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Nanotechnology: an Integrated Approach Towards Agriculture Production and Environmental Stress Tolerance in Plants

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Abstract Nanotechnology is a new approach to enhancing the agriculture sector by offering new strategies for fostering tolerance against different stresses and boosting output. Abiotic stresses, especially drought and salinity, are the foremost constraints that may severely affect plant growth and crop production, posing a direct threat to the food supply required to meet the increasing demands of the growing global population. The use of nanotechnology is a step towards a modernized agriculture system that has revealed the promising role of nanoparticles (NPs) in improving the growth of plants and the development of different abiotic stress tolerances by increasing hormonal production and photosynthesis pigments and reducing oxidative stress by activating antioxidant enzymes. Salinity and drought stress trigger a variety of morphological, physiological, biochemical, and molecular alterations that have a negative impact on a number of metabolic processes related to plant growth and productivity. NPs enter the plant system by several routes, mainly through roots and leaves, and interact with plants at cellular and subcellular levels, promoting changes in morphological, biochemical, physiological, and molecular states. Contamination with heavy metals (HM) is a major issue that hinders crop production and threatens food security. Outside the soil, foliar spraying is another better way to improve plant resistance to HM. Nutrient intake can be increased by applying nanofertilizer, which ultimately reduces nutrient losses, improves crop quality and yield, and reduces environmental degradation risk. Nanoparticulate fertilizer contains other NPs, such as cerium NPs, silicon NPs, carbon NPs, and titanium dioxide, that promote plant growth.

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The review aimed to examine the penetration and transport of nanoparticles in plants in order to comprehend the potential advantages of using nanotechnology in agriculture. Our study focused on presenting the effects of stress conditions on plants, their responses to such conditions, and the nano-based abiotic-mediated mechanisms of plants. Additionally, we also explored the physiochemical characteristics of nano-based metal oxide applications for improving agricultural systems.

Keywords Nanotechnology · Nanomaterials · Abiotic stress tolerance · Metal-based nanoparticles

1 Introduction

Since agriculture creates and supplies the raw ingredients for the food and feed industries, it has historically been the most significant and secures business (El-Beltagi et al., 2022). Advanced agricultural technologies, including nanotechnology, are requisite due to the burgeoning global population, elevated nutrient mining, rising total food grain production, shrinking arable lands, confined water access, declining soil organic matter, climate change, and a number of other factors (Ahmad et al., 2021a, b; Ashry et al., 2018). Various environmental variables impose significant obstacles to agricultural production by causing stress conditions in plants (Clark & Tilman, 2017). When plants undergo biochemical, physiological, or genetic alterations as an outcome of these situations, productivity is constrained, and energy use is boosted. Farming in greenhouses is an alternative to managing unfavorable environmental circumstances, minimizing detrimental impacts, and even raising yield (Clark & Tilman, 2017).

To create materials with unique qualities such as a huge surface area, the intended zone of operation, the gradual release of substances, and the structure of matter must be regulated at the nanoscale. "The Greek word 'Nanos,' which denotes 'small,' is where the name 'Nano' originates. Nanotechnology is primarily concerned with the separation, consolidation, and deformation of materials by atoms, molecules, or ions." Nanoparticles, whether found naturally or made artificially, have at least one dimension between 1 and 100 nm (Fig. 1).

Nanotechnology is an interdisciplinary field that has gained momentum in recent years, introducing engineered nanoparticles (NPs) into the global market. This technology has the potential to advance agricultural science and other related sectors (Dawi et al., 2021; Vithanage et al., 2023). Agricultural practices have increasingly incorporated products containing engineered NPs, such as nanomaterials, nanocapsules, nanocarriers, nanofertilizers, nanopesticides, and nanosensors, and patented technologies and processes (Amer et al., 2021; Dziergowska &

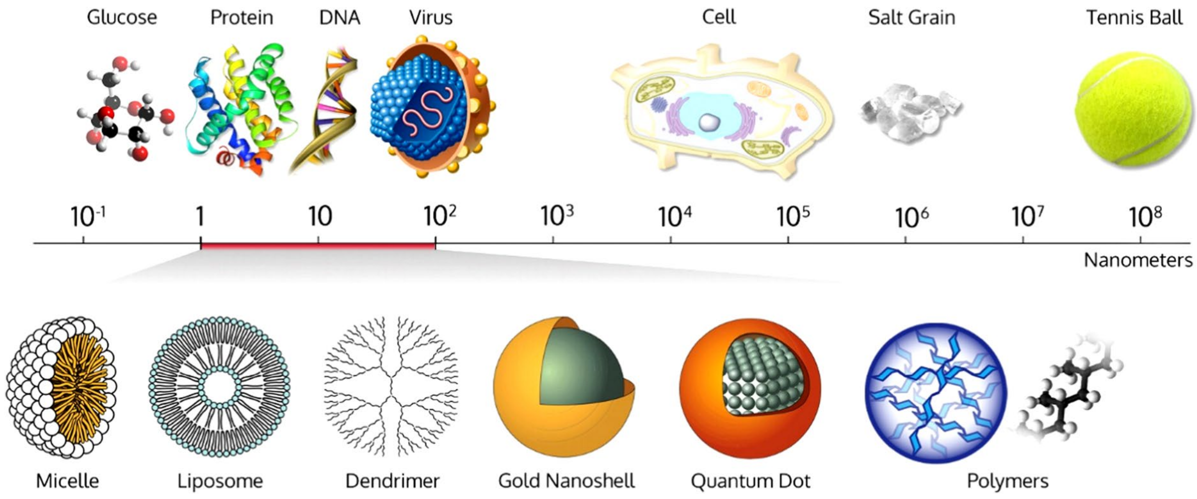


Fig. 1 Scale of nanoparticles: a comparison of nanomaterial sizes

Michalak, 2022; Hassanisaadi et al., 2022; Usman et al., 2020) (Table 1, Fig. 2).

A nanometer is a billionth of a meter. Examples include tiny droplets called nanoemulsions, structures like carbon nanotubes, minuscule particles known as quantum dots, slender nanorods, and even very small capsules (micro and nanoencapsulation). Key properties of nanoparticles include their ability to create reactive oxygen species (ROS) like O_2 and H_2O_2, their size or morphometric ratio, their water-repelling nature (hydrophobicity), their ability to dissolve harmful substances, their surface area, and their characteristics during production or over time, like binding to receptors or forming groups. In short, nanoparticles possess essential attributes that contribute to their functionality and impact, all of which are important for various applications (Somasundaran et al., 2010).

Numerous applications of nanotechnology can be found in the establishments of agricultural production, processing, storing, packaging, transport, and marketing of agricultural products. Nanomaterial application in agriculture aims to cut down on the amount of pesticides required, lessen nutrient losses during fertilization, and raise production through nutritional and pest management. To bump up yield without polluting soil or water and to deliver defense from diverse biotic and abiotic concerns, agriculture employs nanotechnology to construct nanopesticides and nanofertilizers (Abdelsalam et al., 2023). To monitor the integrity of the soil in agricultural areas and manage crop health, nanotechnology may be implemented as sensors (Prasad et al., 2017).

Eliminating locked nutrients, nanoclays, and zeolites can enhance the efficiency with which fertilizers are used while replenishing the fertility of the soil. To address the issues of maintaining perennial weeds and diminishing weed seed banks, nanoherbicides are being devised. Gas sensors and nanosmart dust can be leveraged to swiftly and precisely estimate the degree of pollution in the environment (Abd-Elrahman & Mostafa, 2015a, b).

Additionally, soil analysts are using nanotechnology to improve soil properties such as soil moisture, water holding capacity, and minimum water discharge during the growing season by using nanozeolite and nanoclay composites as well as removing impurities with nanomagnets (Prasad et al., 2017; Vundavalli et al., 2015). With minimum use of resources to get better results, nanofertilizers (Haris et al., 2022) could remove soil harmfulness due to the applied chemical constituent's buildup. They play a big role as nanosensors in the recognition of crop cultivation (such as detecting water and soil contaminants, nutrients and pesticide required amount to apply, and environmental hazards). At trace intensity, heavy metals (HMs) could be identified by nanodetection technology (such as biosensors, optical, electrochemical, and vice versa) (Akladious & Mohamed, 2017; Prasad et al., 2017). Numerous plants exposed to an array of abiotic stressors, including salt, drought, extreme or light temperature, heavy metal exposure, and nutrient deficiency, have improved from the use of nanoparticles (Hernández-Hernández et al., 2018; Raliya et al., 2016).

The use of NPs in agriculture is gaining momentum due to their potential to augment crop growth, soil health, and productivity, as noted by Landa (2021). In recent years, various rare earth metal–based NPs, including ZnO-NPs, Zn-NPs, Ag-NPs, FeS2-NPs, Fe-NPs, CeO_2-NPs, SiO_2-NPs, Au-NPs, TiO_2-NPs, CuO-NPs, and carbon-based NPs (such as carbon nanotubes and fullerols), have been tested in controlled and natural field conditions to help plants survive in various stressed environments. These studies have demonstrated that NPs can have both negative and positive effects on plant growth, depending on the size and dose used (Chen et al., 2015; Singh et al., 2021). Nanotechnology continues to revolutionize the agricultural field by offering a vast array of nanomaterials that enhance food and crop production, as noted by Tighe-Neira et al. (2022) and Vithanage et al. (2023). Exogenous application of NPs in agriculture has emerged as a promising technique for improving crop development and productivity under normal and stressed conditions.

NPs can enter the root epidermis or aerial surface through apoplastic and symplastic pathways, and their uptake and transport depend on their size. Recent investigations suggest that NPs contribute to different physiobiochemical processes regulating plant growth, productivity, and responses to harsh abiotic stresses. Moreover, exogenous application of NPs can increase specific morpho-physiological processes, resulting in increased crop yield. Beneficial NPs can be used as nutrient or fertilizer nanocarriers, with increased efficiency and reduced environmental contamination compared to traditional fertilizers

Table 1 Relevant agricultural applications of nanotechnology

Products	Applications	Examples	References
Plant protection	A comparison of the sizes of nanomaterials	Neem oil (*Azadirachta indica*) nanoemulsion as larvicidal agent	Mali et al. (2020)
Biofertilizer	Active ingredient delivery methods for disease and pest management in plants Improve shelf, and cell viability, and reduce cell sedimentation	Fertilizers rich in macronutrient NPK-controlled delivery and zinc oxide nanoparticle coating chitosan nanoparticles are used in the nanocoating of sulfur	Milani et al. (2015) Corradini et al. (2010)
Soil improvement	Fertilizers with macronutrients like zinc oxide nanoparticles are coated on the surface, and NPK is delivered in a regulated manner. Sulfur nanocoating with chitosan nanoparticles the plants	Water retention and release soil enhancer based on a nanoclay component	Parisi et al. (2015)
Genetic material delivery	DNA	Gold (10–15 nm) Gold (5–25 nm) Starch (50–100	Demirer and Landry (2017) Liu et al. (2008)
Nanosensors and diagnostic devices	Nanomaterials and nanostructures (e.g.,) carbon nanotubes, nanofibers, and fuller sensitive biochemical sensors act as a monitoring tool for environmental conditions, plants, health, and growth	Pesticide detection using a nanobiosensor based on liposomes	
Nanofungicide	ZnO NPs act as an effective fungal and bacteria growth inhibitor Silver NPs are used in reducing growth and aflatoxin production by fungi Copper-based NP interaction with fungi promotes the formation of reactive oxygen species (peroxides) and causes mitochondrial and protein disruption that leads to DNA damage Silver, titanium dioxide, zinc oxide, etc. are effective against various soil-borne pathogens	10 $\mu g\ ml^{-1}$ zinc NPs treatment inhibited fumonisin B1 synthesizing fungus The disease severity was reduced when a different form of nanoparticles (AgNPs and Ag ions) was applied against plant-pathogenic fungi *Bipolaris sorokiniana* and *Magnaporthe grisea* for 3 h Deletion of citrinin from Monascus suspensions by 1 $g\ L^{-1}$ of surface active maghemite nanoparticles" (SAMNs)	Magro et al. (2016)
Nanopesticides	Nano-based pesticides reduce the potential threat to the environment Increase insecticidal efficiency Reduction in pest growth	TiO_2NP (500–800 mg) against *X. perforans* (tomato spot disease-inducing pathogen) CeO_2 NP(50 and 250 mg/L by root and foliar path) was effective against fusarium wilt in tomato MgONP (0.1, 0.5, 0.7, or 1% (growth media: 50% vermiculite and 50% perlite) show resistance to *Ralstonia solanacearum* in tomato plants	Chiranjeeb and Senapati, (2020) Paret et al. (2013) Adisa et al. (2018) Imada et al. (2016)

Table 1 (continued)

Products	Applications	Examples	References
Food packaging	The organic and inorganic NPs or their combination are helpful in the agricultural sector and food safety applications	Nanofiller Antimicrobial properties of nanocomposite films Nanosensor-based smart packaging Nanocellulose Nanostarch Protein nanoparticles Carbon nanotubes Silver nanoparticles Zinc nanoparticles Nanoclay Titanium dioxide nanoparticles(TiO_2-NPs)	Ashfaq et al. (2022)
Nanoherbicides	Friendly system of weed removal improves efficiency, provides long lives, and enhances its absorption by plants	Nanospheres or nanocapsules (polymeric nanoparticle) SiNP-based nanoherbicides protect and stabilize the herbicide and reduce their wastage with easy deposit on the plant leaves	Abigail and Chidambaram, (2017)
Precision farming	Use techniques like nanocapsules (0.1 to 100 nm), nanoparticles nano-encapsulated fertilizers, pesticides Nano-encapsulated particles protect it from degradation, provide longevity to the chemicals, pesticides, and fertilizers, and keep the environment clean ➢ Chitosan nanoparticles are used in controlling fungal infection and seed treatment	Metal oxides Ceramics Magnetic materials Quantum dots Lipids Polymers ➢ Semi-conductors	Chiranjeeb and Senapati (2020)

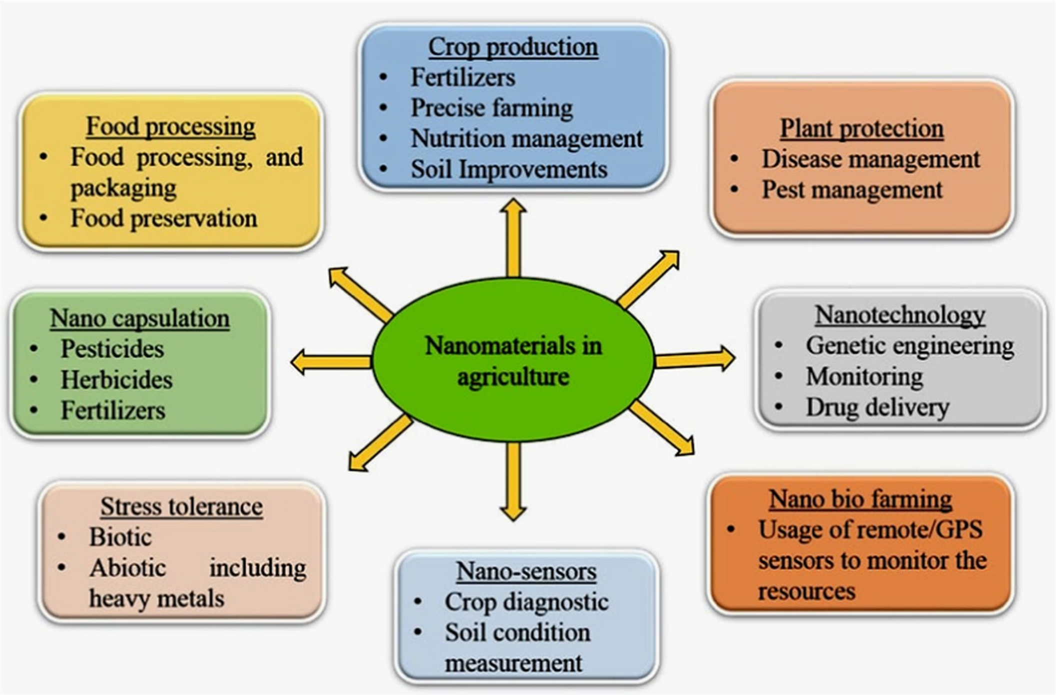


Fig. 2 Application of nanomaterials in agriculture

due to their physio-chemical properties and modes of action (Gohari et al., 2021; Landa, 2021). The present review has attempted to raise and address these key concerns besides providing an updated account of the status of NP-mediated mitigation of major abiotic stresses in crops.

2 Different Kinds of Abiotic Stress

Conversely, issues notably soil salinity, intense heat or cold, a dearth of nutrients, and heavy metals significantly influence production (Ahmad et al., 2021a, b; El-Beltagi et al., 2022; Sofy et al., 2022). Abiotic stress encompasses inert environmental elements capable of exerting adverse effects on plant growth and development. These elements include extremes of temperature, prolonged drought, elevated salinity, and the presence of toxic heavy metals. These stressors exert influence on the morphology of plants, inducing modifications in their structure, size, and forms. Moreover, they cast an impact on vital physiological mechanisms like photosynthesis, respiration, and the absorption of water. Deeper within the biological framework, abiotic stress causes modifications in gene expression and protein synthesis, thereby instigating changes in metabolic processes and the intricate signaling cascades. Plants, being stationary organisms, lack the means to elude severe environmental stimuli, encompassing factors like salinity, drought, temperature fluctuations, and flooding. These elements are detrimental to crop yields (Raza et al., 2023). The amplified instances of salinity and drought stress, owing to the repercussions of global climate change, have engendered a decline in crop growth, thereby imperiling global food security (Wang et al., 2021).

Salinity stress, a combination of osmotic and ionic challenges, emerges from the unfavorable accumulation of salts within the soil (Alam et al., 2021; Gupta et al., 2021; Melino & Tester, 2023). This phenomenon compromises plant vigor by adversely influencing cellular processes due to the ionic cytotoxicity resulting from mineral ion accumulation and exchange involving Na^+ (Johnson & Puthur, 2021; Melino & Tester, 2023; Raza et al., 2022). Drought, a multifaceted abiotic stressor, arises from deficient rainfall and extreme temperature fluctuations. It instigates alterations in plant attributes and developmental trajectories (Bhardwaj & Kapoor, 2021). Predominant in arid and semiarid regions, drought disrupts pivotal plant processes, notably transpiration rate, stomatal conductance, photosynthetic frequency, water potential, and leaf relative water content (RWC), throughout diverse growth stages (Raza et al., 2023; Yang & Qin, 2023).

Moreover, drought-induced stress exerts an impact on cellular division, meiosis, pollen count, and pollen sterility and can lead to plant necrosis (Mohamed et al., 2018). Salinity and drought stress can incite an excessive generation of reactive oxygen species (ROS) by disrupting a plant's inherent defense mechanisms (Hasanuzzaman et al., 2020; Mittler et al., 2022). This occurrence initiates oxidative stress that inflicts damage upon cellular organelles such as DNA, lipids, and proteins, along with perturbing enzymatic arrangements. Ultimately, this cascade culminates in cellular demise (Mittler et al., 2022; Tiwari et al., 2021).

3 Nanotechnology: an Integrated Agriculture Tool to Alleviate Abiotic Stress in Plants

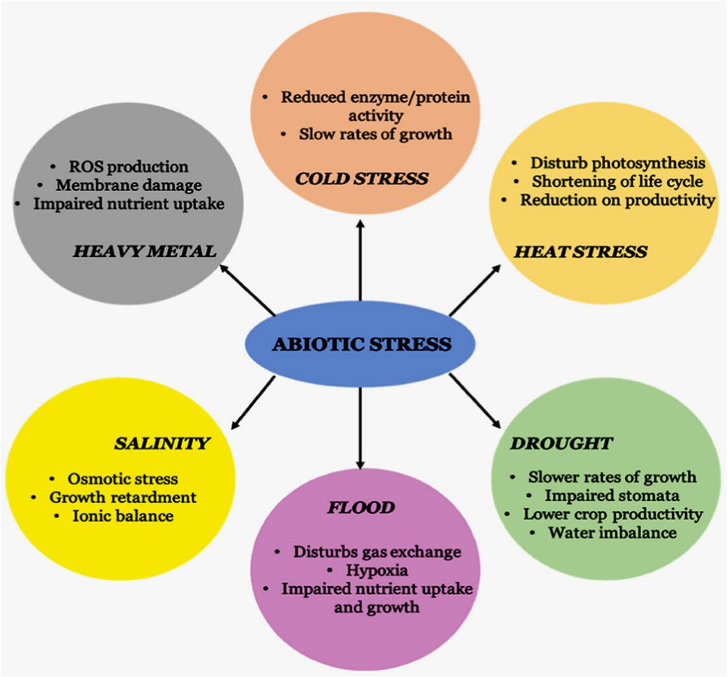
The rising global population, shrinking arable land, and increasing dangers from climate change all put pressure on the need for novel approaches and strategies to boost yield potential under challenging conditions (Ihsan et al., 2023; Mogazy et al., 2022). Several biotic and abiotic factors can trigger stress for plants. These stresses, such as drought, salinity, temperature, and heavy metals, cause significant alterations in plants (Fig. 3). So, one of the main goals of research is to increase crops' ability to withstand stress and meet the increasing demand for food resulting from population growth. There have been significant initiatives over the past few decades to raise agricultural yields through the widespread application of pesticides, which have negative long-term implications on the environment and human health. Therefore, the use of revolutionary technology is required to feed the world's population without harming the environment. A revolutionary strategy for agricultural enhancement is nanotechnology, which offers fresh ideas for increasing resilience to diverse pressures and productivity (Elemike et al., 2019).

To cope with environmental stress, plants have developed a wide range of efficient and comprehensive molecular programs to rapidly sense stressors and adapt accordingly (Khalid et al., 2022). Plants can enhance this response through the interaction of NPs with plants. Nanotechnology promises to increase crop yield by improving plant tolerance mechanisms under abiotic stress conditions. Several studies have shown that NPs play a vital role in improving the tolerance of plants to abiotic stresses by modulating various physiological, biochemical, and molecular processes (Fig. 4).

3.1 Extreme Temperature

Crop cultivation depends on the climatic conditions of an area while variation in such conditions due to various biotic and abiotic factors (i.e., variation in temperature, inadequate light, nutrients disproportion, low water availability) leads to disturbance in plant cellular homeostasis because every plant grows at its own threshold level. Ecosystem adaptability and food safety have recently attracted international attention. Global warming, which is a direct result of human harm to the environment, has a negative impact on food safety and agriculture (Sachdev et al., 2021). Due to increased greenhouse gas concentration and higher temperatures than what is ideal for crops, crop yield has been reduced. While the average increase in temperature for some European regions even exceeds 2 °C, it was only 1 °C in 2018. Abiotic stressors can disrupt cellular homeostasis and cause oxidative stress, which reduces nutrient uptake, throws off the balance of hormones, and hinders plant growth. The increase in the earth's surface temperature is one of the known most harmful factors (Mohamed et al., 2019).

Crop yield is reduced due to heat stress as plant reproductive growth is highly heat sensitive (Thakur et al., 2010), and this sensitivity remains for 10–15 days as certain controlled environment studies have shown high temperature negatively influences flower bud induction (Nava et al., 2009). Crops (legumes and cereals) of temperate and tropical regions are also heat-sensitive, and temperature variation results in lower fruit set (Prashant et al., 2023) and also due to improper water and nutrient transmission (Prashant et al., 2023). Plants can survive to a certain extent through reprogramming of



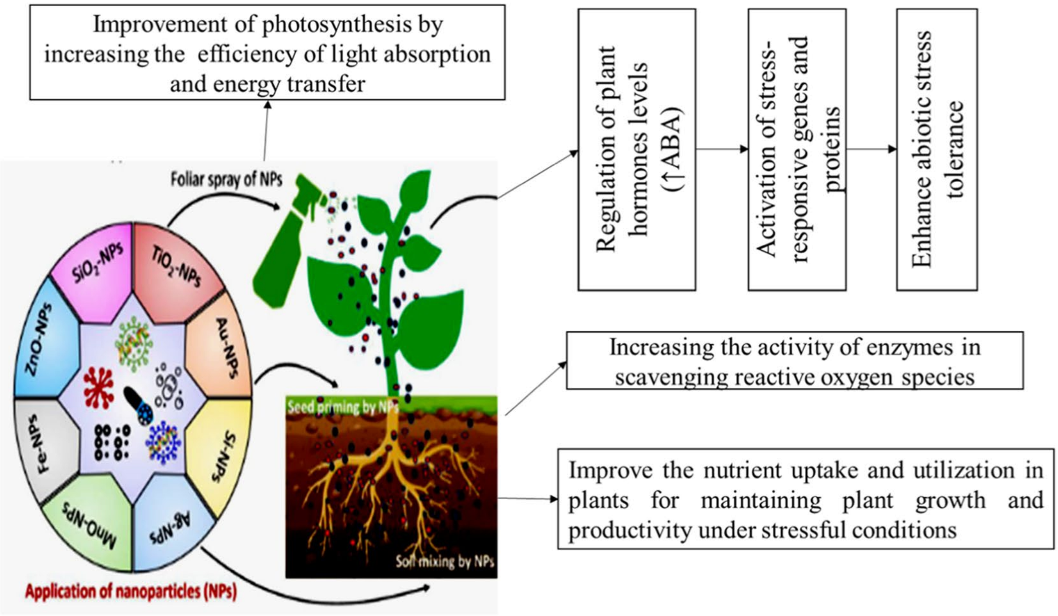


Fig. 3 Role of NP-based fertilizer in plants under abiotic stresses

the transcriptome, proteome, and metabolome, but above that, periodical abortion or plant death occurs due to the initiation of the cell death mechanism (Sanchez-Rodríguez et al., 2011).

Huge production of heat shock proteins (HSPs) occurs during tolerance against heat and plants cope in such conditions as a result of heat-sensitive element restoration, protection from heat damage,

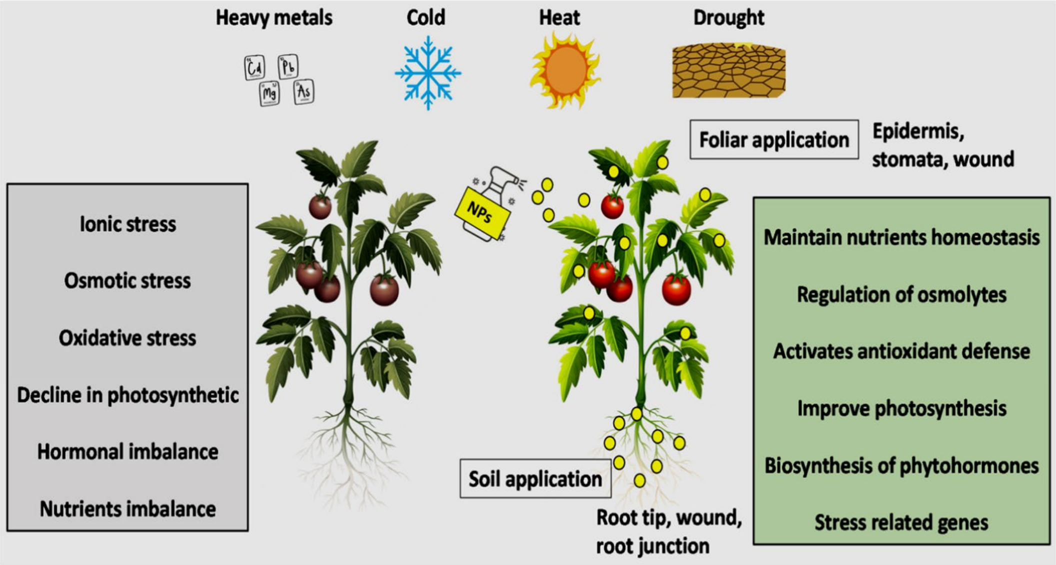


Fig. 4 Mechanisms of NP in alleviating abiotic stress in plants (Khalid et al., 2022)

and metabolic strain (Mohamed et al., 2019). This is because specific biological and metabolic processes, antioxidants, membrane lipid unsaturation, gene appearance and transformation, protein constancy, and the accumulation of harmonious solutes occur at the genetic level as part of the heat tolerance mechanism (Kaya et al., 2001). Highly genotypic attributes towards tolerance led plants to withstand against stresses (Mohamed & Abdel-Hamid, 2013). By enhancing hormone production, photosynthetic pigments, and reducing oxidative stress by activating antioxidant enzymes, NPs have recently been shown to play a promising function in optimizing plant growth and the development of diverse abiotic stress tolerance in modern agriculture systems (Rana et al., 2021; Thakur et al., 2022) (Fig. 5).

According to a recent study, nanotechnology may be able to shield plants from the heat stress brought

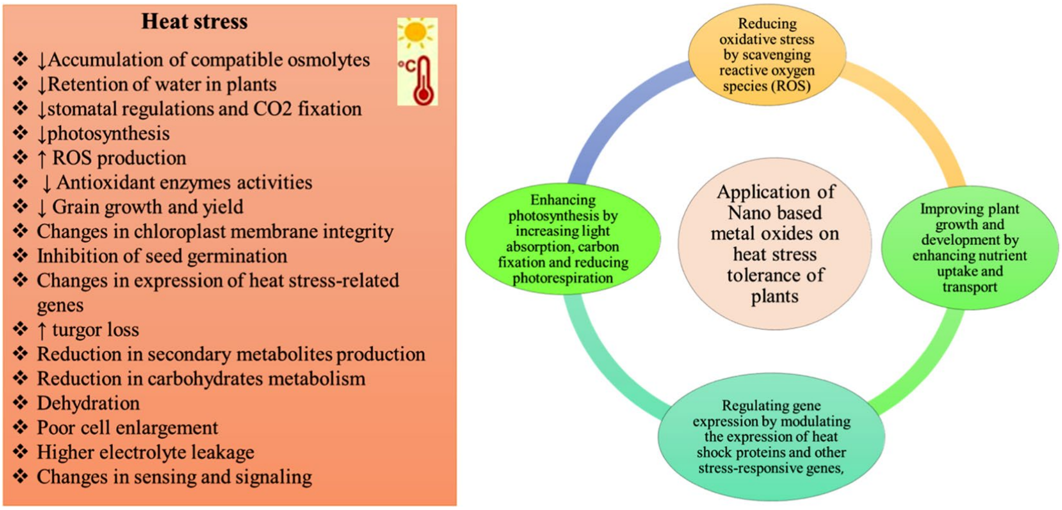


Fig. 5 Heat stress and tolerance development by application of nano-based metal oxides

on by high temperatures and protracted heat waves (Khalid et al., 2022). Se nanoparticles were discovered to enhance tomato plant growth and chlorophyll content (Djanaguiraman et al., 2018a). Additionally, TiO_2 treatment of tomato plants increased photosynthesis and promoted stomatal opening, which cooled the leaves (Qi et al., 2013). Foliar spray with Se NPs improved relative water content, proline, catalase, peroxidase activities, and reduced the effect of heat stress in cucumber plants (Shalaby et al., 2021).

3.2 Salinity Stress

The provision of land for sustainable agriculture is severely constrained by soil salinity, which has also become a significant threat to the world's food security. The amount of irrigated land impacted by salt is thought to be around 62 million hectares (20% of all farmed land worldwide), and it is rising daily, especially in arid and semi-arid regions of the world (Etesami & Noori, 2019). Glycophytic and halophytic plants are both severely harmed by salinity stress (Etesami & Beattie, 2018; Komaresofla et al., 2019). The physiological, biochemical, and metabolic processes associated with plant growth and productivity are negatively impacted by a number of changes brought on by salinity stress. NPs can enter a plant's system in a number of ways, but the roots and leaves are the main entry points. NPs interact with cells and subcellular components after entering plants, which affects morphological, biochemical, physiological, and molecular changes (Khan et al., 2019). Depending on the NPs and the plant species, these interactions could be advantageous or harmful. Effects of NPs on plant systems may depend on the chemical make-up, reactivity, size, and particularly concentration of NPs within or on the plant. According to the available data, distinct NPs can stimulate plant growth and development in salinity-stressed environments at concentrations below specific limitations through a variety of recognized processes (Zulfiqar & Ashraf, 2021). It has been documented that the micronutrient Cu helps plants avoid the negative effects of salinity by improving water relations, photosynthesis, nutrition, upregulating antioxidant defense, and increasing levels of osmoprotectants and amino acids (Iqbal et al., 2018). Hernández-Hernández et al. (2018) investigated the impact of copper nanoparticles on tomato growth under salt stress and found an increase in tomato growth by increasing the expression of the SOD and jasmonic acid genes, which reduced ionic and oxidative stressors. According to the authors, using Cu-NPs could successfully boost salinity tolerance by triggering the antioxidant defense system and the jasmonate octadecanoid pathway (Zulfiqar & Ashraf, 2021) (Fig. 6).

Plants survive in various environmental strains as a result of selenium (Rastogi et al., 2019). Selenium oxide nanoparticles shield plants from salinity stress along with early seedling growth, seed sprouting, and other features in lentil genotypes (Sabaghnia & Janmohammadi, 2015). Against various stresses, plants develop a layer in the root cell wall in case of SiO_2 NP use (Abdel Latef et al., 2018). So, selenium, and SiO_2 NPs have a key role in plant growth continuation during saline conditions (Wang et al., 2011) because, in maize roots and seeds, SiO_2 NPs efficiently absorbed due to smaller size than micro SiO_2, -Na_2SiO_3, or -H_4SiO_4 (Suriyaprabha et al., 2012). In addition, other crops (tomato and squash) also enhance seed sprouting and antioxidant activity after treatment with selenium oxide nanoparticles (Siddiqui et al., 2014). During the growth phases of *Phaseolus vulgaris*, selenium nanoparticle at 300 mg/L helps in plant growth through enhanced seed germination and biomass elongation along with seedling dry and wet matters compared with control (Alsaeedi et al., 2017).

3.3 Heavy Metal Stress

One of the main reasons impeding agricultural production and posing a danger to food security is HM contamination (Javaid et al., 2020). To reduce plant output, heavy metal (HM) has a considerable negative impact on healthy cell development, the antioxidant system, and plant growth. Further significantly, the predicted expansions in global population—to 8.54 billion by 2030 and 9.73 billion by 2050—mean that current food production must rise by 70 to 100% to keep up with demand (Mueller et al., 2012). HM pollution is a problem that is spreading swiftly due to rapid urban and industrial migration, persistent use of agricultural pesticides and fertilizers, irrational mining, and waste management (Abu-Shahba et al., 2022; El-Mahdy et al., 2021). Because HM pollution is so prevalent in food and blood, it has recently come to the attention of the public. Plant growth is affected by HM stress, and through the food chain,

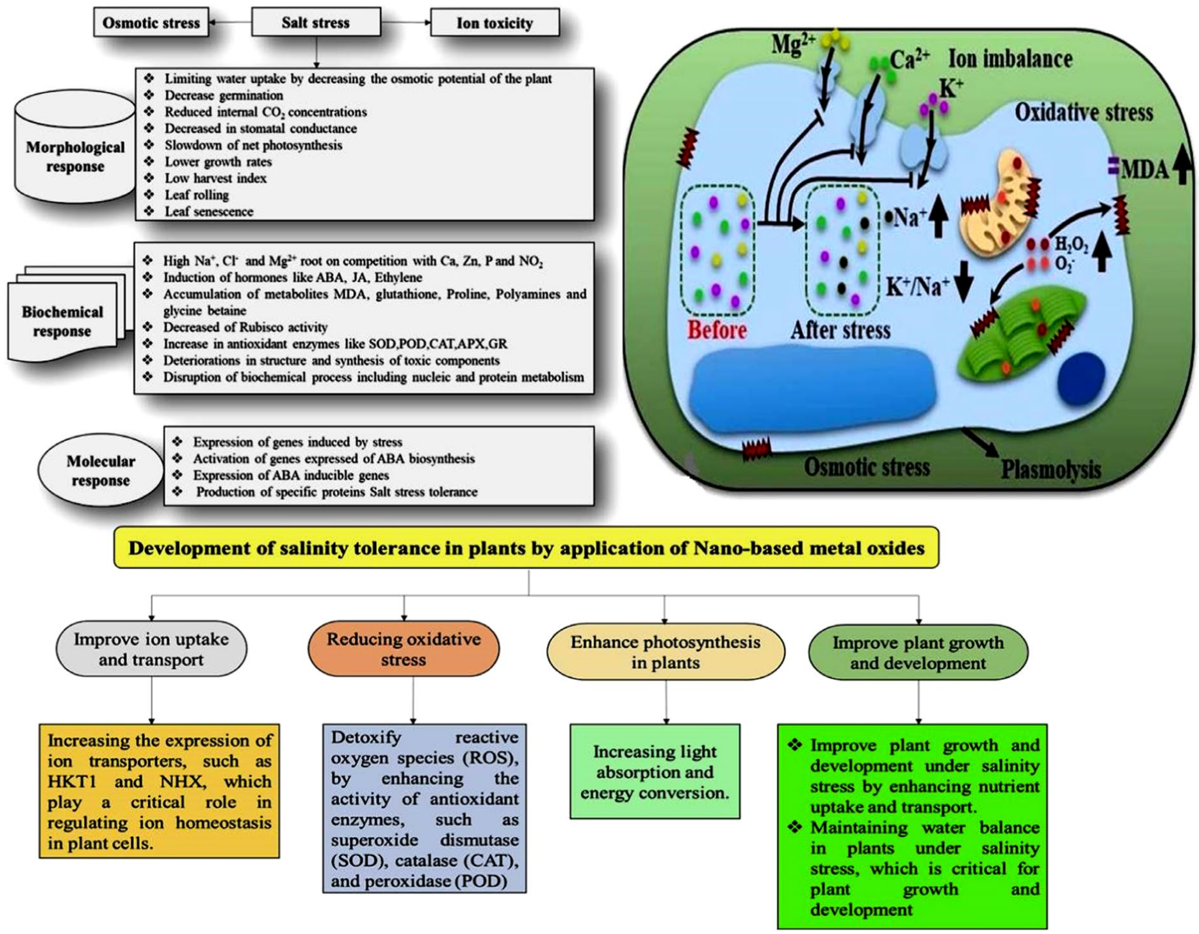


Fig. 6 Potential role of nano-based metal oxide application in alleviating salinity stress

this indirectly affects human health (Arif et al., 2019). In order to eradicate HM from a polluted farm environment, technology must be established and made public. In recent years, the usage of nanoparticles (NPs) in industry, health, agriculture, and the cosmetics industry has substantially surged (Adeel et al., 2019). The bioavailability and mobility of soil HMs can be diminished via absorption and NP conversion. Fe_3O_4 NPs, for instance, decreased the flow of HMs such as Cd to the ground (Sebastian et al., 2019). After 3 years in the field, mercapto Si NPs reportedly changed Cd into a stable environment, according to Wang et al. (2020). Moreover, some NPs can enhance the characteristics of soil, for example, hydroxyapatite NPs can release phosphate and raise soil pH, minimizing the deleterious impacts of HM in soil (Singh & Lee, 2018).

Venkatachalam et al. (2017) reported that the application of zinc oxide nanoparticles alleviates heavy metal stress in plants by the accumulation of antioxidant metabolites and enzymes. Crop yield improved by use of nanoscale TiO_2 nanoparticles (because of enhanced rubisco and antioxidant events, chlorophyll biosynthesis led to more photosynthesis) (Lei et al., 2008). Furthermore, activate various mechanisms to cable plant against abiotic stresses. During Cr stress in pea seedlings, the oxidative stress declined while enzyme (ascorbate peroxidase and superoxide dismutase) activities enhanced due to selenium oxide NPs (Tripathi et al., 2015). Similarly, an antioxidant protection system is initiated in maize plants in order to minimize aluminum poisons as a result of selenium oxide NPs (de Sousa et al., 2019). Wheat from Cd-induced oxidative stress could be prevented through iron oxide NPs (Konate et al., 2017).

Due to the use of selenium nanoparticles in Chinese cabbage, Cd and malondialdehyde in the leaves were reduced, while other characteristics (such as root and shoot mass, chlorophyll, SOD, and plasma glutathione peroxidase) improved under Cd stress (Zhang, 2019). Si NPs have been shown to reduce Cd stress in rice (Wang et al., 2015), and the combined use of biochar and iron oxide NPs (Hussain et al., 2019a, b) or iron oxide NPs and biochar (Rizwan et al., 2019a) has also been shown to minimize Cd stress. According to Rahmatizadeh et al. (2019), applying iron oxide to leaves is more effective than applying it to soil because it increases antioxidant enzyme activity and crop DW while reducing leaf electrolyte leakage and Cd in grains.

The addition of Si NPs to the growing source enhances antioxidant activity and lessens the Cr precipitation in pea seedlings to reduce Cr harmfulness (Tripathi et al., 2015). Furthermore, Cd precipitation gets normal which enhanced rice plant protection against Cd stress with 2.5 mM selenium oxide NPs (Wang et al., 2015) (Fig. 7).

3.4 Drought Stress

According to Ramankutty et al. (2008), agriculture encompasses around 15 million km^2 of the land surface, and 16% of this area has irrigation systems. As a result, drought stress is a common occurrence for plants in several sections of the world. Drought is the single biggest danger to global food security due to a lack of water resources. The previous major famines were sparked by it (Ahmad et al., 2023; Mohamed et al., 2018). The consequences of drought are projected to worsen in the future due to the constrained water accessibility in the world and challenges from a fast-expanding population (Zhao et al., 2023). Particularly in arid and semi-arid areas, drought adversely restricts plant growth, development, and output (Ahmad et al., 2023). In drought-prone locations, the characteristics of plants' responses to drought stress have become a

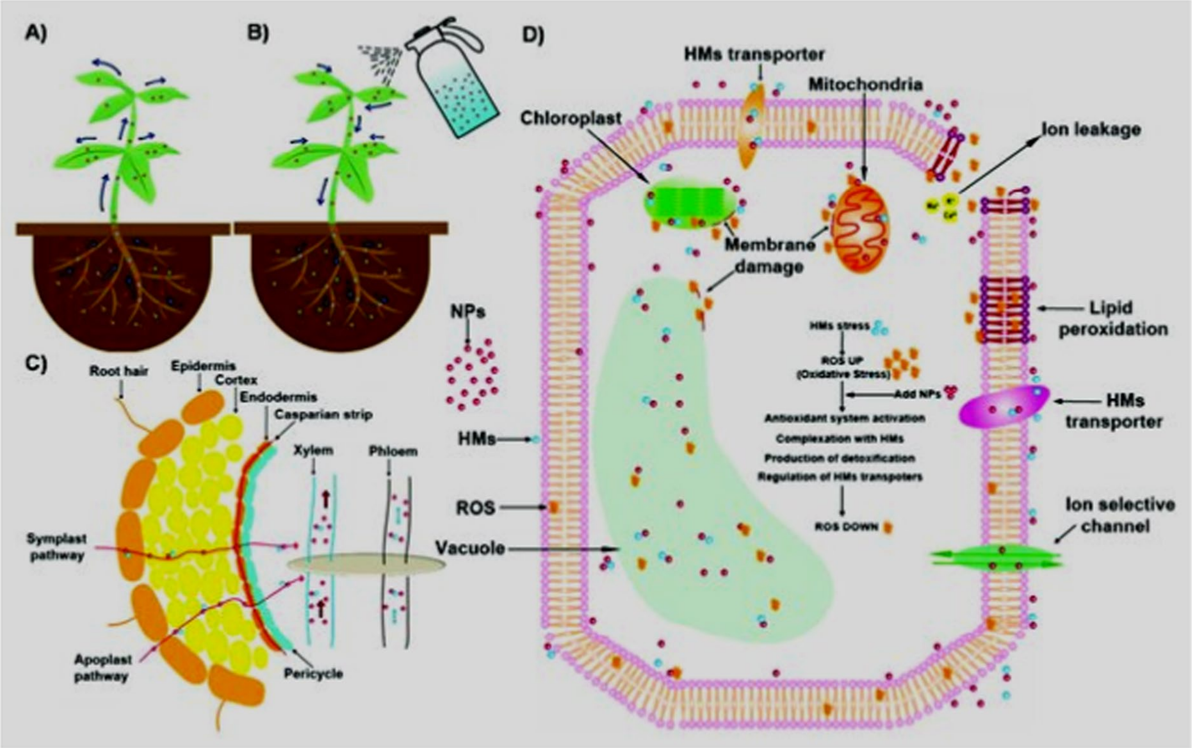


Fig. 7 Overview of alleviating heavy metal (HM) stress by use of nanotechnology

major environmental research topic. Seed germination, a crucial stage in plant development, is especially susceptible to these stressors. The initial phase of a plant's experience with drought is germination. If the seeds are planted eventually and vigorously, germination is also crucial for determining the ultimate plant density (Abd El Mageed et al., 2023). Several investigations have shown that TiO_2 nanoparticles, at concentrations as low as 20 mg/L, significantly enhanced spinach growth by promoting photosynthesis and nitrogen metabolism (Hong et al., 2005a, b). Further investigation by Mahajan et al. (2011) examined the impact of nano-ZnO particles on the development of mung (*Vigna radiata*) and grama plant seedlings (*Cicer arietinum*). They discovered that the seedlings demonstrated a significant increase above controls and that growth was retarded at particular optimum concentrations. Currently, one of the most popular nanomaterials is silver nanoparticles (AgNPs) (González-Pedroza et al., 2023). The colloidal solution of Cu and Zn NPs under drought conditions significantly improved the defense mechanism of wheat plants by accumulating antioxidants, maintaining the relative water content and chlorophyll content and reducing thiobarbituric acid reactive substances (TBARS) in the leaves (Taran et al., 2017). Foliar application of ZnO NPs on tomato crops under drought stress observed an increase in ascorbic acid and free phenol concentrations as well as improved antioxidant enzyme activity (El-Zohri et al., 2021).

It has been established that silver ions, such as AgNPs, can block the action of ethylene. Several researchers have reported that silver ions have this impact on ethylene. In agricultural soils and hydroponic systems, silver kills undesirable microbes. It is applied as a foliar spray to protect plants from fungus, rot, mold, and other ailments. Additionally, radioactive rays, silver salt, silicate, and water-soluble polymers are all great plant growth stimulators (Sharon et al., 2010) Due to the use of Cu and Zn NPs during drought stress, antioxidant, and moisture levels increased while thiobarbituric acid levels decreased, element precipitation was affected, chlorophyll levels increased, and stress levels decreased (Taran et al., 2017) (Fig. 8).

Using SiO2 NPs during the drought conditions in barley reduces membrane damage and superoxide radical production while increasing shoot extent and moisture (Turgeon, 2010). Due to the use of Cu NPs, maize production improves in dry conditions (increased leaf moisture, root and shoot mass, anthocyanin, photosynthetic pigment, and carotenoid) (Van Nguyen et al., 2021).

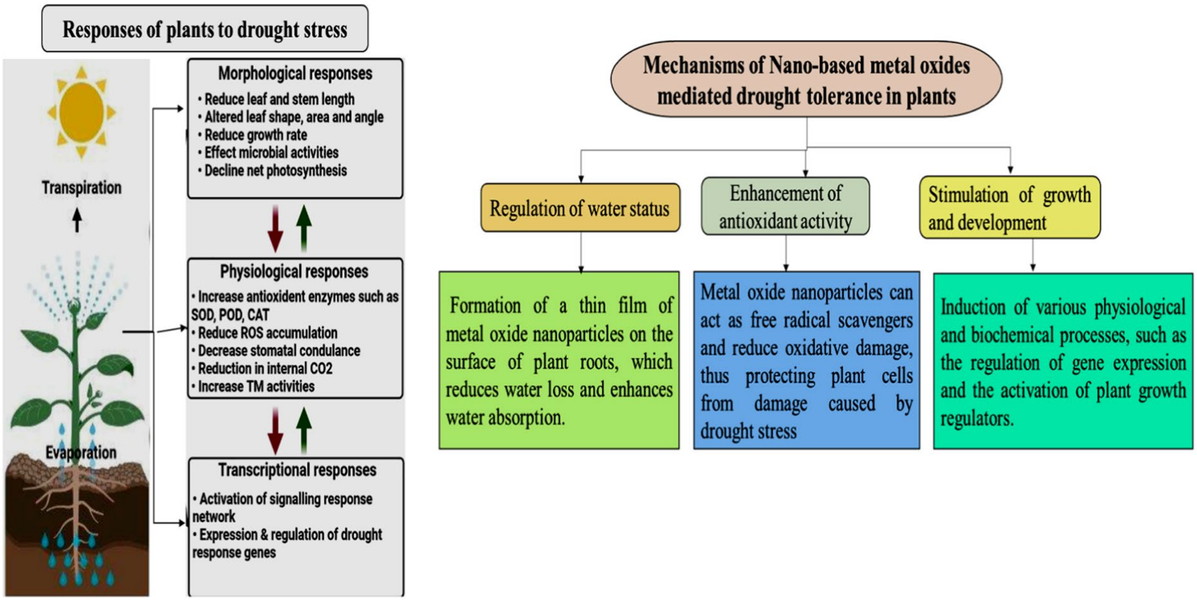


Fig. 8 Possible mechanisms for nano-based metal oxide–mediated mitigation of drought stress

3.5 Oxidative Stress

The changes in genes related to root development, plant stress reactions, dealing with oxidative stress, and the production of brassinosteroids were revealed through transcriptomics investigations concerning the effects of copper-based nanoparticles (NPs) with a size of 50 nm (Aleixandre-Tudó et al., 2020). Studies utilizing copper-based NPs of 40 nm dimensions in metabolomics discovered that certain secondary metabolites, namely 4-aminobutyrate, acetyl glucosamine, and phenyl lactate, accumulate in cucumber (*Cucumis sativus*). Conversely, processes tied to amino acid metabolism, fatty acid production, riboflavin metabolism, and the synthesis of flavonoids are suppressed. Galactose metabolism and the tricarboxylic acid cycle were found to be the primary disrupted areas in a separate metabolomics investigation focusing on the impact of copper NPs (with a mean size of 40 nm) on cucumber fruits (Zhao et al., 2015).

Genes linked to responses against abiotic stress, such as defensin-like proteins, plant thionin, glucosidases, cytochrome P450 proteins, and GST members, were inhibited by silver-based NPs (sized 20–80 nm) in plants grown hydroponically. In analyses of proteomics involving Eruca vesicaria, proteins specific to seeds from the jacalin lectin family and proteins involved in the response to oxidative stress gathered due to exposure to silver-based NPs with a diameter of 10 nm (Vannini et al., 2013). Moreover, treatment with silver NPs led to an increase in cruciferous, which are proteins stored in seeds used as an initial nitrogen source (Vannini et al., 2013). Metabolomic studies of silver-based NPs indicated an accumulation of linolenic and linoleic acids (the most common unsaturated fatty acids in membranes), salicylic acid (a crucial signaling molecule triggering plant defense and systemic acquired resistance), and intermediates of the tricarboxylic acid cycle, antioxidants, and metabolites involved in defense responses (such as phenolic compounds and fatty acids). Conversely, levels of Gln and Asn, two necessary amino acids for nitrogen assimilation and transport, were reduced (Zhang et al., 2018).

Examinations utilizing transcriptomics exhibited that genes associated with responding to oxidative stress, modifying root architecture, regulating protein synthesis and turnover, and maintaining energy balance were influenced by zinc oxide (ZnO) NPs with an average size of 20 nm in *Arabidopsis thaliana* (Landa et al., 2015). The following writers demonstrated the activation of genes that code for proteins involved in metal binding, metal homeostasis, and detoxification (such as metallothioneins) and the repression of genes that make brassinosteroids, which are involved in the heavy metal stress response. As hemicellulose plays a role in adsorbing heavy metal ions, transcripts involved in its modification and disintegration were likewise downregulated. Inhibition of ribosome synthesis and downregulation of transcripts involved in electron transport and energy production were further negative impacts that were noticed (Landa et al., 2015). Another recent work examined the transcriptomics and metabolomics of tomato seedlings treated with foliar sprays of ZnO NPs (20–45 nm size), which boosted growth by boosting chlorophyll content and photosynthetic efficiency (Wang et al., 2020). Based on metabolomics analysis, ZnO NPs enhanced the expression of genes encoding antioxidant enzymes, transporters, and enzymes or regulators involved in secondary metabolism and carbon/nitrogen metabolism (Fig. 9).

Enhanced protochlorophyllide buildup, chloroplast, and photosystem II restoration results due to ZnO NP use (Salama et al., 2019). Okra plants applied with zinc oxide nanoparticles under salinity stress resulted reduction in oxidative injury by enzyme activities (superoxide dismutase and catalase), and a significant change in catalase activity occurs (Alabdallah and Alzahrani, 2020).

3.6 UV-B Radiation Stress

Ultraviolet (UV) rays are electromagnetic radiation emitted by the sun and are categorized on the basis of wavelength (UVA: 320–400 nm, UVB: 280–320 nm, and UVC:100–280 nm). While UVC rays are mostly absorbed by Earth's atmosphere, UVA and UVB rays reach the surface and can have significant effects on living organisms. UVA has a longer wavelength and accounts for the majority of UV radiation reaching the Earth's surface. It penetrates the skin more deeply than UVB and is associated with skin aging, wrinkling, and the development of certain types of skin cancer. UVA can also contribute to the fading of colors in fabrics and materials exposed to sunlight. UVB (ultraviolet B): UVB has a shorter wavelength and is responsible for causing sunburn and more immediate skin damage. It is also a major contributor to the development of

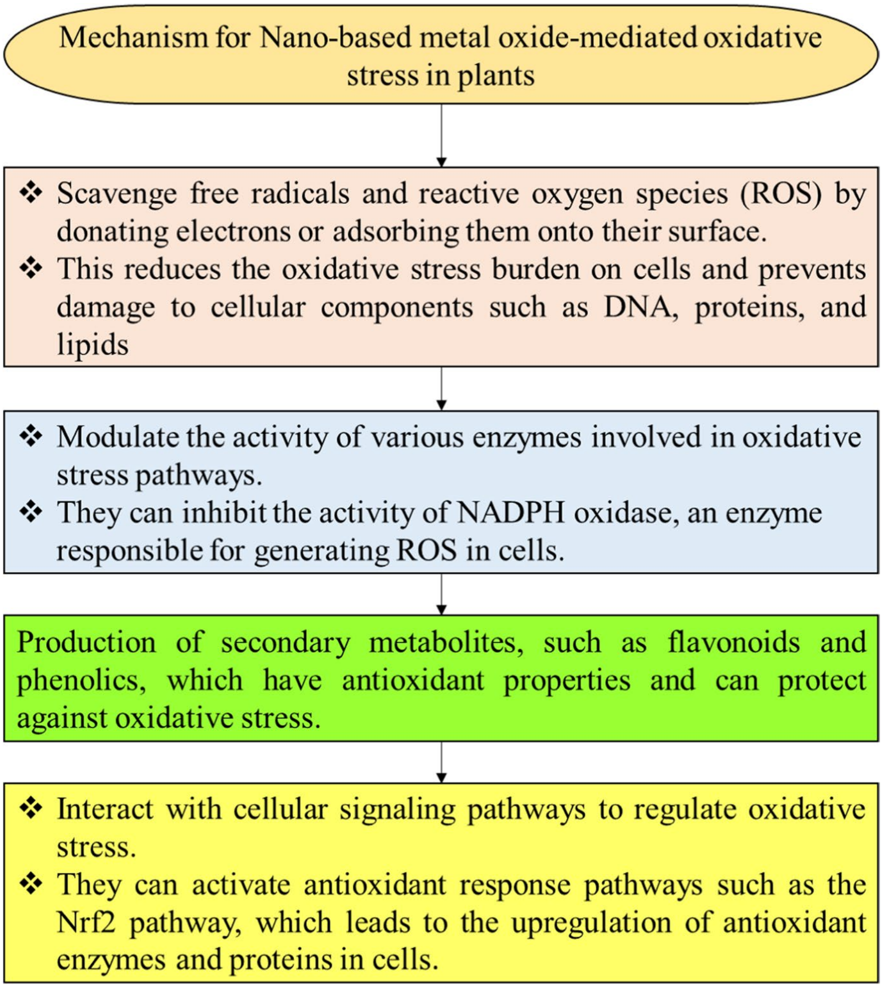


Fig. 9 Mechanisms of nano-based metal oxide–mediated oxidative stress in plants

skin cancer. UVB rays are more intense during the midday and summer months. NPs can help reduce the harmful effects of UVA and UVB radiation by acting as UV filters in sunscreens. Certain types of nanoparticles, like zinc oxide (ZnO) and titanium dioxide (TiO_2), are known for their ability to absorb or scatter UV radiation, thus preventing it from penetrating the skin. These nanoparticles form a protective layer on the skin's surface, reducing the amount of UVA and UVB radiation that reaches deeper skin layers and causes damage (Diffey, 2001; Schroeder & Krutmann, 2010).

Greenhouse gases (CFCs: chlorofluorocarbons and NO*x*: nitrous oxides) have reduced the amount of ozone in the stratosphere, and the ultraviolet spectrum (280–315 nm) increases when it hits the ground superficially (Dawood et al., 2022). The UV spectrum varies depending on various factors (such as time, month, year, day, latitude, and cloudiness level), and it is known to be one of the causes of climatic stress. Such risks will persist for a longer period of time. According to Wang et al. (2012), plants exhibit a variety of biochemical, morphological, and physiological responses in response to UV spectrum.

Various basic injuries (increase of ROS level and agitation of Pn stains, DNA, and cell membrane) come due to UV-B radiation (Chen et al., 2011). To overcome detrimental effects, plants protect themselves through certain strategies (including antioxidants and phenolic compounds) (Dawood et al., 2022). Furthermore, by adsorbing UV rays and lowering oxidative damages, nanomaterial reduces the hazards of UV rays and enhanced light and energy captivation and its conduction along with photosynthetic pigment and rubisco. Although UV rays enhance crop productivity, nanomaterials during UV stress cannot perform well, but they have minimized the UV-B harmful effects. Furthermore, detrimental results of nanomaterials and UV-B have also been reported on crops (Regier et al., 2015) (Fig. 10).

Studies have shown that the application of NP metal oxides can improve the UVB tolerance of plants by reducing the damage caused by UVB radiation. They can do so by acting as a physical barrier, absorbing UVB radiation, and also by scavenging reactive oxygen species (ROS) generated by UVB radiation. Exposure to high levels of UV-B radiation can damage the DNA and proteins in plant cells, leading to reduced photosynthesis, stunted growth, and decreased crop yield. It can also cause changes in plant morphology, such as reduced leaf size, altered leaf shape, and reduced stem elongation (Tripathi et al., 2017a).

4 Impact of Nanofertilizer Application (Particle Size, Surface Area, Charge, etc.)

The first step in the processes of absorption and translocation as well as for the mechanism of action is the contact and penetration of nanoparticles into the plant system. Nanoparticles are absorbed from the root epidermal areas in large part due to osmotic pressure and capillary pressures. Typically, nanoparticles between 3 and 5 nm are quickly absorbed. Small pores allow nanoparticles to pass through the epidermal cell wall of roots and into the plant's system. In some cases, a modest number of nanoparticles that are larger than the typical pores that absorb the nanoparticles can improve the ability to develop their own pores on the cell wall (Al-Khayri et al., 2023). In some instances, the charge of the nanoparticles plays a major role in the initial interaction that occurs with the epidermis region (Al-Khayri et al., 2023). Furthermore, the nanoparticles take both apoplastic and symplastic pathways to reach the target tissue. Usually, the membrane carrier protein accompanies the nanoparticles and helps in transportation using the xylem channels (Pérez-de-Luque, 2017). Later, if there is any aggregation at various regions of the channels, they are sent back to the roots with the help of phloem. The cuticle and stomata are the means of passage through which the nanoparticles reach the internal system of the leaf. Particles less than 5 nm take the cuticular pathway, while particles larger than 5 nm take the latter pathway. Compared to the root, the leaf has a similar internal transport system. The nanoparticles are delivered by phloem tubes via both apoplastic and symplastic pathways to the intended location or organs (Ruttkay-Nedecky et al., 2017).

The utilization of nanofertilizers emerges as a propitious pathway in the endeavor to alleviate abiotic stress in crop plants (Table 2). The efficacy of

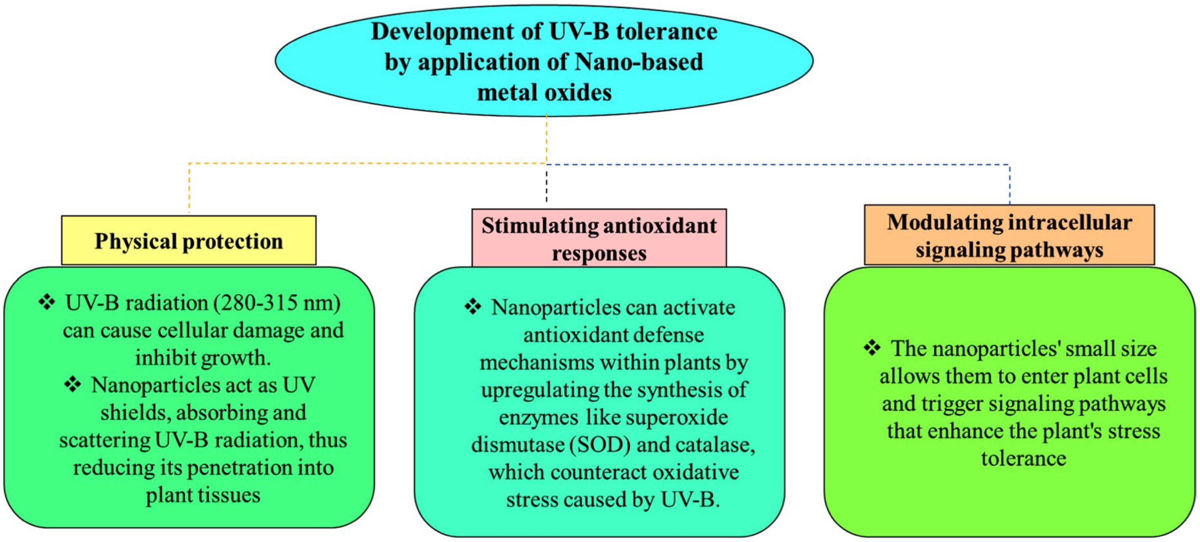


Fig. 10 Development of UV-B stress tolerance by application of nano-based metal oxides

this approach is intricately intertwined with distinct characteristics, including particle size, surface area, charge distribution, and various other pertinent factors. Hernández-Hernández et al. (2018) studied the foliar application effect of Cu NPs (1–100 nm size) on tomatoes under salinity stress and reported that the application of Cu NPs enhanced plant growth and alleviated ionic and oxidative stress by activating antioxidant defense mechanism. Hong et al., (2005a, b) focused on the alleviating approach of TiO_2 against drought stress in spinach and found that lower concentrations of TiO_2 greatly improved the growth of spinach by enhancing photosynthesis and nitrogen metabolism. In contrast, the high dose of TiO_2 nanoparticles observed a slower growth rate and shorter roots of plants as compared to lower concentrations. Similarly, Mosa et al. (2018) studied the response of Cu NPs (40 nm mean size) on the oxidative stress induction, genotoxicity, and changes in SOD gene expression in hydroponically grown cucumber plants and found that application of CuNPs caused in reduction of biomass, photosynthetic contents (chlorophyll a and b), an increase in MDA, H_2O_2, and ion leakage content which induced damage to the cucumber root plasma membrane. They observed the upregulation of Cu–Zn SOD genes and genotoxicity under CuNP application. Farhangi-Abriz and Torabian (2017) observed that the application of SiO_2 NPs (20–30 nm) alleviates the effect of salinity stress by the accumulation of different oxidative enzymes like CAT, POD, APX, and SOD, increasing the potassium content and decreasing the concentration of sodium and lipid peroxidation in root and leaves.

de Sousa et al. (2019) reported that soil application of SiO_2 NPs (20 nm) at 4 mg/kg alleviated the toxicity of aluminum by reducing the photorespiratory enzymes, NADPH oxidase activity, MDA accumulation and stimulating enzymatic and non-enzymatic antioxidants and increasing the accumulation of organic acid and metal detoxification (glutathione-S-transferase activity) in roots. Qi et al. (2013) reported that foliar application of TiO_2 NPs on tomato plants under heat stress noticed an increase in the chlorophyll content, conductance to H_2O, and transpiration rate and decreased the chlorophyll fluorescence and relative electron transport in leaves. Taran et al. (2017) reported that seed treatment of *Triticum aestivum* with the colloidal solution of Cu and Zn NPs improved the defense mechanism of plants under drought stress by accumulating antioxidants, maintaining the relative water content and chlorophyll content, and reducing thiobarbituric acid (TBARS) reactive substances in the leaves. Ghabel and Karamian (2020) studied the response of TiO_2 (average diameter of 10–25 nm) added to culture media at the rate of 0, 2, and 5 ppm on *Cicer arietinum* L. against cold stress and found that indexes of membrane deterioration reduced, and redox status increased. Khan et al. (2023) reported that *Pennisetum glaucum* subjected to AgNPs under salinity stress enhanced the activities of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase and reduced the oxidative damage produced by salinity stress. Seeds of *Phaseolus vulgaris* soaked in Ag NPs for 1.5 h (0.25, 1.25, and 2.5 mg dm^{-3}) enhanced the net photosynthesis, improved seedling quality, and regulated resistance to cold stress (Prazak et al., 2020). Brassica napus plants applied with CeO NPs (average size 20–110 nm) at (200 and 1000 CeO_2 mg kg^{-1} dry mixture) alleviated the adverse effect of oxidative stress caused by NaCl (100 mM) that disturbs the physiological activity of plant (Rossi et al., 2016).

5 Uptake, Translocation, and Accumulation of Nanoparticles (NPs) into the Plants

Translocation and accumulation of NPs within the plant system depend upon various physicochemical properties such as concentration, size, stability, chemical configuration, and surface chemistry as well as different plant species. The high mobility of NPs is decided by van der Waals forces, Brownian motion (diffusion), gravity, and double-layer forces, which are important for their adhering property (Handy et al., 2008). Air and soil act as a source of NPs through which NPs can invade the plant system. Aerosol NPs may penetrate the aerial parts of the plants through stomata, hydathodes, wounds, direct penetration, or through the aerial surface, whereas soil NPs are penetrating through root hairs, ruptures, lenticels, etc. (Hussain et al., 2019a, b). Many authors proposed the plausible mechanism and significance of uptake, translocation, and accumulation of NPs in plants. On exposing the plant system to aerosol NPs, most of the NPs penetrate the plant leaves via cuticular as well as stomatal routes. They accumulate in the stomata or the sub-stomatal region and finally translocate to

Table 2 NP physiochemical characteristics, stress type, and alleviation mechanisms of nano-based metal oxides

NP physiochemical characteristics	NP concentrations and application method	Plant species	Stress type	Alleviation or phytotoxicity mechanisms	References
• Cu-NPs (1–100 nm size and having a spherical or round shape, highly reactive due to large surface area to volume ratio)	(Foliar application of 10 and 50 mg/L)	Tomato (*Lycopersicum esculentum*)	Salinity	Enhanced plant growth and alleviate ionic and oxidative stress by activating antioxidant defense mechanism	Hernández-Hernández et al. (2018)
TiO_2 nanoparticles	• 0, 50, 100, and 200 mg/L • 0, 100, 200, and 400 mg/L	Spinach (*Spinacia oleracea*)	Drought stress	• Promoted photosynthesis and nitrogen metabolism and thus greatly improved the growth of spinach • High dose of TiO_2 nanoparticles observed slower growth rate, and the roots of plants were shorter as compared to lower concentrations	Hong et al., (2005a, b)
Cu NPs (40 nm mean size)	50, 100, and 150 mg/L by drench method	Cucumber (*Cucumis sativus*)	Oxidative stress	Cu NP treatment caused in reduction of chlorophyll a and b contents, and an increase in MDA, H_2O_2, and ion leakage content which induced damage to the cucumber root plasma membrane. Upregulation of Cu–Zn SOD genes under CuNPs application	Mosa et al. (2018)
Ag-based NPs (10 nm diameter)	Foliar (50 mg/L)	Roka or turf grass (*Eruca vesicaria*)	Oxidative stress	Enhanced the accumulation of proteins related to oxidative stress response and the seed-specific proteins belonging to the jacalin lectin family	Vannini et al. (2013)
nO NPs (20–45 nm size)	100 mg/L (foliar)	Tomato (*Lycopersicum esculentum*)	Oxidative stress	Improved plant growth by increasing chlorophyll content and photosynthesis upregulated genes encoding antioxidative enzymes and regulators involved in the production of secondary metabolites	Sun et al. (2020)

Table 2 (continued)

NP physiochemical characteristics	NP concentrations and application method	Plant species	Stress type	Alleviation or phytotoxicity mechanisms	References
SiO_2 NPs (20–30 nm)	Foliar (0, 0.5, 1, and 2 mM)	Soya bean (*Glycine max* L.)	Salinity	Alleviate the effect of salinity stress by the accumulation of different oxidative enzymes like CAT, POD, APX, and SOD and increasing the potassium content and decreasing the concentration of sodium and lipid peroxidation in root and leaves	Farhangi-Abriz and Torabian (2017)
SiO_2 NPs (20 nm)	Soil application (4 mg/kg)	Maize (*Zea mays*)	Heavy metal	• Alleviate the toxicity of Aluminum by reducing the photorespiratory enzymes and NADPH oxidase activity • Stimulation of antioxidants and reduction in MDA accumulation • Increasing the accumulation of organic acid and metal detoxification (glutathione-S-transferase activity) in roots	de Sousa et al. (2019)
$AgNO_3$ NPS (1–100 nm)	Seed treatment (0, 40, 60, and 80 ppm)	Summer savory (*Satureja hortensis*)	Salinity	Improved germination rates; plant shoot length and salinity tolerance	Nejatzadeh (2021)
TiO_2 NPS	Foliar (0.05, 0.1, and 0.2 g L^{-1})	Tomato (*Lycopersicum esculentum*)	Heat stress	Increased the chlorophyll content conductance to H_2O, and transpiration rate and decreased the chlorophyll fluorescence and relative electron transport in leaves	Qi et al. (2013)

Table 2 (continued)

NP physiochemical characteristics	NP concentrations and application method	Plant species	Stress type	Alleviation or phytotoxicity mechanisms	References
Colloidal solution of Cu and Zn NPs	Seed treatment	Wheat (*Triticum aestivum*)	Drought	Improved the defense mechanism of plants by accumulating antioxidants and maintaining the relative water content and chlorophyll content and reduced (TBARS) thiobarbituric acid reactive substances in the leaves	Taran et al. (2017)
Fe NPs + biochar	Foliar application (0, 50, 75, 100 mg/L + soil application biochar (1%w/w)	Rice (*Oryza sativa*)	Heavy metal stress	Mimics the adverse effect of heavy metal (Cd) stress in leaves and roots by combining application of FeNPs and biochar	Rizwan et al. (2019a)
ZnO NPs (20 nm)	Suspension form of ZnO NPs (20 nm) (nano-ZnO particles in suspension (0, 10, 20, 50, 100, 500, 1000, and 2000 ppm for mung bean seeds and 0, 1, 2, 5, 10, 20, 50, 100, 500, 1000, and 2000 ppm for chickpea seeds) added to agar media	Mung bean and black chickpeas (*Vigna radiata* and *Cicer arietinum*)	Drought stress	Improved the growth of plants' seedling	Mahajan et al. (2011)
Ag NPs (18.34 nm)	Irrigated by the colloidal solution of Ag NPs (0, 30, and 60 µg/mL)	Rice (*Oryza sativa* L.)	Oxidative stress	The application of AgNPs negatively influenced rice seedlings and rhizobacteria isolation	Mirzajani et al. (2013)
CeO NPs (average size 20–110 nm)	Drench method (200 and 1000 CeO_2 mg kg^{-1} dry mixture)	Cabbage (*Brassica napus* var. capitate)	Oxidative stress	Mimics the adverse effect of oxidative stress caused by NaCl (100 mM) that disturbs the physiological activity of plant	Rossi et al. (2016)
TiO_2 (average diameter of 10–25 nm)	0, 2, and 5 ppm added to culture media	Black chickpeas (*Cicer arietinum* L.)	Cold stress	Indexes of membrane deterioration reduced, and redox status increased	Ghabel and Karamian (2020)

Table 2 (continued)

NP physiochemical characteristics	NP concentrations and application method	Plant species	Stress type	Alleviation or phytotoxicity mechanisms	References
Ag NPs (1–100 nm)	Seed treatment (0, 40, 60, and 80 ppm)	Summer savory (*Satureja hortensis* L.)	Salinity stress	Improved growth metrics, such as shoot length and an improvement in the germination rate, and enhanced resistance to salt stress	Nejatzadeh (2021)
Ag NPs	Foliar application of 100 mM NaCl (Hoagland solution), 300 ppm AgNPs, and NaCl combined with AgNPs	Wheat (*Triticum aestivum*)	Salinity stress	Activated antioxidant enzymes to reduce oxidative damage brought on by salt stress, and regulated tolerance for salt	Wahid et al. (2020)
Ag NPs	Seed treatment for 1.5 h (0.25, 1.25, and 2.5 mg dm^{-3})	Common beans (*Phaseolus vulgaris* L.)	Cold stress	Raised net photosynthesis, improved seedling quality, and regulated resistance to cold stress	Prazak et al. (2020)
CeO_2 nanoceria	Nanoceria (0, 500, 100 and 200mgL^{-1}) and 0 and 100 µM sodium nitroprusside	Wheat (*Triticum sativum* L.)	Drought stress	• Enhanced the germination percentage and seed vigor index • Alleviate the adverse effect of drought stress by enhancing the antioxidant defense system and reducing lipid peroxidation	Sepehri and Faraji (2020)
Mn_3O_4 NP	Foliar application of Mn_3O_4 NP suspensions (0, 20, or 100 mg L^{-1}	Cucumber (*Cucumis sativus*)	Salinity stress	Net photosynthesis, or the elevation in photosynthetic pigment content, altered the metabolomes of biomass	Lu et al. (2020)

Table 2 (continued)

NP physiochemical characteristics	NP concentrations and application method	Plant species	Stress type	Alleviation or phytotoxicity mechanisms	References
Cs/Ag/MnMgFe$_2$O$_4$	Soaking (control, soaked with low-dose Cs/Ag/MgMnFe$_2$O$_4$ nanocomposite, soaked with high-dose Cs/Ag/MgMnFe$_2$O$_4$ nanocomposite, Cd (100 µM), Cd (100 µM) + soaked with low-dose Cs/Ag/MgMnFe$_2$O$_4$ nanocomposite, Cd (100 µM) + soaked with high-dose Cs/Ag/MgMnFe$_2$O$_4$ nanocomposite	Cabbage (*Brassica napus* var capitate)	Heavy metal stress	Improved photosynthetic pigments, antioxidant and non-antioxidant enzymes	Maksoud et al. (2022)
SiO$_2$ NPs and Zn NPs	foliar spraying using the nano-chelated silicon (containing 2% chelated silicon and absorbable at pH 3–11), nano-chelated Zinc (containing 12% chelated zinc and absorbable at pH 3–11), and nano-chelated boron (containing 9% chelated boron and absorbable at pH 3–11) fertilizers pulverized at 2 g L^{-1} of concentration	Wheat (*Triticum aestivum* L.)	Drought stress	Protein content has increased and drought stress has been lessened	Ahmadian et al. (2021)
ZnO NPs	Foliar (5, 50, and 100 mg/L green ZnO-NPs)	Tomato (*Solanum lycopersicum*)	Drought stress	Increased ascorbic acid and free phenol concentrations, as well as improved antioxidant enzyme activity	El-Zohri et al. (2021)
ZnO and SiO$_2$	Foliar application of 0, 50, and 100 mg L^{-1} zinc oxide (ZnO) nanoparticles and 0, 25, and 50 mg L^{-1} silicon dioxide (SiO$_2$) nanoparticles	Potato (*Solanum tuberosum* L.)	Drought stress	Increased yield and improved quality traits of potato plants	Seleiman et al. (2023)

Table 2 (continued)

NP physiochemical characteristics	NP concentrations and application method	Plant species	Stress type	Alleviation or phytotoxicity mechanisms	References
ZnO NPs	Foliar (50, 100, and 150 ppm)	Wheat (*Triticum aestivum* L.)	Drought stress	• Enhanced the physiology, development, and antioxidant defense • Significant increase in fresh and dry weight of shoot and root, also in chlorophyll a and chlorophyll b	Kausar et al. (2023)
SNPs (48.8 nm	Inoculated with 5 mg/L Cu-amended MS medium supplemented with or without 300 mg/L SNPs exposure	*Brassica napus*	Heavy metal stress	Enhanced enzyme activities, morphological parameters, and reduced Cu in plants	Yuan et al. (2023)
ZnONPs	Soil application (0, 150 and 300 mg/kg)	Wheat (*Triticum aestivum*)	Heavy metal stress	Increased yield, reduced Cd concentration of shoot, while improved Zn concentrations in plants	Usman et al. (2023)
ZnONPs	50 and 100 mg NPs per kg of soil	Wheat (*Triticum aestivum* L.)	Heavy metal stress	Melatonin and ZnONPs together were found to have the lowest grain Cd and the highest Zn levels	Chen et al. (2023)
Si, Se, and Zn NPs	cadmium chloride ($CdCl_2$) at 40 mg kg^{-1} soil for Cd stress and by lead nitrate (Pb NO_3) at 400 mg kg^{-1} soil for Pb stress	Salvia (*Salvia officinalis* L.)	Heavy metals stress	Boosted plant growth by modulating Pb and Cd toxicity	Bakhtiari et al. (2023)
AgNPs (50–100 nm)	Foliar (20 mg/L)	Pearl millet (*Pennisetum glaucum*)	Salinity stress	Enhanced the activities of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase, reduced the oxidative damage	Khan et al. (2023)

various parts of plants via the tracheary element—phloem (Handy et al., 2008; Hussain et al., 2019a, b).

5.1 Size-Dependent Uptake of NPs

Given that the countless impediments stuck inside the plants range in size from micrometer (mm) to nanoscale, the size of the NPs should be taken into account as a significant component for researching plant absorption (nm). For instance, the cuticle membrane is composed of cells that make up the epidermis foliar. Whenever the gas interchange is enabled, a stomata comprised of two guard cells in the epidermis creates a cavity that is 3–12 m broad and 10–30 m long. Hence, these stomata provisions allow NPs to permeate plants. The cuticle layer in the epidermis and the trichrome of the stomata have quite varied attributes from the piercing properties (Smith et al., 2022). On the other hand, the leaf epidermis' cuticle layer displays a substantial score that is only collected in the nm range (Wang et al., 2016). NPs with a size of 4–100 nm have been shown to be able to penetrate the cuticle by dislodging the waxy layer (Larue et al., 2014), and NPs encapsulated in fluorescent materials wider than 50 nm have been shown to aggregate in the epidermis below the cuticle, where stomata are absent (Nadiminti et al., 2013). Only stomata, not the 1-µm-diameter particles, may enable the 43-nm-diameter polymeric NPs to traverse the leaves of *Vicia faba* (Eichert et al., 2008). When NPs penetrate the stomata, they are typically embedded in the cell wall of the sub-stomatal cavity. In transmission electron microscope (TEM) examinations, it was feasible to see tiny NPs, such as 20 nm Fe_3O_4 NPs, contaminating the *Nicotiana benthamiana* plant (Cai et al., 2020).

The maximum size limit was set in particular, for these cell walls of plants usually 3.5 nm and more usually around 5 nm (Palocci et al., 2017). As a result, NPs, smaller than 5 nm, can successfully penetrate strong cell walls. According to the cell wall, they can pass through; it is proposed that NPs stay below the size limit. For instance, it is simple to enter plants using quantum dots (QDs) that are smaller than the seized in of the pores in plant cell walls (sub-10 nm) (Wu et al., 2017a). Li et al. (2020) observed the presence of AgNP size 24.8–38.6 nm inside lettuce leaves when used on the foliar route. Additionally, the biotransformation phenomenon also explained the way; $AgNO_3$ plants with AgNPs can be altered. Large pores are created when NPs interact with the cell wall, which makes it easier for NPs to enter the body (Carlson et al., 2008). Additionally, there are effects on how large NPs gather in the cell wall and subsequently in the cytoplasm, although the discrepancies in the size of the cell wall (which depends on a variety of parameters) and the accumulation of large NPs are still present. For climbing and descending the plant, NPs adhere to two crucial mechanisms: pathways for apoplasts and symplasts. The symplastic pathway enables movement in the cytoplasm of neighboring cells (Roberts & Oparka, 2003); however, the apoplastic pathway permits flow in extracellular regions such as nearby cell walls and xylem vessels (Sattelmacher, 2001). The plasmodesmata, which serve as a cytoplasmic bridge to enable cellular movement between adjacent cells, are responsible for cell-to-cell movement. The diameter of plasmodesmata sets a limit on the size of particles that can traverse them. Typically, molecules with a size of up to 3 nm are capable of passing through these channels. This specific permeability plays a crucial role in governing the range of molecule types and sizes that are permitted to transit between cells, thereby upholding appropriate cellular functionality and communication (Dietz & Herth, 2011) (Fig. 11).

5.2 Surface Charge–Dependent Uptake of NPs

NPs have a high degree of freedom due to their capture, absorption, and trafficking inside plants. The receptors, vehicles, and proteins of some membranes change as a result of increased energy and charging (Juárez-Maldonado et al., 2019). Compared to their real-world counterparts, they have a higher volume of integration and more structures (Hotze et al., 2010). The hydrophobic and hydrophilic components of the biological membrane, or cell wall, in leaves also have an imbalance of negative static costs (higher power of cellulose and lignin, $-15--45$ mV, respectively) (Zeng et al., 2017). Therefore, one possible cause could be that a poorly charged cell wall prefers to acquire well-inserted NPs in the tissue. According to Meychik et al. (2005), the walls of malignant plant cells serve as an additional ion exchange site that may make cationic NP penetration easier than anionic NP penetration. On the other hand, NPs that are weakly charged significantly improve

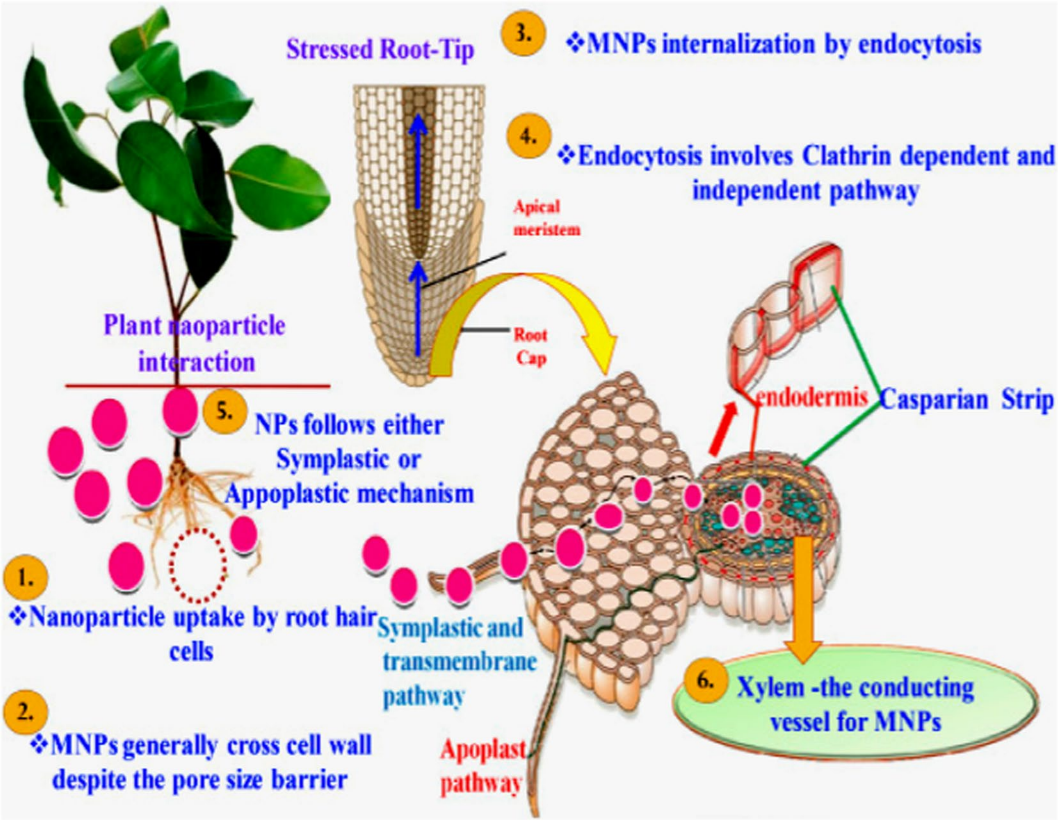


Fig. 11 An overview of size-dependent uptake of NPs in plants (TRI) (Tripathi et al., 2017a, b)

transit efficiency. According to Zhu et al. (2012), the acquisition and transport of AuNPs are surface charge–dependent and show the maximum commercialization of well-charged NPs in root zones. But it is believed that weakly charged NPs have a high rate of entry and transfer (Zhu et al., 2012). Cost-effective CeO NPs are being actively promoted in the root in this situation (free instances), but CeO_2 NPs, which are significantly charged, showed little root growth but were implanted in the upper extremities, mostly by resisting electrostatic expulsion (Liu et al., 2019). The extra-dependent charging of AuNP isolates from roots and their transportation from roots to shoots are also thoroughly established by Milewska-Hendel et al. (2019). As they move from the roots to the shoots, poorly charged NPs may promote symplastic and apoplastic transport in the vascular system. Consequently, surface charge conversion considerably affects the transport efficiency of NPs for all plants. Based on their physical–chemical makeup, NPs combined with agrochemicals can have both beneficial and detrimental impacts on the health of plants.

6 Molecular Mechanisms and Biochemical and Physiological Aspects of Nanoparticles in Plants

Nanoparticles can interact chemically or physically with biological systems like plants (Tripathi et al., 2017b). This unique interaction is primarily caused by nanoparticles' small size, huge surface area, and internal catalytic recycling. Only a limited investigation has attempted to explain how nanoparticles affect antioxidant and cellular levels. Ascorbate peroxidase, guaiacol peroxidase, and catalase become more active when silver nanoparticles are treated with *Brassica juncea*, which lowers the level of active oxygen (Priyadarshini et al., 2014a, b). Furthermore, there is a considerable increase in the content of malondialdehyde and glutathione. Gold nanoparticles (GNPs) greatly increased the activity of antioxidant enzymes like ascorbate peroxidase, guaiacol peroxidase, catalase, and glutathione reductase as well as the high concentration of H_2O_2 and proline content in *Brassica juncea* plants (Gunjan et al., 2014). Ascorbate peroxidase (APX), guaiacol peroxidase (GPX), and other activities were increased to 400 ppm of GNPs, for example, and glutathione reductase (GR) activity is higher than 200 ppm GNPs. The exposure of kidney beans to CeO_2 nanoparticles had a significant impact on the activity of the antioxidant enzymes (ascorbate peroxidase, catalase, and guaiacol peroxidase) in the leaf, root, and stem (Sebastian et al., 2019). They discovered that after prolonged exposure to 500 mg nano-CeO_2/L, the antioxidant enzyme's root activity considerably dropped, but the root of the soluble protein enhanced. Additionally, exposure to nano-CeO_2 augmented the activity of the guaiacol peroxidase enzyme (GPX) in the leaf to preserve cellular homeostasis. New details on the cellular response mechanisms of plants in Ag NPs have been discovered through gene analysis of the genetically modified plant *Arabidopsis* by RT-PCR. Using whole-genome cDNA expression microarrays to analyze the written responses of the *Arabidopsis* plants reflected in Ag NPs, 286 genes were found to be under control, including genes primarily related to metal and oxidative stress (such as vacuolar cation/proton exchanger, superoxide dismutase, cytochrome P450-dependent oxidase, and peroxidase), and 81 genes were found to be under decreased regulation (e.g., gene-regulated auxin involved in organ size (ARGOS), ethylene expression, and systemic acquired resistance (SAR) against viruses). On the other hand, a proteomic analysis of rice-producing proteins revealed that silver nanoparticle impacts were mostly connected to transcription, protein degradation, Ca^{2+} control and signaling, oxidative stress response, cell wall building, cell division, and cell division. Through the aggregation of lower concentrations of MDA and H_2O_2 and greater concentrations of enzymatic antioxidants such as GPX, SOD, CAT, and APX activity, Mohammadi et al. (2014) observed the mitigated role of TiO_2 NPs in cold stress. Through the aggregation of lower concentrations of MDA and H_2O_2 and greater concentrations of enzymatic antioxidants such as GPX, SOD, CAT, and APX activity, Mohammadi et al. (2014) observed the mitigated role of TiO_2 NPs in cold stress. Similar to this, Almutairi (2016) found that applying AgNPs to tomato plants exposed to saline conditions caused the overexpression of the genes AREB, MAPK2, P5CS, and CRK1 and the suppression of the genes TAS14, DDF2, and ZFHD. Wu et al. (2017b) reported the positive effect of Nanoceria plant resistance to salt stress. This effect is achieved by enhancing plant photosynthetic activity and biomass through its direct influence on the production of hydroxyl radicals (•OH) and potassium fluxes (reducing K^+ efflux and enhancing K + retention) throughout the plasma mesophyll (Wu et al., 2018).

7 Nanotechnology-Based Agriculturally Important Nanofertilizers

Worldwide, agriculture is currently faced with a number of difficulties, including nutritional inadequacies, crop failure, soil organism depletion, water depletion, fertilizer deficiencies, depletion due to urbanization and degradation, and staff shortages (Godfray et al., 2010). Nanoscience and nanotechnology are increasingly being used, and new ways of producing inventive materials and desirable materials for maintaining and growing plants are always being offered. It is among the most important theories in the developing field of precise agriculture, where farmers effectively employ fertilizer and other inputs (Manjunatha et al., 2016). In an effort to boost food supply and crop protection, unchecked population growth has resulted in huge fertilizer output, which eventually lowers soil fertility and food quality. These chemical fertilizers have an adverse effect on human health because they are left unused, in addition to aggravating the hidden ecology. According to a report issued by the Food and Agricultural Organization of the United Nations, there will likely be a rise in the need for fertilizer globally in the upcoming years. As a result, it is critical to use clever farming methods, like nanotechnology. Nanofertilizers are intelligent or environmentally friendly fertilizers that can raise fertilizer levels and decrease nutrient loss, particularly phosphorus and nitrogen (Dimkpa & Bindraban, 2017). Applying nanofertilizer can increase nutrient uptake, which in turn lowers nutrient losses, enhances crop quality and output, and lowers the risk of environmental damage (Fig. 12). It has also been demonstrated that these nanofertilizers can relieve plant stress when applied foliarly (Tarafdar et al., 2012). Based on the nutrient requirements of plants, nanofertilizers can be categorized into three groups: (1) macronutrients and nanofertilizers, (2) micronutrient nanofertilizers, and (3) nanoparticulate nanofertilizers (Chhipa, 2017). Macronutrient nanofertilizers are made up of a combination of elements including calcium, phosphorus, nitrogen, potassium, and magnesium. By 2050, it is anticipated that 263 million tonnes (Mt) of macronutrient fertilizer will have been used globally, demonstrating a large need for these fertilizers in the agriculture industry. By inserting leaves, Delfani and his team examined the effects of Mg and Fe nanoparticles on the growth of black-eyed peas (*Vigna unguiculata*) and found that better seed weight and photosynthetic capacity led to higher yields (Delfani et al., 2014). The growth rate and yield of soybeans (*Glycine max*) were dramatically increased by combined hydroxyapatite (Ca_5 $(PO_4)_3$ OH) NPs of size 16 nm in comparison to control. To improve agronomic circumstances and lessen the impact of drought on soybean plants, NPs containing three micronutrients (ZnO, CuO, and B2O3) have been successfully combined (Dimkpa et al., 2017). Other NPs found in nanoparticulate fertilizer, such as CeNTs, TiO_2, and SiO_2, help plants flourish. TiO_2 and SiO_2 together boost soybean seed germination, growth stimulation, and nitrogen fixation.

7.1 Cerium NPs (CeO NPs)

Depending on the focus of exposure, adhesion, local charge, plant species, and growth conditions, nanoceria has a variety of effects on plant health, both beneficial and harmful (Milenković et al., 2019). In the biomedical sector, a family of CeO NPs known as nanoceria is frequently utilized as an antioxidant (Liu & Shi, 2019). Although NPs might have harmful side effects on plants, when we consider their benefits, they exceed these drawbacks and can be employed to boost plants' health (Santás-Miguel et al., 2023). These NPs, as we previously highlighted, have the ability to interact at the nano-bio interface to boost plant tolerance to a variety of stresses by modulating critical processes (Saxena et al., 2016). For instance, abiotic stress

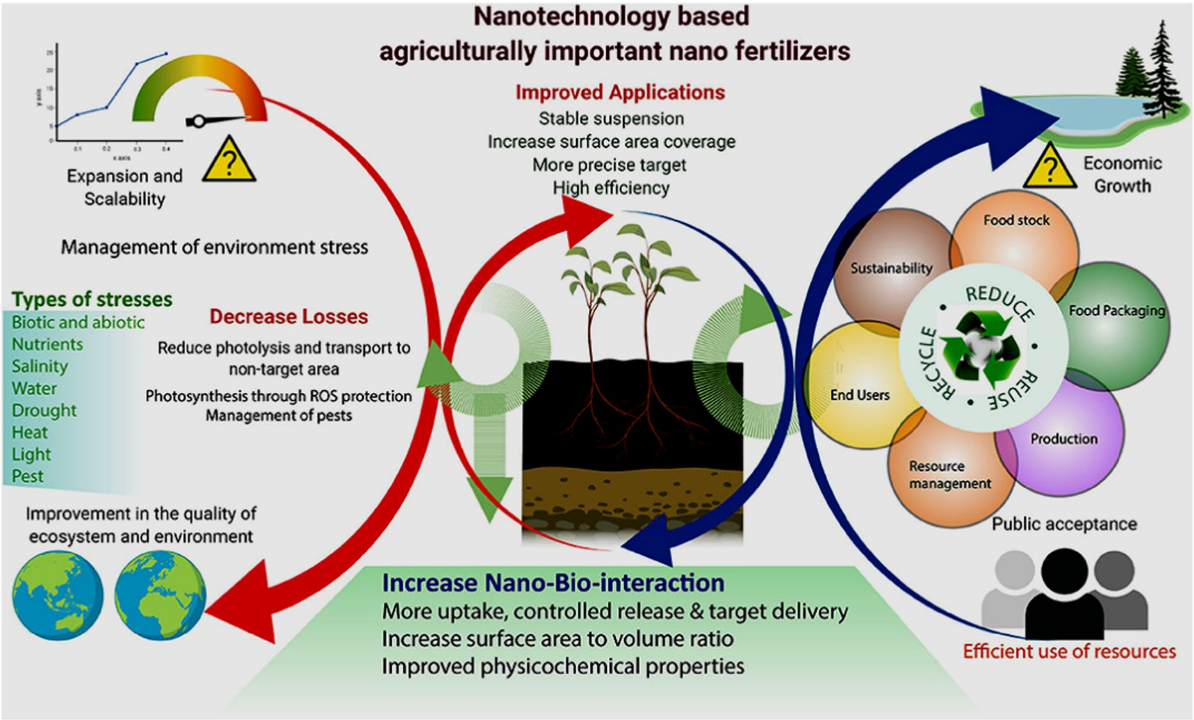


Fig. 12 Nanotechnology-based nanofertilizers alleviate abiotic stresses in plants (Mittal et al., 2020)

increases the creation of excessive ROS, which lowers plant photosynthetic performance and causes biomolecule oxidation (Wakeel et al., 2020). Due to its distinctive redox potential, which is based on the straightforward transition between the oxidation states of Ce^{3+} and Ce^{4+}, Nano-Ce is thus well adapted to counteract this impact and, as a result, serves as a ROS scavenger (Collin et al., 2014). Additionally, CeO NP mimics the activity of catalase with low amounts of Ce^{3+}/Ce^{4+} and exhibits a depletion effect, while CeO NP with high levels of $Ce^{3+/}Ce^{4+}$ mimics superoxide dismutase and creates hydrogen peroxide (Pulido-Reyes et al., 2015; Wang et al., 2012, 2021). Furthermore, the impact of oxidative scavenging extends to additional stressors such as excessive light, heat, and cold. Additionally, it results in a decline in the proliferation of photosystem II, photochemical efficiency, chlorophyll concentration, and morphological alterations in plants (Chen et al., 2020; Gao et al., 2020; Nievola et al., 2017). In response to abiotic stress, such as intense heat, light, darkness, and cold, Wu et al. (2017b) observed the regeneration effect of anionic CeO NPs in plant *A. thaliana*. In a similar manner to oxidative stress, salt stress endangers the physiology of plants. Treatment of *Brassica napus* with 200 and 1000 mg/kg CeO NPs caused an increment in plant biomass, and chlorophyll content (which also enhances Mg^{2+} absorption) under salinity stress (100 mM NaCl (Rossi et al., 2016).

According to Hauser and Horie (2010), maintaining cytosolic acid Na^+/K^+ is one of the indicators of salt stress, and NPs can significantly influence this process. The drought-resistant action of CeO NPs was seen in leaf-fed sorghum plants at a depth of 10 mg/L and was shown to be very effective. Additionally, it lowers the proportion of ROS and lipid peroxidation, which has raised carbon dioxide levels and related pollen grain levels (Djanaguiraman et al., 2018b). CeO NPs can alleviate the effects of salt stress on the seedling phase. While growing under salt stress (200 mM NaCl), poly (acrylic acid)-coated CeO NPs (500 mg/L in water for 24 h) show substantial effects on plant roots, including total length (56%), weight (41%), and root power (114%) compared to control. Reduced oxidative stress and increased resistance to salt stress result from subsequent disruption of the pathways linked to the antioxidant enzyme system, ion binding and Ca^{2+} signaling, and terpene production (An et al., 2020).

7.2 Silicon NPs (SiNPs)

After oxygen, silicon (Si) is regarded as the second-largest commodity on Earth and has attained high agricultural value. Si is regarded as one of the most significant and insignificant plants in plants since it not only ensures plant survival but also provides enough benefits for plants if it exists (Luyckx et al., 2017). These NPs can interact with plants either directly or indirectly, causing physiological and morphological alterations that increase stress tolerance (Babajani et al., 2019). In Hawthorns (*Crataegus* sp.), SiNPs have demonstrated anti-depressant effects in a range of concentrations on drought stress. Plant responses varied depending on the concentration applied to the various stages of drought stress, i.e., mild to severe. These consequences include a greater capacity for photosynthetic activity, water content, a reduction in electrolyte membrane leakage, and elevated concentrations of chlorophyll, carotenoids, and proline (Ashkavand et al., 2015). Proline accumulation increases low-salt tolerance by preserving ionic balance, improving the antioxidant system, and producing more different phytopropanoids, which results in osmotic modification (Abedi et al., 2021). SiO_2 NPs have also been demonstrated to increase water utilization efficiency, stomatal conduction, and respiration rate and diminish chlorophyll depletion during salt stress, resulting in a tolerance to external stimuli (Haghighi & Pessarakli, 2013). The epicuticular wax layer undergoes considerable modifications as a result of salt compression. Contrary to what one might expect, the application of nano-Si in strawberry plants has improved the development and firmness of the epicuticular wax (Avestan et al., 2019). Another study using *Capsicum annuum* L. sweet pepper plants to examine the impact of nano-Si to lessen salt stress has observed substantial differences in quantity compared to their control plants (Tantawy et al., 2015). SiO_2 NPs' concentration effect was also seen in potato plants that had been subjected to 50 and 100 mM NaCl salt stress. At lower concentrations (50 mg/L) and higher concentrations (100 mg/L), NPs can exhibit greater stress tolerance (Gowayed et al., 2017). However, it was discovered that a small concentration was quite powerful. These studies, in contrast to the idea that only NM-hazardous compounds are harmful, strongly imply a better understanding of the benefits or drawbacks of NPs.

7.3 *Titanium Dioxide NPs (TiO_2 NPs)*

Other NPs exert their effects through other mechanisms involving genetic regulation in addition to the anti-oxidative actions of some NPs that release ROS produced in response to threats or stress in plants. For instance, the presence of TiO_2 NP (0.01%) enhanced the amount of chlorophyll and biomass by triggering the activity of antioxidant enzymes, which reduced malondialdehyde (MDA) and hydrogen peroxide while increasing the formation of proline and soluble carbohydrates, maintaining the osmotic equilibrium (Abdel Latef et al., 2018). Similar to this, nano-TiO_2 has been able to start the expression of some significant non-encoding RNA, which is thought to be crucial for resistance to abiotic stress. When TiO_2 NPs (0.1, 1, 2.5, and 5%) were applied to tobacco plants, Frazier et al. (2014) saw that 11 miRNA that had been stored in response to the application had been activated, and this helped the plants recover from severe iron stress. Dehydration is a significant issue in agricultural production since it results in energy loss and seriously harms crops. By raising the activity of the NR enzyme, which in turn promotes the accumulation of osmolytes, nano-TiO_2 can improve the hydration condition of a plant. Nitric oxide (NO), which is produced when the NR enzyme is more active, ultimately causes the synthesis of proline and glycine betaine (Khan et al., 2020). In response to plant stress, TiO_2 NPs often display both an enzymatic and non-enzymatic defense system. It is interesting that TiO_2 NP can control other enzymes like glutamate hydrogenase and glutamine synthase, which results in the accumulation of additional nutrients and the creation of essential oils (Ahmad et al., 2018). In this context, Moldavian balm (*Dracocephalum moldavica* L.) plants were cultivated under serious salt stress (0, 50, and 100 mM NaCl) in a greenhouse test by Gohari et al. (2020) to determine the impact of nano-TiO_2 (0, 50, 100, and 200 mg/L). Under standard conditions, the plants treated with TiO_2 (100 mg/L) produced 1.19% more of the essential oils geranial, z-citral, geranyl acetate, and geraniol. This immediately modifies the key oil production profile and composition of aromatic plants, protecting them from stress (Gohari et al., 2020). Further studies on medicinal plants by Karaman et al. (2020) demonstrated that the effects of methyl jasmonate (200 M), salicylic acid (100 M), and TiO_2 NPs (20 ppm) on drought stress were beneficial. According to the findings, it boosts resistance to water stress by triggering both enzymatic and non-enzymatic antioxidant defense mechanisms.

8 Phytotoxicity of Nanomaterials

Plants, animals, and marine creatures are extremely affected by improper nanoparticle dumping as it has huge use in various fields (beauty products, injury coverings and fabrics, etc.) leading to environmental disturbance. Zinc oxide NPs cause less harm to plant as the injuriousness of MgO and ZnO NPs at 250, 500, and 1000 mg/L enhanced *Citrus maxima* capability to apply it as a nanofertilizer (Xiao et al., 2019).

Plant diversity is affected by NP buildup because it is linked to exposed areas of plants through airborne NPs and then enters through stomata or trichomes for further transmission in tissues while attaching to roots from soil and water (Chaudhary et al., 2016). NPs also negatively affect plant mechanisms (i.e., variation in seed size, xylem in single and double leaf) (Lee et al., 2008). Every crop has its own way of developing and responding to stresses. Root extension in *Lettuce sativa* seedlings occurs due to MnO*x* NPs while at 50 mg/L lessens the germination from 63 to 84% grown in hydroponic media (Ruttkay et al., 2017) (Fig. 13).

All creatures depend on plants for their food in the ecosystem. Any outer entry to such system disturbs its stability. Excessive use of nanomaterials is now a big concern in the ecofriendly community regarding nanomaterial release (Tripathi et al., 2017a). So, work on its harmfulness started in 2000s (Shvedova et al., 2010). Nanomaterial has a direct link with water, soil, and air while indirectly linked through sewage and landfill places (Prasad et al., 2016). Various reports have declared both positive and negative effects on climate as a result of nanomaterials (Kabir et al., 2018; Khin et al., 2012) and also in agriculture. Few nanomaterials also have a role in plant and seed development and also play a role against diseases or use as pesticides (Kah et al., 2019). So, it has an important role in agriculture with huge usage but keeping the toxicity levels to badly influence crops and outcome to the atmosphere. Nanomaterials enter the plant body through leaves and roots (Lee et al., 2012). Based on magnitude, shape, and amount, it enters into the plant body through various means and

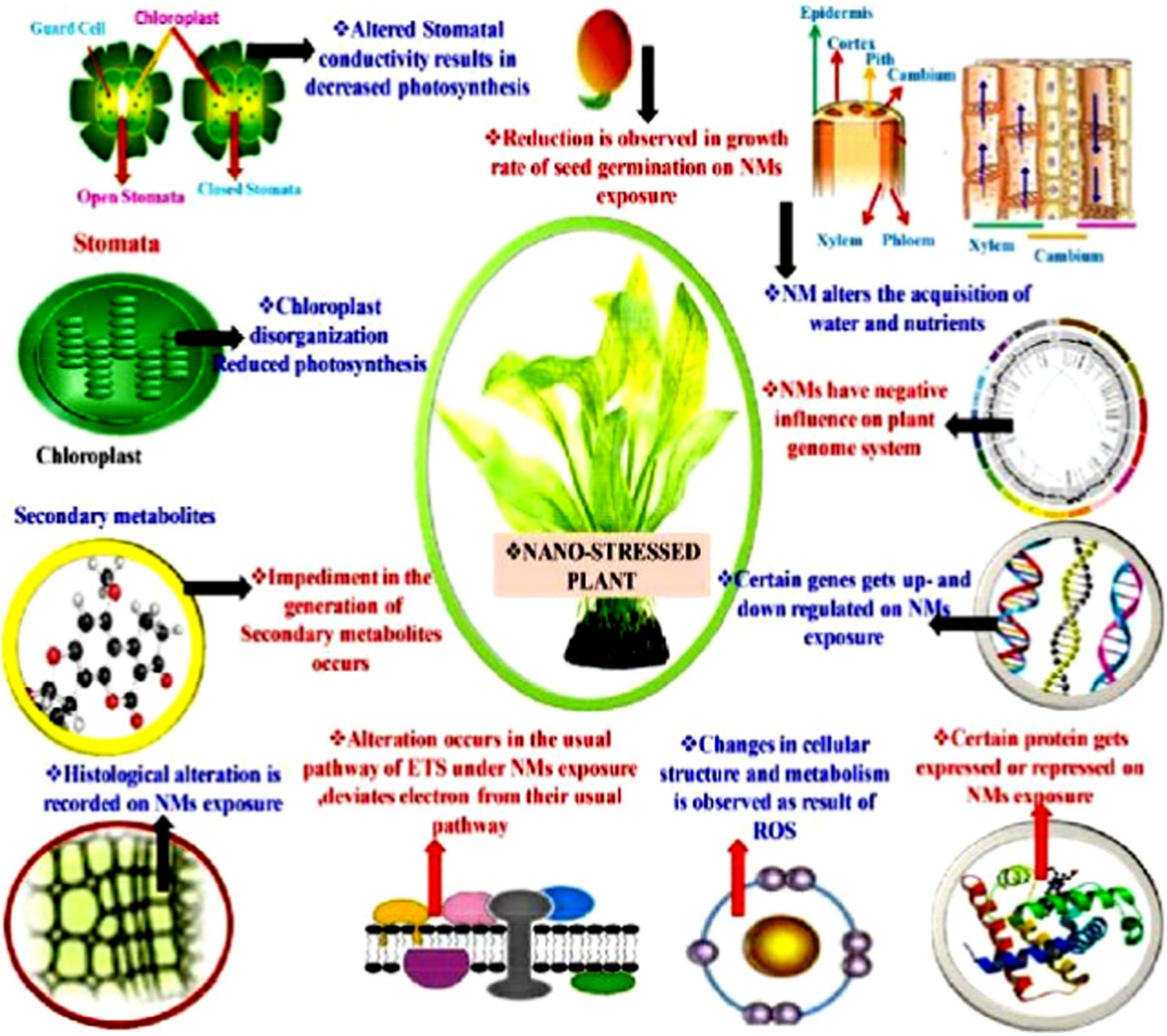


Fig. 13 Phytotoxicity of nanoparticles at the cellular level (Tripathi et al., 2017a)

alters plant response (hydathodes, stomata, abrasions, cuticles, trichomes, and stigma) (Wang et al., 2016). The high amount of AgNPs in *Stevia rebaudiana* negatively affects it while a lower dose extends the shoots (Castro-Gonzalez et al., 2019) while more quantity also affects photosystems and photosynthesis (Rastogi et al., 2019). Toxicity occurs due to improper nutrient movement and buildup of silver NPs (Wu et al., 2020) as chemical and physical features detect nanomaterial harmful level which gets altered as a result of its use. The minimum dose of AuNPs on *Lavandula angustifolia* cv. Munstead enhances growth while maximum causes toxicity (Jadczak et al., 2019). Similar observations were recorded in the case of FeNPs (Khan et al., 2020). At cellular level, alteration could be controlled through certain modifications (i.e., physical action, low photosynthesis, transpiration, and improper nutrient captivation) (Tripathi et al., 2017b). DNA gets disturbed, and more ROS and lipid peroxidation occur due to nanomaterial toxicity (Arruda et al., 2015). The colloidal solution of Ag NPs (0, 30, and 60 µg/mL) negatively influenced rice seedlings and rhizobacteria isolation (Mirzajani et al., 2013).

SeNPs have been synthesized in eco-friendly manners by using plant extracts (consisting of alkaloids, tannin, cinnamic acid, sesquiterpenes, phenolic acid, monoterpenes, and secondary metabolites) rather than microbes (bacteria and fungi) which are cost-efficient and harmless, while plant extracts have probable alleviating and reducing means ability (Alam et al., 2019; Fardsadegh et al., 2019; Cui et al., 2018; Javed et al., 2020). SeNP foliar application could increase crop production under salinity stress because it protects photosynthetic stains to increase its ability; alleviates ROS homeostasis, SOD, POD, and APX antioxidant protective enzymes; activates ZmMPK5, ZmMPK7, and ZmCPK11 genes (salt-stressed genes); increases root biomass and persistence of adequate osmotic position of the cell through ABA and IAA quantity upgrading; and stimulates RWC. Selenium is a crucial component of human and flora enzymes and selenoproteins as well as a cofactor for glutathione, which helps the body withstand environmental stress and oxidative injuries. By using less selenium, you can maintain increased transpiration and maintain amino acids, turgor pressure, sugar buildup, and possibly antioxidant enzymes during salinity. Selenium also aids in reducing membrane damage, ROS species, and chloride ion contents. In addition, due to its high dosage, certain irregularities (ROS overproduction, irregular stomata opening and closing, oxidative injury, less photosynthesis, and selenosis) occur.

9 Conclusions and Future Perspectives

In light of prior research, a thorough discussion of the function of nanotechnology in agricultural crop production and abiotic tolerance was conducted. Global agricultural production has many difficulties, such as climatic changes, the depletion of water and land resources, energy issues, and abiotic pressures. The best answers to these problems need to be more environmentally friendly and sustainable. One of the most significant and promising issues in this context is agri-nanotechnology. Natural nanoparticles are an inherent part of biological systems with a variety of forms and broad-ranging biological functions, including ferritin, lipoproteins, exosomes, magnetosomes, viruses, and nanoclay.

Therefore, the majority of these stress factors can be alleviated by various methods, such as antioxidant defense systems and the provision of less toxic and more effective fertilizers, because of nanotechnology, a new emerging and rapidly developing science. In light of this, it is possible to draw the conclusion that nanomaterials have a significant impact on many agroecosystems, having both good and negative impacts. The accumulation of nanoparticles in the system and their impact need to be evaluated in order to prevent potential negative effects on the environment as a result of rising applications of nanotechnology in industries that reach the environment.

Nevertheless, apprehensions persist regarding the potential phytotoxic effects of NPs, a phenomenon intricately tied to their concentration. Elevated concentrations of NPs have the capacity to induce oxidative harm and disrupt fundamental cellular processes. The mechanisms underpinning NP-induced phytotoxicity encompass the generation of ROS, perturbation of cellular architecture, and interference with vital metabolic pathways. To optimize the mitigation of stress while mitigating phytotoxicity, a range of strategies is proposed. These strategies encompass meticulous control over NP dimensions, modifications to NP surfaces to amplify their stability and affinity for plants, and tailoring the composition of NPs to heighten their specific efficacy.

In spite of notable advancements, uncertainties endure pertaining to both stress mitigation and the mechanisms governing phytotoxicity. The precise modalities by which NPs interface with plant cells and the modulation of their effects by various determinants necessitate further inquiry. A more comprehensive exploration of the cellular stratum is imperative to untangle these intricacies, encompassing the study of NP internalization, intracellular trafficking, and ramifications for cellular organelles and molecular pathways.

Prospective trajectories encompass the refinement of NP design to target stress relief with enhanced safety. The formulation of NPs capable of controlled release under stress-triggered conditions holds the potential to amplify their efficacy. Furthermore, investigations should delve into the enduring consequences of NPs on soil vitality, ecosystem kinetics, and the plausible accumulation of nanoparticles within the food chain.

In summation, this review underscores the potential of NPs, such as Ce NPs, to ameliorate stress in plants via their redox attributes and emulation of enzymatic functionalities. Nonetheless, the equilibrium between stress alleviation and phytotoxicity presents an ongoing challenge. By meticulously engineering NPs with precise attributes and concentrations, coupled with an in-depth exploration of their cellular interplays, researchers can unlock the complete potential of NPs for sustainable agricultural advancement.

Plant abiotic stress mostly causes oxidative stress, which affects all living things. Nanomaterials may assist stressed plants in boosting their defense mechanism, which includes antioxidative enzymes such as peroxidase, superoxide dismutase, and catalase, under this oxidative stress. On the other hand, these nanomaterials at larger concentrations may also stress plants by oxidizing them. Therefore, it is important to look at the physiological and biochemical aspects of how nanomaterials interact with plants under abiotic stress. Further research is required at several levels, including plant molecular and cellular levels, to determine the effect of nanomaterials in reducing the harm caused by abiotic stresses on plants or in suppressing plant growth and toxicity. Furthermore, it is crucial to establish whether nanoparticles function as stress promoters or inhibitors.

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Data availability Not applicable.

Declarations

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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