlling plant metabolism and reducing root cell death (Mustafa et al., 2015). Reducing root cell death indicates improved oxygen uptake and nutrient absorption, contributing to enhanced growth under flood stress. Kareem et al. showed that exogenous application of ZnO NPs dramatically increases the production of osmolytes and antioxidants in late-sown mungbean plants (*Vigna radiata* L.), suggesting a way to resist heat stress (Kareem et al., 2022).

Furthermore, a further study found that foliar application of Fe_3O_4 NPs reduces the impacts of drought stress in soybeans (*Glycine max* (L.) Merr.), resulting in higher plant yield and seed quality (Dola et al., 2022). According to Ahmad et al. (2020), ZnO NPs treatment effectively mitigates the harmful effects of arsenic (As) by limiting As uptake and modulating various biochemical attributes within soybean plants, including the ascorbate-glutathione cycle, glyoxalase system, and antioxidant enzymatic system (Ulhassan et al., 2022). The formation of complexes between nanoparticles and arsenic could be a probable mechanism resulting in a reduction in its uptake by plant roots. These studies suggest that using nanoparticles could offer benefits in addressing abiotic stresses in agriculture. Future research should aim to understand the long-term environmental impacts and optimize nanoparticle formulations for sustainable and effective agricultural practices.

Table 8: Positive effects of various metal oxide nanoparticles on legume plants under abiotic stress conditions

Stress	**Stress conc.**	**Type of MONPs**	**Effective MONPs Concentrations**	**Plant used**	**Experimental Type**	**Mode of Treatment**	**Effects**	**Reference**
Salt Stress	250 mM	ZnO	50 mg/L	*Glycine max* (L.) Merr. cv. Giza 111	Plastic pot culture	Seed priming	Improved growth parameters and photosynthetic performance and reduced proline and MDA level	(Gaafar et al., 2020)
	10, 25, 50, 75 and 100% of seawater	ZnO	10 mg/L	*Vigna unguiculata* L. var. california blackeye NO.46	Pot experiment	Foliar spray	Improved shoot and root length, fresh and dry weight, leaf area, and relative growth rate	(Mohammad Alabdallah and Saeed Alzahrani, 2020)
	150 mM	ZnO	50 mg/L	*Vicia faba* L. cv. Nubaria, 1	Plastic pot culture	Foliar application	Improved plant growth, gathering of antioxidants, secondary metabolites, and osmolytes	(Mogazy and Hanafy, 2022)

	50 and 100 mM	ZnO	50 mg/L	*Vicia faba* L.	Field experiment	Foliar spray	Improved shoot length, numbers of leaves, RWC, shoot and roots fresh and dry weight, photosynthetic pigments, proline content and mineral elements	(Ragab et al., 2022)
	50 and 100 mM	ZnO	50 mg/L	*Vicia faba* L.	Plastic pot culture	Foliar spray	Increased shoot length, number of leaves, RWC, shoot and root fresh and dry weight, photosynthetic pigments, proline, mineral elements, total phenol, and antioxidant enzymes	(Sherif et al., 2022)
	50 and 100 mg/kg	ZnO	50 mg/L	*Medicago sativa* L.	Plastic pot culture	Foliar application	Increased proline, total soluble sugar, and total soluble protein content	(Hassan et al., 2023)
	180 mM	TiO_2	10 mg/L	*Vicia faba* L. cv. Misr-1	Plastic pot culture	Foliar spray	Increased activity of enzymatic antioxidants level, soluble sugars, amino acids, and proline	(Abdel Latef et al., 2017)
	100 and 200 mM	TiO_2	10 or 20 mg/L	*Vicia faba* L. (Sakha 101)	Pot culture	Mixed with irrigated water	Increased cell division, antioxidant genes, heat shock protein genes, and reduced chromosomal aberrations, and DNA damage	(Omar et al., 2023)

	4, 8 and 12 dSm^{-1}	TiO_2	20, 40, and 60 mg/L	*Lathyrus sativus* L.	Petriplate	Seed priming and soaked filter paper	Increased germination and seedling length	(Hojjat et al., 2020)
Drought Stress	Cutting of irrigation in 50% flowering and 50% pod setting stages	ZnO	5000 and 10000 mg/L	*Vigna radiata* L.	Field experiment	Foliar application	Improved height, proline content, grain, and biological yield	(Makarian et al., 2017)
	-0.5 and -1 MPa	ZnO	0.5 and 1 mg/L	*Glycine max* (L.) Merr.	Petriplate	Mixed with culture	Improved germination, non-enzymatic and enzymatic antioxidant enzymatic activity	(Sedghi et al., 2021)
	300 mm	ZnO	75 mg/L	*Vigna radiata* L.	Field experiment	Seed priming	Enhanced shoot and root length, number of leaves, vegetative and reproductive branches, antioxidant defense, osmolytes, yield and reduced MDA and H_2O_2	(Mazhar et al., 2023a)

	Required amount	Fe_2O_3	20 and 50 mg/L	*Pisum sativum* L.	Pot culture	Mixed with irrigated water	Improved root length, tendril Length, RWC, grain weight and count of grains per pod	(Ashraf et al., 2019)
	40% field capacity	Fe_3O_4	200 mg/L	*Glycine max* (L.) Merr.	Pot culture	Foliar application	Increased growth, physiology, yield, and quality of seeds	(Dola et al., 2022)
	300 mm	FeO	75 mg/L	*Pisum sativum* L.	Field experiment	Seed priming	Increased root length, number of leaves, antioxidant enzymes, and yield and reduced MDA and H_2O_2	(Mazhar et al., 2023b)
	40, 60 and 90% field capacity	TiO_2	5, 20, 10 and 40 mg/L	*Cicer arietinum* L.	Field experiment	Foliar spray	Improved total dry weight, fresh weight, and growth	(Ghorbani et al., 2021)
	50% field capacity	TiO_2	10, 100, and 500 mg/L	*Linum usitatissimum* L.	Pot culture	Foliar spray	Improved chlorophyll and carotenoid levels and decreased H_2O_2 and MDA	(Aghdam et al., 2016)

	Polyethylene glycol (PEG), –0.27, –0.53, and –0.80 MPa	TiO_2	20 mg/L	*Lathyrus sativus* L.	Petriplate	Seed priming	Elevate Germination parameter, root length, shoot length, root, and shoot fresh weight and dry weight	(Hojjat, 2020)
	40%, 60%, and 90% field capacity	TiO_2	20 and 40 mg/L	*Cicer arietinum* L.	Pot culture	Poured in soil at seedling stage	Enhanced chlorophyll and carotenoid level, APX, POX, SOD, proline level, total phenols, and 2,2-diphenyl-1-picryl-hydrazyl-hydrate	(Ghorbani et al., 2023)
	60, 100, and 140 mm evaporation	SiO_2	50 and 100 mg/L	*Vigna unguiculata* L.	Field experiment	Foliar spray	Enhanced biological, seed yield, RWC, and decreased TSS, MDA, CAT, and SOD	(Zadegan et al., 2023)
Flood	-	Al_2O_3	50 mg/L	*Glycine max* (L.) Merr.	Plastic case	2-day old plant transferred to solution	Improved plant growth and decreased cell death	(Mustafa et al., 2015)

Heat	<40/25◦ C for S1, >40/25◦ C for S2 and S3	ZnO	15, 30, 45, and 60 mg/L	*Vigna radiata* L. var. NM-2016	Field (Plot) culture	Foliar application	Improved production of antioxidants and osmolytes and chlorophyll contents and gas exchange attributes, seeds per pod and pods per plant	(Kareem et al., 2022)
Cold	4^{0}C	TiO$_2$	5 mg/L	*Cicer arietinum* L.	Pot culture	Foliar spray	Decreased H$_2$O$_2$ content and improved levels of CaLRubisco, CaSRubisco and Cachlorophyll a/bbinding protein genes	(Hasanpour et al., 2015)
Cadmium	50, 100, and 150 mg/kg	TiO$_2$	100, 200, and 300 mg/kg	*Glycine max* (L.) Merr.	Pot culture	Added in soil	Improved photosynthetic pigments and growth	(Singh and Lee, 2016)
Arsenic	10 and 20 µM	ZnO	50 and 100 mg/L	*Glycine max* (L.) Merr.	Pot culture	Foliar spray	Improved shoot and root length, net photosynthetic rate, transpiration, stomatal conductance, and photochemical yield	(Ahmad et al., 2020)

Conclusion

In conclusion, this article comprehensively summarizes recent research on MONPs uptake mechanisms and their impact on leguminous crops. The uptake and accumulation of MONPs in leguminous plants depend on factors such as particle size, application method, and plant species. The role of specific MONPs, such as iron oxide, zinc oxide, copper oxide, titanium dioxide, cerium oxide, silicon dioxide, and magnesium oxide, in legume growth has shown promise but also presents challenges, particularly in understanding optimal concentrations and potential long-term effects. Iron oxide nanoparticles have demonstrated positive impacts on plant growth, but their reactivity raises concerns, necessitating further research to determine optimal conditions and assess potential ecological impacts. Zinc oxide nanoparticles exhibit beneficial and detrimental effects on different leguminous crops, emphasizing the need for careful consideration of concentration and nanoparticle size. Copper oxide nanoparticles' concentration-dependent effects on soybean and mungbean underscore the importance of understanding their influence on plant physiology. Titanium dioxide nanoparticles generally show beneficial effects, but comprehensive research is required to determine optimal concentrations and assess long-term ecological impacts. Cerium oxide nanoparticles exhibit potential benefits in enhancing crop yield, but their effects vary with concentration and plant species. Silicon dioxide nanoparticles have contrasting effects on different leguminous plants, indicating the need for species-specific research to understand interactions fully. Magnesium oxide nanoparticles positively impact chlorophyll content and overall plant growth, necessitating further investigation into influencing factors. The effects of MONPs on nitrogen fixation in leguminous plants are concentration-dependent, with potential benefits at lower levels and adverse effects at higher concentrations. Optimizing MONP use requires a comprehensive understanding of their interactions with diazotrophic bacteria, nodulation processes, and nitrogenase activity. Under abiotic stress conditions, MONPs have shown potential in mitigating the negative impacts of salt and drought stress on leguminous crops. However, further research is needed to determine optimal concentrations, application methods, and long-term environmental impacts.

Practical implications of this research involve using MONPs to enhance crop productivity, nutrient uptake, and stress tolerance in leguminous plants. However, carefully considering concentration, size, and application methods is crucial to avoid potential adverse effects. Future research should focus on standardized techniques, comparative studies, and controlled conditions to establish guidelines for the safe and efficient use of MONPs in agriculture. Additionally, long-term studies are essential to assess ecological risks, soil accumulation, and impacts on non-target organisms. Addressing these knowledge gaps will contribute to developing sustainable agricultural practices incorporating nanotechnology.

References

Abdallah, Y., Hussien, M., Omar, M., Elashmony, R., Alkhalifah, D., Hozzein, W., 2022. Mung Bean (Vigna radiata) Treated with Magnesium Nanoparticles and Its Impact on Soilborne Fusarium solani and Fusarium oxysporum in Clay Soil. Plants 11, 1514. https://doi.org/10.3390/plants11111514

Abdel-Salam, M., 2018. Implications of Applying Nano-Hydroxyapatite and Nano-Iron Oxide on Faba Bean (Vicia faba L.) Productivity. J. Soil Sci. Agric. Eng. 9, 543–548. https://doi.org/10.21608/jssae.2018.36469

Abdel Latef, A., Srivastava, A., Abd El-sadek, M.S., Kordrostami, M., Tran, L.-S., 2017. Titanium Dioxide Nanoparticles Improve Growth and Enhance Tolerance of Broad Bean Plants under Saline Soil Conditions. L. Degrad. Dev. 29. https://doi.org/10.1002/ldr.2780

Abdelfattah, N.A.H., Yousef, M.A., Badawy, A.A., Salem, S.S., 2023. Influence of biosynthesized magnesium oxide nanoparticles on growth and physiological aspects of cowpea (Vigna unguiculata L.) plant, cowpea beetle, and cytotoxicity. Biotechnol. J. 18, 2300301. https://doi.org/https://doi.org/10.1002/biot.202300301

Aghdam, M.T.B., Mohammadi, H., Ghorbanpour, M., 2016. Effects of nanoparticulate anatase titanium dioxide on physiological and biochemical performance of Linum usitatissimum (Linaceae) under well-watered and drought stress conditions. Brazilian J. Bot. 39, 139–146. https://doi.org/10.1007/s40415-015-0227-x

Agrawal, S., Kumar, V., Kumar, S., Shahi, S.K., 2022. Plant development and crop protection using phytonanotechnology: A new window for sustainable agriculture. Chemosphere 299, 134465. https://doi.org/https://doi.org/10.1016/j.chemosphere.2022.134465

Ahmad, P., Alyemeni, M.N., Al-Huqail, A.A., Alqahtani, M.A., Wijaya, L., Ashraf, M., Kaya, C., Bajguz, A., 2020. Zinc Oxide Nanoparticles Application Alleviates Arsenic (As) Toxicity in Soybean Plants by Restricting the Uptake of as and Modulating Key Biochemical Attributes, Antioxidant Enzymes, Ascorbate-Glutathione Cycle and Glyoxalase System. Plants. https://doi.org/10.3390/plants9070825

Akanbi-gada, M.A., Ogunkunle, C.O., Ilesanmi, A.O., Femi-adepoju, A.G., Sidiq, L.O., Fatoba, P.O., 2019. Effects of Zinc Oxide Nanoparticles on Chlorophyll Content , Growth Attributes , Antioxidant Enzyme Activities And Bioaccumulation of Common Bean (Phaseolus Vulgaris L .) Grown In Soil Medium. IOSR J. Environ. Sci. Toxicol. Food Technol. 13, 9–15. https://doi.org/10.9790/2402-1310010915

AL-oubaidi, hashim K.M., Kasid, N.M., 2015. Increasing (Phenolyic and Flavoniods Compoundes of Cicer Arietinum L . From Embryo Explant Using Titanum 4, 1791–1799.

Algarni, T. saad, Al-Mohaimeed, A.M., 2022. Water purification by adsorption of pigments or pollutants via metaloxide. J. King Saud Univ. - Sci. 34, 102339. https://doi.org/https://doi.org/10.1016/j.jksus.2022.102339

Alwan, S., Mahdi, W., Hussain, L., 2022. Preparation and diagnosis of magnetic nanoparticles and their effect on root nodule count in Vicia faba L., AIP Conference Proceedings. https://doi.org/10.1063/5.0121453

Alwan, S.M., Mahdi, W.M., Alwan, L.H., 2022. Preparation and Diagnosis of Magnetic Nanoparticles and Their Effect on Root Nodule Count in Vicia Faba L. AIP Conf. Proc. 2394. https://doi.org/10.1063/5.0121453

Amde, M., Liu, J., Tan, Z.-Q., Bekana, D., 2017. Transformation and bioavailability of metal oxide nanoparticles in aquatic and terrestrial environments. A review. Environ. Pollut. 230, 250–267. https://doi.org/https://doi.org/10.1016/j.envpol.2017.06.064

Annual report 2013-2014, 2014.

Ashraf, S., Zainab, R., Yasmeen, S., Naseer, U., Liaqat, A., Farooq, F., Shaukat, D., Naqv, Z.B., 2019. COMPARATIVE MORPHO-PHYSIOLOGICAL RESPONSES OF PEA GENOTYPES UNDER WATER STRESS WITH THE APPLICATIONS OF IRON OXIDE COMPARATIVE MORPHO-PHYSIOLOGICAL RESPONSES OF PEA GENOTYPES UNDER WATER STRESS WITH THE APPLICATIONS OF IRON OXIDE NANOPARTICLES Correspondi. Int. J. Biol. Res. 2, 338–347.

Avellan, A., Yun, J., Zhang, Y., Spielman-Sun, E., Unrine, J., Thieme, J., Li, J., Lombi, E., Bland, G., Lowry, G., 2019. Nanoparticle Size and Coating Chemistry Control Foliar Uptake Pathways, Translocation and Leaf-to-Rhizosphere Transport in Wheat. ACS Nano 13. https://doi.org/10.1021/acsnano.8b09781

Awad, S.M., Hathout, T.A., El Khallal, S.M., Farroh, K.Y., 2023. Pleotropic Roles of Biosynthesized Cerium Oxide Nanoparticles on Morphological, Physiological and Molecular Aspects on Brassica napus. Egypt. J. Bot. 63, 765–786. https://doi.org/10.21608/ejbo.2023.155777.2097

Basahi, M., 2021. Seed germination with titanium dioxide nanoparticles enhances water supply, reserve mobilization, oxidative stress and antioxidant enzyme activities in pea. Saudi J. Biol. Sci. 28, 6500–6507. https://doi.org/https://doi.org/10.1016/j.sjbs.2021.07.023

Boutchuen, A., Zimmerman, D., Aich, N., Masud, A.M., Arabshahi, A., Palchoudhury, S., 2019. Increased Plant Growth with Hematite Nanoparticle Fertilizer Drop and Determining Nanoparticle Uptake in Plants Using Multimodal Approach. J. Nanomater. 2019, 6890572. https://doi.org/10.1155/2019/6890572

Burke, D., Pietrasiak, N., Situ, S., Abenojar, E., Porche, M., Kraj, P., Lakliang, Y., Samia, A., 2015. Iron Oxide and Titanium Dioxide Nanoparticle Effects on Plant Performance and Root Associated Microbes. Int. J. Mol. Sci. 16, 23630–23650. https://doi.org/10.3390/ijms161023630

Cao, X., Yue, L., Wang, C., Luo, X., Zhang, C., Zhao, X., Wu, F., White, J.C., Wang, Z., Xing, B., 2022. Foliar Application with Iron Oxide Nanomaterials Stimulate Nitrogen Fixation, Yield, and Nutritional Quality of Soybean. ACS Nano 16, 1170–1181. https://doi.org/10.1021/acsnano.1c08977

Cao, Z., Stowers, C., Rossi, L., Zhang, W., Lombardini, L., Ma, X., 2017. Physiological effects of cerium oxide nanoparticles on the photosynthesis and water use efficiency of Soybean (Glycine max (L.) Merr.). Environ. Sci. Nano 4. https://doi.org/10.1039/C7EN00015D

Chai, H., Yao, J., Sun, J., Zhang, C., Liu, W., Zhu, M., Ceccanti, B., 2015. The Effect of Metal Oxide Nanoparticles on Functional Bacteria and Metabolic Profiles in Agricultural Soil. Bull. Environ. Contam. Toxicol. 94, 490–495. https://doi.org/10.1007/s00128-015-1485-9

Chavali, M.S., Nikolova, M.P., 2019. Metal oxide nanoparticles and their applications in nanotechnology. SN Appl. Sci. 1, 607. https://doi.org/10.1007/s42452-019-0592-3

da Cruz, T.N.M., Savassa, S.M., Montanha, G.S., Ishida, J.K., de Almeida, E., Tsai, S.M., Lavres Junior, J., Pereira de Carvalho, H.W., 2019. A new glance on root-to-shoot in vivo zinc transport and time-dependent physiological effects of ZnSO4 and ZnO nanoparticles on plants. Sci. Rep. 9, 10416. https://doi.org/10.1038/s41598-019-46796-3

Dadkhah, M., Tulliani, J.-M., 2022. Green Synthesis of Metal Oxides Semiconductors for Gas Sensing Applications. Sensors. https://doi.org/10.3390/s22134669

De Souza-Torres, A., Govea-Alcaide, E., Gómez-Padilla, E., Masunaga, S.H., Effenberger, F.B., Rossi, L.M., López-Sánchez, R., Jardim, R.F., 2021a. Fe3O4 nanoparticles and Rhizobium inoculation enhance nodulation, nitrogen fixation and growth of common bean plants grown in soil. Rhizosphere 17, 100275. https://doi.org/10.1016/j.rhisph.2020.100275

De Souza-Torres, A., Govea-Alcaide, E., Gómez-Padilla, E., Masunaga, S.H., Effenberger, F.B., Rossi, L.M., López-Sánchez, R., Jardim, R.F., 2021b. Fe3O4 nanoparticles and Rhizobium inoculation enhance nodulation, nitrogen fixation and growth of common bean plants grown in soil. Rhizosphere 17, 100275. https://doi.org/https://doi.org/10.1016/j.rhisph.2020.100275

Deng, C., Tang, Q., Yang, Z., Dai, Z., Cheng, C., Xu, Y., Chen, X., Zhang, X., Su, J., 2022. Effects of iron oxide nanoparticles on phenotype and metabolite changes in hemp clones (Cannabis sativa L.). Front. Environ. Sci. Eng. 16, 134. https://doi.org/10.1007/s11783-022-1569-9

Distéfano, A.M., López, Gabriel Alejandro Setzes, N., Marchetti, F., Cainzos, M., Cascallares, M., Zabaleta, E., Pagnussat, G.C., 2021. Ferroptosis in plants: triggers, proposed mechanisms and the role of iron in modulating cell death. J. Exp. Bot. 72, 2125–2135.

Dola, D., Mannan, M., Sarker, U., Al Mamun, M., Islam, T., Ali, B., Hamzah Saleem, M., Pop, O.L., Marc, R., 2022. Nano Iron Oxide Accelerates Growth, Yield, and Quality of Seed in water-deficits Glycine max. Front. Plant Sci. 13. https://doi.org/10.3389/fpls.2022.992535

Dubey, J., Singh, A., 2019. Green Synthesis of TiO2 Nanoparticles Using Extracts of Pomegranate Peels for Pharmaceutical Application. Int. J. Pharm. Phytopharm. Res. 9, 85–87.

Duran, N.M., Medina-Llamas, M., Cassanji, J.G.B., De Lima, R.G., De Almeida, E., Macedo, W.R., Mattia, D., Pereira De Carvalho, H.W., 2018. Bean Seedling Growth Enhancement Using Magnetite Nanoparticles. J. Agric. Food Chem. 66, 5746–5755. https://doi.org/10.1021/acs.jafc.8b00557

Duran, N.M., Savassa, S.M., Lima, R.G. de, de Almeida, E., Linhares, F.S., van Gestel, C.A.M., Pereira de Carvalho, H.W., 2017. X-ray Spectroscopy Uncovering the Effects of Cu Based Nanoparticle Concentration and Structure on Phaseolus vulgaris Germination and Seedling Development. J. Agric. Food Chem. 65, 7874–7884. https://doi.org/10.1021/acs.jafc.7b03014

Ebrahimi, A, Galavi, M., Ramroudi, M., Moaveni, P., 2016. Study of agronomic traits of pinto bean (Phaseolus vulgaris L.) under nano TiO2 spraying at various growth stages. Int. J. Pharm. Res. Allied Sci. 5, 458–471.

Ebrahimi, Ahmad, Galavi, M., Ramroudi, M., Moaveni, P., 2016. Effect of TiO2 Nanoparticles on Antioxidant Enzymes Activity and Biochemical Biomarkers in Pinto Bean (Phaseolus vulgaris L.). J. Mol. Biol. Res. 6, 58. https://doi.org/10.5539/jmbr.v6n1p58

Elakkiya V., Rajaram K., Rv, M., shankar, K., Periyasamy, S., 2020. Green Synthesis of MgO Nanoparticles Using Sesbania bispinosa and Its In Vitro Effect on Chlorophyll Content in Long Bean Plant. https://doi.org/10.1007/978-981-15-5179-6_13

Faizan, M., Hayat, S., Pichtel, J., 2020. Effects of Zinc Oxide Nanoparticles on Crop Plants: A Perspective Analysis BT - Sustainable Agriculture Reviews 41: Nanotechnology for Plant Growth and Development, in: Hayat, S., Pichtel, J., Faizan, M., Fariduddin, Q. (Eds.), . Springer International Publishing, Cham, pp. 83–99. https://doi.org/10.1007/978-3-030-33996-8_4

Fakhari, S., Jamzad, M., Kabiri Fard, H., 2019. Green synthesis of zinc oxide nanoparticles: a comparison. Green Chem. Lett. Rev. 12, 19–24.

https://doi.org/10.1080/17518253.2018.1547925

Gaafar, R., Diab, R., Halawa, M., Elshanshory, A., El-Shaer, A., Hamouda, M., 2020. Role of Zinc Oxide Nanoparticles in Ameliorating Salt Tolerance in Soybean. Egypt. J. Bot. https://doi.org/10.21608/ejbo.2020.26415.1475

Ganguly, S., Sengupta, J., 2023. Green Synthesis of Metal Oxide Nanoparticles BT - Handbook of Green and Sustainable Nanotechnology: Fundamentals, Developments and Applications, in: Shanker, U., Hussain, C.M., Rani, M. (Eds.), . Springer International Publishing, Cham, pp. 303–327. https://doi.org/10.1007/978-3-031-16101-8_91

Gautam, S., Misra, P., Shukla, P., Ramteke, P., 2016. Effect of Copper Oxide Nanoparticle on the Germination, Growth and Chlorophyll in Soybean (Glycine max (L.). Vegetos- An Int. J. Plant Res. 29, 157. https://doi.org/10.5958/2229-4473.2016.00050.1

Gebre, S.H., Sendeku, M.G., 2019a. New frontiers in the biosynthesis of metal oxide nanoparticles and their environmental applications: an overview. SN Appl. Sci. 1, 1–28. https://doi.org/10.1007/s42452-019-0931-4

Gebre, S.H., Sendeku, M.G., 2019b. New frontiers in the biosynthesis of metal oxide nanoparticles and their environmental applications: an overview. SN Appl. Sci. 1, 928. https://doi.org/10.1007/s42452-019-0931-4

Ghorbani, R., Ganjeali, A., Movafeghi, A., Nabati, J., 2023. Exposure to TiO 2 nanoparticles improves the physiological characteristics of drought-challenged chickpeas (Cicer arietinum L.). Legum. Sci. https://doi.org/10.1002/leg3.208

Ghorbani, R., Movafeghi, A., Gangeali, A., Nabati, J., 2021. Effects of TiO2 nanoparticles on morphological characteristics of chickpea (Cicer arietinum L.) under drought stress. Environ. Stress. Crop Sci. 14, 85–98. https://doi.org/10.22077/escs.2020.2485.1654

Ghosh, B., Datta, A., Pramanik, A., Kumbhakar, D., Das, D., Paul, R., Biswas, J., 2017. Mutagenic Effectivity of Cadmium Sulphide and Copper Oxide Nanoparticles on Some Physiological and Cytological Attributes of Lathyrus sativus L. Cytologia (Tokyo). 82, 267–271. https://doi.org/10.1508/cytologia.82.267

Gilbertson, L.M., Pourzahedi, L., Laughton, S., Gao, X., Zimmerman, J.B., Theis, T.L., Westerhoff, P., Lowry, G. V., 2020. Guiding the design space for nanotechnology to advance sustainable crop production. Nat. Nanotechnol. 15, 801–810. https://doi.org/10.1038/s41565-020-0706-5

Gillispie, E.C., Taylor, S.E., Qafoku, N.P., Hochella Jr, M.F., 2019. Impact of iron and manganese nano-metal-oxides on contaminant interaction and fortification potential in agricultural systems – a review. Environ. Chem. 16, 377–390.

GUTIÉRREZ-RUELAS, N.J., PALACIO-MÁRQUEZ, A., SÁNCHEZ, E., MUÑOZ-MÁRQUEZ, E., CHÁVEZ-MENDOZA, C., OJEDA-BARRIOS, D.L., FLORES-CÓRDOVA, M.A., 2021. Impact of the foliar application of nanoparticles, sulfate and iron chelate on the growth, yield and nitrogen assimilation in green beans. Not. Bot. Horti Agrobot. Cluj-Napoca 49, 12437. https://doi.org/10.15835/nbha49312437

Hasanpour, H., Maali-Amir, R., Zeinali, H., 2015. Effect of TiO2 nanoparticles on metabolic limitations to photosynthesis under cold in chickpea. Russ. J. Plant Physiol. 62, 779–787. https://doi.org/10.1134/S1021443715060096

Hassan, M.U., Kareem, H.A., Hussain, S., Guo, Z., Niu, J., Roy, M., Saleem, S., Wang, Q., 2023. Enhanced salinity tolerance in Alfalfa through foliar nano-zinc oxide application: Mechanistic insights and potential agricultural applications. Rhizosphere 28, 100792. https://doi.org/https://doi.org/10.1016/j.rhisph.2023.100792

Hassan, S.E., Fouda, A., Saied, E., Farag, M.M.S., Eid, A.M., Barghoth, M.G., Awad, M.A., Hamza, M.F., Awad, M.F., 2021. Rhizopus oryzae-Mediated Green Synthesis of Magnesium Oxide Nanoparticles (MgO-NPs): A Promising Tool for Antimicrobial, Mosquitocidal Action, and Tanning Effluent Treatment. J. Fungi. https://doi.org/10.3390/jof7050372

Hernandez Viezcas, J.A., 2013. Determination Of The Effects Of ZnO And CeO2 Nanoparticles In Mesquite (Prosopis Juliflora) And Soybean (Glycine Max): Synchrotron And Spectroscopic Approaches. University of Texas. https://doi.org/https://scholarworks.utep.edu/open_etd/1643/

Herrera-Barros, A., Tejada-Tovar, C., Villabona-Ortiz, A., Gonzalez-Delgado, A., Reyes-Ramos, A., 2018. Synthesis and characterization of cassava, yam and lemon peels modified with TiO2 nanoparticles. Contemp. Eng. Sci. 11, 1863–1871. https://doi.org/10.12988/ces.2018.84186

Hojjat, S., 2020. Effects of TiO2 Nanoparticles on Germination and Growth Characteristics of Grass Pea (Lathyrus sativus L.) Seed under Drought Stress. Nanotechnologies Russ. 15, 204–211. https://doi.org/10.1134/S199507802002010X

Hojjat, S., Nabati, J., Mirmiran, S., Hojjat, H., 2020. Titanium Dioxide Nanoparticles mitigates the adverse effects of salinity stress on Grass pea (Lathyrus sativus L.) Germination and Seedling development. Azarian J. Agric. 7, 17–25. https://doi.org/10.29252/azarinj.025

Huang, D., Dang, F., Huang, Y., Chen, N., Zhou, D.-M., 2021. Uptake, translocation, and transformation of silver nanoparticles in plants. Environ. Sci. Nano. https://doi.org/10.1039/D1EN00870F

Huang, Y.C., Fan, R., Grusak, M.A., Sherrier, J.D., Huang, C.P., 2014. Effects of nano-ZnO on the agronomically relevant Rhizobium–legume symbiosis. Sci. Total Environ. 497–498, 78–90. https://doi.org/https://doi.org/10.1016/j.scitotenv.2014.07.100

Iannone, M.F., Groppa, M.D., de Sousa, M.E., Fernández van Raap, M.B., Benavides, M.P., 2016. Impact of magnetite iron oxide nanoparticles on wheat (Triticum aestivum L.) development: Evaluation of oxidative damage. Environ. Exp. Bot. 131, 77–88. https://doi.org/https://doi.org/10.1016/j.envexpbot.2016.07.004

Irum, S., Jabeen, N., Ahmad, K.S., Shafique, S., Khan, T.F., Gul, H., Anwaar, S., Shah, N.I., Mehmood, A., Hussain, S.Z., 2020. Biogenic iron oxide nanoparticles enhance callogenesis and regeneration pattern of recalcitrant Cicer arietinum L. PLoS One 15, 1–19. https://doi.org/10.1371/journal.pone.0242829

Issam, N., Naceur, D., Nechi, G., Maatalah, S., Zribi, K., Mhadhbi, H., 2021. Green synthesised ZnO nanoparticles mediated by Olea europaea leaf extract and their antifungal activity against Botrytis cinerea infecting faba bean plants. Arch. Phytopathol. Plant Prot. 54, 1083–1105. https://doi.org/10.1080/03235408.2021.1889859

Jaber, G.S., Khashan, K.S., Abbas, M.J., 2021. Study the antibacterial activity of zinc oxide nanoparticles synthesis by laser ablation in liquid. Mater. Today Proc. 42, 2668–2673. https://doi.org/https://doi.org/10.1016/j.matpr.2020.12.646

Kamali-Andani, N., Fallah, S., Peralta-Videa, J.R., Golkar, P., 2022. A comprehensive study of selenium and cerium oxide nanoparticles on mung bean: Individual and synergistic effect on photosynthesis pigments, antioxidants, and dry matter accumulation. Sci. Total Environ. 830, 154837. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.154837

Kamali, M., Persson, K.M., Costa, M.E., Capela, I., 2019. Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: Current status and future outlook. Environ. Int. 125, 261–276. https://doi.org/https://doi.org/10.1016/j.envint.2019.01.055

Kareem, H.A., Saleem, M., Saleem, S., Rather, S., Wani, S., Siddiqui, M., Alamri, S., Saklani, R., Gaikwad, N., Guo, Z., Niu, J., Wang, Q., 2022. Zinc Oxide Nanoparticles Interplay With Physiological and Biochemical Attributes in Terminal Heat Stress Alleviation in Mungbean (Vigna radiata L.). Front. Plant Sci. 13. https://doi.org/10.3389/fpls.2022.842349

Karmous, I., Tlahig, S., Loumerem, M., Lachiheb, B., Bouhamda, T., Mabrouk, M., Debouba, M., Chaoui, A., 2022. Assessment of the risks of copper- and zinc oxide-based nanoparticles used in Vigna radiata L. culture on food quality, human nutrition and health. Environ. Geochem. Health 44, 4045–4061. https://doi.org/10.1007/s10653-021-01162-z

Kashyap, D., Siddiqui, Z.A., 2021. Effect of silicon dioxide nanoparticles and Rhizobium leguminosarum alone and in combination on the growth and bacterial blight disease complex of pea caused by Meloidogyne incognita and Pseudomonas syringae pv. pisi. Arch. Phytopathol. Plant Prot. 54, 499–515. https://doi.org/10.1080/03235408.2020.1843306

Kaur, H., Garg, N., 2021. Zinc toxicity in plants: a review. Planta 253, 129. https://doi.org/10.1007/s00425-021-03642-z

Kavitha, K., Arockia John Paul, J., Kumar, P., Archana, J., Faritha Begam, H., Karmegam, N., Biruntha, M., 2022. Impact of biosynthesized CuO nanoparticles on seed germination and cyto-physiological responses of Trigonella foenum-graecum and Vigna radiata. Mater. Lett.

313, 131756. https://doi.org/https://doi.org/10.1016/j.matlet.2022.131756

Khan, I., Awan, S.A., Rizwan, M., Hassan, Z.U., Akram, M.A., Tariq, R., Brestic, M., Xie, W., 2022. Nanoparticle’s uptake and translocation mechanisms in plants via seed priming, foliar treatment, and root exposure: a review. Environ. Sci. Pollut. Res. 29, 89823–89833. https://doi.org/10.1007/s11356-022-23945-2

Khan, M., Khan, M.S.A., Borah, K.K., Goswami, Y., Hakeem, K.R., Chakrabartty, I., 2021. The potential exposure and hazards of metal-based nanoparticles on plants and environment, with special emphasis on ZnO NPs, TiO2 NPs, and AgNPs: A review. Environ. Adv. 6, 100128. https://doi.org/https://doi.org/10.1016/j.envadv.2021.100128

Khan, S., Akhtar, N., Rehman, S.U., Jamil, M., 2023. Iron Oxide Nanoparticles: Plant Response, Interaction, Phytotoxicity and Defense Mechanisms, in: Nanomaterials and Nanocomposites Exposures to Plants. Springer Nature Singapore, Singapore, pp. 227–245. https://doi.org/10.1007/978-981-99-2419-6_11

Khan, Z., Shahwar, D., Yunus Ansari, M.K., Chandel, R., 2019. Toxicity assessment of anatase (TiO2) nanoparticles: A pilot study on stress response alterations and DNA damage studies in Lens culinaris Medik. Heliyon 5, e02069. https://doi.org/10.1016/j.heliyon.2019.e02069

Koçak, R., Haliloglu, K., Universitesi, A., Fakultesi, Z., Alayli, A., Nadaroglu, H., 2021. Determination of the Effect of Magnesium Oxide Nanoparticles (MgO-NP) on in Vitro Culture of Cowpea (Vigna Unguiculata L. Walp) 1–11. https://doi.org/10.21203/rs.3.rs-1088469/v1

Koçak, R., Okcu, M., Haliloğlu, K., Türkoğlu, A., Pour-Aboughadareh, A., Jamshidi, B., Janda, T., Alaylı, A., Nadaroğlu, H., 2023. Magnesium Oxide Nanoparticles: An Influential Element in Cowpea (Vigna unguiculata L. Walp.) Tissue Culture. Agronomy. https://doi.org/10.3390/agronomy13061646

Kokina, I., Plaksenkova, I., Jermaļonoka, M., Petrova, A., 2020. Impact of iron oxide nanoparticles on yellow medick (Medicago falcata L.) plants. J. Plant Interact. 15, 1–7. https://doi.org/10.1080/17429145.2019.1708489

Kolenčík, M., Ernst, D., Komár, M., Urík, M., Šebesta, M., Ďurišová, L., Bujdoš, M., Černý, I., Chlpík, J., Juriga, M., Illa, R., Qian, Y., Feng, H., Kratošová, G., Barabaszová, K.Č., Ducsay, L., Aydın, E., 2022a. Effects of Foliar Application of ZnO Nanoparticles on Lentil Production, Stress Level and Nutritional Seed Quality under Field Conditions. Nanomaterials 12, 1–15. https://doi.org/10.3390/nano12030310

Kolenčík, M., Ernst, D., Komár, M., Urík, M., Šebesta, M., Ďurišová, Ľ., Bujdoš, M., Černý, I., Chlpík, J., Juriga, M., Illa, R., Qian, Y., Feng, H., Kratošová, G., Barabaszová, K.Č., Ducsay, L., Aydın, E., 2022b. Effects of Foliar Application of ZnO Nanoparticles on Lentil Production, Stress Level and Nutritional Seed Quality under Field Conditions. Nanomaterials. https://doi.org/10.3390/nano12030310

Koul, B., Poonia, A.K., Yadav, D., Jin, J.-O., 2021. Microbe-Mediated Biosynthesis of Nanoparticles: Applications and Future Prospects. Biomolecules. https://doi.org/10.3390/biom11060886

Kumar, P., Burman, U., Santra, P., 2015. Effect of nano-zinc oxide on nitrogenase activity in legumes: an interplay of concentration and exposure time. Int. Nano Lett. 5, 191–198. https://doi.org/10.1007/s40089-015-0155-6

Kushwah, K.S., Patel, S., 2020. Effect of Titanium Dioxide Nanoparticles (TiO2 NPs) on Faba bean (Vicia faba L.) and Induced Asynaptic Mutation: A Meiotic Study. J. Plant Growth Regul. 39, 1107–1118. https://doi.org/10.1007/s00344-019-10046-7

Kushwah, K.S., Patel, S., Verma, D.K., 2022a. Synthesis and effect of TiO2 nanoparticles on phytotoxicity and genotoxicity in Pisum sativum L. Vegetos 35, 204–211. https://doi.org/10.1007/s42535-021-00236-8

Kushwah, K.S., Patel, S., Verma, D.K., 2022b. Synthesis and effect of TiO2 nanoparticles on phytotoxicity and genotoxicity in Pisum sativum L. Vegetos 35, 204–211. https://doi.org/10.1007/s42535-021-00236-8

Lee, H., Lee, W.-J., Park, Y.-K., Ki, S.J., Kim, B.-J., Jung, S.-C., 2018. Liquid Phase Plasma Synthesis of Iron Oxide Nanoparticles on Nitrogen-Doped Activated Carbon Resulting in Nanocomposite for Supercapacitor Applications. Nanomaterials.

https://doi.org/10.3390/nano8040190

Leher, S., 2022. Magnesium Homeostasis in Plants.

Lian, J., Wu, J., Xiong, H., Zeb, A., Yang, T., Su, X., Su, L., Liu, W., 2020. Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (Triticum aestivum L.). J. Hazard. Mater. 385, 121620. https://doi.org/https://doi.org/10.1016/j.jhazmat.2019.121620

Liu, C., Yu, Y., Liu, H., Xin, H., 2021. Effect of different copper oxide particles on cell division and related genes of soybean roots. Plant Physiol. Biochem. 163, 205–214. https://doi.org/https://doi.org/10.1016/j.plaphy.2021.03.051

Liu, W., Zeb, A., Lian, J., Wu, J., Xiong, H., Tang, J., Zheng, S., 2020. Interactions of metal-based nanoparticles (Mbnps) and metal-oxide nanoparticles (monps) with crop plants: A critical review of research progress and prospects. Environ. Rev. 28, 294–310. https://doi.org/10.1139/er-2019-0085

Lv, J., Christie, P., Zhang, S., 2019. Uptake, translocation, and transformation of metal-based nanoparticles in plants: recent advances and methodological challenges. Environ. Sci. Nano 6, 41–59. https://doi.org/10.1039/C8EN00645H

Lyu, J.-Y., Chen, S., He, W., Zhang, X.-X., Tang, D., Liu, P.-J., Yan, Q.-L., 2019. Fabrication of high-performance graphene oxide doped PVDF/CuO/Al nanocomposites via electrospinning. Chem. Eng. J. 368, 129–137. https://doi.org/https://doi.org/10.1016/j.cej.2019.02.170

Mahdieh, M., Sangi, M.R., Bamdad, F., Ghanem, A., 2018. Effect of seed and foliar application of nano-zinc oxide, zinc chelate, and zinc sulphate rates on yield and growth of pinto bean (Phaseolus vulgaris) cultivars. J. Plant Nutr. 41, 2401–2412. https://doi.org/10.1080/01904167.2018.1510517

Majeed, S., Danish, M., Mohamad Ibrahim, M.N., Sekeri, S.H., Ansari, M.T., Nanda, A., Ahmad, G., 2021. Bacteria Mediated Synthesis of Iron Oxide Nanoparticles and Their Antibacterial, Antioxidant, Cytocompatibility Properties. J. Clust. Sci. 32, 1083–1094.

https://doi.org/10.1007/s10876-020-01876-7

Makarian, H., Shojaei, H., Damavandi, A., Dehsorkhi, A.N., Akhyani, A., 2017. The effect of foliar application of Zinc oxide in common and nanoparticles forms on some growth and quality traits of Mungbean (Vigna radiata L.) under drought stress conditions. Iran. J. Pulses Res. 8, 166–180. https://doi.org/10.22067/ijpr.v8i2.51644

Malek, T., Chaki, S., Tailor, J., Chaudhary, M., Deshpande, M., 2018. Effect of Mn Doping on Fe3O4 Nanoparticles Synthesized by Wet chemical Reduction Technique. Iran. J. Energy Environ. 9, 121–129. https://doi.org/10.5829/ijee.2018.09.02.07

Manzoor, N., Ali, L., Ahmed, T., Rizwan, M., Ali, S., Shahid, M.S., Schulin, R., Liu, Y., Wang, G., 2022. Silicon oxide nanoparticles alleviate chromium toxicity in wheat (Triticum aestivum L.). Environ. Pollut. 315, 120391. https://doi.org/10.1016/j.envpol.2022.120391

Mathew, S.S., Sunny, N.E., Shanmugam, V., 2021. Green synthesis of anatase titanium dioxide nanoparticles using Cuminum cyminum seed extract; effect on Mung bean (Vigna radiata) seed germination. Inorg. Chem. Commun. 126, 108485. https://doi.org/https://doi.org/10.1016/j.inoche.2021.108485

Mathumba, P., Kuvarega, A.T., Dlamini, L.N., Malinga, S.P., 2017. Synthesis and characterisation of titanium dioxide nanoparticles prepared within hyperbranched polyethylenimine polymer template using a modified sol–gel method. Mater. Lett. 195, 172–177. https://doi.org/https://doi.org/10.1016/j.matlet.2017.02.108

Mazhar, M.W., Ishtiaq, M., Maqbool, M., Akram, R., 2023a. Seed priming with zinc oxide nanoparticles improves growth, osmolyte accumulation, antioxidant defence and yield quality of water-stressed mung bean plants. Arid L. Res. Manag. 37, 222–246. https://doi.org/10.1080/15324982.2022.2132547

Mazhar, M.W., Ishtiaq, M., Maqbool, M., Ullah, F., Sayed, S.R.M., Mahmoud, E.A., 2023b. Seed priming with iron oxide nanoparticles improves yield and antioxidant status of garden pea (Pisum sativum L.) grown under drought stress. South African J. Bot. 162, 577–587. https://doi.org/https://doi.org/10.1016/j.sajb.2023.09.047

Medina-Velo, I.A., Barrios, A.C., Zuverza-Mena, N., Hernandez-Viezcas, J.A., Chang, C.H., Ji, Z., Zink, J.I., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2017. Comparison of the effects of commercial coated and uncoated ZnO nanomaterials and Zn compounds in kidney bean (Phaseolus vulgaris) plants. J. Hazard. Mater. 332, 214–222. https://doi.org/https://doi.org/10.1016/j.jhazmat.2017.03.008

Mir, A.R., Pichtel, J., Hayat, S., 2021. Copper: uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. BioMetals 34, 737–759. https://doi.org/10.1007/s10534-021-00306-z

Mogazy, A., Hanafy, R., 2022. Foliar Spray of Biosynthesized Zinc Oxide Nanoparticles Alleviate Salinity Stress Effect on Vicia faba Plants. J. Soil Sci. Plant Nutr. 22. https://doi.org/10.1007/s42729-022-00833-9

Mohammad Alabdallah, N., Saeed Alzahrani, H., 2020. Impact of ZnO Nanoparticles on Growth of Cowpea and Okra Plants under Salt Stress Conditions. Biosci. Biotechnol. Res. Asia 17, 329–340. https://doi.org/10.13005/bbra/2836

Mukherjee, A., Sun, Y., Morelius, I., Tamez, C., Bandyopadhyay, S., Niu, G., White, J., peralta-videa, J., Gardea-Torresdey, J., 2016. Differential Toxicity of Bare and Hybrid ZnO Nanoparticles in Green Pea (Pisum sativum L.): A Life Cycle Study. Front. Plant Sci. 6. https://doi.org/10.3389/fpls.2015.01242

Muñoz-Márquez, E., Soto-Parra, J.M., Noperi-Mosqueda, L.C., Sánchez, E., 2022. Application of Molybdenum Nanofertilizer on the Nitrogen Use Efficiency, Growth and Yield in Green Beans. Agronomy. https://doi.org/10.3390/agronomy12123163

Mustafa, G., Sakata, K., Komatsu, S., 2015. Proteomic analysis of flooded soybean root exposed to aluminum oxide nanoparticles. J. Proteomics 128, 280–297. https://doi.org/https://doi.org/10.1016/j.jprot.2015.08.010

Nair, G.M., Sajini, T., Mathew, B., 2022. Advanced green approaches for metal and metal oxide nanoparticles synthesis and their environmental applications. Talanta Open 5, 100080. https://doi.org/https://doi.org/10.1016/j.talo.2021.100080

Ochoa, L., Medina-Velo, I.A., Barrios, A.C., Bonilla-Bird, N.J., Hernandez-Viezcas, J.A., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2017a. Modulation of CuO nanoparticles toxicity to green pea (Pisum sativum Fabaceae) by the phytohormone indole-3-acetic acid. Sci. Total Environ. 598, 513–524. https://doi.org/10.1016/j.scitotenv.2017.04.063

Ochoa, L., Medina-Velo, I.A., Barrios, A.C., Bonilla-Bird, N.J., Hernandez-Viezcas, J.A., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2017b. Modulation of CuO nanoparticles toxicity to green pea (Pisum sativum Fabaceae) by the phytohormone indole-3-acetic acid. Sci. Total Environ. 598, 513–524. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.04.063

Ochoa, L., Zuverza-Mena, N., Medina-Velo, I.A., Flores-Margez, J.P., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2018. Copper oxide nanoparticles and bulk copper oxide, combined with indole-3-acetic acid, alter aluminum, boron, and iron in Pisum sativum seeds. Sci. Total Environ. 634, 1238–1245. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.04.003

Omar, S., Elsheery, N., Pashkovskiy, P., Kuznetsov, V., Allakhverdiev, S., Zedan, A., 2023. Impact of Titanium Oxide Nanoparticles on Growth, Pigment Content, Membrane Stability, DNA Damage, and Stress-Related Gene Expression in Vicia faba under Saline Conditions. Horticulturae 9, 1030. https://doi.org/10.3390/horticulturae9091030

Osman, S.A., Salama, D.M., Abd El-Aziz, M.E., Shaaban, E.A., Abd Elwahed, M.S., 2020. The influence of MoO3-NPs on agro-morphological criteria, genomic stability of DNA, biochemical assay, and production of common dry bean (Phaseolus vulgaris L.). Plant Physiol. Biochem. 151, 77–87. https://doi.org/https://doi.org/10.1016/j.plaphy.2020.03.009

Osuntokun, J., Onwudiwe, D.C., Ebenso, E.E., 2019. Green synthesis of ZnO nanoparticles using aqueous Brassica oleracea L. var. italica and the photocatalytic activity. Green Chem. Lett. Rev. 12, 444–457. https://doi.org/10.1080/17518253.2019.1687761

Palacio-Márquez, A., Ramírez-Estrada, C.A., Gutiérrez-Ruelas, N.J., Sánchez, E., Barrios, D.L.O.-, Chávez-Mendoza, C., Sida-Arreola, J.P., 2021a. Efficiency of foliar application of zinc oxide nanoparticles versus zinc nitrate complexed with chitosan on nitrogen assimilation, photosynthetic activity, and production of green beans (Phaseolus vulgaris L.). Sci. Hortic. (Amsterdam). 288, 110297. https://doi.org/https://doi.org/10.1016/j.scienta.2021.110297

Palacio-Márquez, A., Ramírez-Estrada, C.A., Gutiérrez-Ruelas, N.J., Sánchez, E., Barrios, D.L.O., Chávez-Mendoza, C., Sida-Arreola, J.P., 2021b. Efficiency of foliar application of zinc oxide nanoparticles versus zinc nitrate complexed with chitosan on nitrogen assimilation, photosynthetic activity, and production of green beans (Phaseolus vulgaris L.). Sci. Hortic. (Amsterdam). 288. https://doi.org/10.1016/j.scienta.2021.110297

Palchoudhury, S., Jungjohann, K.L., Weerasena, L., Arabshahi, A., Gharge, U., Albattah, A., Miller, J., Patel, K., Holler, R.A., 2018. Enhanced legume root growth with pre-soaking in α-Fe2O3 nanoparticle fertilizer. RSC Adv. 8, 24075–24083. https://doi.org/10.1039/c8ra04680h

Panakkal, H., Gupta, I., Bhagat, R., Ingle, A.P., 2021. Effects of Different Metal Oxide Nanoparticles on Plant Growth. Nanotechnol. Plant Growth Promot. Prot. 259–282. https://doi.org/10.1002/9781119745884.ch13

Paul, A., Raha, P., Prajapati, B., Kundu, A., 2020a. Impact assessment of engineered nanotitanium dioxide seed priming on oxidoreductase enzyme activities in seedlings of Kidney bean (Phaseolus vulgaris L.). J. Pharmacogn. Phytochem. 9, 624–628. https://doi.org/10.22271/phyto.2020.v9.i4i.11770

Paul, A., Raha, P., Prajapati, B., Kundu, A., 2020b. Impact assessment of engineered nanotitanium dioxide seed priming on oxidoreductase enzyme activities in seedlings of Kidney bean (Phaseolus vulgaris L.) 9, 624–628. https://doi.org/10.22271/phyto.2020.v9.i4i.11770

Pawar, V., Ambekar, J., Kale, B., Apte, S., Laware, S., 2019. Response in chickpea (Cicer arietinum L.) seedling growth to seed priming with iron oxide nanoparticles. Int. J. Biosci. Law. https://doi.org/10.12692/ijb/14.3.82-91

Pawar, V.A., Ambekar, J., Kale, B., Laware, S.L., 2019. Response in chickpea (Cicer arietinum L.) seedling growth to seed priming with iron oxide nanoparticles. Int. J. Biosci. 14, 82–91.

https://doi.org/10.12692/ijb/14.3.82-91

Peiris, M.M.K., Gunasekara, C., Jayaweera, P., Fernando, N., 2018. TiO_2 Nanoparticles from Baker's Yeast: A Potent Antimicrobial. J. Microbiol. Biotechnol. 28. https://doi.org/10.4014/jmb.1807.07005

Poddar, K., Sarkar, D., Sarkar, A., 2020. Nanoparticles on Photosynthesis of Plants: Effects and Role, in: Patra, J.K., Fraceto, L.F., Das, G., Campos, E.V.R. (Eds.), . Springer International Publishing, Cham, pp. 273–287. https://doi.org/10.1007/978-3-030-39246-8_13

Prakash, V., Peralta-Videa, J., Tripathi, D.K., Ma, X., Sharma, S., 2021a. Recent insights into the impact, fate and transport of cerium oxide nanoparticles in the plant-soil continuum. Ecotoxicol. Environ. Saf. 221, 112403. https://doi.org/https://doi.org/10.1016/j.ecoenv.2021.112403

Prakash, V., Peralta-Videa, J., Tripathi, D.K., Ma, X., Sharma, S., 2021b. Recent insights into the impact, fate and transport of cerium oxide nanoparticles in the plant-soil continuum. Ecotoxicol. Environ. Saf. 221, 112403. https://doi.org/10.1016/j.ecoenv.2021.112403

Priya, B., Mukherjee, S., Srinivasarao, M., 2020. TiO2 nanoparticles can enhance germination and seedling growth of mung bean (Vigna radiata L.). Pharma Innov. J. 9, 107–112.

Purohit, J., Chattopadhyay, A., Singh, N.K., 2019. Green Synthesis of Microbial Nanoparticle: Approaches to Application. Nanotechnol. Life Sci. 35–60. https://doi.org/10.1007/978-3-030-16534-5_3

Ragab, S., Turoop, L., Runo, S., Nyanjom, S., 2022. Nanoparticle Treatments Based on Zinc Oxide and Moringa oleifera Leaf Extracts Alleviate Salinity Stress in Faba Bean (Vicia faba L.). J. Agric. Chem. Environ. 11, 42–65. https://doi.org/10.4236/jacen.2022.111004

Rai, S., Singh, P.K., Mankotia, S., Swain, J., Satbhai, S.B., 2021. Iron homeostasis in plants and its crosstalk with copper, zinc, and manganese. Plant Stress 1, 100008. https://doi.org/https://doi.org/10.1016/j.stress.2021.100008

Rani, N., Kumari, K., Sangwan, P., Barala, P., Yadav, J., Vijeta, Rahul, Hooda, V., 2022. Nano-Iron and Nano-Zinc Induced Growth and Metabolic Changes in Vigna radiata.

Sustainability. https://doi.org/10.3390/su14148251

Rapson, T., Gregg, C., Allen, R., Ju, H., Doherty, C., Mulet, X., Giddey, S., Wood, C., 2020. Insights into Nitrogenase Bioelectrocatalysis for Green Ammonia Production. ChemSusChem 13. https://doi.org/10.1002/cssc.202001433

Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H.M., He, X., Mbarki, S., Brestic, M., 2017. Impact of metal and metal oxide nanoparticles on plant: A critical review. Front. Chem. 5, 1–16. https://doi.org/10.3389/fchem.2017.00078

Ross, S., Owen, M., Pedersen, B., Liu, G., Miller, W., 2016. Using Mung Beans as a Simple, Informative Means To Evaluate the Phytotoxicity of Engineered Nanomaterials and Introduce the Concept of Nanophytotoxicity to Undergraduate Students. J. Chem. Educ. 93. https://doi.org/10.1021/acs.jchemed.5b01038

Rui, M., Ma, C., Hao, Y., Guo, J., Yukui, R., Tang, X., Zhao, Q., Fan, X., Zhang, Z., Tianqi, H., Zhu, S., 2016. Iron Oxide Nanoparticles as a Potential Iron Fertilizer for Peanut (Arachis hypogaea). Front. Plant Sci. 7. https://doi.org/10.3389/fpls.2016.00815

Saebnoori, E., Koupaei, N., Hassanzadeh Tabrizi, S.A., 2022. The solution plasma synthesis, characterisation, and antibacterial activities of dispersed CuO nanoparticles. Mater. Technol. 37, 1220–1229. https://doi.org/10.1080/10667857.2021.1929719

Saha, R., Subramani, K., Petchi Muthu Raju, S.A.K., Rangaraj, S., Venkatachalam, R., 2018. Psidium guajava leaf extract-mediated synthesis of ZnO nanoparticles under different processing parameters for hydrophobic and antibacterial finishing over cotton fabrics. Prog. Org. Coatings 124, 80–91. https://doi.org/https://doi.org/10.1016/j.porgcoat.2018.08.004

Sahoo, S.K., Dwivedi, G.K., Dey, P., Praharaj, S., 2021. Green synthesized ZnO nanoparticles for sustainable production and nutritional biofortification of green gram. Environ. Technol. Innov. 24, 101957. https://doi.org/https://doi.org/10.1016/j.eti.2021.101957

Salama, Dina M, Osman, S.A., Abd El-Aziz, M.E., Abd Elwahed, M.S.A., Shaaban, E.A., 2019. Effect of zinc oxide nanoparticles on the growth, genomic DNA, production and the quality of common dry bean (Phaseolus vulgaris). Biocatal. Agric. Biotechnol. 18, 101083.

https://doi.org/https://doi.org/10.1016/j.bcab.2019.101083

Salama, Dina M., Osman, S.A., Abd El-Aziz, M.E., Abd Elwahed, M.S.A., Shaaban, E.A., 2019. Effect of zinc oxide nanoparticles on the growth, genomic DNA, production and the quality of common dry bean (Phaseolus vulgaris). Biocatal. Agric. Biotechnol. 18, 101083. https://doi.org/10.1016/j.bcab.2019.101083

Saleem, S., Khan, M.S., 2023. Phyto-interactive impact of green synthesized iron oxide nanoparticles and Rhizobium pusense on morpho-physiological and yield components of greengram. Plant Physiol. Biochem. 194, 146–160. https://doi.org/https://doi.org/10.1016/j.plaphy.2022.11.013

Salehi, H., Chehregani, A., Lucini, L., Majd, A., Gholami, M., 2018a. Morphological, proteomic and metabolomic insight into the effect of cerium dioxide nanoparticles to Phaseolus vulgaris L. under soil or foliar application. Sci. Total Environ. 616–617, 1540–1551. https://doi.org/10.1016/j.scitotenv.2017.10.159

Salehi, H., Chehregani, A., Lucini, L., Majd, A., Gholami, M., 2018b. Morphological, proteomic and metabolomic insight into the effect of cerium dioxide nanoparticles to Phaseolus vulgaris L. under soil or foliar application. Sci. Total Environ. 616–617, 1540–1551. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.10.159

Salehi, H., Chehregani Rad, A., Raza, A., Chen, J.-T., 2021a. Foliar Application of CeO2 Nanoparticles Alters Generative Components Fitness and Seed Productivity in Bean Crop (Phaseolus vulgaris L.). Nanomaterials. https://doi.org/10.3390/nano11040862

Salehi, H., Chehregani Rad, A., Sharifan, H., Raza, A., Varshney, R., 2022. Aerially Applied Zinc Oxide Nanoparticle Affects Reproductive Components and Seed Quality in Fully Grown Bean Plants (Phaseolus vulgaris L.). Front. Plant Sci. 12, 808141. https://doi.org/10.3389/fpls.2021.808141

Salehi, H., De Diego, N., Chehregani Rad, A., Benjamin, J.J., Trevisan, M., Lucini, L., 2021b. Exogenous application of ZnO nanoparticles and ZnSO4 distinctly influence the metabolic response in Phaseolus vulgaris L. Sci. Total Environ. 778. https://doi.org/10.1016/j.scitotenv.2021.146331

Salehi, H., De Diego, N., Chehregani Rad, A., Benjamin, J.J., Trevisan, M., Lucini, L., 2021c. Exogenous application of ZnO nanoparticles and ZnSO4 distinctly influence the metabolic response in Phaseolus vulgaris L. Sci. Total Environ. 778, 146331. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.146331

Salehi, H., Miras-Moreno, B., Chehregani Rad, A., Pii, Y., Mimmo, T., Cesco, S., Lucini, L., 2020. Relatively Low Dosages of CeO2 Nanoparticles in the Solid Medium Induce Adjustments in the Secondary Metabolism and Ionomic Balance of Bean (Phaseolus vulgaris L.) Roots and Leaves. J. Agric. Food Chem. 68, 67–76. https://doi.org/10.1021/acs.jafc.9b05107

Salem, D.M.S.A., Ismail, M.M., Aly-Eldeen, M.A., 2019. Biogenic synthesis and antimicrobial potency of iron oxide (Fe3O4) nanoparticles using algae harvested from the Mediterranean Sea, Egypt. Egypt. J. Aquat. Res. 45, 197–204. https://doi.org/https://doi.org/10.1016/j.ejar.2019.07.002

Santos, E., Graciano, D., Falco, W., Caires, A., Arruda, E., 2021. Effects of copper oxide nanoparticles on germination of Sesbania virgata (FABACEAE) plants. An. Acad. Bras. Cienc. 93, e20190739. https://doi.org/10.1590/0001-3765202120190739

Sarkar, N., Sharma, R.S., Kaushik, M., 2021. Innovative application of facile single pot green synthesized CuO and CuO@APTES nanoparticles in nanopriming of Vigna radiata seeds. Environ. Sci. Pollut. Res. 28, 13221–13228. https://doi.org/10.1007/s11356-020-11493-6

Sarraf, M., Vishwakarma, K., Kumar, V., Arif, N., Das, S., Johnson, R., Janeeshma, E., Puthur, J.T., Aliniaeifard, S., Chauhan, D.K., Fujita, M., Hasanuzzaman, M., 2022. Metal/Metalloid-Based Nanomaterials for Plant Abiotic Stress Tolerance: An Overview of the Mechanisms. Plants. https://doi.org/10.3390/plants11030316

Sedghi, M., Sheikhnavaz Jahed, P., Gholi-Tolouie, S., 2021. Zinc oxide nano particles alleviate drought stress effects on soybean antioxidant system during germination. Iran. J. Plant Physiol. 11, 3769–3778. https://doi.org/10.30495/ijpp.2021.684985

Sharma, Priya, Gautam, A., Kumar, V., Guleria, P., 2022a. MgO nanoparticles mediated seed priming inhibits the growth of lentil (Lens culinaris). Vegetos 35, 1128–1141.

https://doi.org/10.1007/s42535-022-00400-8

Sharma, Priya, Gautam, A., Kumar, V., Guleria, P., 2022b. MgO nanoparticles priming promoted the growth of black chickpea. J. Agric. Food Res. 10, 100435. https://doi.org/https://doi.org/10.1016/j.jafr.2022.100435

Sharma, Priya, Gautam, A., Kumar, V., Guleria, P., 2022c. In vitro exposed magnesium oxide nanoparticles enhanced the growth of legume Macrotyloma uniflorum. Environ. Sci. Pollut. Res. 29, 13635–13645. https://doi.org/10.1007/s11356-021-16828-5

Sharma, P., Gautam, A., Kumar, V., Guleria, P., 2021. In vitro exposure of magnesium oxide nanoparticles adversely affects the vegetative growth and biochemical parameters of black gram. Environ. Nanotechnology, Monit. Manag. 16, 100483. https://doi.org/10.1016/j.enmm.2021.100483

Sharma, P, Kumar, V., Guleria, P., 2022. In vitro exposure of magnesium oxide nanoparticles negatively regulate the growth of Vigna radiata. Int. J. Environ. Sci. Technol. 19, 10679–10690. https://doi.org/10.1007/s13762-021-03738-9

Sherif, M.R., Losenge, T., Steven, R., Steven, N., 2022. The effect of foliar application of zinc oxide nanoparticles and Moringa oleifera leaf extract on growth, biochemical parameters and in promoting salt stress tolerance in faba bean. African J. Biotechnol. 21, 252–266. https://doi.org/10.5897/AJB2022.17485

Shivaraj, S.M., Mandlik, R., Bhat, J.A., Raturi, G., Elbaum, R., Alexander, L., Tripathi, D.K., Deshmukh, R., Sonah, H., 2022. Outstanding Questions on the Beneficial Role of Silicon in Crop Plants. Plant Cell Physiol. 63, 4–18. https://doi.org/10.1093/pcp/pcab145

Siddiqui, Z., Khan, A., Khan, M., Abd Allah, E.F., 2018. Effects of zinc oxide nanoparticles (ZnO NPs) and some plant pathogens on the growth and nodulation of lentil (Lens culinaris Medik.). Acta Phytopathol. Entomol. Hungarica 53, 195–211. https://doi.org/10.1556/038.53.2018.012

Singh, A., Singh, N.B., Afzal, S., Singh, T., Hussain, I., 2018. Zinc oxide nanoparticles: a review of their biological synthesis, antimicrobial activity, uptake, translocation and biotransformation in plants. J. Mater. Sci. 53, 185–201. https://doi.org/10.1007/s10853-017-1544-1

Singh, A., Singh, N.B., Hussain, I., Singh, H., Yadav, V., 2017. Synthesis and characterization of copper oxide nanoparticles and its impact on germination of Vigna radiata (L.) R. Wilczek. Trop. Plant Res. 4, 246–253. https://doi.org/10.22271/tpr.2017.v4.i2.034

Singh, J., Dutta, T., Kim, K.-H., Rawat, M., Samddar, P., Kumar, P., 2018. 'Green' synthesis of metals and their oxide nanoparticles: applications for environmental remediation. J. Nanobiotechnology 16, 84. https://doi.org/10.1186/s12951-018-0408-4

Singh, J., Lee, B.-K., 2016. Influence of nano-TiO2 particles on the bioaccumulation of Cd in soybean plants (Glycine max): A possible mechanism for the removal of Cd from the contaminated soil. J. Environ. Manage. 170, 88–96. https://doi.org/https://doi.org/10.1016/j.jenvman.2016.01.015

Singh, S., Arkoti, N.K., Verma, V., Pal, K., 2022. Nanomaterials and Their Distinguishing Features BT - Nanomaterials for Advanced Technologies, in: Katiyar, J.K., Panwar, V., Ahlawat, N. (Eds.), . Springer Nature Singapore, Singapore, pp. 1–18. https://doi.org/10.1007/978-981-19-1384-6_1

Skiba, E., Michlewska, S., Pietrzak, M., Wolf, W.M., 2020. Additive interactions of nanoparticulate ZnO with copper, manganese and iron in Pisum sativum L., a hydroponic study. Sci. Rep. 10, 13574. https://doi.org/10.1038/s41598-020-70303-8

Skiba, E., Pietrzak, M., Glińska, S., Wolf, W.M., 2021. The Combined Effect of ZnO and CeO2 Nanoparticles on Pisum sativum L.: A Photosynthesis and Nutrients Uptake Study. Cells. https://doi.org/10.3390/cells10113105

Skiba, E., Pietrzak, M., Michlewska, S., Gruszka, J., Malejko, J., Godlewska-Żyłkiewicz, B., Wolf, W.M., 2024. Photosynthesis governed by nanoparticulate titanium dioxide. The Pisum sativum L. case study. Environ. Pollut. 340, 122735. https://doi.org/https://doi.org/10.1016/j.envpol.2023.122735

Skiba, E., Wolf, W.M., 2019. Cerium Oxide Nanoparticles Affect Heavy Metals Uptake by Pea in a Divergent Way than Their Ionic and Bulk Counterparts. Water, Air, Soil Pollut. 230, 248. https://doi.org/10.1007/s11270-019-4296-5

Stałanowska, K., Szablińska-Piernik, J., Okorski, A., Lahuta, L.B., 2023. Zinc Oxide Nanoparticles Affect Early Seedlings’ Growth and Polar Metabolite Profiles of Pea (Pisum sativum L.) and Wheat (Triticum aestivum L.). Int. J. Mol. Sci. https://doi.org/10.3390/ijms241914992

Stowers, C., King, M., Rossi, L., Zhang, W., Arya, A., Ma, X., 2018. Initial Sterilization of Soil Affected Interactions of Cerium Oxide Nanoparticles and Soybean Seedlings (Glycine max (L.) Merr.) in a Greenhouse Study. ACS Sustain. Chem. Eng. 6, 10307–10314. https://doi.org/10.1021/acssuschemeng.8b01654

Su, Y., Ashworth, V., Kim, C., Adeleye, A.S., Rolshausen, P., Roper, C., White, J., Jassby, D., 2019. Delivery, uptake, fate, and transport of engineered nanoparticles in plants: A critical review and data analysis. Environ. Sci. Nano 6, 2311–2331. https://doi.org/10.1039/c9en00461k

Sun, H., Peng, Q., Guo, J., Zhang, H., Bai, J., Mao, H., 2022. Effects of short-term soil exposure of different doses of ZnO nanoparticles on the soil environment and the growth and nitrogen fixation of alfalfa. Environ. Pollut. 309, 119817. https://doi.org/https://doi.org/10.1016/j.envpol.2022.119817

Sun, W., Sun, M., Meng, X., Zheng, Y., Li, Z., Huang, X., Humayun, M., 2023. Alkynyl carbon functionalized N-TiO2: Ball milling synthesis and investigation of improved photocatalytic activity. J. Alloys Compd. 939, 168826. https://doi.org/https://doi.org/10.1016/j.jallcom.2023.168826

Sundrarajan, M., Bama, K., Bhavani, M., Jegatheeswaran, S., Ambika, S., Sangili, A., Nithya, P., Sumathi, R., 2017. Obtaining titanium dioxide nanoparticles with spherical shape and antimicrobial properties using M. citrifolia leaves extract by hydrothermal method. J. Photochem. Photobiol. B Biol. 171, 117–124. https://doi.org/10.1016/j.jphotobiol.2017.05.003

Suresh, S, Karthikeyan, S., Jayamoorthy, K., 2016a. Effect of bulk and nano-Fe2O3 particles on peanut plant leaves studied by Fourier transform infrared spectral studies. J. Adv. Res. 7, 739–747. https://doi.org/https://doi.org/10.1016/j.jare.2015.10.002

Suresh, S., Karthikeyan, S., Jayamoorthy, K., 2016. FTIR and multivariate analysis to study the effect of bulk and nano copper oxide on peanut plant leaves. J. Sci. Adv. Mater. Devices 1, 343–350. https://doi.org/10.1016/j.jsamd.2016.08.004

Suresh, S, Karthikeyan, S., Jayamoorthy, K., 2016b. FTIR and multivariate analysis to study the effect of bulk and nano copper oxide on peanut plant leaves. J. Sci. Adv. Mater. Devices 1, 343–350. https://doi.org/https://doi.org/10.1016/j.jsamd.2016.08.004

Tasar, N., 2022. Mitotic effects of copper oxide nanoparticle on root development and root tip cells of Phaseolus vulgaris L. seeds. Microsc. Res. Tech. 85, 3895–3907. https://doi.org/10.1002/jemt.24239

Taziwa, R., Meyer, E., Katwire, D., Ntozakhe, L., 2017. Influence of Carbon Modification on the Morphological, Structural, and Optical Properties of Zinc Oxide Nanoparticles Synthesized by Pneumatic Spray Pyrolysis Technique. J. Nanomater. 2017, 9095301. https://doi.org/10.1155/2017/9095301

Thabet, A.F., Galal, O.A., El-Samahy, M.F.M., Tuda, M., 2019. Higher toxicity of nano-scale TiO2 and dose-dependent genotoxicity of nano-scale SiO2 on the cytology and seedling development of broad bean Vicia faba. SN Appl. Sci. 1, 956. https://doi.org/10.1007/s42452-019-0960-z

Thakur, K., Khurana, N., Rani, N., Hooda, V., 2021. Enhanced growth and antioxidant efficiency of Vigna radiata seedlings in the presence of titanium dioxide nanoparticles synthesized via the sonochemical method. Isr. J. Plant Sci. 69, 25–42. https://doi.org/https://doi.org/10.1163/22238980-bja10048

Tombuloglu, H., Anıl, I., Akhtar, S., Turumtay, H., Sabit, H., Slimani, Y., Almessiere, M., Baykal, A., 2020. Iron oxide nanoparticles translocate in pumpkin and alter the phloem sap metabolites related to oil metabolism. Sci. Hortic. (Amsterdam). 265, 109223. https://doi.org/https://doi.org/10.1016/j.scienta.2020.109223

Ulhassan, Z., Khan, I., Hussain, M., Khan, A.R., Hamid, Y., Hussain, S., Allakhverdiev, S.I., Zhou, W., 2022. Efficacy of metallic nanoparticles in attenuating the accumulation and toxicity of chromium in plants: Current knowledge and future perspectives. Environ. Pollut. 315, 120390. https://doi.org/https://doi.org/10.1016/j.envpol.2022.120390

Verma, D.K., Patel, S., Kushwah, K.S., 2020. Synthesis of Titanium dioxide (TiO2) nanoparticles and impact on morphological changes, seeds yield and phytotoxicity of Phaseolus vulgaris L. Trop. Plant Res. 7, 158–170. https://doi.org/10.22271/tpr.2020.v7.i1.021

Verma, R., Dwivedi, G.K., Singh, J.P., Singh, A.P., Tamta, N., Kumar, A., 2023. Characterization of synthesized zinc oxide nanoparticles and their effect on growth , productivity and zinc use efficiency of wheat and field pea in the Indian Himalayan foothills. Curr. Sci. 124, 1319–1328.

Vijayakumar, M.D., Surendhar, G.J., Natrayan, L., Patil, P.P., Ram, P.M.B., Paramasivam, P., 2022. Evolution and Recent Scenario of Nanotechnology in Agriculture and Food Industries. J. Nanomater. 2022, 1280411. https://doi.org/10.1155/2022/1280411

Vithanage, M., Zhang, X., Gunarathne, V., Zhu, Y., Herath, L., Peiris, K., Solaiman, Z.M., Bolan, N., Siddique, K.H.M., 2023. Plant nanobionics: Fortifying food security via engineered plant productivity. Environ. Res. 229, 115934. https://doi.org/https://doi.org/10.1016/j.envres.2023.115934

Wang, X., Jiang, J., Dou, F., Sun, W., Ma, X., 2021. Simultaneous mitigation of arsenic and cadmium accumulation in rice (Oryza sativa L.) seedlings by silicon oxide nanoparticles under different water management schemes. Paddy Water Environ. 19, 569–584. https://doi.org/10.1007/s10333-021-00855-6

Wang, X., Xie, H., Wang, P., Yin, H., 2023. Nanoparticles in Plants: Uptake, Transport and Physiological Activity in Leaf and Root. Materials (Basel). https://doi.org/10.3390/ma16083097

Xie, W., Zhenhu, G., Gao, F., Gao, Q., Wang, D., Liaw, B., Cai, Q., Sun, X., Wang, X., Zhao, L., 2018. Shape-, size- and structure-controlled synthesis and biocompatibility of iron oxide nanoparticles for magnetic theranostics. Theranostics 8, 3284–3307. https://doi.org/10.7150/thno.25220

Xiong, T., Zhang, T., Xian, Y., Kang, Z., Zhang, S., Dumat, C., Shahid, M., Li, S., 2021. Foliar uptake, biotransformation, and impact of CuO nanoparticles in Lactuca sativa L. var. ramosa Hort. Environ. Geochem. Health 43, 423–439. https://doi.org/10.1007/s10653-020-00734-9

Yang, X., Alidoust, D., Wang, C., 2020. Effects of iron oxide nanoparticles on the mineral composition and growth of soybean (Glycine max L.) plants. Acta Physiol. Plant. 42, 128. https://doi.org/10.1007/s11738-020-03104-1

Yang, Y., Li, R., Wang, L., Bi, H., Peng, Z., Li, J., Guo, C., Bi, Y., Lai, Y., Guo, D., 2023. Enhanced Germination and Growth of Alfalfa with Seed Presoaking and Hydroponic Culture in Fe2O3 Magnetic Nanoparticles. J. Nanomater. 2023, 1–11. https://doi.org/10.1155/2023/9783977

Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2022a. Responses of soybean (Glycine max [L.] Merr.) to zinc oxide nanoparticles: Understanding changes in root system architecture, zinc tissue partitioning and soil characteristics. Sci. Total Environ. 835, 155348. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.155348

Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2022b. Responses of soybean (Glycine max [L.] Merr.) to zinc oxide nanoparticles: Understanding changes in root system architecture, zinc tissue partitioning and soil characteristics. Sci. Total Environ. 835. https://doi.org/10.1016/j.scitotenv.2022.155348

Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2020a. Zinc oxide nanoparticles (ZnONPs) as a novel nanofertilizer: Influence on seed yield and antioxidant defense system in soil grown soybean (Glycine max cv. Kowsar). Sci. Total Environ. 738. https://doi.org/10.1016/j.scitotenv.2020.140240

Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2020b. Zinc oxide nanoparticles (ZnONPs) as a novel nanofertilizer: Influence on seed yield and antioxidant defense system in soil grown soybean (Glycine max cv. Kowsar). Sci. Total Environ. 738, 140240.

https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.140240

Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2020c. Particle size and concentration dependent toxicity of copper oxide nanoparticles (CuONPs) on seed yield and antioxidant defense system in soil grown soybean (Glycine max cv. Kowsar). Sci. Total Environ. 715, 136994. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.136994

Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2020d. Root System Architecture, Copper Uptake and Tissue Distribution in Soybean (Glycine max (L.) Merr.) Grown in Copper Oxide Nanoparticle (CuONP)-Amended Soil and Implications for Human Nutrition. Plants. https://doi.org/10.3390/plants9101326

Zadegan, K., Monem, R., Pazoki, A., 2023. Silicon Dioxide Nanoparticles Improved Yield, Biochemical Attributes, and Fatty Acid Profile of Cowpea (Vigna unguiculata [L.] Walp) Under Different Irrigation Regimes. J. Soil Sci. Plant Nutr. 23, 3197–3208. https://doi.org/10.1007/s42729-023-01297-1

Zhang, W., Huang, Y., Gong, H., Dang, F., Zhou, D., 2019. Different Uptake of Metal Dioxide Nanoparticles (Ceria Nanoparticles, Zirconia Nanoparticles and Silica Nanoparticles) by Wheat. Bull. Environ. Contam. Toxicol. 103, 199–205. https://doi.org/10.1007/s00128-019-02638-6

Zhu, J., Li, J., Shen, Y., Liu, S., Zeng, N., Zhan, X., White, J.C., Gardea-Torresdey, J., Xing, B., 2020. Mechanism of zinc oxide nanoparticle entry into wheat seedling leaves. Environ. Sci. Nano 7, 3901–3913. https://doi.org/10.1039/d0en00658k

Zia-ur-Rehman, M., Naeem, A., Khalid, H., Rizwan, M., Ali, S., Azhar, M., 2018. Responses of Plants to Iron Oxide Nanoparticles, Nanomaterials in Plants, Algae, and Microorganisms. Elsevier Inc. https://doi.org/10.1016/B978-0-12-811487-2.00010-4