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Nanoparticles: An Emerging Soil Crops Saviour under Drought and Heavy Metal Stresses

Mohammad Faizan [1], Pravej Alam[2]*, Vishnu D. Rajput [3], Sadia Haque Tonny [4], Mohammad Yusuf [5], Shafaque Sehar [6], Muhammad Faheem Adil [6], Shamsul Hayat [7]

1 Botany Section, School of Sciences, Maulana Azad National Urdu University, Hyderabad 500032, India
2 Department of Biology, College of Science and Humanities, Prince Sattam bin Abdulaziz University, Alkharj 11942, Saudi Arabia
3 Academy of Biology and Biotechnology, Southern Federal University, Rostov-on-Don 344006, Russia
4 Faculty of Agriculture, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh
5 Department of Biology, College of Science, United Arab Emirates University, Al Ain 15551, United Arab Emirates
6 Zhejiang Key Laboratory of Crop Germplasm Resource, Department of Agronomy, College of Agriculture and Biotechnology, Zhejiang University, Hangzhou 310027, China
7 Department of Botany, Faculty of Life Sciences, Aligarh Muslim University, Aligarh 202002, India

IN AGRICULTURE, crops that feed exponentially increasing populations are often exposed to harmful stresses in soil as well as in plants. These are serious pollution that can affect plant production and yield. Such stresses lead to the formation of reactive oxygen species, membrane injury, and disruption in metabolic activities within plants to reduce crop yield. To counteract these stresses, plant defense methods should be applied to restore their morpho-physiological activities and increase their yield. The advancement of nanotechnology in agriculture has gained much attention in recent years for the production of sustainable crop and abiotic stresses remediation approaches. Compared with conventional methods, the use of nanoparticles (NPs) is a very promising approach to mitigate the toxicity caused by drought and heavy metal (HM) stress in plants. NPs play important roles in seed germination, growth, photosynthesis, and antioxidant enzymes activity. In plants, NPs may be used as nanofertilizers, nano-remediators, and nanosensors, which play an important role in developing modern agricultural practices. Several studies have confirmed that NPs alter biosynthetic pathways and improve plant stress tolerance by accelerating metabolic fluxes and enhancing the cellular pool through the upregulation of enzymatic activities. Although many beneficial outputs of NPs have been described in plants, the translocation mechanism of NPs inside the cell remains unclear. In this perspective, the transportation mechanism of NPs within the plant cell and their action mechanism in the alleviation of HMs stress for sustainable crop production have been focused on in this review. In addition, authors also highlighting the NPs-mediated gene delivery towards stress tolerance.

Keywords: NPs signaling; transportation mechanism; stress resilience; Soil; physiological functions.

1. Introduction

Plants play a key role in sustainable agriculture to ensure food security for the increasing global population. According to estimation by the Food and Agriculture Organization (FAO), the global population will soon reach approximately 9.6 billion, for whom food production should be increased by 70% (Rodrigues et al. 2017). Sustaining crop production in response to environmental stresses is a major task for scientists' because various abiotic stressors significantly influence the environment and climatic surroundings and decrease crop production (Awwad et al. 2022). Among the various stresses, heavy metals (HMs), drought, salinity, and heat stress are major constraints that lead to yield losses and economic downturns (Hasan et al. 2021; Ghazia et al. 2022). Reactive oxygen species (ROS), including alkoxyl radicals, superoxide radicals, singlet oxygen, and peroxy radicals, are produced by drought and HMs stress and are responsible for toxicity in plants. This ultimately affects the soil

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*Corresponding author e-mail: alamprez@gmail.com
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productivity, fertility, quality, and yield. In instances of excessive stress, metabolic processes, such as carbon absorption, photosynthetic competence, lipid peroxidation, and membrane penetrability, are hindered (Tripathi et al. 2017). Oxidative stress is also a key barrier in antioxidant enzymatic activities of superoxide dismutase (SOD), peroxidase (POX), glutathione peroxidase (GPXs), catalase (CAT), malondialdehyde (MDA), etc. These enzymes mitigate stressful conditions while maintaining hydrogen peroxidase (H_2O_2) homeostasis (Ahmed et al. 2021). However, developing stress-resistant varieties is a time-consuming process that requires multiple trials in scientific laboratories and natural environments. Several procedures are used to boost resistance against abiotic stresses, including the formation of genetically modified varieties against abiotic stress (Jeelani et al. 2020). Nanotechnology is a fast-growing field that has a profound impact on all branches of science (Hulla et al. 2015). The recent expansion of nanotechnology has aided in approaching restrictions to enhance civilization by improving supervision and abridging agricultural contributions. This will assist in augmenting crop consumption by modifying submissions and reducing yield losses. Pathogen diagnosis, agricultural mechanisms, and advanced cropping systems using aggregated nanomaterials have been introduced in modern generations (Pérez-de-Luque and Rubiales 2009). Nanotechnology has various applications in agriculture, engineering, and materials science.

The use of nanoparticles (NPs) for drought and HMs stress resilience is an innovative approach for sustainable agriculture and food productivity. NPs encounter toxicity caused by drought and HMs stress and restore crop production in a challenging environment (El-Ramady et al. 2020). The large surface area, small size, ability to augment solutes, increased reactivity, pore size, weight ratio, and transportation in plants are useful properties of NPs (Roco 2003; Salajegheh et al. 2020). In molecular biology, NPs are utilized to achieve sustainability, increase radical detoxification capacity, and enzymatic activity (Nejatzadeh et al. 2021). The use of metal-containing NPs such as zinc oxide (ZnO), titanium oxide (TiO_2), copper oxide (CuO), silicon (Si), molybdenum trioxide (MoO_3), iron oxide (Fe_3O_4), chromium dioxide (CrO_2), and silver (Ag) is increasing in the agricultural industry. These NPs function as stabilizing agents to mitigate environmental pollution (Kumari et al., 2022). NPs play important roles in biochemical pathway regulation, physiological functioning, and stress management (Kumari et al., 2022). Several studies have reported the use of controlled NP application, which ultimately aids the plant's overall yield. Application of ZnO NPs (1000 ppm) promoted seed germination and shoots and root formation in *Arachis hypogaea* (Prasad et al 2021). In the foliar fertigation of ZnO NPs (1.5 ppm) over *Cicer arietinum* leaves, biomass accumulation and germination ability significantly improved (Burman et al., 2013). Titanium oxide NPs also help increase photosynthetic attributes, protein content, and seed germination efficiency in *Spinacea oleracea* and *Brassica napus*, respectively (Mahmoodzadeh et al. 2013). In addition, silicon oxide NPs are effective in the construction of biochemicals, photosynthetic attributes, and protein content in *Zea mays* (Suriyaprabha et al. 2012). NPs also enhance the resistance of plants against various hazardous elements including chromium, cadmium, iron, aluminum, and manganese (Shen et al. 2009; Skiba and Wolf 2019; Zadeh et al. 2019). The application of NPs decreased the transport of Cd, Mn, and Pb in *Triticum aestivum*, *Helianthus annuus*, and *Oryza sativa*, respectively (Faraji et al. 2018; Ragab and Saad-Allah 2020; Cai et al. 2017). In addition to these morpho-physiological functions, NPs are also involved in the regulation of environmental ROS production, toxicological chemicals, and hormonal imbalances (Amira et al. 2015). The ability of crop plants to withstand abiotic stress using concentration-dependent NPs is an important result of nanotechnology (Dimpka et al. 2017; Abd-Elzaher et al. 2022). Within plants, the movement of NPs is important for understanding their accumulation and action. In plants, NPs enter leaves (Faizan et al. 2022) and roots (Faizan et al. 2019). In the leaves, NPs reach the mesophyll cells with the help of stomata and cuticles. The size and charge of NPs play important roles in cell wall movement. Plasmodesmata and plastids also regulate the movement of NPs within the cells (Wang et al. 2023). After entering the leaves, NPs can move to other parts of the plant, including flowers, stems, roots, and fruits, followed by either apoplastic or symplastic movement (figure 1) (Pérez-de-Luque 2017). Apoplastic movement occurs on the outer surface of the plasma membrane; however, symplastic movement occurs through the cytoplasm of adjoining cells with the help of plasmodesmata (Roberts and Oparka 2003). In the aerial parts, NPs help with the xylem and flow of transpiration. Unlike the leaves, the roots absorb NPs with the help of root hair cells. After passing through the cell wall, NPs enter the endothelial cells via symplastic movement. Through apoplastic movement, the NPs arrive at the innermost cylinder of the root and vascular tissues for additional transportation to the aerial portion (Zhao et al. 2012). Similarly, SiO_2 NPs increased the expression of the Os-NAC protein, which is helpful in the response to abiotic stresses in plants (Khan et al. 2019). Ag, TiO_2, CuO, and ZnO NPs also exert beneficial effects on plant growth and development (Wahab et al. 2023; Reza and Daneshvar 2023; Faraz et al. 2023; Ibrahim and Hegab, 2022). The importance of NPs in crop plants has been reviewed, also their beneficial and harmful aspects in terms of morphological, physiological and biochemical aspects; nevertheless, it is missing a review article pointed on NPs-mediated genes delivery for stress tolerance along with transportation and action mechanism under drought and HMs stress. Thus, from this perspective, the current work focused on impact, transportation and action mechanism of NPs in the alleviation of drought and HMs stress. This review will let readers to increase inclusive knowledge about the mechanism of NPs under drought and HMs stress.

2. Transportation Mechanism of Nanoparticles and their Impact

The regulation of plant functions such as growth, production, and yield is significantly influenced by NPs. The protective nature of plants treated with NPs is evident in their resistance to stress, cross-signaling, genetic control, transpiration, water conductance, and other factors (Haghighi et al. 2014). The transportation and signaling of NPs occur via two pathways: lipophilic and hydrophilic (Skiba and Wolf 2019). Hydrophilic substances with diameters ranging from 0.6–0.8 nm diameter are transferred via stomata (Eichert, et al. 2008). NPs can translocate from the leaves to the roots via the phloem (figure 1). The xylem is a key transportation vehicle for NPs (Sun et al. 2014). Transport proteins such as Lsi1, Lsi2, and Lsi6 have a consequential effect on the transportation and spare mass infiltration abilities of NPs into plants (Asgari et al. 2018). The assimilation and intake of NPs can be determined through their concentration, size, and chemical composition (Rico et al. 2011). In plants, NPs can be inserted in different ways, such as through cell isolation, injection, foliar spraying, biolistic guns, and hydroponic culture (Bautista-Diaz et al. 2021). Multi-walled carbon nanotubes showed a noteworthy impact on Ag, Si, Zn, and Cu using hydroponic methods that strengthened shelf life of crop plants (Hassan et al. 2014). Several mobile NPs, such as aquaporins, sulfur transporters, and potassium transporters, can pass through plant cells (Akter et al. 2018).

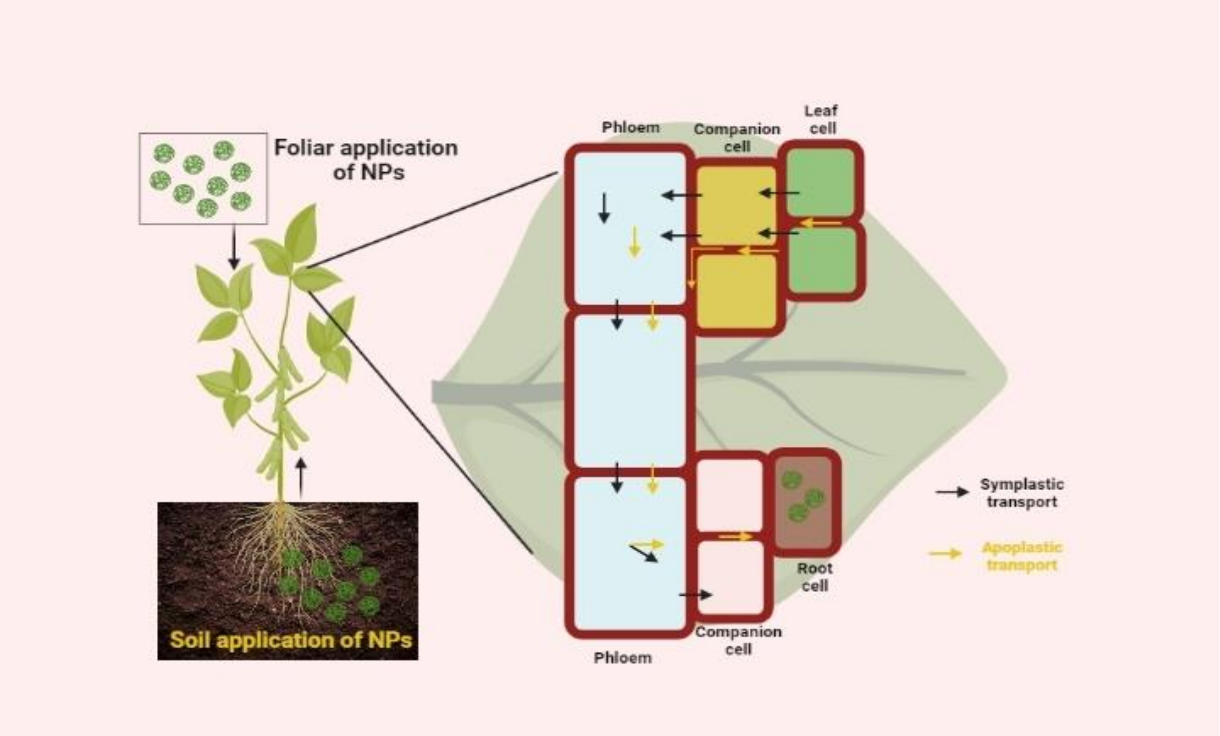

Fig. 1. Diagrammatic representation of nanoparticle transport within plant cells through apoplastic and symplastic pathway.

Previous studies have reported that different NPs, including ZnO, CuO, TiO_2, and Ag NPs, can be transported within plants where they exert promising results. These results agree with those of Adhikari et al. (2015), Su et al. (2019), and Schwab et al. (2016). Chen et al. (2018) analyzed *Oryza sativa* shoot tips using Transmission Electron Microscopy and concluded that ZnO NPs were transported in plant cells and accumulated in the cell wall and cytoplasm of the root elongation zone and cortex calls, respectively. Another study conducted by Tong et al. (Tong et al. 2017) on *O. sativa* using fluorescence labeling with Cy5 revealed intracellular NPs accumulation. A similar result was obtained in Rani et al. (2023) with different NPs.

Moreover, several NPs have been used to mitigate the toxicity caused by HMs stress (Table 1). The biomass, pigment, and protein content of plants, as well as their growth, were significantly reduced when Cd was added to the soil (Singh and Lee 2016). Under HMs stress, NPs maintained membrane stability, increased chloroplast pigment levels, and enhanced photosynthesis. Noman et al. (2020) reported that Cu NPs increased plant enlargement and nutrient content while reducing Cd translocation from the soil to *T. aestivum*. According to another study, FeO NPs improved Cd stress tolerance by boosting plant growth, antioxidant levels, and the chlorophyll index in *T. aestivum* (Manzoor et al. 2021). Likewise, the addition of nano-TiO_2 enhanced photosynthesis and growth parameters, and mitigated the effects of Cd on *Glycine max* (Singh and Lee 2016). The application of NPs has also been shown to alleviate oxidative stress in plants by controlling the levels of antioxidant enzymes (SOD, CAT, and POX) (Azeez et al. 2021). NPs decrease the movement and bioavailability of HMs and limit their accumulation in plant cells. Because of their size range, NPs can pass through the cell wall, and their width makes it easier for them to interact with other molecules. The use of Cu NPs reduced Cd accumulation in *Brassica* by increasing antioxidant enzyme activity. The interaction effect of ZnO NPs on *T. aestivum* was reported by Hussain et al. (2018), who concluded that ZnO NPs increased SOD and POD activities, whereas the Cd concentration was reduced.

Table 1. Impacts of nanoparticles on the plants under HMs stress.

NPs	**Plant Species**	**Concentration**	**Effects**	**References**
FeO	*T. aestivum*	100 mg /kg	Enhance morpho-physiological attributes along with antioxidative enzymes and reduce Cd uptake	(Manzoor et al. 2021)
FeO	*T. aestivum*	100 mg/kg	Increase growth indices, chlorophyll index, and lessen Cd amount	(Adrees et al. 2020)
Cu	*T. aestivum*	100 mg/kg	Boosted growth, nutrient amount, however reduce Cd concentration	(Noman et al. 2020)
Si	*T. aestivum*	0–1200 mg/kg	Reduce oxidative stress and Cd uptake, while increasing growth indices	(Riaz et al. 2022)
Si	*Coriandrum sativum*	1.5 mM	Augmented weight and decreased oxidative stress and Pb amount	(Fatemi et al. 2020)
FeO	*Solanum lycopersicum*	100 mg/L	Chlorophyll index and carotenoids increase and reduce Cr amount	(Brasili et al. 2020)
TiO_2	*Z. mays*	250 mg/L	Reduce Cd concentration	(Lian et al. 2020)
MgO	*O. sativa*	50–200 mg/L	Increase growth parameters, antioxidant enzymes activity and decrease As content	(Skiba and Wolf 2019)
ZnO	*T. aestivum*	0.12 g/pot	Boost the phenotypic attributes under salt stress	Adil et al. 2022)
ZnO	*T. aestivum*	150 and 300 mg/kg	ZnO NPs altered the yields, Zn and Cd content and caused maximum increase in dry weights	(Usman et al. 2023)
ZnO	*O. sativa*	60, 80, 100 nm	Augmented the root length, weight, K+ level, and antioxidative enzymes activity in salt stress	(Singh et al. 2023)

ZnO NPs have been applied to *O. sativa* grains to reduce phytotoxicity and significantly reduce As and Cd accretion in plants (Ma et al. 2020). Wu et al. (2020) demonstrated that ZnO NPs enhanced *O. sativa* development and weight under As stress by lowering As accretion and enhancing Zn uptake. The addition of Fe and ZnO NPs improved Cd accretion in *Boehmeria nivea* (Gong et al. 2017) and *Leucaena leucocephala* (Venkatachalam et al. 2017), respectively. These findings demonstrate that the plant species, NPs form, and nature of the metal can all impact the effect of NPs on metal absorption. Pb stress reduced plant biomass and vitamin C levels while enhancing flavonoid levels. The 1.5 mM application of Si NPs reduced the negative effects of Pb on *Coriandrum sativum* by reducing MDA accumulation in plant tissue and increasing antioxidant enzyme (POD, CAT, and SOD) activity under Pb stress (Fatemi et al. 2020). The application of 5 g/kg nano-hydroxyapatite resulted in a significant increase in ryegrass biomass and lowered the concentration of Pb in ryegrass (Jin et al. 2016). Si NPs application resulted in increased antioxidant activity (SOD and POX), decreased Cr content and oxidative stress, and improved the antioxidant defense system and nutrient content (Tripathi et al. 2015). The effects of citrate-coated magnetite NPs were used in *T. aestivum* to study the impact on Cd and Cr (Lopez-Luna et al. 2015). In the presence of Cd and Cr root length of wheat decreased by 50%, however, magnetite NPs were increased the above parameters by 25% and 50% respectively (Lopez-Luna et al. 2015).

Drought is a climatic hazard that restricts crop yield and efficiency. NPs can overcome drought stress by exerting effects on the plants. NPs can increase the photosynthetic efficacy of plants by altering the cycle and antioxidant enzyme activity and controlling the photosynthetic pigments necessary for plant development (Lowry et al. 2019). The effectiveness of NPs on plant germination and growth indices varied depending on the type of NPs and host plant (Table 2). Improvements in growth, physiology, and biochemistry have been observed when different crops have been treated with Si and ZnO NPs. Silicon NPs have been shown to maintain the biochemical and physiological functions of plants under stress, thereby improving the tolerance of *Crataegus* sp. to drought stress (Ashkavand et al. 2015). In comparison to a control treatment, Sedghi et al. (2013) found that the submission of ZnO NPs (0.5 and 1.0 g/L) improved *G. max* under water stress conditions.

Table 2. Effects of nanoparticles on the plants under drought stress.

NPs	Plant Species	Concentration of NPs	Effect	Reference
TiO_2	*T. aestivum*	10.8, 21.7, and 43.7 mmol/L	Increased chlorophyll index and carotenoids, gas exchange attributes along with antioxidant enzymes activity and decreased malondialdehyde and hydrogen peroxide amount.	(Faraji et al. 2020)
	Gossypium barbadense	0.5, 1.0, 2.1 and 4.3 mmol/L	Enhanced protein, phenolics, proline and free amino acid contents and antioxidant enzymes activity	(Shallan et al. 2016)
	Ocimum basilicum	2.1 and 6.6 mmol/L	Increased relative water and anthocyanin content along with catalase activity	(Kiapour et al. 2015)
	Lallemantia iberica	6.6 mmol/L	Boosted phenolic and flavonoid content with antioxidative machinery	(Sattari et al. 2020)
ZnO	*Z. mays*	100 mg/L	Augmented yield and reduced oxidative stress	(Sun et al. 2020)
	S. lycopersicum	25 and 50 mg/L	Higher content of ascorbic acid and free phenols content with antioxidative enzymes	(El-zohri et al. 2021)
Cu	*Z. mays*	3.333, 4.444 and 5.556 mg/L	Advancement of antioxidant defense system under drought stress	(Van Nguyen et al. 2021)
Si	*Tanacetum parthenium*	1.5 and 3.0 mmol/L	Boosted growth and phosphorous absorption	(Ghani et al. 2022)
Cu, Fe and Zn	*G. max*	50 mg/L	Upregulated expression of drought-sensitive genes	(Mohammadi et al. 2014)

Drought stress lowers nutrient assimilation by decreasing active transport, transportation flux, and membrane stability (Dimkpa et al. 2017). In contrast, NPs can provide various nutrients to plants, particularly during drought. Supplementation with 25 and 100 mg/L ZnO NPs during the growth phase of *C. sativus* enhanced nutrient uptake, chlorophyll synthesis, and photosynthetic rate, which increased plant dry mass (Ghani et al. 2022). One explanation is that NPs have a larger surface area, which enables them to generate fresh pores or enlarge existing roots, improving water and nutrient transport within the plants and boosting their growth and development (Faizan et al. 2023). Nano-TiO_2 has various effects on various environmental factors, crop species, and substrate concentrations. Mohammadi et al. (2014) found that the biochemical and morpho-physiological characteristics of *Dracocephalum parviflorum* were affected by nano-TiO_2 concentrations. Under water-shortage stress, TiO_2 promotes plant growth and essential oil production (Mohammadi et al. 2014). In another study, ZnO and CuO NPs were combined to create fertilizer. The results showed that under simulated drought stress, root growth was inhibited at various NPs doses; however, Zn NPs prolonged the lateral root structure and Cu NPs promoted the propagation and lengthening of root hairs in *T. aestivum* seedlings (Yang et al. 2017).

Several studies have confirmed that drought stress results in increased ROS levels and oxidative damage. ZnO significantly increases the antioxidant activity by decreasing ROS levels and promoting plant growth and development (Rehman et al. 2019). Following treatment with ZnO NPs, *C. sativus* showed a decrease in oxidative damage and an improvement in antioxidative activity (Ghani et al. 2022). Foliar application of Si-NPs (10 mg/L) to *Sorghum bicolor* under drought stress stimulates the antioxidant defense system, increases pollen germination, and leads to increased seed yield (Djanaguiraman et al. 2018). Excessive NP application has been reported to cause oxidative stress, resulting in protein regulation, cell cycle arrest, enzyme activity induction, and cell death (Polyakov et al. 2023), whereas plants treated with NP showed marked reductions in MDA levels (Mohammadi et al. 2014) and free radicals such as H_2O_2 during drought conditions (Faraji and Sepehri 2020). However, it was confirmed that the application of TiO_2 boosts the activities of antioxidant enzymes in *Phaseolus vulgaris* L. due to the activation of the plant antioxidative system (Ebrahimi et al. 2016). Figure 2 shows the mechanism of action of NPs on plant proteomic profiles and metabolism under abiotic stress.

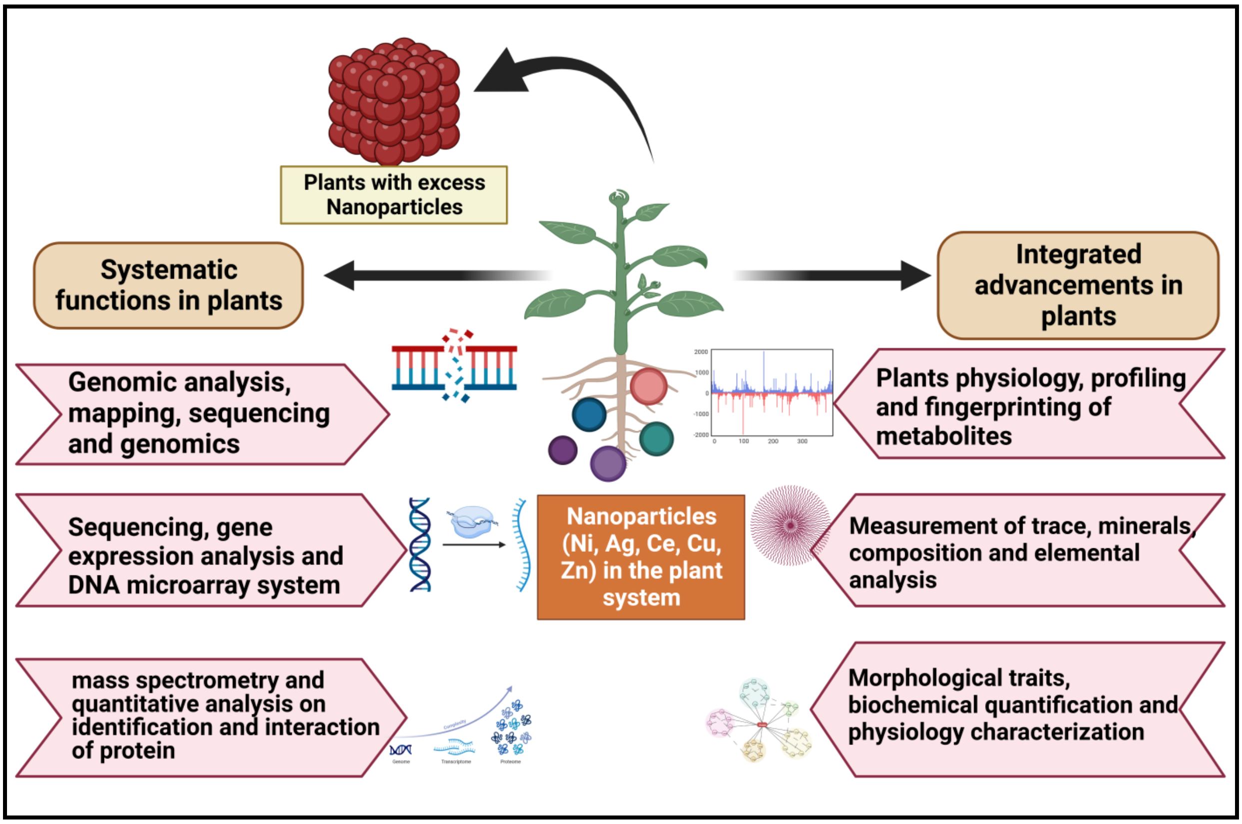

Fig. 2. Action mechanism of nanoparticles on proteomic profiling and metabolism of the plant (Ni: Nickel; Ag: Silver; Ce: Cerium; Cu: Copper; Zn: Zinc).

3. Action Mechanism of Nanoparticles in the Amelioration of Heavy Metal and Drought Stress

Increasing environmental pollution is increasing the apprehension about the impact on the surroundings on a global scale. The ecosystem and public health are at risk due to industrial sector toxic element emissions into the air, water, and soil, and ongoing urbanization (Liu et al. 2022). HMs in soil, which is difficult to degrade, are extremely poisonous to the surroundings and human health (Kumari et al. 2018). Owing to their highly reactive oxidative states, HMs can alter plant physiology by deactivating enzymes, denaturing proteins, replacing essential metals, and destroying membranes (Salehi-Lisar et al. 2016). These changes can occur at the protein level. HM stress limits photosynthesis and alters the biochemical performance of the plant (Kaur and Asthir 2017). The use of NPs as nanofertilizers and nanopesticides to remediate HMs stress in plants with minimal side effects is growing rapidly in the developing world (Manoj et al. 2020). HMs stress remediation through NPs is more effective, has less impact on the environment, and does not create poisonous by-products compared to bioremediation and other conventional methods. In plants, NPs decrease the toxicity of HMs by reducing the number of HMs present in the soil, increasing the expression of HM transport genes, boosting antioxidant enzyme activity, and increasing the accumulation of organic acids and phytochelatins (Zhou et al. 2020; Wang et al. 2022). NPs also inhibited the accumulation of Pb and Cd in the roots and shoots. Foliar fertigation with NPs alters the Cd and Pb transporters by manipulating metal accretion in plant cells (Hussain et al. 2020). The size and surface of NPs provide an easy approach to enter plant cells and boost their tolerance to stress (Pérez-Labrada et al. 2020).

NPs can reduce drought toxicity through changing physiological and biochemical parameters and controlling the expression of genes related to drought stress (figure 3). The key mechanisms through which NPs relieve osmotic stress caused by water scarcity include enhanced root length, upgradation of aquaporins, and enhancement of cell water metabolism in drought-induced plants. By closing the stomata, NPs prevent abscisic acid (ABA) accumulation and cause excessive leaf water loss. NPs also mitigate the effects of oxidative stress by lowering ROS levels and activating antioxidant defense mechanisms. Under drought stress, the application of Al_2O_3 maintained the regulation of proteins that guard glycolysis to sustain metabolism and damage, ultimately providing stress tolerance (Pérez-Labrada et al. 2020). CuO NPs stimulate glycolysis, the tricarboxylic acid cycle, and deprivation of starch, consequently increasing tolerance against stress (Yasmeen et al. 2017). Other studies have also demonstrated that Fe and ceria NPs increase protein expression, which is important for stress tolerance in *T. aestivum* and *Phaseolus vulgaris,* respectively. Notably, HMs and drought stress significantly reduce crop productivity and yield by disturbing physiological, biochemical, and transcriptomic activities. However, the application of NPs completely or partially neutralized the toxicity caused by HMs and drought stress in plants.

4. Nanoparticles-mediated Gene Delivery towards Stress Tolerance

This genomic approach provides accurate information on the effects of NPs on crop plants. However, few studies have focused on NP-mediated alterations in different crop plants at the gene level, particularly when plant species are exposed to abiotic stress (Pérez-Labrada et al. 2020). It has been reported that Ag-NPs induce salt-mediated stress resilience in *L. esculentum* by overexpressing CRK1, P5CS, MAPK2, and AREB (Pérez-Labrada et al. 2020). P5CS is responsible for proline biosynthesis, and its expression results in increased abiotic stress tolerance in plants (Rai and Penna 2013). AREB/ABF are transcriptional controllers necessary for AREB gene regulation, which encodes abscisic acid and is important for enhancing tolerance to drought and salt stress (Yoshida et al. 2015). TiO_2 NPs enhance stress tolerance in *Cicer arietinum* via alterations in different genes, signaling mechanisms, and metabolic pathways (Amini et al. 2017). In addition, photosynthesis-related genes were activated by the application of TiO_2 NPs in *A. thaliana*. Almutairi (2016) revealed that the genes CRK1, TAS14, AREB, and NCED3 were activated by the treatment of *S. lycopersicum* with SiNPs; however, the other genes DDF2, ERF5, MAPK2, MAPK3, RBOH1, and APX2 were negatively regulated. Moreover, Si-NPs stimulate other stress-related genes, such as OsLsi1 and OsHMA3, in *O. sativa*. The regulation of SLR1, AXR2, and AXR3 was considerably increased in the presence of CuO NPs. These genes are responsible for auxin signaling in plants and abiotic stress resilience in *A. thaliana*. CuO NPs also stimulated BIP3 expression in *Cucurbita pepo* (Pagano et al. 2017). The above information proves that NPs actively participate in gene regulation and alter gene expression to provide tolerance against various abiotic stresses.

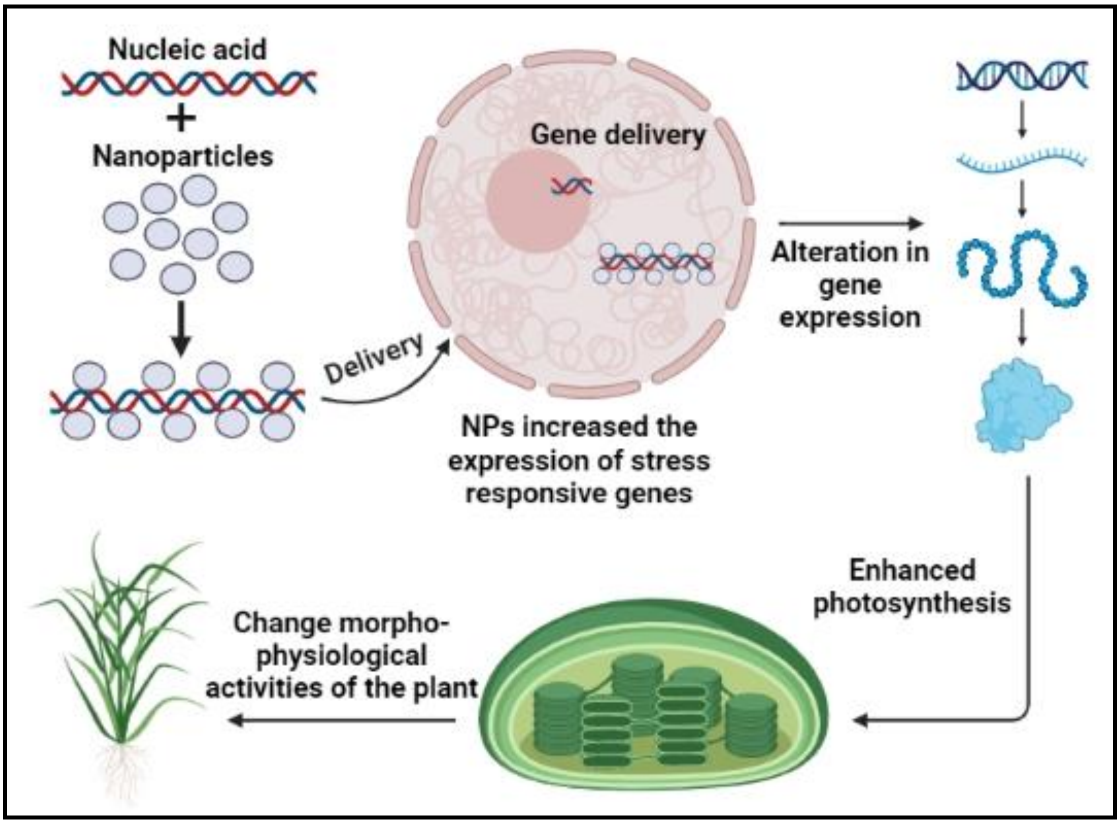

Fig. 3. Nanoparticles-mediated changes in plants under stress.

5. Conclusions and Future Prospects

The global population is continuously increasing at an alarming rate. The prime function of a nation is to provide sufficient food for its growing population. As the population increases, environmental pollution also increases. These environmental pollutants lead to the accumulation of toxic metals and scarcity of water for plants. New and emerging technologies are more beneficial than traditional approaches for sustainable agricultural practices. Similarly, the use of NPs as mobile elements is a novel approach that reduces the toxicity of environmental stressors and sustains the physiological and biochemical activities of plants. NPs play an important role in plants from seed germination to harvesting. The use of NPs as mobile carriers is an effective approach through which NPs enter the plant cell (either root or shoot) and change the expression of different genes responsible for stress tolerance. It also alters the photosynthetic rate and antioxidant enzyme activity after transportation within plant cells. The invasion of these particles may also play an important role in increasing carbon flux, leading to high enzymatic flow by upregulating the enzymatic cascade. The enhanced carbon flow may provide better growth and yield counter to HMs and drought stress and promote sustainable agriculture. Before commercialization, trials should be conducted.

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