Role of Zinc and Zinc Oxide Nanofertilizer in Enhancing Crop Production

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Abstract Food demand is rising as the world's population expands, yet agricultural yield declines due to climate change, low soil fertility, and nutrient deficiency are serious concerns in crop production. Nanomaterials, especially metal and metal oxide nanoparticles used as nanopesticides, herbicides, fungicides, and fertilizers, have become a new-age material in the last decade, transforming modern agriculture. Among other metal nanoparticles, zinc and zinc oxide nanoparticles (ZnONPs) have attracted undoubted attention for sustainable plant performance as it stimulates germination of seed, early flowering, enzyme activity, and higher yield. Although physiological indices determine ZnONPs, they affect structural modifications, including stomatal and trichome morphology, induced vacuole in root cortex cells, protoplast shrinkage, and thylakoid degradation, indicating the toxicity of ZnONPs in the photosynthetic apparatus. In addition, applying these nanoparticles to plants arrests the cell cycle and induces apoptosis, which causes severe damage to DNA. The beneficial or adverse response usually depends on the species' type, size, concentration, treatment methods, stage of development, and the genotype of the species or environmental conditions. However, increased use certainly leads to the accumulation of ZnONPs in the ecosystem. In order to properly use and regulate the release of nanopreparations, it is necessary to understand how they change and behave in complex systems.

Keywords Zinc oxide nanoparticles · Plant growth · Productivity · Photosynthesis · Toxicity · Seed germination

1 Introduction

Nanotechnology holds great promise to significantly impact the agricultural and food sectors by improving food security and productivity, which are required by the projected growth of the world's population (Husen, 2022, 2023; Husen & Siddiqi,

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2023). In reality, the special characteristics of nanoscale materials make them appropriate candidates for the creation of new technologies to help sustainable agriculture (Fraceto et al., 2016). Using nanopesticides and nanofertilizers to boost production, improving soil quality, stimulating plant development using nanomaterials, and managing plant and soil health are just a few uses of nanotechnology in agriculture sectors. Novel nanomaterials based on inorganic and polymer improve plant productivity by immobilizing nutrients and their release as intelligent nanosystems. Zinc (Zn) is an essential micronutrient required for plant growth and development that performs vital metabolic reactions (Awan et al., 2021). In order to boost agricultural output and efficiency and minimize environmental impact, Zn can be administered to the soil in various ways, including zinc and zinc oxide nanoparticles (ZnONPs) as nanofertilizers (Mittal et al., 2020). ZnONPs are non-toxic, environmentally friendly, biologically safe and biocompatible, soluble, and sensitive compared to conventional ZnO fertilizers due to their nanoscale size and precise surface area. These nanofertilizers significantly impact corn's fatty acid profiles, yield, and plant development (Taheri et al., 2016).

ZnONPs improve soybean plants' total plant growth and root biomass (De la Rosa et al., 2013). In lowland rice, using ZnONPs at sowing dramatically boosted plant height and demonstrated improved responsiveness to shoot length at maturity (Hosseini & Maftoun, 2008). Additionally, exposure to ZnONPs improves germination of seed, maize plant root length, and oat and berseem plant shoot length (Meena et al., 2017). Foliage spray of Zinc NPs can remarkably increase the leaf area and dry mass of maize (Taheri et al., 2016). ZnONPs promote Zn bioavailability to plants and gradually release fertilizer, which raises plant growth and dry matter and fresh and dry matter in the roots. This enhanced plant development by enhancing elemental absorption and nutrient utilization. In order to boost Zn availability for plant nutritional demands in Zn-deficient soils, traditional Zinc fertilizer can be replaced with ZnONPs. This increases fertilizer usage efficiency and can benefit the environment (Adil et al., 2022).

ZnONPs can modify the food and agriculture sector by enhancing productivity globally in reversing oxidative stress symptoms even under stressful conditions. Foliar application of conventional and ZnO nanofertilizers induces morpho-physiological characteristics and harvest index in sunflowers under water deficit stress, and seed treatment with such nanoparticles reduces salt stress in lupine plants (Abdel Latef et al., 2016; Asadazade et al., 2015). Under salt stress, it accelerates plant growth, yield, and antioxidant enzymes in wheat (*Triticum aestivum*) as foliar nanofertilizers (Babaeia et al., 2017). The positive effects of ZnONPs on the secretion of phosphorus mobilizing enzymes and gum concentrations in beans and the sustainable production of *Atriplex halimus* in saline habitats were demonstrated (Raliya & Tarafdar, 2013; Tawfik et al., 2017). Furthermore, it alleviates chilling stress and adverse effects of cadmium in *Oryza sativa* by regulating the antioxidant defense system and chilling response transcription factors, even greatly influencing the rhizospheric environment (Faizan et al., 2021a; Song et al., 2021). Hence, ZnONPs seem to modify interkingdom cell signaling processes relevant to crop performance and production (Anderson et al., 2017). However, the higher concentration of these nanoparticles adversely affects the plants suggesting the toxic effect on plant growth and metabolism in different periods of development (Faizan et al., 2021b; Liu et al., 2022). The high solubility of the particles, which led to cytotoxicity, oxidative stress, and mitochondrial dysfunction, was blamed for these harmful consequences. The degree of ZnONPs' impact is influenced by increased nanoscale reactivity, dosage, plant species and age, exposure route and duration, and environmental factors, including pH and surface interactions with other soil components (Dimkpa et al., 2019a). Taken together, the present chapter explores the pragmatic and negative effect of ZnO nanofertilizer, its properties, and role in the antioxidant systems, and their efficient utilization in agriculture for future sustainability.

2 Synthesis Methods of Zn and ZnONPs

ZnONPs may be produced using various preparation techniques, including spray pyrolysis, vapor transfer, sol–gel, deposition, and hydrothermal processes. The biogenic production of ZnONPs currently frequently uses diverse plant extracts. Through this procedure, NPs of various sizes and shapes may be produced. Various synthesis methods and their properties are delineated in Fig. 1.

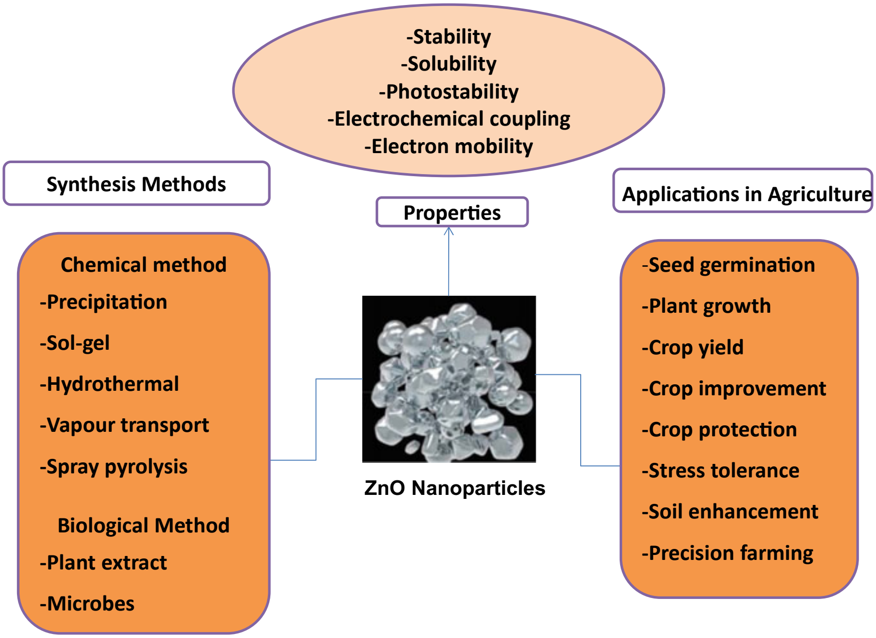

Fig. 1 Synthesis methods and properties of ZnO nanoparticles

2.1 Precipitation Method

Through the direct precipitation method, ZnONPs can be synthesized using zinc nitrate/acetate (0.2 M) and KOH/NaOH (0.4 M) as precursors (Ghorbani et al., 2015). In this method, zinc acetate solution in a beaker is placed on a magnetic stirrer with a hot plate at 30 °C for 40 min, after which NaOH (0.2 M) is added dropwise to the solution with constant stirring. Once the solution became white from the precipitation of ZnO and $Zn(OH)_2$, it was agitated for an additional hour and then allowed to stand for 50 min. The previously synthesized zinc acetate dihydrate (0.1 M) can also be refluxed at 180 or 220 °C in diethylene glycol or trimethylene glycol to produce ZnONPs (Mahamuni et al., 2018). This technique has excellent yield, purity, surface effect, no requirement for organic solvents, simple repeatability, and low cost as its benefits.

2.2 Sol–Gel Method

Chelating chemicals are added after the metal alkoxide has been dissolved in an organic solvent to create a homogenous solution. Coating the substrate, followed by drying, thermal breakdown, and annealing, produces inorganic thin films. By employing zinc acetate dehydrate as a precursor, ethanol as a solvent, sodium hydroxide, and distilled water as a media, ZnONPs can be created (Hasnidawani et al., 2016). High purity and uniformity may be attained by using ethanol at a low temperature. In this liquid-phase synthesis, the dispersion can be stabilized by covering the particles with the appropriate ligands.

2.3 Hydrothermal Process

One of the most popular techniques for creating nanomaterials is this one. This is a solution-reaction strategy. Nanomaterials may be created at various temperatures, from very low to extremely high, regarding hydrothermal synthesis. Depending on the vapor pressure of the base composition in the reaction, either low or high-pressure conditions can influence the materials' morphology (Bulcha et al., 2021). ZnONPs by hydrothermal method contain $Zn(NO_3)_2 \cdot 6H_2O$ and NaOH precursors. 1 M NaOH aqueous ethanol solution is added dropwise to 0.6 M ethanol $Zn(NO_3)_2 \cdot 6H_2O$ aqueous solution, which is placed in a magnetic stirrer for 45 min (Yong et al., 2020).

2.4 Vapor Transport Method

The following steps make up the synthesis process. First, when the precursor (ZnO:C) and substrate were suitably positioned in the tube furnace, the furnace temperature was increased from 22 °C (room temperature) to 900–1000 °C (growth temperature) over 15 min while maintaining a continuous flow of Ar (carrier gas) of 70–200 cm. The specific growth temperature was then maintained for reaction times varying from 30 to 120 min. The substrates were taken out when the tube furnace had cooled to room temperature. Growth, temperature, reaction time, and Ar flow rate all impact the creation of a product (Yu et al., 2010).

2.5 Spray Pyrolysis Method

When a solution is sprayed over a heated surface, the contents react to produce a chemical product, leaving behind a thin film. This process is known as spray pyrolysis. The chemical reactants are selected to make the target molecule and any additional products volatile at the deposition temperature. Spray pyrolysis may create ZnONPs at different concentrations between 5 and 25 weight percent. Under various atomizing pressures, precursor solution breakdown occurs at 800, 1000, and 1200 ºC (Ghaffariana et al., 2011).

2.6 Green Synthesis

The bioreduction of metal ions into their elemental form in the range of 1–100 nm size is accomplished by using plants or plant parts in ZnONPs green synthesis, which is an environmentally benign process. Zinc nitrate/acetate is added to the produced plant extracts using a magnetic stirrer for 120 min, and then dropwise additions of NaOH solution are made (Haripriya et al., 2018). For the manufacture of biogenic ZnONPs, the metabolites present in the aqueous plant extract serve as oxidizing, reducing, and capping agents (Godeto et al., 2023). By adjusting the reaction conditions, it is possible to optimize the size and form of NPs during their production using microorganisms. *Aspergillus aeneus*, *Pichia kudriavzevii* yeast strain, and Lactic acid bacteria are heavily utilized for the microbial-mediated production of ZnONPs for their antibacterial properties (Mohd Yusof et al., 2019, 2020).

3 Properties

ZnONPs are often found in clusters and come in a variety of forms, including rod-, star-, and isometric ones. Among the exceptional qualities are high chemical stability and solubility, high photostability, high electrochemical coupling coefficient, and a broad spectrum of radiation absorption. ZnO will concurrently be present in a formulation as a combination of solubilized Zn ions and a significant portion of undissolved ZnONPs, each exhibiting distinct diffusion and uptake properties. The dissolution rate describes the solubilization of ZnONPs in a certain fluid matrix over time, which is also relevant to nanoparticles. The dissolving rate will vary significantly depending on the fluid composition. ZnONPs have a variety of advantageous optoelectronic characteristics, including strong electron mobility, a broadband gap, and superior transparency. With a broadband gap of 3.37 eV and an exciton binding energy of up to 60 meV even at ambient temperature, ZnONPs are also known as n-type multi-functional semiconductor materials (Haque et al., 2020).

3.1 ZnONPs in Plant Growth, Development, and Productivity

Improving yield was necessary to feed a growing population and, at the same time, reduce the environmental impact of food production. Plant productivity hinges on environmental factors, the availability of nutrients in the soil and water, and the photosynthetic capacity of plants. Inappropriate use of fertilizers degrades the soil and results in poor yield. Replacing traditional Zn fertilizer with ZnONPs can help increase Zn availability for plant nutrient needs in Zn-deficient soils. Nanofertilizer provides the plant with nutrients and restores the soil to an organic state without the harmful factors of chemical fertilizer.

ZnONPs can be used as a fertilizer that is released in a controlled manner so that nutrients only reach plants and are not lost to unwanted targets such as soil, water, and microbes. A nanoscale zinc oxide particle promotes germination, growth, and yield in peanut and wheat plants (Prasad et al., 2012; Rizwan et al., 2019). Zinc nanoparticle delivery in maize boosts the plant's grain development, yield, and zinc content (Subbaiah et al., 2016). Different concentrations ZnONPs were applied to peanut seeds to promote germination of seed, seedling vigor, and plant growth. These ZnONPs also effectively promote stem and root growth in peanuts. The average particle size was 25 nm at 1000 ppm concentration.

Nanoparticles are introduced into the pores of the seed coat to increase the penetration of water molecules and stimulate the activity of starch-degrading and ROS-producing enzymes, which physiologically increase the germination of seeds (Javed et al., 2022). An organic synthesized cow dung-based nanomaterial has recently been reported for future good agricultural practices and seed preparation applications in the agricultural seed sector. Enhancing development and vigor depends heavily on NMs' capacity to pierce the tough seed and let water inside. Additionally, a promising technique is nanotechnology's seed priming technology, which boosts the potential of high-yielding plants before seeding (Acharya et al., 2020; Anand et al., 2020). An antioxidant system that boosts phytohormones like indoleacetic acid (IAA) in roots as a result of foliar application of ZnONPs to *Cicer arietinum* promotes growth and root growth (Burman et al., 2013; Pandey et al., 2010). Similarly, applying ZnONPs to rice and pearl millet plants' leaves boosted plant height, root length, and dry biomass (Song et al., 2021; Tarafdar et al., 2014).

According to a study on *Capsicum annuum* seeds treated with ZnONPs, germination rates, root length, and stem length, all increased (Afrayeem & Chaurasia, 2017). Researchers (Atteya et al., 2018; Gheith et al., 2018) discovered that jojoba and maize plants' growth and yield metrics were improved by zinc treatment. The soil components may be impacted by the movement of ZnONPs, which will then impact plant structure. This study demonstrated the synergistic effect of compost and nanoparticles on the growth and yield of flax plants by increasing flax chlorophyll and related molecules, free amino acids, and carbohydrates (Sadak & Bakry, 2020). Treatment of flax plants with ZnO and nano-ZnO improved flax productivity growth, quantity, and quality. The rate of photosynthesis would rise with a more significant concentration of overall photosynthetic pigments and, boosting the process of output, which enhanced growth of plants (Tawfik et al., 2017).

Another study on ZnO-nanorod's impact on the symbiotic connection between *P. indica* and *B. oleracea* demonstrates a synergistic effect of *P. indica* and this nanorod on the growth of *B. oleracea* as well as the biomass of *P. indica.* Investigation on *Arachis hypogaea* has exhibited that exposure of seeds with ZnONPs enhances seed germination percentage and seedling vigor, causing earlier flowering and pod production by 34%. ZnONPs may enter plant cells due to their small size, which helps in seed germination and growth. In order to improve germination of seed and seedling growth, ZnONPs at low dosages can function as a seed priming agent (Srivastav et al., 2021). The ability to use ZnONPs as nanofertilizer in two Brassicaceae family species such as *B. napus* and *Camelina sativa* showed a positive effect on seed germination and improves vigor index, rootlet, and plumule growth (Sarkhosh et al., 2022). Venkatachalam et al., (2017a, 2017b) reported the plant growth-promoting role of ZnONPs coated with molecules in cotton with P supplementation. These nanoparticles increase wheat yield, plant height, root fresh and dry weight, and grain weight, indicating that applying ZnNPs is a more effective method of raising agricultural production (Adil et al., 2022). After adding ZnONPs in low and high doses to *H. sativum* grown in hydroponic systems, Voloshina et al. (2022) looked at the physiological and biochemical responses. The dose, plant species, age, exposure route, length of exposure, and environmental conditions, such as pH and surface interactions with other soil components, all influence the extent of the ZnONPs impact. Exposure route and duration have an impact on nanoscale reactivity as well (Dimkpa et al., 2020a, 2020b). Table 1 shows the effects of zinc and ZnONPs on several plant development metrics.

Table 1 Impact of zinc and zinc oxide nanoparticles in plant growth and development

Nanoparticle	Plant	Response	References
ZnONPs	Wheat, Maize	Increased root and shoot length, antioxidant enzymes (superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, and catalase)	Srivastav et al. (2021)
ZnO NPs	Tomato	Changes in photosynthetic efficiency and antioxidant system	Faizan et al. (2018)
Phycomolecules coated zinc oxide nanoparticles	Cotton (*Gossypium hirsutum* L.)	Enhanced plant growth	Venkatachalam et al. (2017a, 2017b)
Hybrid ZnONPs	Green pea (*Pisum sativum* L.)	Plant growth	Mukherjee et al. (2016)
ZnONPs	Tomato plants	Growth, photosynthetic traits, and antioxidative enzymes	Wang et al. (2018)
Zinc nanoparticles	Wheat	Plant growth	Du et al. (2019)
Nano-CuO + nano-ZnO	Plants	Plant development	Dimkpa et al. (2015)
ZnONPs and salicylic acid	Rice	Modulation of cellular redox status and antioxidant defense system	Faizan et al. (2021b)
ZnONPs and its bulk form	*Hordeum vulgare* L	Growth, antioxidant defense system, and expression of oxidative stress-related genes	Azarin et al. (2022)
ZnONPs	Spring barley	Physiological and anatomical indices	Rajput et al. (2021)
Nanoscale ZnONPs	Peanut	Germination, growth, and yield	Prasad et al. (2012)
Organic fertilizer and zinc oxide nanoscale	Wheat	Wheat performance and grain nutrient accumulation	Dimkpa et al. (2020a, 2020b)
ZnONPs	Tomato	Physiological and molecular changes	Pejam et al. (2021)
ZnONPs	*Lactuca sativa*	Seedling growth	Galindo-Guzmán et al. (2022)
ZnO nano and ZnO bulk particles	Tobacco	Growth responses, photosynthetic pigment content, and gene expression pattern	Mardi et al. (2022)

(continued)

Table 1 (continued)

Nanoparticle	Plant	Response	References
ZnONPs	*Pleioblastus pygmaeus*	Stimulating antioxidant defense and reducing the metal accumulation and translocation	Emamverdian et al. (2022)
ZnONPs	Soybean plants	Induced shoot and root, net photosynthetic rate, transpiration, stomatal conductance, photochemical yield	Ahmad et al. (2020)
ZnONPs and bacteria	Rice (*Oryza sativa* L.)	Enhanced plant growth and reduced heavy metal toxicity	Akhtar et al. (2021)
Green synthesized (ZnONPs) + *Bacillus cereus* + *Lysinibacillus macroides*)	Rice (*Oryza sativa* L.)	Plant growth and germination	Akhtar et al. (2022)
ZnONPs	*Brassica oleracea* var *italic*	Plant growth	Awan et al. (2021)
ZnONPs	*Chenopodium murale* L	Increased proline content and catalase (CAT), guaiacol peroxidase (GPX), and superoxide dismutase (SOD)	Zoufan et al. (2020)
ZnONPs-based seed priming	Fragrant rice	Modulates early growth and enhances physio-biochemical and metabolic profiles	Li et al. (2020)
Zinc and ZnONPs	*Allium cepa* L	Germination and seedling growth	Tymoszuk and Wojnarowicz (2020)
ZnONPs	*Leucaena leucocephala* seedlings	Plant growth and alleviate heavy metal toxicity	Venkatachalam et al. (2017a, 2017b)
Zinc and iron oxide nanoparticles	Wheat	Improved the plant growth and reduced the oxidative stress	Javed et al. (2022)
Biogenic zinc nanoparticles	*Brassica napus* L	Growth and development	Sohail et al. (2022)
ZnONPs	Alfalfa, tomato, and cucumber	Germination, increased root biomass	De la Rosa et al. (2013)

(continued)

Table 1 (continued)

Nanoparticle	Plant	Response	References
Nano-priming of zinc oxide	rapeseed (*Brassica napus* L.)	Modulation of salinity impact on early seedling stage	El-Badri et al. (2021)
ZnONPs	Onion	Growth, flowering, and seed productivity	Laware and Raskar (2014)
Biosynthesized nanoscale ZnO	*Brassica juncea*	Morphological, biochemical, and molecular aspects	Mazumder et al. (2020)
ZnONPs	Maize	Seed germination	Meena et al. (2017)
Iron-doped zinc oxide nanoparticles	Green peas (*Pisum sativum* L.)	Plant growth	Mukherjee et al. (2014)
ZnONPs and AM fungi	Wheat	Upregulate antioxidant system	Raghib et al. (2020)
ZnONPs	Clusterbean (*Cyamopsis tetragonoloba* L.)	Gum contents	Raliya and Tarafdar (2013)
Titanium dioxide and ZnONPs	Tomato (*Solanum lycopersicum* L.)	Physiological impact	Raliya et al. (2015)
Zinc nanoparticles	*B. napus* L	In vitro germination and biochemical profiling	Sohail et al. (2019)
Nano zinc	Rapeseed	Nutritional enhancement and antioxidant system	Sohail et al. (2020)
ZnONPs	Corn	Plant growth, increased leaf area, and dry biomass	Taheri et al. (2016)
ZnONPs	Sunflower cultivars	Growth and ion concentration	Torabian et al. (2016)
ZnONPs	Brassica nigra seedlings	Growth and antioxidative response	Zafar et al. (2016)
ZnONPs and biofertilizer	Safflower	Regulating ion homeostasis and antioxidant defense responses	Yasmin et al. (2021)
ZnONPs	Wheat (Triticum aestivum L.)	Improved the growth and decreased cadmium concentration in grains	Adrees et al. (2021)
ZnONPs	Fenugreek (*Trigonella foenum-graecum*) plants	Improved seed germination and root development	Shaik et al. (2020)

3.2 Impact of ZnONPs on Antioxidant Enzymes

Based on the plant type, the dose, and duration, the antioxidant activity of enzymes in plants subjected to the harmful effects of ZnONPs varies substantially. Depending on the formation of ZnONPs, the comparative activity of antioxidant enzymes may cause the plant to begin a robust antioxidant response. According to studies, there is an increase in low-molecular-weight antioxidants. ZnONPs exhibit antioxidant capabilities because of the electron density transfer at the O atoms, which depends on the atomic arrangement (Zeghoud et al., 2022). Under stress, the concentration of proline, free amino acids, and total soluble sugars is essential for osmotic adjustment, protecting the structure of macromolecules and cell membranes. Increased levels of H_2O_2, MDA, and proline, as well as antioxidant enzyme activity (superoxide dismutase, catalase, and peroxidase) in rice plants, resulted in significantly higher levels of superoxide dismutase, catalase, and peroxidase gene expression (Song et al., 2021). The formation of O_2 and OH radicals from hydrogen peroxide is catalyzed by superoxide dismutase (SOD), significantly reducing the toxicity caused by superoxide. It regulates ROS damage in addition to controlling ROS signaling. The direct or indirect effects of NPs on the SOD gene expression or ROS level might be due to an increase or reduction in superoxide dismutase activity (Voloshina et al., 2022). Because of its well-known function as a cofactor of SOD, zinc serves as an antioxidant and aids plants in quenching ROS. This element functions as a crucial cofactor or a part of the oxidative reactions in several enzymes. ZnONPs have been shown to affect tomato plant development, photosynthetic properties, and antioxidative enzymes, according to Wang et al. (2018).

The ascorbate–glutathione detoxification cycle for H_2O_2 and metal chelation include Glutathione (GSH), an essential non-enzymatic antioxidant. The quantity of synthesis and degradation of plants' balance throughout development scenarios make up GSH's component part, which is a critical redox buffer for plant activity. *Hordeum vulgare* cultivated in hydroponic systems showed higher glutathione in roots and shoots by nanozinc oxide controlling plant growth indices (Voloshina et al., 2022). High Zn concentrations, however, primarily cause plants to impede root development, thicken, and disturb cell division. Superoxide dismutase, ascorbate peroxidase, and guaiacol peroxidase are antioxidant enzymes that help wheat and maize plants develop more successfully (Srivastav et al., 2021). High Zn concentrations, however, primarily cause plants to impede root development, thicken, and disturb cell division. Superoxide dismutase, ascorbate peroxidase, and guaiacol peroxidase are antioxidant enzymes that help wheat and maize plants develop more successfully.

3.3 Impact of ZnONPs Under Stress Situations

By modifying important physiological parameters, ZnONPs have been discovered to operate as a natural regulator for plants in both stressed and non-stressed environments, hence promoting plant growth and development. When developing fertilizers using nanotechnology for soil application, product effectiveness in field crop production may be impacted by unavoidable occurrences like dryness, which affects nutrient mobility in soil and, as a result, plant absorption. Indeed, the impact of drought on soil nutrient availability and agricultural yield continue to be disastrous in some parts of the world (Lesk et al., 2016; Moreno-Jiménez et al., 2019). Due to Zn's part in metabolic mechanisms that control water dynamics, it can mechanically minimize the effects of drought on crops (Dimkpa et al., 2017; Karim et al., 2012). For instance, plants create more abscisic acid (ABA) under water stress to maximize stomatal closure and preserve water. Zn is known to boost abscisic acid production in plants, improving its ability to regulate stomata when water is scarce (Karim & Rahman, 2015; Yang et al., 2018; Zengin, 2006).

Adding ZnONPs increased soybean percentage of seed germination and rate, while decreasing seed fresh and dry weight under drought stress. Additionally, when exposed to salt stress, ZnONPs significantly enhance sunflower and wheat plant growth and development (Song et al., 2021). By promoting wheat growth and Zn concentrations while lowering plant Cd concentrations, ZnONPs also reduced wheat's cadmium (Cd) toxicity.

Flag leaf and grain head were delayed by drought; however, Dimpka et al. (2019a) examined the acceleration of sorghum growth by ZnONPs, finding that ZnONPs reduced this delay. As a result, under drought conditions, the start of reproductive development in wheat was sped up in the presence of ZnONPs. The use of nanoscale micronutrients in field applications may be made more accessible, the problem of smaller and larger nutrient particle segregation in bulk fertilizer blends may be solved, and one-time Zn-urea application may be made easier by coating urea or other N-fertilizers with nano-scale micronutrients like Zn. Coating might not have a bigger impact on output than separate Zn and urea treatments. Therefore, increasing the coating effectiveness of ZnONPs by modifying the urea coating method will further enhance crop performance and Zn uptake. Also, Dimpka and coworkers (2019a) exhibited the positive influence of ZnONPs on shoot/root length, plant height, biomass, chlorophyll, grain yield, and uptake in wheat crops, under 40% field capacity of moisture.

The physiological and metabolic processes of rice are negatively impacted by cooling stress, which lowers the yield. However, by controlling the gene expression of transcription factors involved in the chilling reaction, ZnONPs applied topically to rice may effectively reduce the toxicity of chilling stress. This suggests that ZnONPs were crucial in controlling the chilling response. Additionally, ZnONPs exhibited significant and varied impacts on plant development and chlorophyll production, ultimately boosting antioxidant capability and ROS scavenging capabilities under freezing stress (Song et al., 2021).

Increased cropping system resilience, continued food/feed and nutrition security for humans and animals, and a reduction in nutrient losses and environmental pollution brought on by N-fertilizers are all strongly impacted by ZnONPs' capacity to speed up plant development, increase yield, fortify edible grains with crucial nutrients like Zn, and improve N acquisition under drought stress. The induction of drought tolerance genes by ZnONPs, which effectively facilitated wheat deficiency tolerance, mitigates drought stress's undesirable effects, as reported by Sadati et al. (2022).

3.4 ZnONPs in Crop Protection

Crop plant diseases caused by microorganisms significantly affect productivity and yield loss. Zinc and copper nanoformulations have shown to be the top performers in creating various commercially available agricultural bio-/pesticides used to control weeds and plant diseases. Applying ZnONPs prevents *Sclerospora graminicola* from causing downy mildew in pearl millet, which is reduced by 35%. The study of defense enzymes revealed that the treatment with NPs noticeably increased the defense enzyme activities, namely, peroxidase, phenylalanine ammonia-lyase, lipoxygenase, and polyphenol oxidase. This showed that the defense enzyme genes were overexpressed in seedlings that had received treatment, indicating that ZnONPs could boost growth and generate systemic resistance in pearl millet against *S. gramini* (Nandhini et al., 2019). They function similarly to chemical pesticides and transport bioactive pesticide components, host defense-inducing chemicals, to the target pathogens (Khan et al., 2019). Nanoformulated zinc oxide was known for its potential to control citrus canker on sweet orange (*Citrus sinensis*) and 'Ruby red' grapefruit trees. Citrus scab and melanose, two fungal diseases that affect grapefruit, were also successfully treated by it. This success may be attributable to the translaminar transport of Zinkicide (Graham et al., 2016).

A new platform for environmentally friendly and efficient ways to manage plant diseases has been created by the green synthesis of nanoparticles, which enables the creation of nanoparticles containing bioactive compounds from plants and bacteria (Bachheti et al., 2023; Sabir et al., 2014). According to Wagner et al. (2016), zinc and ZnONPs are potent suppressors of spore germination of *Peronospora tabacina* and infectiousness on tobacco leaves. The growth of *Hordeum vulgare* L., the antioxidant defense system, and the expression of genes related to oxidative stress are all impacted by ZnONPs and their bulk form (Azarin et al., 2022). According to Thunugunta et al. (2018), ZnONPs can effectively increase aubergine development under greenhouse circumstances by enhancing seed germination, photosynthetic pigments, carbohydrates, protein and raising the activity of antioxidant enzymes. In place of synthetic fungicides, ZnONPs synthesized by *Penicillium expansum* prevented *Fusarium* wilt disease in grown aubergine (*Solanum melongena*), enhanced growth characteristics, and improved metabolic functions (Abdelaziz et al., 2022).

ZnONPs have been used to treat various plant diseases and acceleration of plant growth (Khan & Siddiqui, 2018; Siddiqui et al., 2018). The unique use of *Syzygium aromaticum* flower bud extract in the fabrication of ZnONPs allows for the control of *Fusarium graminearum* development and mycotoxins. The effectiveness of ZnONPs as an antifungal and anti-mycotoxin against Fusarium sp. may be attributed to elevated levels of lipid peroxidation, reactive oxygen species (ROS), and shifting ergosterol concentration, which changed the membrane integrity and shape of macroconidia (Lakshmeesha et al., 2019). The synthesis of metal nanoparticles using plant-derived saponins as efficient capping agents and their potential use as antibacterial and anticancer agents are reported in many publications (Nandhini et al., 2019). In order to prevent *Tetranychus urticae* oviposition, Pavela et al. (2017) created silver nanoparticles with saponin caps made from *Saponaria officinalis* root extract.

3.5 Impact of ZnONPs on the Environment

It is significant to note that the process utilized to create nanoparticles affects how dangerous they are. It has been demonstrated that ZnONPs have beneficial and adverse impacts on plant growth and metabolism at various developmental stages. They are absorbed, transported, and accumulated by plants depending on their anatomy and the characteristics of the NPs (Singh et al., 2018). The transfer of water and nutrients in plants' above-ground tissues is halted by the root tissue's ability to absorb nanoparticles, pierce plant cell walls, enter the apoplast, and proceed to the aerial section. By causing cell cycle arrest and inducing apoptosis, which severely damages DNA and protects plants, the accumulation of such ZnONPs in leaf tissues also triggers a plant defense mechanism. Nanofertilizers enter the xylem vessels through the root epidermis and endodermis, then go to the aerial parts of the plant.

Furthermore, the phloem and leaf stomata can carry these nanoparticle nutrients to various plant parts. Arbuscular mycorrhizae have been shown by Wang et al. (2016) to reduce the detrimental effects of ZnONPs and zinc buildup in maize plants. Despite the benefits, studies show that nanoparticles pose potential environmental harm. ZnONPs dramatically decreased the biomass of ryegrass, shrank the root tip, and caused the root epidermal and cortical cells to become extensively vacuolated and collapse, according to toxicology tests. The bulk of ZnONPs remained attached to the root's surface, and particular NPs were also discovered in the root endodermis, stele, and apoplast. Toxic effects of ZnONPs on bacteria, *Daphnia magna*, and freshwater microalga were also reported (Sabir et al., 2014). The photosynthesis features may be significantly hampered by a highly high NP concentration, which might stunt or even kill plant development. Therefore, there has to be a thorough reexamination of NP release into the environment, NP contact with plants, and NP effects on plants, ecosystems, and the overall environment.

4 Conclusion

The early availability of nutrients to roots and, subsequently, an improvement in crop yield are made possible by metal and metal oxide nano-fertilizers, which offer enormous potential in sustainable agriculture. Excessive amounts of nanoparticles are inadequate for plants, although their traces might benefit them. Therefore, there is a need for further study to comprehend the molecular mechanism of plant nanoparticle interaction in order for nanotechnology to improve agricultural productivity in the future and assure food security.

References

Abdel Latef, A. A. H., Abu Alhmad, M. F., & Abdelfattah, K. E. (2016). The possible roles of priming with ZnO nanoparticles in mitigation of salinity stress in lupine (*Lupinus termis*) plants. *Journal of Plant Growth Regulation.* https://doi.org/10.1007/s00344-016-9618-x

Abdelaziz, A. M., Salem, S. S., Khalil, A. M. A., El-Wakil, D. A., Fouda, H. M., & Hashem, A. H. (2022). Potential of biosynthesized zinc oxide nanoparticles to control *Fusarium* wilt disease in eggplant (*Solanum melongena*) and promote plant growth. *BioMetals, 35*, 601–616.

Acharya, P., Jayaprakasha, G. K., Crosby, K. M., Jifon, J. L., & Patil, B. S. (2020). Nanoparticle-mediated seed priming improves germination, growth, yield, and quality of watermelons (*Citrullus lanatus*) at multi-locations in texas. *Science and Reports, 10*, 5037.

Adil, M., Bashir, S., Bashir, S., Aslam, Z., Ahmad, N., Younas, T., Asghar, R. M. A., Alkahtani, J., Dwiningsih, Y., & Elshikh, M. S. (2022). Zinc oxide nanoparticles improved chlorophyll contents, physical parameters, and wheat yield under salt stress. *Frontiers in Plant Science, 13*, 932861.

Adrees, M., Khan, Z. S., Hafeez, M., Rizwan, M., Hussain, K., Asrar, M., Alyemeni, N., Wijaya, L., & Ali, S. (2021). Foliar exposure of zinc oxide nanoparticles improved the growth of wheat (*Triticum aestivum* L.) and decreased cadmium concentration in grains under simultaneous Cd and water deficient stress. *Ecotoxicology and Environmental Safety, 208*, 111627.

Afrayeem, S. M., & Chaurasia, A. (2017). Effect of zinc oxide nanoparticles on seed germination and seed vigour in chilli (*Capsicum annuum* L.). *Journal of Pharmacognosy and Phytochemistry, 6*, 1564–1566.

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, 9*, 825.

Akhtar, N., Khan, S., Réhman, S. U., Rehman, Z. U., Khatoon, A., Rha, E. S., & Jamil, M. (2021). Synergistic effects of zinc oxide nanoparticles and bacteria reduce heavy metals toxicity in rice (*Oryza sativa* L.). *Plant Toxics, 9*(5),113.

Akhtar, N., Khan, S., Rehman, S. U., Rha, E. S., & Jamil, M. (2022). Combined effect of zinc oxide nanoparticles and bacteria on osmolytes and antioxidative parameters of rice (*Oryza sativa* L.). *Plant Grown in Heavy Metal-Contaminated Water*, 4148765. https://doi.org/10.1155/2022/4148765

Anand, K. V., Anugraga, A. R., Kannan, M., Singaravelu, G., & Govindaraju, K. (2020). Bio-engineered magnesium oxide nanoparticles as nano-priming agent for enhancing seed germination and seedling vigor of green gram (*Vigna radiata* L.). *Materials Letters, 8*, 127792.

Anderson, A. J., McLean, J. E., Jacobson, A. R., & Britt, D. W. (2017). CuO and ZnO nanoparticles modify interkingdom cell signaling processes relevant to crop production. *Journal of Agricultural and Food Chemistry, 66*(26), 6513–6524.

Asadazade, N., Moosavi, S. G., & Seghatoleslami, M. J. (2015). Effect of low irrigation and Zn and SiO2 nano-fertilizers and conventional fertilizers on morphophysiological traits and seed yield of sunflower. *Biological Forum, 7*(1), 357–364.

Atteya, A. K., Esmail, G., Genaidy, G. E., & Hamdy, Z. A. (2018). Chemical constituents and yield of Simmondsia chinensis plants as affected by foliar application of gibberellic acid and zinc sulphate. *Bioscience Research, 15*(3), 1528–1541.

Awan, S. J., Shahzadi, K., Javad, S., Tariq, A., Ahmad, A. H., & Ilyas, S. (2021). A preliminary study of the influence of zinc oxide nanoparticles on growth parameters of *Brassica oleracea* var *italic*. *Journal of the Saudi Society of Agricultural Sciences, 20*, 18–24.

Azarin, K., Usatov, A., Minkina, T., Plotnikov, A., Kasyanova, A., Fedorenko, A., Duplii, N., Vechkanov, E., Rajput, V. D., & Mandzhieva, S. (2022). Effects of ZnO nanoparticles and its bulk form on growth, antioxidant defense system and expression of oxidative stress-related genes in *Hordeum vulgare* L. *Chemosphere, 287*, 132167. https://doi.org/10.1016/j.chemosphere.2021.132167

Babaeia, K., Sharifia, R. S., Pirzadb, A., & Khalilzadeha, R. (2017). Effects of biofertilizer and nano Zn-Fe oxide on physiological traits, antioxidant enzymes activity and yield of wheat (*Triticum aestivum* L.) under salinity stress. *Journal of Plant Interactions, 12*(1), 381–389.

Bachheti, R. K., & Bachheti, A. (Eds.). (2023). *Secondary metabolites from medicinal plants: Nanoparticles synthesis and their applications*. CRC Press. https://doi.org/10.1201/9781003213727

Bulcha, B., Tesfaye, J. L., Anatol, D., Shanmugam, R., Priyanka, L., Dwarampudi, N., Nagaprasad, V. L., Bhargavi, N., & Krishnaraj, R. (2021). Synthesis of zinc oxide nanoparticles by hydrothermal methods and spectroscopic investigation of ultraviolet radiation protective properties. *Journal of Nanomaterials, 2021*, 8617290.

Burman, U., Saini, M., & Kumar, P. (2013). Effect of zinc oxide nanoparticles on growth and antioxidant system of chickpea seedlings. *Toxicological and Environmental Chemistry, 95*(4), 605–612.

Dimkpa, C. O., Andrews, J., Fugice, J., Singh, U., Bindraban, P. S., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2020a). Facile coating of urea with low-dose ZnO nanoparticles promotes wheat performance and enhances Zn uptake under drought stress. *Frontiers in Plant Science, 11*, 168.

Dimkpa, C. O., Andrews, J., Sanabria, J., Bindraban, P. S., Singh, U., Elmer, W. H., & White, J. C. (2020b). Interactive effects of drought, organic fertilizer, and zinc oxide nanoscale and bulk particles on wheat performance and grain nutrient accumulation. *Science of the Total Environment, 722*, 137808.

Dimkpa, C., Bindraban, P., Fugice, J., Agyin-Birikorang, S., Singh, U., & Hellums, D. (2017). Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agronomy for Sustainable Development, 37*, 5.

Dimkpa, C. O., McLean, J. E., Britt, D. W., & Anderson, A. J. (2015). Nano-CuO and interaction with nano-ZnO or soil bacterium provide evidence for the interference of nanoparticles in the metal nutrition of plants. *Ecotoxicol, 24*, 119–129.

Dimkpa, C. O., Singh, U., Bindraban, P. S., Adisa, I. O., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2019a). Addition-omission of zinc, copper, and boron nano and bulk particles demonstrate element and size-specific response of soybean to micronutrients exposure. *Science of the Total Environment, 665*, 606–616.

Dimkpa, C. O., Singh, U., Bindraban, P. S., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2019b). Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. *Science of the Total Environment, 688*, 926–934.

Du, W., Yang, J., Peng, Q., Liang, X., & Mao, H. (2019). Comparison study of zinc nanoparticles and zinc sulfate on wheat growth: From toxicity and zinc biofortification. *Chemosphere, 227*, 109–116.

El-Badri, A. M., Batool, M., Mohamed, I. A., Khatab, A., Sherif, A., Wang, Z., Salah, A., Nishawy, E., Ayaad, M., Kuai, J., Wang, B., & Zhou, G. (2021). Modulation of salinity impact on early seedling stage via nano-priming application of zinc oxide on rapeseed (*Brassica napus* L.). *Plant Physiology and Biochemistry, 166*, 376–392.

Emamverdian, A., Hasanuzzaman, M., Ding, Y., Barker, J., Mokhberdoran, F., & Liu, G. (2022). Zinc oxide nanoparticles improve *Pleioblastus pygmaeus* plant tolerance to arsenic and mercury by stimulating antioxidant defense and reducing the metal accumulation and translocation. *Frontiers in Plant Science, 13*, 841501. https://doi.org/10.3389/fpls.2022.841501

Faizan, M., Faraz, A., Yusuf, M., Khan, S. T., & Hayat, S. (2018). Zinc oxide nanoparticle-mediated changes in photosynthetic efficiency and antioxidant system of tomato plants. *Photosynthetica, 56*, 678–686.

Faizan, M., Bhat, J. A., Hessini, K., Yu, F., Ahmad, P. (2021a). Zinc oxide nanoparticles alleviate the adverse effects of cadmium stress on *Oryza sativa* via modulation of the photosynthesis and antioxidant defense system. *Ecotoxicology and Environmental Safety, 1*(220), 112401.

Faizan, M., Sehar, S., Rajput, V. D., Faraz, A., Afzal, S., Minkina, T., Sushkova, S., Adil, M. F., Yu, F., Alatar, A. A., Akhter, F., & Faisal, M. (2021b). Modulation of cellular redox status and antioxidant defense system after synergistic application of zinc oxide nanoparticles and salicylic acid in rice (*Oryza sativa*) plant under arsenic stress. *Plants, 10*, 2254.

Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in Agriculture: Which Innovation Potential Does It Have? *Frontiers in Environmental Science, 4*, 20.

Galindo-Guzmán, A. P., Fortis-Hernández, M., Rosa-Reta, C. V., Zermeño-González, H., & Galindo-Guzmán, M. (2022). Chemical synthesis of zinc oxide nanoparticles and their evaluation in *Lactuca sativa* seedlings. *Remexca.* https://doi.org/10.29312/remexca.v13i28.3284

Ghaffariana, H. R., Saiedi, M., Sayyadnejad, M. A., & Rashidi, A. M. (2011). Synthesis of ZnO nanoparticles by spray pyrolysis method. *Iranian Journal of Chemistry and Chemical Engineering, 30*(1), 1–6.

Gheith, E. M. S., Shafik, M. M., El-Badry, O. Z., Abdul Kareem, B. M. (2018). Growth and productivity of maize (Zea mays L.) as affected by nitrogen and zinc fertilizer levels: Growth analysis. *Bioscience Research, 15*(1), 54–59.

Ghorbani, H. R., Mehr, F. P., Pazoki, H., & Rahmani, B. M. (2015). Synthesis of ZnO nanoparticles by precipitation method. *Oriental Journal of Chemistry, 31*(2), 1219–1221.

Godeto, Y. G., Ayele, A., Ahmed, I. N., Husen, A., & Bachheti, R. K. (2023). Medicinal plant-based metabolites in nanoparticles synthesis and their cutting-edge applications: An overview. In *Secondary metabolites from medicinal plants* (pp. 1–34). CRC Press.

Graham, J. H., Johnson, E. G., Myers, M. E., Young, M., Rajasekaran, P., Das, S., & Santra, S. (2016). Potential of nano-formulated zinc oxide for control of citrus canker on grapefruit trees. *Plant Disease, 100*(12), 2442–2447.

Haque, M. J., Bellah, M. M., Hassan, M. R., & Rahman, S. (2020). Synthesis of ZnO nanoparticles by two different methods & comparison of their structural, antibacterial, photocatalytic and optical properties. *Nano Ex., 1*, 010007.

Haripriya, P., Stella, P. M., Anusuya, S. (2018). Foliar spray of zinc oxide nanoparticles improves salt tolerance in finger millet crops under glasshouse condition. *SCIOL Biotechnology*, 20–29.

Hasnidawani, J. N., Azlina, H. N., Norita, H., Bonnia, N. N., Ratim, S., & Ali, E. S. (2016). Synthesis of ZnO Nanostructures Using Sol-Gel Method. *Procedia Chemistry, 19*, 211–216.

Hosseini, Y., & Maftoun, M. (2008). Effects of nitrogen levels, nitrogen sources, and zinc rates on the growth and mineral composition of lowland rice. *JAST, 10*, 307–316.

Husen, A., & Siddiqi, K. S. (2023). *Advances in smart nanomaterials and their applications.* Elsevier Inc. https://doi.org/10.1016/C2021-0-02202-1

Husen, A. (2022). *Engineered nanomaterials for sustainable agricultural production, soil improvement and stress management*. Elsevier Inc. https://doi.org/10.1016/C2021-0-00054-7

Husen, A. (2023). *Nanomaterials and nanocomposites exposures to plants (Response, Interaction, Phytotoxicity and Defense Mechanisms).* Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-99-2419-6

Javed, Z., Tripathi, G. D., Mishra, M., Meghana, G., & Kavya, D. (2022). Cow dung extract mediated green synthesis of zinc oxide nanoparticles for agricultural applications. *Science and Reports, 12*, 20371.

Karim, M. R., & Rahman, M. A. (2015). Drought risk management for increased cereal production in Asian least developed countries. *Weather and Climate Extremes, 7*, 24–35.

Karim, M. R., Zhang, Y. Q., Zhao, R. R., Chen, X. P., Zhang, F. S., & Zou, C. Q. (2012). Alleviation of drought stress in winter wheat by late foliar application of zinc, boron, and manganese. *Journal of Soil Science and Plant Nutrition, 175*, 142–151.

Khan, M., & Siddiqui, Z. A. (2018). Zinc Oxide nanoparticles for the management of *Ralstonia solanacearum*, *Phomopsis vexans* and *Meloidogyne incognita* incited disease complex of eggplant. *Indian Phytopathol, 71*(3), 355–364.

Khan, M. R., Rizvi, T. F., & Ahamad, F. (2019). Application of nanomaterials in plant disease diagnosis and management. *Nanobiotechnology Applications in Plant Protection,* 19–33

Lakshmeesha, T. R., Kalagatur, N. K., Mudili, V., Mohan, C. D., Rangappa, S., Prasad, B. D., Ashwini, B. S., Hashem, A., Alqarawi, A. A., Malik, J. A., Abd_Allah, E. F., Gupta, V. K., Siddaiah, C. N., & Niranjana, S. R. (2019). Biofabrication of zinc oxide nanoparticles with *Syzygium aromaticum* flower buds extract and finding its novel application in controlling the growth and mycotoxins of *Fusarium graminearum. Frontiers in Microbiology, 10*, 1244

Laware, S. L., & Raskar, S. (2014). Influence of zinc oxide nanoparticles on growth, flowering and seed productivity in onion. *International Journal of Current Microbiology and Applied Sciences, 3*, 874–881.

Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature, 529*, 84–87.

Li, Y., Liang, L., Li, W., Ashraf, U., Ma, L., Tang, X., Pan, S., Tian, H., & Mo, Z. (2020). ZnO nanoparticle-based seed priming modulates early growth and enhances physio-biochemical and metabolic profiles of fragrant rice against cadmium toxicity. *Journal of Nanbiotechnology, 19*, 75.

Liu, L., Nian, H., & Lian, T. (2022). Plants and rhizospheric environment: Affected by zinc oxide nanoparticles (ZnO NPs) A review. *Plant Physiology and Biochemistry, 185*, 91–100.

Mahamuni, P. P., Patil, P. M., Dhanavade, M. J., Badiger, M. V., Shadija, P. G., Lokhande, A. C., & Bohara, R. A. (2018). Synthesis and characterization of zinc oxide nanoparticles by using polyol chemistry for their antimicrobial and antibiofilm activity. *Biochemistry and Biophysics Report, 17*, 71–80.

Mardi, A., Mohajjel Shoja, H., & Kazemi, M. E. (2022) Comparative study of growth responses, photosynthetic pigment content, and gene expression pattern in tobacco plants treated with ZnO nano and ZnO bulk particles. *Journal of Nano Research, 24*(10). https://doi.org/10.1007/s11051-022-05583-4.

Mazumder, J. A., Khan, E., Perwez, M., Gupta, M., Kumar, S., Raza, K., & Sardar, M. (2020). Exposure of biosynthesized nanoscale ZnO to *Brassica juncea* crop plant: Morphological, biochemical and molecular aspects. *Science and Reports, 10*, 8531.

Meena, D. S., Jayadeva, H. M., Gautam, C., & Meena, H. M. (2017). Effects of nano zinc oxide (ZnO) particles on germination of maize (*Zea mays* L.) seeds. *International Journal of Plant and Soil Science, 16*, 1–5.

Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology, 2*, 579954.

Mohd Yusof, H., Abdul Rahman, N., Mohamad, R., Zaidan, U. H., & Samsudin, A. A. (2020). Biosynthesis of zinc oxide nanoparticles by cell-biomass and supernatant of *Lactobacillus* *plantarum* TA4 and its antibacterial and biocompatibility properties. *Science and Reports, 10*, 19996.

Mohd Yusof, H., Mohamad, R., Zaidan, U. H., & Abdul Rahman, N. A. (2019). Microbial synthesis of zinc oxide nanoparticles and their potential application as an antimicrobial agent and a feed supplement in animal industry: A review. *Journal of Animal Science and Biotechnology, 10*, 57.

Moreno-Jiménez, E., Plaza, C., Saiz, H., Manzano, R., Flagmeier, M., & Maestre, F. T. (2019). Aridity and reduced soil micronutrient availability in global drylands. *Nature Sustainability, 2*, 371–377.

Mukherjee, A., Pokhrel, S., Bandyopadhyay, S., Madler, L., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2014). A soil mediated phyto-toxicological study of iron-doped zinc oxide nanoparticles (Fe@ ZnO) in green peas (*Pisum sativum* L.). *Chemical Engineering, 258*, 394–401.

Mukherjee, A., Sun, Y., Morelius, E., Tamez, C., Bandyopadhyay, S., Niu, G., & Gardea-Torresdey, J. L. (2016) Differential toxicity of bare and hybrid ZnO nanoparticles in green pea (*Pisum sativum* L.): A life cycle study. *Frontiers in Plant Science, 6*, 1242.

Nandhini, M., Rajini, S. B., Udayashankar, A. C., Niranjana, S. R., Lund, O. S., Shetty, H. S., & Prakash, H. S. (2019). Biofabricated zinc oxide nanoparticles as an eco-friendly alternative for growth promotion and management of downy mildew of pearl millet. *Crop Protection, 121*, 103–112.

Pandey, A. C., Sanjay, S. S., & Yadav, R. S. (2010). Application of ZnO nanoparticles in influencing the growth rate of *Cicer arietinum. Journal of Experimental Nanoscience, 5*(6), 488–497.

Pavela, R., Angelo, C., Giovanni, B., & Murugan, K. (2017). *Saponaria officinalis*-synthesized silver nanocrystals as effective biopesticides and oviposition inhibitors against *Tetranychus urticae* Koch. *Industrial Crops and Products, 97*, 338–344.

Pejam, F., Ardebili, Z. O., Ladan-Moghadam, A., & Danaee, E. (2021). Zinc oxide nanoparticles mediated substantial physiological and molecular changes in tomato. *PLoS ONE, 16*. https://doi.org/10.1371/journal.pone.0248778

Prasad, T. N. V. K. V., Sudhakar, P., Sreenivasulu, Y., Latha, P., Munaswamy, V., Reddy, K. R., Sree Prasad, T. S., Sanjanla, P. R., & Pradeep, T. (2012). Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. *Journal of Plant Nutrition, 35*, 905–927.

Raghib, F., Naikoo, M. I., Khan, F. A., Alyemeni, M. N., & Ahmad, P. (2020). Interaction of ZnO nanoparticle and AM fungi mitigates Pb toxicity in wheat by upregulating antioxidants and restricted uptake of Pb. *Journal of Biotechnology, 323*, 254–263.

Rajput, V. D., Minkina, T., Fedorenko, A., Chernikova, N., Hassan, T., Mandzhieva, S., Sushkova, S., Lysenko, V., Soldatov, M. A., & Burachevskaya, M. (2021). Effects of zinc oxide nanoparticles on physiological and anatomical indices in spring barley tissues. *Nanomater, 30*, 1722.

Raliya, R., Nair, R., Chavalmane, S., Wang, W. N., & Biswas, P. (2015). Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (*Solanum lycopersicum* L.) plant. *Metallomics, 7*, 1584–1594.

Raliya, R., & Tarafdar, J. C. (2013). ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in cluster bean (*Cyamopsis tetragonoloba* L.). *Agricultural Research, 2*, 48–57.

Rizwan, M., Ali, S., Ali, B., Adrees, M., Arshad, M., Hussain, A., Ur Rahman, M. Z., & Waris, A. A. (2019). Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. *Chemosphere, 214*, 269–277.

De la Rosa, G., Lopez-Moreno, M. L., de Haro, D., Botez, C. E., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2013). Effects of ZnO nanoparticles in alfalfa, tomato, and cucumber at the germination stage: Root development and X-ray absorption spectroscopy studies. *Pure and Applied Chemistry, 85*, 2161–2174.

Sabir, S., Arshad, M., & Chaudhari, S. K. (2014). Zinc oxide nanoparticles for revolutionizing agriculture: synthesis and applications. *The Scientific World Journal, 2014*, 925494.

Sadak, M. S., & Bakry, B. A. (2020). Zinc-oxide and nano ZnO oxide effects on growth, some biochemical aspects, yield quantity and quality of flax (*Linum uitatissimum* L.) in absence and presence of compost under sandy soil. *Bulletin of the National Research Centre, 44*, 98.

Sadati, R. S. Y., Godehkahriz, J. S., Ebadi, A., & Sedghi, M. (2022). Zinc oxide nanoparticles enhance drought tolerance in wheat via physio-biochemical changes and stress genes expression. *Iranian Journal of Biotechnology, 20*(1), e3027.

Sarkhosh, S., Kahrizi, D., Darvishi, E., Tourang, M., Haghighi-Mood, S., Vahedi, P., & Ercisli, S. (2022). Effect of zinc oxide nanoparticles (ZnO-NPs) on seed germination characteristics in two Brassicaceae family species: *Camelina sativa* and *Brassica napus* L. *Journal of Nanomaterials,*1892759. https://doi.org/10.1155/2022/1892759

Shaik, A. M., David Raju, M., & Rama Sekhara Reddy, D. (2020). Green synthesis of zinc oxide nanoparticles using aqueous root extract of *Sphagneticola trilobat*e Lin and investigate its role in toxic metal removal, sowing germination and fostering of plant growth. *Inorganic and Nano-Metal Chemistry, 50*, 569–579.

Siddiqui, Z. A., Khan, A., Khan, M. R., 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 et Entomol Hungarica, 53*(2), 195.

Singh, A., Singh, N. B., Afzal, S., Afzal, S., Singh, T., & Hussain, I. (2018). Zinc oxide nanoparticles: A review of their biological synthesis, antimicrobial activity, uptake, translocation and biotransformation in plants. *Journal of Materials Science, 53*, 185–201.

Sohail, K. K., Kemmerling, B., Shutaywi, M., & Mashwani, Z. U. R. (2020). Nano zinc elicited biochemical characterization, nutritional assessment, antioxidant enzymes, and fatty acid profiling of rapeseed. *PLoS ONE, 15*, e0241568.

Sohail, A. U., Shad, S., Ilyas, N., Manaf, A., Raja, N. I., & Mashwani, Z. U. (2019). In vitro germination and biochemical profiling of *B. napus* L. in response to biosynthesized zinc nanoparticles. *IET Nanobiotechnology, 13*, 46–51.

Sohail, S. L., Ferrari, E., Stierhof, Y. D., Kemmerling, B., & Mashwani, Z. R. (2022). Molecular effects of biogenic zinc nanoparticles on the growth and development of *Brassica napus* L. Revealed by proteomics and transcriptomics. *Frontiers in Plant Science, 13*, 798751.

Song, Y., Jiang, M., Zhang, H., Li, R. (2021). Zinc oxide nanoparticles alleviate chilling stress in rice (*Oryza Sativa* L.) by regulating antioxidative system and chilling response transcription factors. *Molecules, 26*(8), 2196.

Srivastav, A., Ganjewala, D., Singhal, R. K., Rajput, V. D., Minkina, T., Voloshina, M., Srivastava, S., & Shrivastava, M. (2021). Effect of ZnO nanoparticles on growth and biochemical responses of wheat and maize. *Plants, 10*(12), 2556.

Subbaiah, L. V., Prasad, T. N., Krishna, T. G., Sudhakar, P., Reddy, B. R., & Pradeep, T. (2016). Novel effects of nanoparticulate delivery of zinc on growth, productivity, and zinc biofortification in maize (*Zea mays* L.). *Journal of Agricultural and Food Chemistry, 64*(19), 3778–3788.

Taheri, M., Qarache, H. A., Qarache, A. A., & Yoosefi, M. (2016). The effects of zinc-oxide nanoparticles on growth parameters of corn (SC704). *STEM Fellowship J, 1*, 17–20.

Tarafdar, J. C., Raliya, R., Mahawar, H., & Rathore, I. (2014). Development of zinc nanofertilizer to enhance crop production in pearl millet (*Pennisetum americanum*). *Agricultural Research, 3*(3), 257–262.

Tawfik, M. M., Bakhoum, G. S., Sadak Mervat, S., & Kabesh, M. O. (2017). Application of ZnO nanoparticles for sustainable production of *Atriplex halimus* in saline habitats. *Bulletin of the NRC, 41*(2), 286–305.

Thunugunta, T., Reddy, A. C., Seetharamaiah, S. K., Ramanna Hunashikatti, L., Gowdra Chandrappa, S., Cherukatu Kalathil, N., Dhoranapalli Chinnappa Reddy, L. R. (2018) Impact of zinc oxide nanoparticles on eggplant (*S. melongena*): studies on growth and the accumulation of nanoparticles. *IET Nanobiotechnol, 12*(6), 706–713.

Torabian, S., Zahedi, M., & Khoshgoftar, A. H. (2016). Effects of foliar spray of two kinds of zinc oxide on the growth and ion concentration of sunflower cultivars under salt stress. *Journal of Plant Nutrition, 39*, 172–180.

Tymoszuk, A., & Wojnarowicz, J. (2020). Zinc oxide and zinc oxide nanoparticles impact on in vitro germination and seedling growth in *Allium cepa* L. *Mater, 13*(12), 2784.

Venkatachalam, P., Jayaraj, M., Manikandan, R., Geetha, N., Rene, E. R., Sharma, N. C., Sahi, S. V. (2017). Zinc oxide nanoparticles (ZnONPs) alleviate heavy metal-induced toxicity in *Leucaena leucocephala* seedlings: A physiochemical analysis. *Plant Physiology and Biochemistry, 110*, 59–69.

Venkatachalam, P., Priyanka, N., Manikandan, K., Ganeshbabu, I., Indiraarulselvi, P., Geetha, N., & Sahi, S. V. (2017b). Enhanced plant growth promoting role of phycomolecules coated zinc oxide nanoparticles with P supplementation in cotton (*Gossypium hirsutum* L.) *Plant Physiol Biochem, 110*, 118–127.

Voloshina, M., Rajput, V. D., Minkina, T., Vechkanov, E., Mandzhieva, S., Mazarji, M., Churyukina, E., Plotnikov, A., Krepakova, M., & Wong, M. H. (2022). Zinc oxide nanoparticles: physiological and biochemical responses in barley (*Hordeum vulgare* L.). *Plants, 11*, 2759.

Wagner, G., Korenkov, V., Judy, J. D., & Bertsch, P. M. (2016). Nanoparticles composed of Zn and ZnO inhibit *Peronospora tabacina* spore germination in vitro and *P. tabacina* infectivity on tobacco leaves. *Nanomater (Basel), 6*(3), 50.

Wang, X. P., Li, Q. Q., Pei, Z. M., & Wang, S. C. (2018). Effects of zinc oxide nanoparticles on the growth, photosynthetic traits, and antioxidative enzymes in tomato plants. *Biologia Plantarum, 62*, 801–808.

Wang, F., Liu, X., Shi, Z., Tong, R., Adams, C. A., & Shi, X. (2016). Arbuscular mycorrhizae alleviate negative effects of zinc oxide nanoparticle and zinc accumulation in maize plants–a soil microcosm experiment. *Chemosphere, 147*, 88–97.

Yang, K. Y., Doxey, S., McLean, J. E., Britt, D., Watson, A., Al Qassy, D., Jacobson, A., & Anderson, A. J. (2018). Remodeling of root morphology by CuO and ZnO nanoparticles: Effects on drought tolerance for plants colonized by a beneficial pseudomonad. *Botany, 96*, 175–186.

Yasmin, H., Mazher, J., Azmat, A., Nosheen, A., Naz, R., Hassan, M. N., Noureldeen, A., & Ahmad, P. (2021). Combined application of zinc oxide nanoparticles and biofertilizer to induce salt resistance in safflower by regulating ion homeostasis and antioxidant defense responses. *Ecotoxicology and Environmental Safety, 218*, 112262.

Yong, X. G., Jayatissa, A. H., Yu, Z., Chen, X., & Li, M. (2020). Hydrothermal synthesis of nanomaterials. *Journal of Nanomaterials*, 8917013.

Yu, D., Trad, T., McLeskey, J. T., Craciun, V., & Taylor, C. R. (2010). ZnO nanowires synthesized by vapor phase transport deposition on transparent oxide substrates. *Nanoscale Research Letters, 5*, 1333.

Zafar, H., Ali, A., Ali, J. S., Haq, I. U., & Zia, M. (2016). Effect of ZnO nanoparticles on *Brassica nigra* seedlings and stem explants: Growth dynamics and antioxidative response. *Frontiers in Plant Science, 7*, 535.

Zeghoud, S., Hemmami, H., Seghir, B. B., Amor, I. B., Kouadri, I., Rebiai, A., Messaoudi, M., Ahmed, S., Pohl, P., & Simal-Gandara, J. (2022). A review on biogenic green synthesis of ZnO nanoparticles by plant biomass and their applications. *Materials Today Communications, 33*, 104747.

Zengin, F. K. (2006). The effects of Co_{2+} and Zn_{2+} on the contents of protein, abscisic acid, proline and chlorophyll in bean (*Phaseolus vulgaris* cv. *strike*) seedlings. *Journal of Environmental Biology, 27*, 441–448.

Zoufan, P., Baroonian, M., & Zargar, B. (2020). ZnO nanoparticles-induced oxidative stress in *Chenopodium murale* L, Zn uptake, and accumulation under hydroponic culture. *Environmental Science and Pollution Research, 27*, 11066–11078.