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REVIEW

A comprehensive review on mitigating abiotic stresses in plants by metallic nanomaterials: prospects and concerns

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Abstract

Nanotechnology seems to have the potential to improve crop yields and help to meet the United Nations 2030 Goal 2: Zero Hunger. The literature is abreast with numerous reports on the application of various metallic, non-metallic, and other nanoparticles (NPs) that have been administered to various crop species over the last decade with fruitful results. The application of NPs has recently been considered as a viable option to alleviate the adverse effects of abiotic stresses on agricultural production. Typically, abiotic stress conditions include salinity, radiation, floods, heat, heavy metals, and drought. By influencing the physiological state of plants at different levels of their organization, NPs' application has shown promising results in mitigating the negative effects of abiotic stresses. In contrast, many reports emphasize upon the toxic effects of NPs on plants, especially at higher concentrations. Therefore, adequate research is required to understand the effects of different concentrations of NPs before nanotechnology can be successfully used in commercial agricultural systems. Simultaneously, it is equally important to promulgate the statutory regulations associated with the judicial and safe use, disposal, and toxicity studies of NPs as well as approval and release of the nano-products. In the present review, we have dwelled upon the forementioned aspects related to NPs application besides summarizing an updated account of the status of NPs-mediated mitigation of major abiotic stresses in crops.

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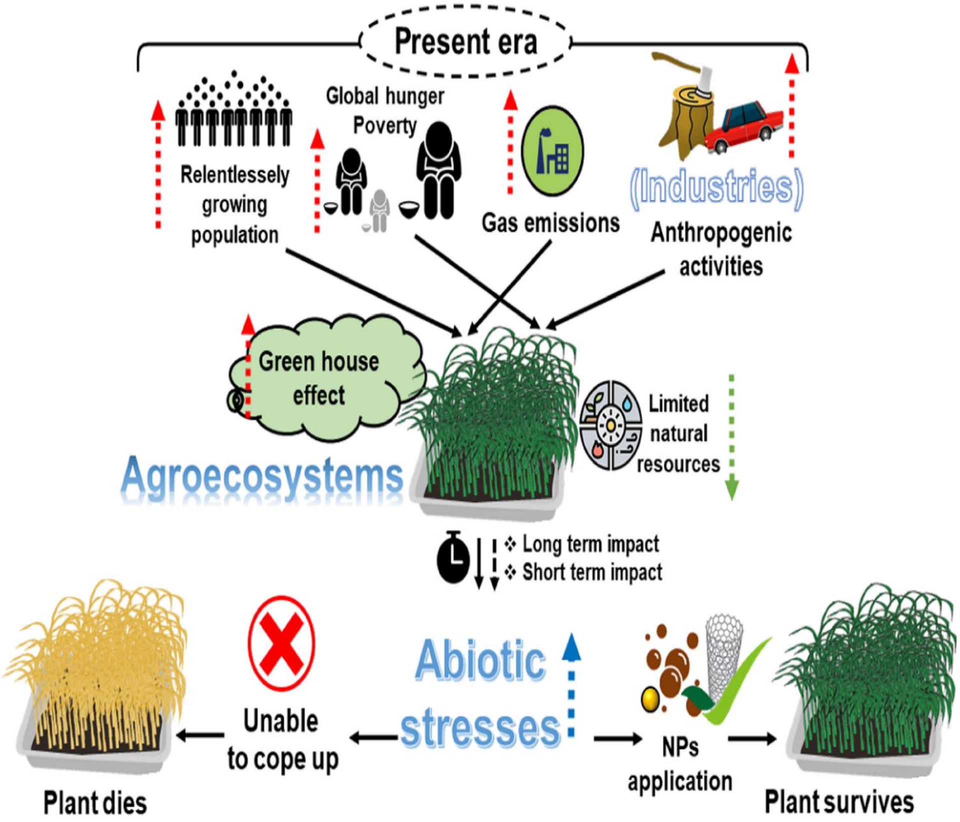
Graphical abstract



Keywords Global climate change · Crop productivity · Abiotic stresses · Nanoparticles · Nanotechnology · Nanotoxicity · Regulatory laws

Introduction

Since the last century, global climate change is critically viewed as one of the biggest challenges to mankind (Shahzad et al. 2021). This alarming threat has arisen because of rapid urbanization and anthropogenic activities including industrialization. As a result, significant negative externalities are being observed in both developed and developing nations of the world (Malhi et al. 2021). Over the past two decades, global climate changes have progressively disrupted the fine balance of ecological factors in nature and resulted in profound consequences in the form of floods, heatwaves, salinity, and droughts (Bandh et al. 2021; Singh et al. 2022). The crop species and the plants growing in the wild are most vulnerable to such extreme weather conditions and stresses (Malhi et al. 2021). Numerous published reports have emphasized upon the negative effect of climate change on the reduction of the world's agricultural total productivity (Zilli et al. 2020; Ortiz-Bobea et al. 2021; Nguyen and Scrimgeour 2022). Being a multifaceted system of alterations, global climate changes directly impact both abiotic and biotic components of the plant niche(s). While, the growth, multiplication, spread, severity/infestation, and the emergence of many plant pathogens/insect pests are directly impacted by the biotic factors (Vilela et al. 2018), in the case of abiotic components, alterations both in terms of intensity and frequency, are observed for rainfall intensity, CO_2 concentration, temperature fluctuations (high and low), and salinity (Singh et al. 2022).

Together, these environmental stresses act as the most common deterrents to food production and global food security. The stresses cause a cascade of morphological, physiological, anatomical, biochemical, and molecular changes in plants that eventually negatively impact their growth and productivity (Fig. 1). The stress-induced changes include ion toxicity, reactive oxygen species (ROS) production (O_2^-, H_2O_2, O, α-O, and OH^-), nutritional problems, redox/osmotic imbalances, changes in leaf water content, chlorophyll content, photosynthetic

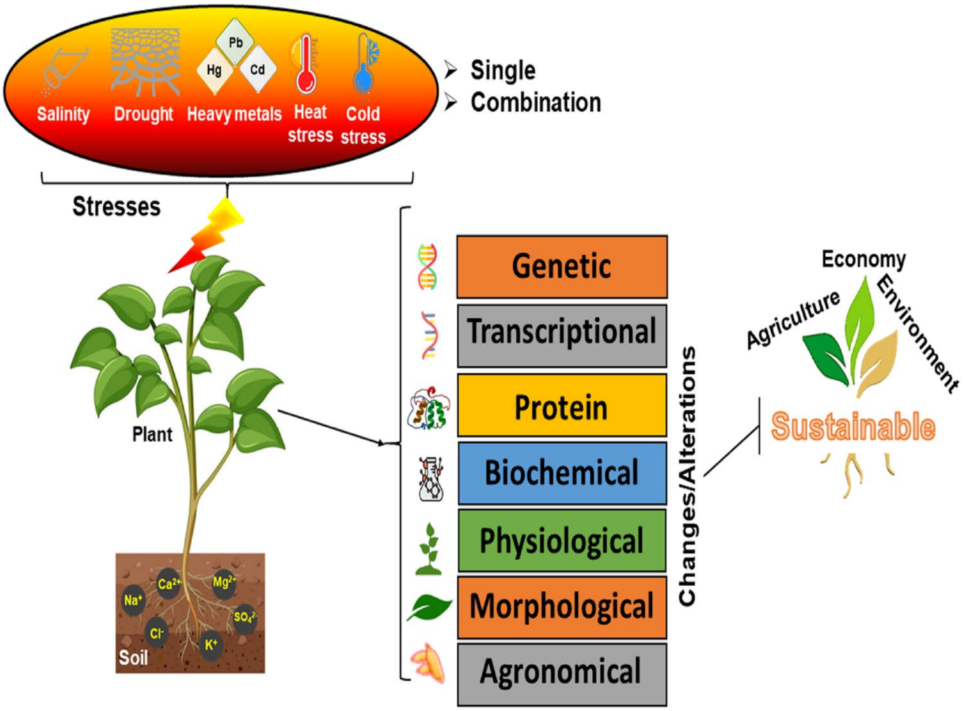


Fig. 1 Impact of various abiotic stresses on plant growth, development, and productivity. Abiotic stresses, individually or in combination, affect a wide variety of plants. Exposure to stresses brings alterations at genetic, transcriptional, biochemical, morphological, as well as agronomical levels in plants. A combination of environmental stresses in the field conditions is predicted to aggravate the adverse effects

capacities, and turgor pressure (Mehta et al. 2020; Zhou et al. 2021). Additionally, these stresses disrupt the ultrastructure of cellular and organellar membranes leading to the disruption of normal cellular physiological functions. Plants employ a variety of mechanisms to cope with these stresses including ion homeostasis and compartmentalization, electron transport chain, biosynthesis of osmoprotectants and phytohormones, regulation of nitric oxide production, antioxidant defenses, water balance, osmotic regulation, and changes in the expression (Gohari et al. 2020a, b; Van Zelm et al. 2020). However, the yield losses still remain substantial and farmers throughout the world are able to collect only 50% of their optimal yield potential (FAO 2014; Bayat et al. 2021). The 'yield gap' between actual and prospective production is caused by these stresses (Moshelion and Altman 2015).

Phytonanotechnology has been projected as one of the most effective and promising modern technologies with the ability to protect plants from environmental stresses, and to offer practical answers to the United Nations 'Zero Hunger 2030 Goal' (Jiang et al. 2021; Agrawal et al. 2022). Being submicroscopic particles by nature that range in size from 1 to 100 nm, nanoparticles (NPs) can be chemically, physically, or biologically generated from a variety of materials. upon application, the NPs aid plants in coping with abiotic stresses by increasing free radical scavenging (Ghareib et al. 2019), antioxidant enzymatic activities (Geremew et al. 2023), osmoprotectant concentration (Al-Khayri et al. 2023), bioavailability, and uptake of essential nutrients (Rasheed et al. 2022), all of which help to limit the cellular osmotic and oxidative damage and thus increase growth and yield potential. Because of these reasons, nanotechnology has been recognized as the 'Key enabling technology' by the European Union (Parisi et al. 2015). Recently, NPs have been put to commercial usage in the agriculture industry as nanofertilizers (Xu et al. 2023), nanoherbicides (Kannan et al. 2023), nanopesticides (Manzoor et al. 2023), nanofungicides (Wen et al. 2023), and nanosensors (Iavicoli et al. 2017). Indian Farmers Fertilizer Cooperative Limited (IFFCO) recently launched World's 1st Nano Urea Liquid (Yamuna et al. 2023) for improved crop productivity. Various nano-enabled products being used in agriculture around the globe have been previously compiled by Rajput et al. (2021).

Although the effects of NPs on crop productivity vary depending on their origin, size, form, concentration, mode of exposure, period of exposure, as well as the specialization of plant genotypes, NPs have generally been observed to exert positive effects on plant growth when applied at low or medium concentrations (Fig. 2) and help crop plants in tolerating various types of abiotic stresses by bringing about changes at genetic, biochemical, anatomical, and physiological levels (Mittal et al. 2020). However, at elevated concentrations, the NPs tend to induce metabolic alterations or even inhibit vital life processes. The mitigation of abiotic stresses by application of NPs has although been dwelled upon in some excellent reviews (Rajput et al. 2021; El-Saadony et al. 2022; Al-Khayri et al. 2023; Abdel-Aziz et al. 2023; Zia-Ur-Rehman et al. 2023), pertinent safety issues related to the commercial usage of NPs in agriculture

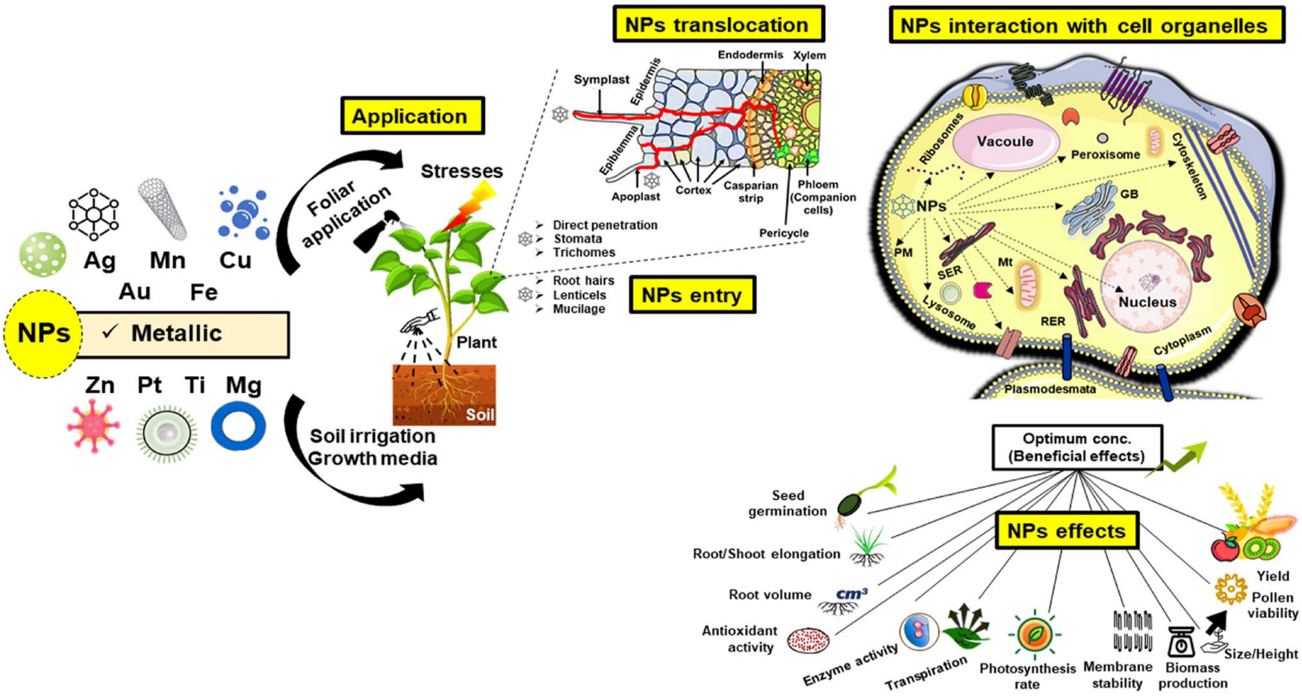


Fig. 2 Overview of the application of various NPs on plants' functional traits. The entire diagrammatic illustration can be divided into four parts (Preparation, Application, Transport (within the plant system), and Effects). The NPs, whether lab-generated or commercial agro-nano-products are applied at multiple doses. When applied at an optimum dose, these NPs (metallic or metal oxide) enter the plant system via various modes and ultimately exert positive effects on the plants by bringing changes at genetic, biochemical, anatomical, and physiological levels under a plethora of abiotic conditions. However, at toxic concentrations, these NPs induce metabolic alterations or inhibit vital life processes

such as (i) understanding the possible causes of toxicity of NPs at higher doses and its management and (ii) the promulgation of uniform regulatory laws related to NPs application, disposal, eco-toxicity and approval of nano-products still need to be addressed by the scientific community. Resolving these issues is important before nanobiotechnology is considered as a safe and rewarding technology to aid in global food security. The present review has attempted to raise and address these key concerns besides providing an updated account of the status of NPs mediated mitigation of major abiotic stresses in crops.

Abiotic stresses in crops and their mitigation by metal nanomaterials

Salinity and sodicity rank top among the principal abiotic stresses and represent the most potent limiting factors to agricultural production, crop yield, and usable land area (Gangwar et al. 2020; Mukhopadhyay et al. 2021). Similarly, drought is considered as the most common abiotic stress that has impacts on the crop productivity especially in the dry areas of the world (Ahmad et al. 2018; Seleiman et al. 2021; Ilyas et al. 2021). The severity of drought conditions is increasing worldwide due to changing climate and poor water resource management and every year, drought stress costs billions of dollars in crop yield losses (Alabdallah et al. 2021). The development of drought-tolerant cultivars is a time taking process and such genomic resources are not available in all crop species. This situation raises serious concerns about adequate food supply in drought-prone geographies of the world (Nuccio et al. 2018). Cumulatively, high salinity of soil, drought, and temperature stress have been observed to be the leading cause of crop loss globally (Praveen et al. 2023).

In the same vein, heavy metals (HM) contamination has become another increasingly alarming issue around the world due to disproportionate urbanization, industrialization, and mining activities (Tóth et al. 2016; Adimalla et al. 2019; Wan et al. 2021; Hananingtyas et al. 2022). Over the recent past, HMs have been reported to be present in exceedingly higher amounts than the permissible limits in agricultural soils (Wan et al. 2021; Oladoye et al. 2022) negatively affecting plant growth and eventually human health.

In this context, nanotechnology has shown promising results and metallic NPs such as ZnO, CuO, Fe_2O_3, TiO_2, and Ag based NPs have successfully been used to combat various abiotic stresses, including heavy metal (Hussain et al. 2018; Khan et al. 2019; Rizwan et al. 2019a, b; Jiang et al. 2020; Bashir et al. 2020), drought (Foroutan et al. 2020; Dimkpa et al. 2019; Sun et al. 2020; Adrees et al. 2021; Semida et al. 2021), cold (Song et al. 2021), salinity (Alabdallah and Alzahrani 2020; Elsheery et al. 2020a; Noohpisheh et al. 2021; Faizan et al. 2021a; Kareem et al. 2022a, b), and high-temperature (Kareem et al. 2022a, b) stresses. Specific NPs have been found to improve productivity in many crop species affected by abiotic stresses. For instance, the use of TiO_2 NPs has helped crops such as wheat, Dragon's head, rice, chickpea (Mohammadi et al. 2013, 2014; Amini et al. 2017), tomato, and maize in mitigating cold, drought, high temperature (Qi et al. 2013; Thakur et al. 2021), heavy metals, lead (Pb) and cadmium (Cd), and salt (Khan 2016; Cai et al. 2017; Dai et al. 2019; Shoarian et al. 2020; Lian et al. 2020; Mustafa et al. 2021) stresses. Silicon (Si) and Silicon dioxide (SiO_2) in nanoforms have been observed to exert a positive effect on the metabolism and physiology of stressed plants. Ag NPs display peculiar physico-chemical properties that lie between copper (Cu) and gold (Au) and have been used to combat heavy metal and salinity stress in plants like tomato (Almutairi 2016), fenugreek (Hojjat and Kamyab 2017), grass pea (Hojjat 2019), *Lilium* (Salachna et al. 2019), pearl millet (Khan et al. 2020a, b), Yellow Lupin, wheat (Wahid et al. 2020), and *Satureja hortensis* (Nejatzadeh 2021; Jaskulak et al. 2019) (Tables 1, 3).

Rui et al. (2016) evaluated the effectiveness of Fe_2O_3 NPs with a chelated Fe-fertilizer in peanut (*Arachis hypogaea*) seedlings. Foliar sprays of Fe_2O_3 NPs improved the activities of polyphenol oxidase (PPO), catalase (CAT), and peroxidase (POD) enzymes (Torabian et al. 2018) in sunflower (cv. Alestar). Fe_2O_3 NPs usage resulted in improved photosynthetic efficiency with a reduced Cd content in the wheat grains (Hussain et al. 2019a, b) thereby combating heavy metal stress (Table 3). Interestingly, Fe_2O_3 NPs complexed with salicylic acid have recently been utilized to reveal both positive and negative impacts on plants under salinity stress (Mozafari et al. 2018). While, positive effects included enhanced activities of antioxidant enzymes Superoxide dismutase (SOD), CAT, and POD, increase in K^+ uptake and K^+/Na^+ ratio, and improvement in plant growth by prevention of nutrient balance by enhanced activities of H^+-ATPase and H^+ PPase seen in *Trachyspermum ammi* L. (Abdoli et al. 2020; Ghassemi-Golezani and Abdoli 2021), reduction in chlorophyll content and degradation and plasma membrane damage was reported in *Pistacia vera* by Karimi et al. (2020). Overall, the application of various NPs has shown great promise in mitigating abiotic stresses in crops, the details of which have been tabulated stress-wise in the following sub-sections.

Salinity stress

Around 800 million hectares of arable land are affected by soil salinity around the world (Gohari et al. 2020b). The salinity resultant ionic imbalances, nutritional and hormonal abnormalities, and osmotic stress lead to metabolic and growth alterations in plants and reduced yield and crop quality (Liu et al. 2021). To cope with sodicity, plants use several strategies such as osmotic regulation, increased chlorophyll content, electron transport chain, antioxidant responses, harmful ion uptake, and ROS production (Gohari et al. 2020b). The positive effects of ZnO NPs have been attributed to the release of zinc which plays a vital role in plant physiology primarily by stabilizing the proteins and biomembranes under stress conditions (Kareem et al. 2022a, b). Zn NPs, at a concentration of 10 mg/L upregulated the osmolyte biosynthesis and antioxidant system in *Brassica napus* L. when subjected to salinity (Farouk and Al-Amri 2019) (Table 1). At a similar concentration, ZnO NPs induced an increase in the photosynthetic pigments, CAT and SOD activities, and growth parameters in *Abelmoschus esculentus L.* (Okra) grown under saline conditions (Nadiya et al. 2020). Being a SOD cofactor and a key component of CA (Carbonic anhydrase), zinc is also involved in ROS scavenging (in cytosol and chloroplast) and photosynthesis (Khan et al. 2021a, b; Faizan et al. 2021b). In addition, the accumulation of both total soluble sugar and proline was observed to reduce in Okra, which helped in keeping the turgor pressure and enhanced the membrane stabilization by acting as ROS scavengers. In crop plants, when applied as foliar sprays, Zn maintains water balance, regulates indole-3-acetic acid (IAA), affects the metabolism of lipids and carbohydrates, and regulates the membrane integrity and enzymatic activities (Caldelas and Weiss 2017). Moreover, ZnO NPs have also been tested in combination with zeolite, Si, and boron NPs in potatoes (Mahmoud et al. 2020), leading to increased photosynthetic efficiency, nutrient uptake, and antioxidant properties. Zinc oxide in combination with Si NPs increased the yield and quality of fruits in mango (Elsheery et al. 2020b). When applied along with biochar (Ali et al. 2019a; Bashir et al. 2020), iron oxide (Rizwan et al. 2019a, b), Fe, Cu, or Co (Linh et al. 2020), the stress mitigation effects of NPs were further improved in crop plants like wheat, rice, barley, soybean, sugarcane, and maize (Table 2).

Copper (Cu) is a metallic micronutrient that is essential for various vital processes in plants including photosynthesis (Yruela 2005, 2009). Besides, Cu also mediates several redox reactions to reduce the harmful effects of salinity by regulating photosynthesis, water relations, and nutrition. It has also been observed to upregulate antioxidant defense and levels of osmoprotectants with a higher Na^+/K^+ ratio in tomatoes (Hernández-Hernández et al. 2018; Perez Lebrada

Table 1 Effects of various simple and complexed nanoparticles (NPs) on different plant species under salinity stress conditions

S. No.	NPs used	Crop species	Effective Concentration	Response	References
1.	CeO_2 NPs (Polyacrylic acid-coated nanoceria)	Canola (*Brassica napus* L.)	50 mg/L	Root anatomical modifications, shortening of root apoplastic barriers, increased transport of Na^+ to shoots resulting in reduced accumulation	Rossi et al. (2017a, b)
2.	CeO_2 NPs	Mouse-ear-cress (*Arabidopsis thaliana* L.)	50 mg/L	Increase in chlorophyll content, photosynthesis, biomass, and leaf mesophyll potassium ion retention, ROS scavenging	Wu et al. (2018)
3.	CeO_2 NPs	Cotton (*Gossypium* sp. L.)	0.9 mM	Increase in plant growth; better phenotypic and photosynthetic performance coupled with an increase in chlorophyll content and carbon assimilation rate, higher leaf K^+ retention, and Na^+ leaf exclusion	Liu et al. (2021)
4.	CeO_2 NPs	Moldavian Balm (*Dracocephalum moldavica* L.)	50 mg/L	Improvement in agronomic traits, photosynthetic efficiency, antioxidant enzymes, decrease in MDA, and H_2O_2	Mohammadi et al. (2021)
5.	CeO_2 NPs	Rice (*Oryza sativa* L.)	1 μM, 98 μg L^{-1}	Higher shoot length, chlorophyll content, and fresh and grain weight	Zhou et al. (2021)
6.	CeO_2 NPs	Rapeseed (*Brassica napus* L.)	–	Nanoceria application led to improved salt tolerance in rapeseed through improved chlorophyll content, carbon assimilation, fresh weight, and leaf size	Li et al. (2022)
7.	Mn NPs	Rice (*Oryza sativa* L.)	0.5 mM	Recovery from chlorosis and restricted growth, ROS detoxification, increase in the content of phenolic compounds, and enzymatic activities of AsA, MDHAR, DHAR, SOD, and CAT	Rahman et al. (2016)
8.	Mn NPs	Mung bean (*Vigna radiata* (L.) R. Wilczek)	0.5 mg/L	Improvement in membrane stability index, chlorophyll content, and nitrate reductase activity	Shahi and Srivastava (2018)
9.	Mn NPs	Bell Peppers (*Capsicum annuum* L.)	0.1, 0.5, and 1 mg/L	Formation of NP-corona complex, Improvement in germination of seeds, and growth of roots	Ye et al. (2020)

Table 1 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
10.	Mn_3O_4 NPs	Cucumber (*Cucumis sativus* L.)	1 mg per plant	Increase in chlorophyll content, net photosynthesis, biomass, altered metabolome, enhanced endogenous antioxidants production, Reduction in oxidative stress response	Lu et al. (2020)
11.	Ag NPs	Tomato (*Solanum lycopersicon* L.)	1.5 mg/L	Improved seed germination, Increase in dry and fresh seedling weight, and root length along with altered molecular responses	Zainab (2015)
12.	Ag NPs	Fenugreek (*Trigonella foenumgraecum* L.)	> 10 ug/mL	Improved seed germination percentage	Hojjat and Kamyab (2017)
13.	Ag NPs	Grass pea (*Lathyrus sativus* L.)	10 ppm	Improved seed germination, fresh and dry seedling weight, increase in metallothioneins, and GPX activity	Hojjat (2019)
14.	Ag NPs	Lily (*Lilium* sp. L. cv. Mona Lisa)	100 ppm	Improved growth and flowering, increase in leaf and bulb biomass, Increased chlorophyll content in leaves	Salachna et al. (2019)
15.	Ag NPs	Wheat (*Triticum aestivum* L.)	10 mg/L	Improvement in seed germination, antioxidant machinery, ABA production, chlorophyll content, and proline accumulation	Wahid et al. (2020)
16.	Ag NPs	Pearl millet (*Pennisetum glaucum* (L.) Morrone)	20 mM	Increase in antioxidative stress, proline content, relative water content upregulation of phenolic and flavonoid content	Khan et al. (2020a, b)
17.	Ag NPs	*Summer savory* (*Satureja hortensis* L.)	80 ppm	Improved germination average, plant root, and shoot length, plant height	Nejatzadeh (2021)
18.	ZnO NPs	Rapeseed (*Brassica napus* L.)	10 mg/L	Upregulated the osmolyte biosynthesis and antioxidant system	Farouk and Al-Amri (2019)
19.	ZnO NPs	Okra (*Abelmoschus esculentus* L. Moench)	–	Increase in chlorophyll, proline, and antioxidant enzymes	Nadiya et al. (2020)
20.	ZnO NPs	Tomato (*Solanum lycopersicon* L.)	10, 50, 100 mg/L	Enhanced shoot and root length, biomass, and photosynthetic efficiency. Increase in protein content and antioxidative enzymatic potential of POD, SOD, and CAT	Faizan et al. (2021a, b, c, d, e)

Table 1 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
21.	ZnO NPs	Fenugreek (*Trigonella foenumgraecum* L.)	–	Alteration in biochemical and physiological parameters	Noohpisheh et al. (2021)
22.	Zn, Zeolite, Si and Boron	Potato (*Solanum tuberosum* L.)	–	Increased photosynthetic efficiency, nutrient uptake, and antioxidant properties	Mahmoud et al. (2020)
23.	ZnO and Si NPs	Mango (*Mangifera indica* L.)	100 mg/L nZnO and 150 mg/L nSi	Improvement in plant growth, nutrient uptake, and carbon assimilation increase in annual cop load and fruit quality	Elsheery et al. (2020b)
24.	CuO NPs	Tomato (*Solanum lycopersicon* L.)	10 mg	Regulation of ionic and oxidative stress by upregulation of *JA* and *SOD* genes expression	Hernández-Hernández et al. (2018)
25.	CuO NPs	Tomato (*Solanum lycopersicon* L.)	250 mg/L	Increase in Vit C, phenols, and glutathione. Enhanced antioxidant activity and higher Na^+ and K^+ ratio	Perez-Lebrada et al. (2019)
26.	Se NPs, Si NPs, and Cu NPs	Bell Peppers (*Capsicum annuum* L.)	10, 20, and 100 mg/L	In Leaves: Increase in chlorophyll, beta-carotene, lycopene, and glutathione peroxidase In fruits: Enhanced Enzyme activity and reduction in glutathione and flavonoid levels. Increase in yellow carotenoid and phenols levels	González-García et al. (2023)
27.	Fe_2O_3 NPs	Sunflower (*Helianthus annus* L.)	2 g/L	Improved activities of PPO, CAT, and POD enzymes	Torabian et al. (2018)
28.	Fe_2O_3 NPs	Moldavian balm (*Dracocephalum moldavica* L.)	60 ppm	Increase in fresh and dry weight of bot root and shoot, leaf length and leaf area, Altered Amino acids and enzyme activities	Moradbeygi et al. (2020)
29.	Fe_2O_3 NPs	Forest red gum (*Eucalyptus tereticornis* L.)	25 ppm	Biochemical changes like an increase in SOD, sugars, and proline levels, increased gene expression of antioxidant enzymes, decrease in MDA, and increase in physiological growth parameters like shoot length	Singh et al. (2021)
30.	Fe_2O_3 NPs and potassium silicate	Grape (*Vitis vinifera* L. cv. Koshnaw)	0.8 ppm (Fe_2O_3 NPs) and 1 and 2 mM (potassium silicate)	Increase in total protein content and reduction in proline, enzyme antioxidant capacity, and H_2O_2 increase in membrane stability	Mozafari et al. (2018)

Table 1 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
31.	Fe complexed with Salicylic acid (nFe-SA)	Pistachio (*Pistacia vera* L.)	2.9 mg/L	Reduction in chlorophyll degradation and plasma membrane damage	Karimi et al. (2020)
32.	Nano Fe_2O_3 and salicylic acid	Ajowan (*Trachyspermum ammi L.*)	1 mM (Fe) and 3 mM (SA)	Enhanced activities of antioxidant enzymes (SOD, CAT, POD), increase in K^+ uptake and K^{+}/Na^+ ratio	Abdoli et al. (2020)
33.	Nano Fe_2O_3 and salicylic acid	Ajowan (*Trachyspermum ammi* L.)	1 mM (Fe) and 3 mM (SA)	Improvement in plant growth by prevention of nutrient balance by enhanced activities of H^+-ATPase and H^+ PPase	Ghassemi-Golezani and Abdoli (2021)
34.	SiO_2 NPs	Basil (*Ocimum basilicum* L.)	10 ml/L	Alteration in physiological and morphological traits. Increase in leaf fresh and dry weight, chlorophyll content, and growth	Kalteh et al. (2018)
35.	SiO_2 NPs	Cucumber (*Cucumis sativus* L.)	200 mg/kg	Regulation of ion homeostasis and stomatal opening, increase in K^+ uptake and K^{+}/Na^+ ratio, water, and nutrient use efficiency	Alsaeedi et al. (2019)
36.	SiO_2 NPs	Strawberry (*Fragaria x ananassa* L.)	50 mg/L	An increase in chlorophyll, carotenoid content, increased epicuticular wax deposition, decrease in proline content	Avestan et al. (2019)
37.	SiO_2 NPs	Common Bean (*Phaseolus vulgaris* L.)	100 mg/L	Increase in seed germination percentage, Length and dry mass of roots and shoots, fruits yield	Al-Saeedi (2020)
38.	SiO_2 NPs	Tomato (*Solanum lycopersicon* L.)	500 mg L^{-1}	Increase in Chlorophyll, Vit C concentration, Enhanced GSH, and PAL activity	Pinedo-Guerrero et al. (2020)
39.	SiO_2 NPs	'Valencia' sweet orange plants	0, 200, 400, and 600 mM	Increased chlorophyll content, root growth, osmotic levels, and reduced salinity induced damages in stressed plants	Mahmoud et al. (2022)
40.	TiO_2 NPs	Spinach (*Spinacia oleracea* L.)	0.25%	Increase in rubisco and antioxidant enzymes, chlorophyll formation and photosynthetic rate, higher crop yield	Lei et al. (2008)
41.	TiO_2 NPs	Tomato (*Solanum lycopersicon* L.)	20 mg/L	Growth inhibition; increase in growth, yield, and quality	Khan (2016)

Table 1 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
42.	TiO_2 NPs	Broad bean (*Vicia faba* L.)	0.01%	Increase in plant growth, soluble sugars, antioxidant enzymes, amino acids, and proline content, and a decrease in MDA and H_2O_2 contents	Abdel Latef et al. (2018)
43.	TiO_2 NPs	Moldavian balm (*Dracocephalum moldavica* L.)	100 mg/L	Increase in plant growth; increased antioxidant enzyme activity and reduction of H_2O_2 levels to prevent oxidative damage, activation of the enzymatic defense system, increase in essential oil components	Gohari et al. (2020b)
44.	TiO_2 NPs and *Funneliformis mosseae*	Common bean (*Phaseolus vulgaris* L.)	100 mg/kg	Increase in mycorrhizal colonization in root tissues, arbuscular frequency, and relative density of AMF	El-Gazzar et al. (2020)
45.	TiO_2 NPs and Chitosan functionalized Selenium (Cs-Se)	Stevia (*Stevia rebaudiana* Bertoni)	100 and 20 mg/L	Increase in plant growth, photosynthetic performance, and antioxidant potential, stevioside and rebaudioside	Sheikhalipour et al. (2021)
46.	C NPs	Lettuce (*Lactuca sativa* L.)	0.3%, seed priming	Improved seed germination, Slight inhibition of primary roots but lateral root growth promoted. Enhanced chlorophyll accumulation in seedlings	Baz et al. (2020)
47.	MW-CNTs (Multi-walled Carbon nanotubes	Rapeseed (*Brassica napus* L.)	20 mg/L	Resetting of ion homeostasis and redox balance	Zhao et al. (2020)
48.	Polyhydroxy Fullerenes NPs	Wheat (*Triticum aestivum* L.)	10 mg/L	Increased antioxidant activities of CAT, POD, and APX enzymes, chlorophyll, free sugars, and ascorbic acid content. Reduction in levels of MDA and H_2O_2	Shafiq et al. (2019)
49.	MW-CNT-COOH (Multi-walled Carbon nanotubes)	Sweet Basil (*Ocimum basilicum* L.)	50 mg/L	Enhanced chlorophyll, phenolics, and carotenoid content. Increase in antioxidant enzymes APX, CAT, and GP activity	Gohari et al. (2020a)
50.	SWCNHs (Single-walled Carbon nanohorns)	Sophora (*Sophora alopecuroides* L.)	50 mg/L	Increase in total protein, soluble sugars, and Cu content in leaves. Enhanced PSII activity, glycolysis, and TCA cycle to generate more energy to maintain membrane integrity	Wan et al. (2020)

Table 1 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
51.	CW-CNT (Carbonized wood-derived carbon nanotube)	Tomato (*Solanum lycopersicon* L.)	–	Enhanced water uptake in seed and improved seed germination	Dutta et al. (2021)
52.	Chitosan NPs	Mung Bean (*Vigna radiata* L.)	–	Reduction in MDA and H_2O_2 content leads to increased chlorophyll content and better growth and metabolism	Sen et al. (2020)
53.	Chitosan NPs	Madagascar Periwinkle (*Catharanthus roseus* (L.) G.Don)	1%	Activation of the antioxidant defense system, ROS scavenging. Expression of *MAPK3*, *GS*, and *ORCA3* genes that led to higher alkaloid accumulation to protect against salinity stress	Hassan et al. (2021)
54.	Au NPs	Wheat (*Triticum aestivum* L.)	300 ppm	Modulation of multiple traits such as chlorophyll content, defense system, and growth traits led to improved salinity tolerance	Wahid et al. (2022)
55.	ZnO NPs	Faba bean (*Vicia faba* L.)	0, 50, and 100 mg/L	ZnO NPs treatment resulted in a higher accumulation of the photosynthetic pigments, macro- and micronutrients, amino acids, antioxidants as well as secondary metabolites	Mogazy and Hanafy (2022)
56.	Se NPs	Pineapple Mint (*Mentha suaveolens* Ehrh.)	0, 10, and 20 mg/L	Se NPs improved the pineapple mint growth, essential oil content, and secondary metabolites especially piperitenone oxide under saline conditions	Kiumarzi et al. (2022)
57.	Ag NPs	Pearl millet (*Pennisetum glaucum* L.)	0 and 20 mg/L	Combined applications of NaCl + Ag NPs ameliorated the oxidative damage by increasing antioxidant enzymes activities as well as upregulated 500 + transcripts associated with various molecular and metabolic functions	Khan et al. (2023)

Search Strategy: An exhaustive literature electronic search was carried out by two of the authors (VRR and SM) on June 20, 2022, November 30, 2022, and May 10, 2023, from Google scholar (https://scholar.google.co.in/) and PubMed (https://www.ncbi.nlm.nih.gov/pubmed/) for the period 2015–2023. The rationale of the research was to account for the number of publications related to the use of different metallic nanomaterials for alleviating various abiotic stresses. There was a restriction on publication time (January 01, 2015–May 10, 2023) with language restrictions including only English. The search keywords were "nanoparticles, metallic nanoparticles, plants, abiotic stress, salt stress, heat stress, drought stress, cold stress, and alleviating." The search was made in the title of the article with all of the words, with the exact phrase, and with at least one of the words. Full-length articles were also assessed if the title and abstract were not enough to conclude and decide. The disagreement related to the eligibility criteria of articles was discussed with SP, TM, VDR, and RD as adjudicators. Additionally, a thorough manual search was performed for the articles cross-referred from the relevant articles' reference lists

Table 2 Effects of various simple and complexed NPs on different plant species under drought conditions

S. No.	NPs used	Crop species	Effective Concentration	Response	References
1.	Chitosan NPs	Barley (*Hordeum vulgare* L.)	60 and 90 ppm	Increase in leaf area and color, grain yield and harvest index, grain protein content	Behboudi et al. (2018)
2.	Chitosan NPs	Wheat (*Triticum aestivum* L.)	90 ppm	Increase in chlorophyll and relative water content, leaf area, photosynthetic rate, SOD and CAT activities, biomass, and yield	Behboudi et al. (2019)
3.	Chitosan NPs	Madagascar Periwinkle (*Catharanthus roseus* (L.) G.Don)	1%	Induction of antioxidant potential and gene expression of alkaloid biosynthesis. Increase in proline, CAT, and POD content. Reduced H_2O_2 and MDA accumulation, preserving membrane integrity	Ali et al. (2021)
4.	S-nitrosoglutathione (GSNO) encapsulated Chitosan NPs	Sugarcane (*Saccharum officinarum* L.)	–	Increase in photosynthesis and root biomass. Improvement in root/shoot ratio. Enhanced NO-induced benefits	Silveira et al. (2019)
5.	ZnO NPs	Moringa tree (*Moringa peregrina* (Forssk.) Fiori)	0, 0.05 and 0.1% Foliar spray	Reduced Na/K ratio and carbohydrate content. Increased enzymes' (POD and PPO), and osmoprotectants' (proline) activities	Foroutan et al. (2018)
6.	ZnO NPs	Sorghum (*Sorghum bicolor* (L.) Moench)	5 mg/Kg	Increased absorption of Nitrogen, Potassium, and essential nutrients, accelerated plant development, enhanced yield	Dimkpa et al. (2019)
7.	ZnO NPs	Maize (*Zea mays* L.)	100 mg/L	Increase in Melatonin synthesis and activation of the antioxidant enzyme system. Upregulation of relative transcript abundance of SOD, CAT, APX, CAT, TDC, and SNAT	Sun et al. (2020)
8.	ZnO NPs	Eggplant (*Solanum melongena* L.)	50 and 100 ppm	Increase in photosynthetic efficiency and fruit yield. Improved stem and leaf anatomical characteristics	Semida et al. (2021)
9.	ZnO NPs	Tomato (*Solanum lycopersicon* L.)	25 and 50 mg/L	An increase in root and shoot biomass, Reduced oxidative stress. Enhanced activity of SOD, CAT, and ascorbate peroxidase enzymes	El-Zohri et al. (2021)
10.	ZnO NPs	Wheat (*Triticum aestivum* L.)	25, 50, and 100 mg/L	Enhanced leaf chlorophyll content and reduced oxidative stress with increased activities of SOD and POD. Improved growth and yield	Adrees et al. (2021)

Table 2 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
11.	ZnO NPs	Cucumber (*Cucumis sativus* L.)	25 and 100 mg/L	Increased antioxidant defense system, osmolyte accumulation, and nutrient absorption	Ghani et al. (2022)
12.	ZnO NPs, Fe NPs, Cu NPs, and Co NPs	Soybean (*Glycine max* (L.) Merr.)	50 mg/L of Fe, ZnO, and Cu NPs and 0.05 mg/L CO NP	Improvement in relative water content, drought tolerance index, and biomass reduction rate. Upregulation of gene expression of drought-responsive genes especially *GmERD1* in both roots and shoots	Linh et al. (2020)
13.	Cu NPs	Maize (*Zea Mays* L.)	69.4 uM	Higher water content in the leaf and biomass, Enhanced chlorophyll, anthocyanin, and carotenoid content Increase in seed number and grain yield. Increase in ROS scavenging enzyme activities	Van Nguyen et al. (2021)
14.	Cu NPs and Zn NPs	Wheat (*Triticum aestivum* L.)	–	Increased photosynthetic activity, relative water content and the levels of antioxidative enzymes, and reduced levels of thiobarbituric acid reactive substances (TBARS)	Taran et al. (2017)
15.	Cu NPs and Ag NPs	Wheat (*Triticum aestivum* L.)	Cu: 0, 3, 5 and 7 mg/L Ag: 0, 10, 20 and 30 mg/L	Higher chlorophyll stability index (CSI), leaf succulence (LS), and leaf K (LK) content stomatal conductance (SC) in plants	Ahmed et al. (2021)
16.	Cu NPs and CuO NPs	Bok choy (*Brassica chinensis* L.)	0, 3, 5, 7 and 10 mg/L	CuO NPs positively impacted the biomass, root length, and root tip number whereas Cu NPs exposure reduced the Mg, Ca, and Mn conc. in edible part	Di et al. (2023)
17.	TiO_2 NPs	Dragon's head (*Lallemantia iberica* (M.Bieb.) Fisch. & C.A.Mey.)	-	Increase in flavonoids, phenolic compounds, and antioxidant activity. Raised levels of CAT and SOD. Production of vanillic acid, ferulic acid, and syringic acid	Shoarian et al. (2020)
18.	TiO_2 NPs complexed with Sodium nitroprusside (SNP)	Wheat (*Triticum aestivum* L.)	TiO_2: 0, 500, 1000 and 2000 mg/L SNP: 0 and 100 uM	Enhanced germination percentage and rate, Increase in root and shoot fresh weight and vigor index. Reduction in mean germination time, improved seedling growth	Faraji and Sepehri (2019)

Table 2 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
19.	TiO_2 complexed with Calcium Phosphate	Wheat (*Triticum aestivum* L.)	40 ppm	Increase in root and shoot length, fresh and dry weight. Improvement in chlorophyll content, relative water content, yield, membrane stability index, proline, and sugar content. Enhancement in levels of SOD, POD, and CAT	Mustafa et al. (2021)
20.	Se NPs	Wheat (*Triticum aestivum* L.)	10, 20, 30 and 40 mg/L	Increase in plant height, length of shoot and root, dry weight of shoot and root, and length of the leaf	Ikram et al. (2020)
21.	Se NPs	Wheat (*Triticum aestivum* L.)	100 ug/mL	Increase in growth and productivity	El-Saadony et al. (2021b)
22.	SiO_2 NPs	Hawthorn (*Crataegus* sps.)	0,10, 50, 100 mg/L	Increased plant biomass, xylem water potential, and MDA content Decreased proline and carbohydrate content	Ashkavand et al. (2018)
23.	SiO_2 NPs and Se NPs	Strawberry (*Fragaria x ananassa* L.)	50 and 100 mg/L	Increase in photosynthetic pigment and osmolytes like Proline and sugars. Enhanced antioxidant enzyme activities of CAT, APX, GPX, and SOD. Increase in water retention capacity, relative water content, and water use efficiency. Pronounced anthocyanins, phenolics, and Vit C	Zahedi et al. (2020)
24.	Fe_2O_3 NPs	Ginger (*Zingiber officinale*)	0.3, 0.6, 0.9, and 1.2 mM	Increased chlorophyll, carotenoid, and POD content	Noor et al. (2022)
25.	Fe NPs complexed with Salicylic acid	Strawberry (*Fragaria* X *ananassa* Duch.) (cv. Queen Elisa)	-	Improved plantlets and other measured traits. Production of a higher quantity of quality strawberries	Dedejani et al. (2021)
26.	Iron oxide (IO NPs) and Hydrogel NPs (HG NPs)	Rice (*Oryza sativa* L.)	100 mg/Kg of soil	Increased photosynthetic efficiency, nutrient acquisition, biomass, and antioxidant enzyme contents. Decrease in ROS	Ahmed et al. (2021)
27.	CuO NPs	Maize (*Zea mays* L.)	52, 69.4, and 86.8 µM	Increased anthocyanin, carotenoid, and chlorophyll content in drought-stressed plants	Van Nguyen et al. (2022)
28.	CuO NPs, ZnO NPs, and SiO_2 NPs	Wheat (*Triticum aestivum* var. juniper)	20, 30, and 200 mg/Kg	Reduction in shoot biomass, root biomass, shoot water content, and quantum yield of PSII	Potter et al. (2021)

Table 2 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
29.	C NPs	Chili pepper (*Capsicum annuum* L.)	6 and 12 mg/L	C NPs exogenous application increased relative water content, chlorophyll-related parameters, proline content, and antioxidant activities under drought stress	Alluqmani and Alabdallah (2023)
30.	Zn NPs	Turnip (*Brassica rapa* L.)	40 nm	Improved turnip height, biomass, root/length, diameter, antioxidants system, secondary metabolites, and photosynthetic pigments	Li et al. (2023)

et al. 2019), thereby helping the plant negotiate and ameliorate salinity stress.

The NPs application is manifested in terms of better phenotypic and photosynthetic performance coupled with an increase in chlorophyll content and carbon assimilation rate. The other coupled changes include an increase in antioxidant enzymes and a reduction in reactive oxygen species (ROS) and malondialdehyde (MDA). The use of CeO_2 NPs, including polyacrylic acid-coated nanoceria (PNC) has been shown to improve the plant's tolerance to salinity stress in *Brassica napus* (Rossi et al. 2017a, b), *Arabidopsis thaliana* (Wu et al. 2018), rice (Zhou et al. 2020), cotton (Liu et al. 2021), and in *Dracocephalum moldavica* (Mohammadi et al. 2021) by improvement in agronomic traits, photosynthetic efficiency, and antioxidant enzymes. Abdel Latef et al. (2018) reported an increase in plant growth, soluble sugars, antioxidant enzymes, amino acids, and proline content, and a decrease in MDA and H_2O_2 contents in broad beans with the application of TiO_2 NPs (0.01%) under salinity conditions. The effects of TiO_2 NPs have been tested on the agronomic traits in Moldavian balm (*Dracocephalum moldavica* L.) plants grown under different salinity levels (Gohari et al. 2020b). The analyzed agronomic traits were observed to be negatively affected by salinity at all the tested levels. However, the application of TiO_2 NPs at 100 mg/L concentration resulted in increased antioxidant enzyme activity and reduction of H_2O_2 levels to prevent oxidative damage, thereby, activating the enzymatic defense system of the plant to alleviate all the negative effects associated with salinity stress. Further, the NPs treated plants showed a significant increase in the oil content warranting its commercial application for growth promotion and salinity stress amelioration. The crops such as broad bean, tomato, cotton, spinach, *Stevia*, and Moldavian balm, have been observed to exhibit an improvement in RuBisCO levels, antioxidant enzymes levels, chlorophyll content, and photosynthetic rates in response to TiO_2 NPs application (Lei et al. 2008; Khan 2016; Abdel Latef et al. 2018; Gohari et al. 2020b; Sheikhalipour et al. 2021).

In another study, Kalteh et al. (2018) reported alteration in physiological and morphological traits, increase in leaf fresh and dry weight, chlorophyll content, and growth upon the application of Si NPs in the holy Basil (*Ocimum basilicum* L.) grown under salinity stress. Similarly, Asgari et al. (2018) compared the effects of sodium silicate with nanosilicon at concentrations of 5 mM and 10 mM in oat plants (*Avena sativa* L.) grown hydroponically. They focused on xylem cell wall lignification, leaf and root cells ultrastructure, low silicon 1 (*Lsi1*), and phenylalanine ammonia-lyase (PAL) expression. Si NPs helped in the regulation of ion homeostasis and stomatal opening, increase in K^+ uptake and K^+/Na^+ ratio, and water and nutrient use efficiency in cucumber (*Cucumis sativus* L.) under salt stress (Alsaeedi

Table 3 Effects of application of different NPs on various plant species subjected to heavy metals stress conditions

S. No.	NPs used	Crop species	Effective Concentration	Response	References
1.	SiO_2 NPs	Rice (*Oryza sativa* L. Cv Youyou 128)	2.5 mM	Increase in Chlorophyll a, growth, Mg, Fe, and Zn nutrition. Higher GSH and other antioxidant enzyme activities. Reduced MDA and Cd accumulation and translocation in the shoot	Wang et al. (2015)
2.	SiO_2 NPs	Wheat (*Triticum aestivum* L.)	600 mg/L	Cd tolerance; increase in SOD and POD activity. Increase in dry biomass of roots, shoots, grains, and spikes. Increase in chlorophyll a and b content. Reduction in Cd concentration in grains	Ali et al. (2019a)
3.	SiO_2 NPs	Wheat (*Triticum aestivum* L.)	600 mg/L	Cd tolerance; increase in photosynthetic pigments, SOD, POD, and other antioxidant enzymes and growth and decrease in oxidative stress. Reduction in Cd content in roots, shoots, and grains, increase in yield	Hussain et al. (2019a, b)
4.	SiO_2 NPs	Maize (*Zea mays* L.)	600 mg/L	Amelioration of Aluminum toxicity. Stimulation of antioxidant enzymatic activities of SOD, CAT, and AsA. Increase in organic acids accumulation and metal detoxification in roots	de Sousa et al. (2019)
5.	SiO_2 NPs	Wheat (*Triticum aestivum* L.)	25, 50, and 100 mg/L	Improvement in photosynthesis and plant growth indicators. Increase in SOD and peroxide activities. Reduction in oxidative stress in terms of reduced production of hydrogen peroxide in leaves. Reduced electrolyte leakage and amount of MDA	Khan et al. (2020a, b)
6.	SiO_2 NPs	Soybean (*Glycine max* (L.) Merr.)	25 mM	Mercury toxicity	Li et al. (2020)
7.	SiO_2 NPs	Wheat (*Triticum aestivum* L.)	3 mM	Cd tolerance; increase in photosynthetic pigments, SOD, POD, and other antioxidant enzymes and growth and decrease in oxidative stress. Reduction in Cd content in roots, shoots, and grains, increase in yield	Thind et al. (2021)
8.	SiO_2 NPs	Wheat (*Triticum aestivum* L.)	3 mmol/L	Cd tolerance: by limiting uptake, accumulation, and translocation of Cd, Increase nutrients uptake and antioxidative stress	Ur Rahman et al. (2021)
9.	Se NPs and Si NPs	Rice (*Oryza sativa* L.)	5, 10, and 20 mg/L	Improved biomass, growth, grain quality, yield, and Se content in brown rice. Reduction in Cd and Pb toxicity in the grains	Hussain et al. (2020)

Table 3 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
10.	SiO_2 NPs and Pb-resistant microbes	Coriander (*Coriandrum sativum* L.)	1.5 mM	Improvement in photosynthetic efficiency, growth, and antioxidant enzymatic activities of the plants	Fatemi et al. (2020)
11.	ZnO NPs	Wheat (*Triticum aestivum* L.)	25, 50, and 100 mg/L	Increase in photosynthesis, growth, and Zn concentration in the shoots, roots, and grains. Increased SOD and POD activities in leaves. Reduction in electrolyte leakage and Cd toxicity in roots and shoots	Hussain et al. (2018)
12.	ZnO NPs	Wheat (*Triticum aestivum* L.)	25, 50, and 100 mg/Kg	Reduction in oxidative stress, and Cd accumulation in tissues and grains. Increase in biomass and tissue dry weight	Khan et al. (2019)
13.	ZnO NPs	Maize (*Zea mays* L.)	50, 75, and 100 mg/L	Increase in chlorophyll content, number of leaves, gaseous exchange, plant height, root, and shoot biomass. Improvement in antioxidant enzymes. Reduction in electrolyte leakage, hydrogen peroxide, and MDA content	Rizwan et al. (2019a, b)
14.	ZnO NPs	Rice (*Oryza sativa* L.)	–	Reduction in arsenic and Cd content in both roots and shoots	Ma et al. (2020)
15.	ZnO NPs	Tomato (*Solanum lycopersicon* L.)	50 mg/mL	Increase in fresh and dry weight, leaf area, net photosynthesis, transpiration rate, stomatal aperture, reduced malonaldehyde, and superoxide radicals	Faizan et al. (2021)
16.	ZnO NPs	Australian Spinach (*Chenopodium murale* L.)	10 mg/L and above	Increase in oxidative stress and damage to membranes, decrease in chlorophyll content, soluble proteins, and growth	Zoufan et al. (2020)
17.	ZnO NPs	Broad Bean (*Vicia faba* L.)	100 and 200 mg/L	Chromosomal aberrations and formation of vacuolated nuclei, ring formation, laggards and bridges, altered patterns of PODs, α and β esterases	Youssef and Elamawi (2020)
18.	ZnO NPs	Muskmelon (*Cucumis melo* L.)	20 mg/Kg	An increase in growth and antioxidant activities Reduction in Cd uptake	Shah et al. (2021)
19.	ZnO NPs	Wheat (*Triticum aestivum* L.)	25, 50, and 100 mg/L	Increase in leaf chlorophyll content, SOD and POD activity, reduction in oxidative stress	Adrees et al. (2021)
20.	ZnO NPs	Rice (*Oryza sativa* L.)	50 mg/L	Improved biomass, photosynthetic efficiency, protein, antioxidant enzymes, and reduction of Cd levels in grains	Faizan et al. (2021c)

Table 3 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
21.	ZnO NPs	Rice (*Oryza sativa* L.)	0, 25, 50 and 100 mg/mL	Improved seed germination, early growth, and physio-chemical parameters. Increase in root fresh weight, root-shoot length, SOD, and POD activity	Li et al. (2021)
22.	ZnO NPs	Rice (*Oryza sativa* L.)	5 mg/L	Increase in growth of plants, reduced bioaccumulation index and metallothionein (MT), Pb, and Cu tolerance	Akhtar et al. (2021)
23.	ZnO NPs and Biochar	Rice (*Oryza sativa* L.)	100 mg/L	Reduction in Cd concentration in roots and shoots by approximately 30%. Increase in soil pH. Improvement in net photosynthesis and biomass of the plant	Ali et al. (2019b)
24.	ZnO NPs and composted biochar and farmyard manure	Wheat (cv. Lasani-2008)	200 mg/L and 1–2%	Increase in chlorophyll concentration, biomass, and yield. Enhanced activities of POD and SOD. Reduction in electrolyte leakage and Cd concentration in roots, shoots, grain, and husks	Bashir et al. (2020)
25.	ZnO NPs and 24 -Epibrassinolide	Tomato (*Solanum lycopersicon* L.)	50 mg/L	Enhanced leaf gas exchange parameters, net photosynthetic activity, and protein content. Increase in antioxidant and ROS scavenging activity, alleviation of Cu toxicity	Faizan et al. (2021d)
26.	ZnO NPs and Fe_3O_4 NPs	Wheat (*Triticum aestivum* L.)	ZnO: 50 mg/L Fe_3O_4: 10 mg/L	Increased chlorophyll, biomass, and nutrients content and decreased oxidative stress and Cd toxicity	Rizwan et al. (2019a, b)
27.	Fe_2O_3 NPs	Wheat (*Triticum aestivum* L.)	5, 10, 15 ad 20 ppm	Reduction of leaf electrolyte leakage. Increase in antioxidant enzyme activities, photosynthesis, and dry weight of grains. Reduced Cd content in seeds	Hussain et al. (2019a, b)
28.	Fe_3O_4 NPs	Rice (*Oryza sativa* L.)	5 ppm	Increased germination, fresh root and shoot length, weight, and shoot/root ratio. Better dry matter percentage of root and shoot. Alleviation of arsenic toxicity	Khan et al. (2021a, b)
29.	Nano Zerovalent Iron (nZVI) NPs	Sunflower (*Helianthus annuus* L.)	100 mg/L	Reduction in accumulation of heavy metals. Enhanced growth and increase in enzymatic activities of SOD and POD	Michálková et al. (2017)
30.	Nano Zerovalent Iron (nZVI) NPs	Rice (*Oryza sativa* L.)	100 mg/L	Downregulation of Fe transporters (IRT1, IRT2, YSL2, YSL15) responsible for Cd and Fe uptake. Overexpression of *OsV1T1* and *OsCAX4* genes that led to Cd sequestration in vacuoles	Guha et al. (2020)

Table 3 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
31.	CeO_2 NPs	Soybean (*Glycine max* (L.) Merr.)	500 mg/Kg	Influence on root apoplastic barriers, No effect on metal scavenging in Cd contaminated soils, Ce NPs accumulation	Rossi et al. (2017a, b)
32.	CeO_2 NPs	Rice (*Oryza sativa* L.)	100 mg/L	No effect on the accumulation of As (III) and As (V) in hydroponic systems	Wang et al. (2018)
33.	CeO_2 NPs	Rice (*Oryza sativa* L.)	200 mg/L	Upregulation of the antioxidant system, inhibition of Cd accumulation	Wang et al. (2019)
34.	TiO_2 NPs	Soybean (*Glycine max* (L.) Merr.)	100–300 mg/Kg	Increase in photosynthetic rate and improved physiological parameters, Limiting toxicity of Cd	Singh and Lee (2016)
35.	TiO_2 NPs	Rice (*Oryza sativa* L.)	10, 100 and 1000 mg/L	Reduction in damage by Cd stress. Improved root length, Chlorophyll content, net photosynthesis, plant height, hormone levels, antioxidant enzyme activity, and physiological parameters	Ji et al. (2017)
36.	TiO_2 NPs	Rice (*Oryza sativa* L.)	10 and 1000 mg/L	Decrease in Pb accumulation in roots by more than 80% and in shoots by 77 to 97%	Cai et al. (2017)
37.	TiO_2 NPs	Maize (*Zea mays* L.)	100 and 250 mg/L 250 mg/L	Reduction in shoot Cd content. Increased SOD and GST activities. Upregulation of glycine, serine, and threonine metabolism. Efficient galactase metabolism and citrate cycle Increased Cd accumulation in roots and shoots, Reduction in plant dry mass and chlorophyll content	Lian et al. (2020)
38.	TiO_2 NPs and SiO_2 NPs coated with Sodium dodecylbenzene sulphonate	Wheat (*Triticum aestivum* L.)	TiO_2: 4.2 mg/g SiO_2: 7.16 mg/g	Increase in adsorption of Cd, enhanced root length, reduced Cd phytotoxicity	Dai et al. (2019)
39.	Ag NPs	Yellow Lupin (*Lupinus luteus* L.)	25 mg/kg	Increase in GPX activity and upregulation of housekeeping genes and metallothionein expression level	Jaskulak et al. (2019)
40.	NiO NPs, CuO NPs, and ZnO NPs	Okra (*Abelmoschus esculentus* L.)	100 mg/L and above	Suppression in plant growth, increase in ROS generation	Baskar et al. (2021)
41.	CuO NPs	Lettuce (*Lactuca sativa L.*) and Cabbage (*Brassica* var. *capitata* L.)	250 mg/plant	Decrease in net plant weight, photosynthesis, Cu-rich necrotic areas visible near deformed stomata	Xiong et al. (2017)
42.	CuO and ZnO NPs	Raddish (*Raphanus sativus* L.)	> 10 mg/plant	Poor seed germination, reduction in growth parameters in terms of length and weight	Singh and Kumar (2019)
43.	CuO and ZnO NPs	Spinach (*Spinacia oleracea* L.)	1.2×10^{-2} mol/kg	Reduction in biomass	Singh and Kumar (2020)

Table 3 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
44.	Hydroxyapatite NPs (HAp NPs)	Pakchoi (*Brassica chinensis* L.)	5, 10, 15, 20, and 30 g/kg	Increase in chlorophyll, vitamin C, and biomass. Enhanced activities of SOD, CAT, and POD. Reduction in Cd and MDA contents	Li and Huang (2014)
45.	HAp NPs	Rice (*Oryza sativa* L.)	5 g/pot	Reduction in Cd content. Increase in immobilization ability of Pb. Decrease in immobilization ability of Zn, Cd, and Cu after three years	Jin-Feng et al. (2016)
46.	HAp NPs	Rape plant (*Brassica napus* subsp. Napus L.) and Cabbage (*Brassica oleracea* L.)	5, 10, 15, 20 g/kg	Decrease in Cd accumulation and toxicity. Increase in phosphatase activity	Zhu et al. (2019a, b)
47.	HAp NPs	Rye grass (*Lolium perenne*)	0.5 g/pot	Immobilization of heavy metals in contaminated soils. Zn and Cu immobilized as solid amorphous Phosphate Increases in biomass of the plant. Reduction in bioaccessible concentrations of Zn and Cu	Sun et al. (2016)
48.	HAp NPs	Shiny Elsholtzia (*Elsholtzia splendens* Nakai ex F.Maek.)	–	Increase in soil pH, Phosphate, and organic Carbon. Increase in colloid and dust migration of Cu and Cd	Xu et al. (2021)
49.	Chitosan NPs	Tomato (*Solanum lycopersicum* L.)	100 ug/mL	Increase in shoot dry weight, net photosynthetic rate, SPAD index, and decrease in H_2O_2	Faizan et al. (2021b)
50.	Charged Au NPs	Barley (*Hordeum vulgare* L.)	5 nm	Altered cell wall composition, differential distribution of pectin and arabinogalactan protein in cell walls of roots	Milewska-Hendel et al. (2021)
51.	Au NPs	Rice (*Oryza sativa* L.)	200 um	Increase in melatonin content in roots and leaves. Enhanced chlorophyll synthesis and antioxidative enzymatic activities. Inhibition of Cd-induced gene expression of metal transport-related genes *OsHMA2*, *OsHMA3*, *OsIRT1*, *OsIRT2*, *OsNramp1*, *OsNramp5*, and *OsLCT1* in the roots	Jiang et al. (2020)
52.	Astaxanthin NPs (Ast NPs)	Wheat (*Triticum aestivum* L.)	100 mg L^{-1}	Restricted translocation of Cd in aerial parts of the plant, improved length and nutrient profile of wheat seedlings under Cd stress	Zeshan et al. (2022)

Table 3 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
53.	Si NPs, Se NPs, and Zn NPs	Sage (*Salvia officinalis* L.)	–	NPs decreased Pb accumulation (> 35%), and Cd concentration (> 29%) as well as improved plant weight, yield, and essential oils (1,8-cineole, α-thujone, β-thujone, and camphor) in sage leaves	Bakhtiari et al. (2023)
54.	S NPs	Oilseed rape (*Brassica napus* L.)	300 mg/L	Enhancement in plant characteristics, antioxidant defense system, and nutrients accumulation along with a significant decline in lipid peroxidation	Yuan et al. (2023)
55.	Nano Zerovalent Iron (nZVI) NPs	Wheat (*Triticum aestivum* L.)	100 mg/L	Enhanced wheat growth by increasing photosynthetic and antioxidant enzymatic activities under Pb toxic conditions	Mahamood et al. (2023)

et al. 2019). Likewise, Avestan et al. (2019), observed an increase in photosynthetic pigments (chlorophyll and carotenoid), increased epicuticular wax deposition, and a decrease in proline content in salt-stressed strawberries (*Fragaria* x *ananassa* L.). SiO_2 NPs (200 mg/Kg of soil) increased seed germination percentage, length, and dry mass of roots and shoots, fruits yield in common bean (*Phaseolus vulgaris* L.) under salinity conditions (Alsaeedi et al. 2020). When Si NPs were applied in combination with plant growth-promoting rhizobacteria (PGPR) in salt-stressed maize (*Zea mays* L.) a decline in oxidative stress was observed to be regulated by enzymes CAT, SOD, and POD. The resultant maintenance of K^+/Na^+ ionic balance resulted in a higher photosynthetic rate, growth, reduced proline content, and electrolyte leakage (Hafez et al. 2021). Although the forementioned and other reports have established the significance of Si NPs in regulating salt stress tolerance in plants, a better understanding of biochemical and molecular mechanisms and intracellular interactions of Si NPs in plant systems is highly desired.

Mn NPs can serve as micronutrients that aid plant growth by improving membrane stability index, chlorophyll content, and nitrate reductase activity in *Vigna radiata* (Shahi and Srivastava 2018) and protect them against various abiotic stresses (Ye et al. 2020). Similarly, Rahman et al. (2016) observed that salinity-stressed rice plants recovered from chlorosis and restricted growth, ROS detoxification, and showed an increase in the content of phenolic compounds and enzymatic activities of AsA (ascorbate), MDHAR (monodehydroascorbate reductase), DHAR (dehydroascorbate reductase), SOD and CAT in response to Mn NPs' application. In bell peppers (*Capsicum annuum* L.), both scanning electron microscopy and energy-dispersive spectroscopy revealed that Mn NPs formed an NPs-Protein corona complex and resulted in improvement in the germination of seeds and growth of roots at 100 mM NaCl (Ye et al. 2020). Compared to other NPs, reports documenting the abiotic stress-mitigating potential of Mn NPs are scarce in the literature. Therefore, future research with Mn NPs will further unravel their role in mitigating other stresses as well.

Drought stress

Limited studies have been reported on the application of NPs to combat drought stress. In many cases, the ability of TiO_2 in mitigating drought has been fortified by their functionalization either with sodium nitroprusside (SNP), a nitric oxide donor, or calcium phosphate (Table 2). The TiO_2 NPs-based increment in vital functions hints toward its role as a stimulant to activate different enzymatic defense mechanisms as well as an inducer of secondary metabolite production against various abiotic stress factors. A significant decrease in the number of root tips has been reported upon exposure to TiO_2 NPs leading to reduced root hydraulic conductivity. Further, it has been observed that a large portion of TiO_2 NPs might be taken up mainly through root ruptures instead of the typical uptake route.

SiO_2 NPs have been found to be useful in alleviating drought stress in Hawthorn (*Crataegus* sp.) (Ashkavand et al. 2015) wherein their application resulted in improvement in growth parameters. Zahedi et al. (2020) reported an increase in the photosynthetic parameters in strawberries grown under drought conditions in the presence of SiO_2 and Se NPs (Table 2). Further, Cu NPs alone (Van Nguyen et al. 2021) or in combination with Zn (Taran et al. 2017) and Ag NPs (Ahmed et al. 2021) have been shown to successfully counter drought stress in maize and wheat, respectively. Similarly, Iron oxide (IO NPs) and Hydrogel NPs (HG NPs) (Ahmed et al. 2021) have been used in strawberries and rice, respectively to successfully negotiate drought stress and improve vital metabolic parameters. Just like Mn NPs, the use of Cu NPs in combating various abiotic stresses is still in the infancy stage and more research is desired to establish the mode of action of Cu NPs to exploit their full potential for agricultural productivity.

Metal stress

ZnO NPs alone or in combination with other NPs (Tables 1 and 3) have been observed to result in increased chlorophyll content, number of leaves, gaseous exchange, germination, plant height, fresh roots, shoot length, and root and shoot biomass. While improvement was observed in antioxidant enzymes, a reduction in electrolyte leakage, hydrogen peroxide, MDA content, and heavy metal accumulation has also been observed. More recently, Shah and colleagues affirmed that a combination of K silicate and ZnO NPs modulated the antioxidant system, membranous H^+-ATPase, and nitric oxide content in faba bean (*Vicia faba*) seedlings when exposed to As toxicity (Shah et al. 2022).

Cerium oxide (CeO_2), is a pale yellow-white powder that is also known as ceric oxide, ceria, or cerium dioxide. While, Rossi et al. (2017a, b) and Wang et al. (2018) showed no effect of CeO_2 NPs on heavy metal stress amelioration in soybean (at 500 mg CeO_2 NPs/Kg of dry soil) and rice (at 100 mg/L), respectively. On the other hand, Wang et al. (2019) reported a positive impact of the same on mitigation of heavy metal stress in rice at 100 mg /L of CeO_2 NPs. While tolerance against drought was observed in wheat and Dragon's head, tolerance against heavy metal stress was observed in rice, maize, and wheat. In a study by the group led by Lui, the foliar application (at 250 mg/L) mitigated heavy metal stress, while the root application had negative repercussions (Lian et al. 2020). The basic reason behind this observation rested upon the stronger effect of foliar spray on changing the water and metabolite profiling which could have occurred due to better uptake and translocation of NPs via leaves. In contrast, NPs are poorly accumulated by plants through roots under soil conditions due to mucilage and root exudates that are reported to trap NPs or modify their surface (Shang et al. 2019). Several such studies have been listed in Table 3.

Low-temperature stress

Plants need an optimum temperature for their growth and reproduction. Due to climate change-inflicted fluctuations and extremities of average global temperature in terms of chilling and freezing or heat stress, the crops in field conditions have been negatively affected (Adhikari et al. 2022; Al-Khayri et al. 2023; Shakeh et al. 2023) with a significant reduction in agricultural productivity.

Low temperature or chilling and freezing stress leads to many physiological disorders in plant cells resulting in slow growth and altered metabolism (El-Mahdy et al. 2018; Sharma et al. 2020; Hassan et al. 2021; Aslam et al. 2022). Cold stress adversely affects cellular membrane structure and photosynthetic rates (Barajas-Lopez et al. 2021; Burnett and Kromdijk 2022). Different NPs have been used to cope with cold stress in various crops (Kim et al. 2017). For instance, Si NPs and cold plasma have been successfully used in *Astragalus fridges* to alleviate cold stress (Moghanloo et al. 2019). Chitosan and TiO_2 NPs have been used in many studies in chickpea to impart cold stress tolerance (Mohammadi et al. 2013, 2014; Hasanpour et al. 2015; Amini et al. 2017). Under cold stress conditions, the application of TiO_2 NPs elevated glycyrrhizin content in licorice (Ghabel and Karamian 2020), Chitosan NPs reduced ROS and enhanced osmoprotectants in banana (Wang et al. 2021), ZnO NPs in a foliar application stimulated the antioxidative system and transcriptional machinery in rice and increase in SOD, MDA and electrolyte leakage in summer and winter cultivars of wheat (Song et al. 2021; Shakeh et al. 2023) and Si NPs increased the photosynthetic ability in sugarcane (Elsheery et al. 2020b) to combat chilling stress. The cold stress ameliorating properties of many other NPs in wheat, rice, *Eruca sativa*, *Astragalus*, plum, and strawberry crops along with the combined use of many NPs such as SiO_2, ZnO, and Se have been detailed in Table 4.

High-temperature stress

High temperature known as heat stress prevalent for a persistent period, potentially jeopardizes the plant's normal cellular functions and prolonged exposure to abnormally high temperatures causes a significant yield loss (Hu et al. 2020; Zhao et al. 2020; Bharti et al. 2021). Heat stress also causes both osmotic and oxidative stresses at the secondary level. In order to tackle high-temperature stress, plants

Table 4 Effects of various NPs on different plant species under cold stress conditions

S. No.	NPs used	Crop species	Effective Concentration	Response	References
1.	TiO_2 NPs	Chickpea (*Cicer arietinum* L.)	5 ppm	Decrease in electrolyte leakage index and oxidative stress. Improved redox status	Mohammadi et al. (2013)
2.	TiO_2 NPs	Tobacco (*Nicotiana tabacum* L.)	0.1, 1, 2.5, and 5%	Changes in the expression profiles of non-coding micro RNAs. miR395 and miR399 showed as much as 285-fold and 143-fold changes, respectively. Significant decrease in growth in tobacco seedlings, with roots showing maximum sensitivity	Frazier et al. (2014)
3.	TiO_2 NPs	Chickpea (*Cicer arietinum* L.)	–	Induction of lipoxygenase activity, chlorophyll and carotenoids content, Improved defense system, and reduction in the level of injuries	Mohammadi et al. (2014)
4.	TiO_2 NPs	Chickpea (*Cicer arietinum* L.)	50 mg/L	Decrease in electrolyte leakage index and oxidative stress. Differential expression of transcription-derived fragments to combat chilling stress	Amini et al. (2017)
5.	TiO_2 NPs + Spermine	Licorice (*Glycyrrhiza glabra* L.)	2 ppm + 1 mM	Reduction in oxidative damage by reducing the levels of MDA, ROS, and H_2O_2. Increase in phenolics, proteins, sugars, and osmoprotectants levels. Increase in glycyrrhizin content	Kardavan Ghabel and Karamian (2020)
6.	Fe_3O_4 NPs	Rocket (*Eruca sativa* Mill.)	1, 2 and 4 mg/L	Improved seed germination, root-shoot elongation, Chlorophyll a, and growth	Plaksenkova et al. (2019)
7.	ZnO NPs	Rice (*Oryza sativa* L.)	100 mg/L	Improvement in plant height, root length, chlorophyll accumulation, and biomass. Decrease oxidative stress by reducing MDA and H_2O_2 levels. Induction of chilling induced gene and transcriptional factors' expression	Song et al. (2021)
8.	ZnO NPs and CuO NPs	Rice (*Oryza sativa* L.)	-	Negative regulation of auxin biosynthesis, chlorophyll, and biomass accumulation	Jiang et al. (2020)
9.	Si NPs and Cold plasma	Astragalus (*Astragalus fridge* L.)	5, 40, and 80 mg/L	Modified activities of PAL in roots and leaves. The higher expression rate of universal stress protein (USP), Anatomical, physiological, and molecular changes reinforcing plant growth and protection	Moghanloo et al. (2019)
10.	SiO_2 NPs, ZnO NPs, Se NPs, and GNRs (Graphene nano-ribbons)	Sugarcane (*Saccharum officinarum* Cv Guitang 49)	–	Maintenance of maximum efficiency of PSI and PSII. Increase in the content of chlorophylls and carotenoids for improved light harvesting, enhanced photosynthesis, and improved photoprotection and growth	Elsheery et al. (2020a, b)

Table 4 (continued)

S. No.	NPs used	Crop species	Effective Concentration	Response	References
11.	Chitosan NPs	Banana (*Musa acuminata* Var. Baxi)	100–400 mg/L	Increase in photosynthetic pigments, antioxidant enzymes, fresh and dry weight, and osmoprotectants. Reduction in oxidative stress by decreasing the levels of MDA, ROS, H_2O_2, hydroxyl radicals, and superoxide anions	Wang et al. (2021)
12.	Au NPs	Wheat (*Triticum aestivum* L.)	20 µg/mL	Au NPs maintained the photosynthetic activity of plants under cold stress resulting in improved stress tolerance	Venzhik et al. (2022)
13.	Glycine betaine coated-chitosan NPs (CTS-GB NPs)	Plum (*Prunus domestica* L.)	0.5 and 1% (w/v)	CTC-GB NPs application was able to alleviate chilling injury in plants by lowering electrolyte leakage and H_2O_2 content and further increasing the activity of PAL and other phenolic compounds	Mahmoudi et al. (2022)
14.	Proline-coated chitosan NPs	Strawberry (*Fragaria × ananassa*)	0.1% (w/v)	Fruit coated with CTS-Pro NPs reduced lipid peroxidation, decay, and weight loss as well as preserved fruit quality	Bahmani et al. (2022)

employ various cellular, physiological, and molecular modifications to sustain cellular homeostasis (Bharti et al. 2021). The application of various NPs such as Se NPs in *Sorghum* ameliorated membrane damage, reduced pollen germination and yield inflicted due to increased temperature (Djanaguiraman et al. 2018). Likewise, Ag NPs (Iqbal et al. 2019) and Zn NPs (Hassain et al. 2018) resulted in increased growth and antioxidant enzymes and a reduction in lipid peroxidation to combat heat stress in wheat plants. The foliar application of Si NPs in tomato helped the plants cope with the heat stress (Kim et al. 2017). Table 5 highlights NPs mediated heat stress amelioration reports in various crop species.

Combined use of NPs to combat abiotic stresses

Global climatic changes have resulted in the exacerbation of various stresses and co-occurrence of multiple stresses in the farmers' fields complicating the situation further. Considering this, scientists around the globe have started working on elucidating the interactive effects of multiple NPs used simultaneously in plants to cope with the stressful environment (Ramegowda and Senthil-Kumar 2015; Pandey et al. 2015). For instance, to combat salinity stress, Se, Si, and Cu NPs were used together in bell peppers, and an increase in chlorophyll, B carotene, and lycopene, glutathione peroxidase was observed in the leaves, while fruits showed enhanced enzyme activity and reduction in glutathione and flavonoids level (González-García et al. 2023). In another study by Mozafari et al. (2018), iron (Fe) and K silicate NPs were used together in grapes (Koshnaw cv.) and an increase in total protein content and reduction in proline and H_2O_2 and an increase in membrane stability were observed. The combined application of ZnO and Si NPs in mango improved plant growth, nutrient uptake, carbon assimilation, increased annual crop load, and fruit quality under salinity stress (Elsheery et al. 2020b). Likewise, the combined use of Zn, B, Si, and zeolite NPs in potatoes (*Solanum tuberosum L.*) under salinity stress, improved plant height, branching, shoot dry weight, chlorophyll content, net photosynthetic rate, stomatal conductance, tuber yield, and nutrient concentration along with protein and carbohydrates content (Mahmoud et al. 2020). In another report, TiO_2 and chitosan-functionalized Selenium (Cs-Se) NPs used together helped in combating salinity stress in *Stevia rebaudiana* and resulted in an increase in plant growth, photosynthetic performance, antioxidant potential, and steviosıde and rebaudioside contents (Sheikhalipour et al. 2021). Although the above-mentioned reports show that NPs had a positive impact on salinity stress amelioration, the combined use of CeO_2 and TiO_2 NPs in barley (*Hordeum vulgare* L.) showed a negative impact and resulted in growth inhibition and generation of oxidative stress in terms of generation of ROS (Mattiello 2015). Similarly, the combined application

Table 5 Effects of various NPs on different plant species under high-temperature stress conditions

S. No.	NPs used	Crop species	Effective Concentration	Response	References
1.	Ag NPs	Arabidopsis (*Arabidopsis thaliana* L.)	1 mL	Enhanced rate of photosynthesis, altered gene expression, and hormone signaling pathways of auxin, abscisic acid, and ethylene	Syu et al. (2014)
2.	Ag NPs	Wheat (*Triticum aestivum* L.)	75 mg/L	Improve plant root and shoot length, root number, plant fresh dry weight	Iqbal et al. (2019)
3.	Au NPs	Maize (*Zea mays* L.)	74 mg/L	Improve percent germination and seedling vigor	Tovar Jimenez et al. (2020)
4.	Fe NPs	Wheat (*Triticum aestivum* L.)	20 mg/L	Improved height of the plant, spike length, shoot and root dry weights, and plant yield	Rizwan et al. (2019a, b)
5.	Fe_3O_4 NPs	Barley (*Hordeum vulgare* L.)	500 mg/L	Enhance chlorophyll content, total soluble protein, chloroplasts number, and plant vigor	Tombuloglu et al. (2019)
6.	Si NPs	Wheat (*Triticum aestivum* L.)	1.66 mM	Stimulated expressions of *TaPIP1* (*Triticum aestivum* plasma membrane intrinsic protein) and *TaNIP2* (*Triticum aestivum* nodulin 26-like intrinsic protein) and relative water content	Younis et al. (2020)
7.	Se NPs	*Sorghum*	100 mg/L	Activated antioxidant defense system, ameliorated membrane damage, reduced pollen germination and crop yield	Djanaguiraman et al. (2018)
8.	Se NPs	Wheat (*Triticum aestivum* L.)	100 µg/mL	Promote plant growth and productivity and reduce crown root rot disease severity	El-Saadony et al. (2021a)
9.	AlO NPs	Tobacco (*Nicotiana tabacum* L.)	296 µmoles/L	Decrease plant growth and development	Goswami et al. (2019)
10.	TiO_2 NPs	Tomato (*Solanum lycopersicum* L.)	0.2 g/L	Decrease the free radicals production and enhance the activities of SOD, CAT, and POD	Qi et al. (2013)
11.	TiO_2 NPs	Rice (*Oryza sativa* L.)	10 ppm	Upregulate antioxidants enzyme activities and lower MDA and hydrogen peroxide contents	Thakur et al. (2021)
12.	ZnO NPs	Rapeseed (*Brassica napus* subsp. napus L.)	500 mg/L	Reduced germination and simultaneously inhibit root growth	Goswami et al. (2019)
13.	ZnO NPs	Maize (*Zea mays* L.)	10 mg/L	Improved seed germination and shoot length, shoot width, root length, root width, and vigor index	Itroutwar et al. (2020)
14.	ZnO NPs	Mungbean (*Vigna radiata* L.)	30 mg/L	Upregulated antioxidants and osmoprotectants	Kareem et al. (2022a, b)
15.	ZnO NPs	Wheat (*Triticum aestivum* L.)	10 ppm	Improved wheat growth, biomass, nutrients, and chlorophyll led to improved stress tolerance	Azmat et al. (2022)
16.	ZnO NPs	Alfalfa (*Medicago sativa* L.)	90 mg/L	Heat stress-mediated membrane damage, lipid peroxidation, and oxidative stress were reduced upon NPs application due to the stimulated antioxidant system and enhancing osmolyte contents	Kareem et al. (2022a, b)

of CeO_2 NPs and ZnO NPs on *Pisum sativum* L. at two different concentrations revealed that the CeO_2 NPs stimulated the photosynthesis rate, while ZnO NPs prompted stomatal and biochemical limitations. However, in the mixed ZnO and CeO_2 treatments, the latter effects were decreased (Skiba et al. 2021).

All the above reports convincingly indicate that NPs have an important role to play in combating various stresses and assisting food production amidst the changing climatic scenario. Therefore, extensive research especially in understanding the intracellular interactions of different NPs applied singly or in combination, nano-bio interface, and impact analysis is the need of the hour.

Environmental concerns of NPs usage in coping abiotic stress

As discussed in the above sections, nanotechnology offers immense applications in the agriculture sector with the potential to increase overall agricultural productivity and yield, protect against environmental stresses, and reduce chemical pollutants in the environment (Tables 1, 2, 3, 4, and 5). The bibliographic survey reveals that the positive effects of NPs directly depend upon specific genotype/cultivar, shape, size, dose, composition, surface area, surface coatings, redox state, application procedures, and growth matrices (Sarraf et al. 2022). However, various NPs like CeO_2, Se, TiO_2, and ZnO have been shown to produce toxic effects in many plant species including soybean, Sorghum, broad bean, sweet basil, tomato, wheat, onion, and barley (Lopez-Moreno et al. 2010; Djanaguiraman et al. 2018; Rastogi et al. 2019; Filho 2019; Kushwah and Patel 2020; Gohari et al. 2020a, b; Thwala et al. 2021; Feizi et al. 2022) (Table 6).

The NPs' phytotoxicity results from the interaction with the cellular biomolecules and damage to DNA and/or membranes. For example, by using an FT-interacting protein 7 (*Osftip7*) mutant, a group of scientists from China demonstrated that the (*OsFTIP7*) facilitates the toxic effects of CuO NPs and ZnO NPs in rice (Jiang et al. 2021). A loss of function of *OsFTIP7* reduced the toxicity of Zn and Cu NPs by improving auxin biosynthesis, biomass, and chlorophyll content. It is noteworthy that *OsFTIP7* is a transmembrane protein with several metal binding domains, therefore, a direct interaction of this protein with metallic NPs is possible.

The toxicity of NPs toward plants is not the only concern of the present times, but a growing body of evidence also indicates the possibility of detrimental effects of NPs on the tertiary consumers, humans (Dudefoi et al. 2017; Rajput et al. 2020; Bischoff et al. 2022). For instance, E171 (a TiO_2 NPs-based food additive), which is added in foods such as ice creams, candies, gums, and puddings, was recently shown to facilitate colorectal tumor formation and progression by affecting the processes like inflammation, immune responses, cancer signaling, and cell cycle in mouse system (Bischoff et al. 2022).

The negative impacts of NPs on plants are reflected in terms of reduction in seed germination and root elongation, reduction in photosynthetic efficiency, biomass, growth inhibition, hampered mineral uptake; oxidative stress (ROS), induction of e^- hole pairs, damage to the cell wall and cell membrane, and aggregation of NPs leading to increased ROS species and tissue toxicity (Fig. 3). At the cytological levels changes in mitotic index, chiasma frequency, and the number of univalents have been shown in onion and faba bean (Patlolla et al. 2012; Rajeshwari et al. 2016; Kushwah and Patel 2020).

The NPs toxicity, however, has been observed to depend on various factors like specific plant species and genotype, concentration, and size of the NPs, and the duration of the exposure and indicates the involvement of certain factors that are governed by these conditions. Interestingly, one such actor known as NPs protein corona (PC) is formed upon the entry of NPs into the cell by the adsorption of proteins from their surroundings (Muller et al. 2018). Protein corona has been extensively studied by medical and environmental scientists but it has remained poorly deciphered in plants until recently (Prakash and Deswal 2019; Li et al. 2019; Kurepa et al. 2020; Ye et al. 2020; Khanna et al. 2021). Our group recently reviewed the current status of NPs associated protein corona in plants (Prakash et al. 2022a) and showed that protein corona determines NPs uptake, translocation, its effects, and fate as well. Recent efforts to understand corona formed in plants showed the ability of PC to influence major cellular pathways or plant responses like energy synthesis, pathogenesis, salt tolerance, and leaf senescence. More research studies are required to corroborate these findings in various groups of plants. Therefore, future research should be aimed to elucidate molecular mechanisms of NPs action under tightly controlled reaction conditions such as the NPs concentration, size, and duration of exposure in desirable plant species before they can be exploited in a commercial agricultural system.

It is imperative to first understand the effect of various physiochemical characteristics, means of introduction, uptake, translocation, aggregation, and parameters like size, number, concentration, surface activity, modification, and most importantly intracellular interaction of NPs with cellular organelles and its effects on cellular metabolism, before nanobiotechnology becomes fruitful to be utilized commercially (Sarraf et al. 2022). Therefore, keeping in mind these limitations, the future course of research must be focused on finding possible solutions to the safe and efficient use of NPs in agriculture. Additionally, more efforts need to be directed toward studies about the nano-bio interface

Table 6 Negative impacts of NPs on various crop species

S. No.	NPs	Concentration	Crop species	Response	References
1.	TiO_2 NPs	-	Spinach (*Spinacia oleracea* L.)	Growth inhibition; Generation of oxygenated and carbon-centered free radicals	Fenoglio et al. (2009)
2.	TiO_2 NPs	2.5%	Tobacco (*Nicotiana tabacum L.*)	Growth inhibition; Oxidative stress (ROS), induction of electron–hole pairs, damage to the cell wall and cell membrane, and lipid peroxidation	Hou (2019)
3.	TiO_2 NPs	1000 mg/L	Onion (*Allium cepa* L.)	Growth inhibition; Nucleolar alterations, increased lytic vacuoles, oil bodies	Filho et al. (2019)
4.	TiO_2 NPs	> 5 mg/L	Wheat (*Triticum aestivum* L.)	Growth inhibition; downregulation of various antioxidant enzymes	Silva (2019)
5.	TiO_2 NPs	200 mg/L	Moldavian balm (*Dracocephalum moldavica* L.)	Growth inhibition; aggregation of NPs leading to increased ROS species	Gohari et al. (2020a, b)
6.	TiO_2 NPs	15, 30, 60, 120 and 240 mg/L	Faba bean (*Vicia faba* L.)	Chromosomal abnormalities at meiosis in the form of chromosome stickiness, reduction in chiasma, and increase in the number of univalents	Kushwah and Patel (2020)
7.	CeO_2 nanoceria	2000 mg/L	Alfalfa (*Medicago sativa*), Corn (*Zea mays* L.), Cucumber (*Cucumis sativus* L.), and Tomato (*Solanum lycopersicum* L.)	Reduction in seed germination and root elongation	Zhu et al. (2019a, b)
8.	CeO_2 NPs, TiO_2 NPs	500 mg/L	Barley (*Hordeum vulgare* L.)	Growth inhibition; Oxidative stress in terms of generation of ROS and ATP content	Mattiello (2015)
9.	ZnO NPs	60 mg/L	Wheat (*T. turgidum* L.ssp. *durum* (Desf.) cv. Cappelli)	Alteration in root morphology, increase in oxidative stress, organ damage, inhibition of growth, the cumulative negative effect of salinity and Zn priming	Spano et al. (2020)
10.	ZnO NPs	100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1200 ppm	Mung bean (*Vigna radiata*) and Wheat (*Triticum aestivum*)	Both plants at higher concentration exposure observed a decline in percent germination, root, and shoot length	Modi et al. (2022)
11.	ZnO NPs and CeO_2 NPs	2000 and 4000 mg/L	Soybean (*Glycine max* (L.) Merr.)	Genotoxic effects as evidenced by the appearance of new bands in random amplified polymorphic DNAs	Lopez-Moreno et al. (2010)
12.	ZnO NPs and Phenanthrene	NPs and bulk at 500 and 1000 mg/L and phenanthrene 1 mg/L	Wheat (*Triticum aestivum* L.)	Decrease in chlorophyll content and inhibition of Hill's reaction, Genotoxicity, and DNA damage to root cells. Decrease in SOD and CAT enzymatic activities	Zhu et al. (2019a, b)
13.	$CoFe_2O_4$ NPs	1000 mg/L	Tomato (*Solanum lycopersicum* L.)	Reduction in Magnesium uptake, Decrease in CAT activity in leaves and roots, Effect on macronutrient uptake	Lopez-Moreno et al. (2016)

Table 6 (continued)

S. No.	NPs	Concentration	Crop species	Response	References
14.	Au NPs	0.1, 1.0 and 10 ug/mL of Au15, Au30 and Au40 nm	Onion (*Allium cepa* L.)	The mitotic indices were found to be directly proportional to the NPs concentration and inversely proportional to the size	Rajeshwari et al. (2016)
15.	Ag NPs	12.5, 25, 50, and 100 mg/L	Faba Bean (*Vicia faba* L.)	Induction of genotoxicity reflected in terms of a significant increase in chromosomal aberrations, micronuclei, and reduction in mitotic index	Patlolla et al. (2012)
16.	Ag NPs	5 mM	Wheat (*Triticum aestivum* var. Corso)	Suppression of photosynthetic activity and growth parameters. Destruction of photosystems, improper regulation of PSI electron transport, and disruption of chloroplast structure	Rastogi et al. (2019)
17.	MW-CNT-COOH (Multi-walled Carbon nanotubes)	100 mg/L	Sweet Basil (*Ocimum basilicum* L.)	Tissue toxicity	Gohari et al. (2020a, b)
18.	CuO NPs	75, 150, and 225 mg/L	Melon (*Cucumis melo* L.)	CuO NPs suppressed the growth rate and affected physiological and biochemical activities significantly	Shah et al. (2023)
19.	Cu NPs and CuO NPs	20 mg/L	Brassica (*Brassica campestris* L.)	Increase in oxidative damage and reduced the nutritional value	Wang et al. (2022)

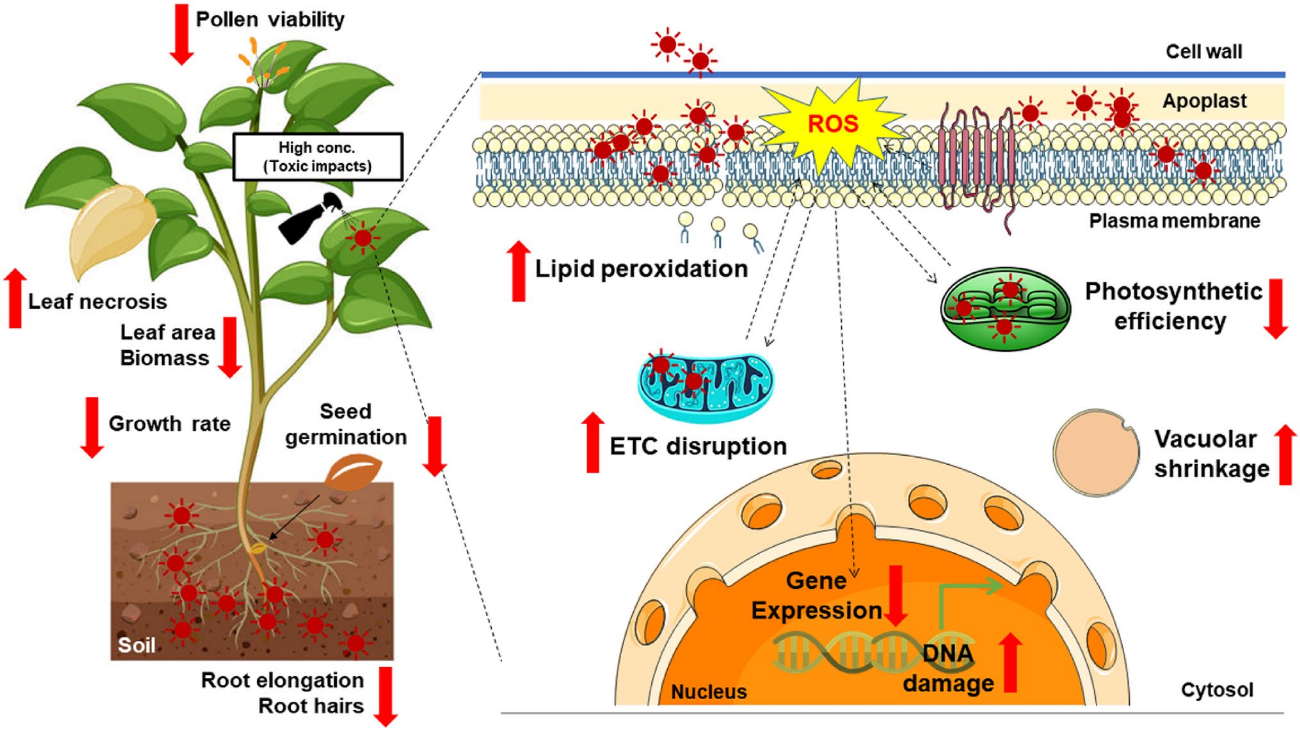


Fig. 3 Negative implications of NPs application on the genetic, morpho-physiological, and biochemical traits of various plant species. NPs are taken up by plant tissues (above-ground and under-ground) followed by their translocation to various sites (stem, leaf, flower, etc.). At higher concentrations, NPs produce excess ROS, thereby causing cytotoxicity, genotoxicity (DNA damage/chromosomal aberrations), membrane damage (lipid peroxidation), vacuole shrinkage, chlorophyll degradation, as well as a decline in photosynthetic efficiency. Ultimately, the NPs application negatively impacts biomass, leaf area, pollen viability, root elongation, and seed germination rate

and impact analysis to avoid ecotoxicological risks for both plants and humans (Prakash et al. 2022a; Singh et al. 2022). Yet another important aspect that needs the attention of the scientific community is the safe disposal of NPs. The given guidelines for the NPs' disposal state that NPs should be discarded in sealed boxes in an area dedicated to hazardous materials or they must be incinerated. However, unfortunately, NPs are being used in several laboratories/institutions around the world that lack such facilities. It is absolutely essential to have proper safety protocols and regulations in place for the use and disposal of NPs (Paramo et al. 2020). The present review recommends the use of NPs with caution in the current scenario.

Regulatory laws on the application of NPs and NPs-based commercial products

As described earlier, the application of NPs on plant species largely has a positive effect on plant growth and metabolic processes under abiotic stress conditions. With the advent of nanotechnology, many nano-based chemicals have been commercialized throughout the world (Mittal et al. 2020). However, the major pool of patented chemicals relates to controlling biotic stresses only (Vijayakumar et al. 2022). The commercial products that directly relate to abiotic stress mitigation are scarce and only a few have been used as nanofertilizers like Nano urea, Nubiotek, Fértil Calmag, Nano Bor, and Nano Zinc.

As a whole, several ordinances, regulatory laws, governance structures, and policies have been formed over the past fifty years related to the judicial use of nanotechnology in the laboratory and in field conditions. The list includes the European Food Safety Authority National Nanotechnology Initiative (by National Science and Tech. Council for Enhancement of Nanotechnology), BMBF (Federal German Ministry for Education and Research), NANOKOMMISION, Regulation (EC) No. 1107/2009, Regulation (EC) No. 396/2005, and REACH Regulation (EC) No. 1907/2006 (discussed in Vijayakumar et al. 2022).

In case of developing countries like India, regulatory frameworks and policies have been recently drafted by the Department of Biotechnology (DBT), Ministry of Science and Technology, Government of India, on August 1, 2019. The policy aims to ensure the safe usage of nano-Agri input products (NAIP) and nano-agriproducts (NAP) to prevent environmental and human health hazards. Similarly, as part of the Nano Mission, a Nano Science and Technology

Initiative (NSTI), launched by the Department of Science and Technology (DST), India has issued "Guidelines and Best Practices for Safe Handling of Nanomaterials in Research Laboratories and Industries".

The evaluation of nano-products used in agriculture and food is challenging with the existing assessment procedures. The major limitation associated with nano-products assessment and evaluation is the lack of unanimously acceptable international guidelines and definitions for nanomaterials and nano-agriproducts. The US FDA and environmental protection agency (EPA) are yet to consider 'nanomaterials' as the new chemicals. Further, adding to the woes, existing methods for environmental risk assessment have been questioned by various groups of scientists around the world (Kookana et al. 2014; Mwaanga 2018). Though the industrial stakeholders rigorously promote the risk-free usage of NPs, delays in approvals of nano-products which are being assessed on a case-to-case basis become a deterrent in the commercialization of NP-based products in agriculture. Therefore, uniform and transparent guidelines need to be formulated for regulatory frameworks, approvals, safe disposal, environmental risk, and toxicity assessments for all nations across the world (Prakash et al. 2022b). Considering that nanobiotechnology is a relatively new domain, all the above important concerns need to be urgently addressed by world leaders and policymakers for effective and fruitful commercial utilization of nanotechnology for the enhancement of agricultural output.

Concluding remarks and future perspectives

Under the shade of globalization and industrialization, the agriculture sector faces several challenges, especially in the form of biotic and abiotic stresses. Over the past few decades, NPs have gained immense popularity in the agricultural sector due to their tunable physio-chemical properties and ability to penetrate plants. In this review, we have highlighted the most recent reports on the beneficial effects of NPs in several plant species exposed to the most common detrimental abiotic stresses, such as drought, salinity, heavy metals contamination as well as both high- and low-temperature-based conditions. Generally, NPs exert positive effects at the molecular, metabolic, and physiological levels in plants. The NPs-induced positive responses are manifested through the expression of various genes, improvement in antioxidant defense, osmotic potential, chlorophyll content, photosystem performance, root exudation, influenced uptake of nutrients, and through discouraging secondary stresses when observed under controlled greenhouse and field conditions.

The positive impact of all types of NPs has been observed to be dependent on several factors that include the type of NPs used, application method, dose, simultaneous or individual use of NPs, and extent of stress exposure. Besides the forementioned advantages, there are a few reports documenting the toxic effects of NPs generally at high concentrations in a few plant species. Nevertheless, overall NPs display an immense potential for improving plant performance under abiotic stresses but most of the studies have been carried out in laboratory conditions. It is of utmost importance to replicate the performance of NPs in stress amelioration in field conditions for nanotechnology to be used as a sustainable strategy and to offer practical solutions for enhancing the abiotic stress tolerance capability.

In the future, it is foremost essential to understand the exact mechanism of synthesis of NPs from a variety of biological entities. Detailed investigations also need to be carried out to better understand the mode and mechanisms of action of NPs in plants. Further, it is important to investigate the synergistic effect of the different NPs with growth-promoting microbes against abiotic stresses to find out the best possible combinations and doses. More focused research studies need to be planned on the combined application of NPs against simultaneously occurring stresses in a practical scenario in field conditions. Knowledge of how different NPs influence the signaling mechanisms and plant antioxidant machinery using multi-omics technologies will be quite helpful in understanding the mode of action of various NPs for their better utilization. Future research should also focus on fabricating novel metallic/non-metallic NPs using untapped elements from the periodic table. Finally, the standard guidelines and protocols for evaluation of optimum dosages, disposal protocols, and risk analysis of the possible accumulation of NPs in edible plant parts, their safe and acceptable limits for human consumption, and the effect of different nanoformulations on different organisms (biotic components) and environments (abiotic components of the ecosystem) must be performed before we develop biodegradable/self-degradable, non-toxic, cheap, and environmentally safe NPs that can be commercially utilized in crop systems for sustainable agriculture production to fruitfully utilize nanotechnology for human welfare.

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Declarations

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