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The role of nanoparticles in cadmium stress alleviation in plants

Harshita Gupta, Nilu Singh, Amit Kumar Dixit, Girish Chandra Pathak*
Department of Botany, Plant Nutrition and Stress Physiology Laboratory, University of Lucknow, Lucknow, Uttar Pradesh, India
Corresponding Author: Dr. Girish Chandra Pathak
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Abstract
Cadmium (Cd) toxicity adversely affects various developmental and physiological processes in plants, leading to significant reductions in crop growth, biomass accumulation, and yield. Exposure of excess Cd disrupts essential metabolic activities and induces the overproduction of reactive oxygen species (ROS), affects various developmental processes in plants. An increase in the production of reactive oxygen species damages cellular components, including DNA, lipids, and proteins, owing to their strong oxidizing properties. In response, plants activate both enzymatic and non-enzymatic antioxidant defense systems to mitigate oxidative damage. A comprehensive understanding of cadmium-induced toxicity is crucial for managing heavy metal contamination in agricultural soils and promoting sustainable crop production. Such knowledge also facilitates the development of targeted mitigation strategies to enhance plant tolerance to heavy metal stress. Among these approaches, nanotechnology has emerged as a promising tool. Nanoparticles mitigated oxidative stress by reducing reactive oxygen species accumulation, preserving cell membrane integrity, decreasing lipid peroxidation, electrolyte leakage, and restricting heavy metal uptake and translocation within plants. Overall, this review enhances our understanding of plant-metal interactions and highlights the potential of nanoparticle-based interventions for improving crop productivity, stress tolerance, and food safety in Cd-contaminated environments.

Keywords: Cadmium toxicity, reactive oxygen species, oxidative damage, lipid peroxidation, antioxidative enzymes, nanoparticles

Introduction

Cadmium is a non-essential, highly toxic heavy metal that severely affects plant growth, productivity, and food safety. Because Cd is readily taken up from contaminated soils and irrigation water, it can accumulate in edible parts of plants and enter the food chain. Recent research shows that engineered nanoparticles (NPs), particularly metal and metal oxide nanoparticles, can help plants tolerate Cd stress by improving antioxidant defense, nutrient balance, and metal detoxification. Heavy metals (HMs) occurs in soil naturally as trace elements. However according to Tyler *et al.* (1989) [42], anthropogenic activities have increased the release of heavy metals into biologically available forms, posing potential risks to both natural and human-managed ecosystems. Heavy metals are generally classified into two categories: essential and non-essential heavy metals (Ali *et al*., 2019) [5]. Essential heavy metals, such as zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), and nickel (Ni), are required in small quantities for normal plant growth and metabolic functions. In contrast, non-essential heavy metals, including cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As), have no known biological role and can be toxic even at low concentrations. Whereas non-essential heavy metals like silver, lead, and cadmium have very little biological activity, and exposure above acceptable limits causes harmful effects on biological systems. Cadmium (Cd) is a toxic heavy metal with an atomic number of 48 and an atomic mass of 112.41 amu. Owing to its persistence, bioaccumulation, and detrimental effects on human health, it has been ranked among the top 20 most hazardous substances, occupying the seventh position in terms of potential risk.

Eric Drexler coined the term “Nanotechnology”. Nanoparticles (NPs) are extremely fine particles.and their sizes range from 1 to 100 nanometers in at least two dimensions (Afzal *et al*., 2022NPs applicationhas been seento increasegrowth and productivity of plants. The main objective of using nanoparticles is to increase the quality and overall production of crops all over the world. NPs are of different types, for example, inorganic nanoparticles, carbon-based nanoparticles, dendrimers and composites (Srivastava *et al*.,2015) [40]. Examples of Carbon-based nanoparticles are fullerenes and carbon nanotubes, which can be either multi-walled or single-walled Inorganic nanoparticles are divided into metals like Al, Ag, and Au, and metal oxides (NiO, ZnO, TiO_2, Fe_2O_3, CeO_2, etc.). Nano-sized polymer networks made up of branched units.are known as dendrimers, whereas composite nanoparticles are made by means of combining one form of nanoparticles with another form.

As the harmful effects of cadmium on plant become increasingly evident, the potential of nanoparticle-mediated remediation emerges as a crucial strategy for sustainable agriculture. Recent findings indicate the efficacy of various NPs, such as zinc oxide (ZnO-NPs), in enhancing plants stress tolerance against Cd toxicity by improving physiological processes, including photosynthesis and nutrient uptake, and reducing Cd accumulation within plant tissues, as well as modulating reactive oxygen species (ROS). This not only helps pave ways towards developing methods of enhancing yield of crops grown in polluted soil but also serves to stress the importance of further research into how precisely NPs work to deliver positive results.

Table 1: Cadmium toxicity impact on different plant species

Plants	Effects	References
1. *Spinacia oleracea*	Leaf chlorosis and necrotic patches on leaf margins	Pandey *et al*. (2009)
2. *Pisum sativum*	Reduction in photosynthetic rate and density of stomata.	Greger *et al*. (1993) [15]
3. *Solanum Lycopersicum*	Decreased seed germination, root elongation and growth of plant.	Baruah *et al*. (2019) [7]
4. *Triticum*	Reduction in the plant height, dry mass production root elongation	Zhang *et al*. (2000) [48]
5. *Oryza sativa*	Leaf chlorosis and reduction in photosynthesis.	Hsu and Kao (2007) [18]
6. *Zea mays*	Root elongation inhibition, minimized nutrient uptake and dry yield.	Shen *et al*. (2006) [39]
7. *Cicer arietinum*	Minimized photosynthetic activity, low yield and low protein content in grain	Athar and Ahmad (2002) [4]
8. *Beta vulgaris*	Decreased the stomatal density and photosynthesis.	Greger *et al*. (1993) [15]

Cadmium toxicity in the plants

Source of Contamination

Cadmium is introduced into the surroundings through natural and anthropogenic systems. In natural systems, volcanic emissions, fire in forest area, decomposition of rocks containing Cd, and wastewater are the key route oflithospheric Cdmobilization (Zhao *et al*.,2015) [49]. Anthropogenic activities are the primary source of cadmium that released into the environment, which causes nearly 90% of total Cd present in surface water.

Effect on Plant Growth and Yield

Cadmium is known to negatively impact plant growth (Shanmugaraj *et al*., 2019) [36]. When concentrations exceed acceptable levels—for agricultural soils,8 ppm, and for plants, 3–30 ppm, even at a minimal concentration of 0.05 µM (Ismael *et al*., 2019) [22], it can lead to chlorosis, reduced growth, and diminished yield. Its excessive buildup in plants is associated with several phytotoxic characteristics, such as reduced water stress and oxidative damage, germination index, disruptions in nutrient absorption and metabolic activities, impaired enzymatic functions, and disrupted metabolism of carbon, ultimately resulting in decreased crop yield.

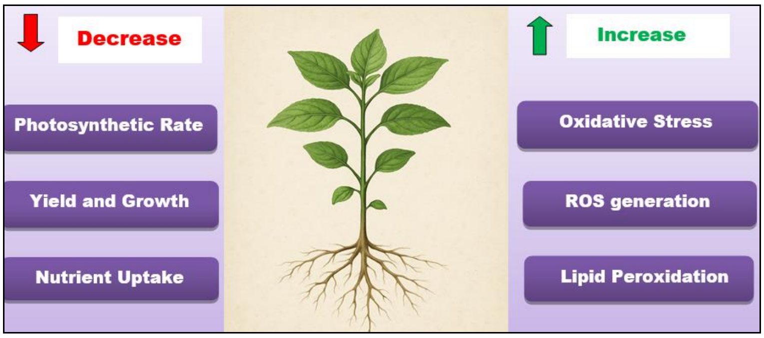

Fig 1: Cadmium toxicity effect on plants

ROS generation and Oxidative stress

Miller *etal*., (2010) and Matayoshi *et al*., (2022) reported that reactive oxygen species are known for their crucial role in managing both abiotic and biotic stresses, influencing thedevelopment of plants. Cd induces oxidative stress, which leads to the production of reactive oxygen species, suppresses the antioxidant defense system in plants (Abbas *et al*., 2017) [2], and causes redox imbalance (Petrov *et al*., 2015) [1] this leads to oxidative damage and lipid peroxidation (Younis *et al*., 2016) [47].

Although Cd is a non-redox element, it is known to generate reactive oxygen species such as superoxide anion (O_2^-), singlet oxygen ($1O_2$), hydroxyl radicals (OH^-) andhydrogen peroxide (H_2O_2) through indirect mechanisms (Iannone*et al*., 2010) [23]. When plants are exposed to Cd-induced oxidative stress, they activate a defense system against reactive oxygen species (Horvath *et al*., 2007) [17], which includes enzymatic antioxidants like GPX (glutathione peroxidase),CAT(catalase), APX(ascorbate peroxidase),POD(peroxidase),GST(glutathione-S-transferases), GR (glutathione reductase), MDHAR (monodehydroascorbate reductase),DHAR (dehydroascorbate reductase), superoxide dismutase (SOD), and non-enzymatic scavengers like GSH(glutathione), carotenoids, phytochelatins, tocopherols, ascorbic acid, phenolic compounds and thiols (Shanthala *et al*.,2006) [37]. They act as acrucial defensive system to reduce Cd toxicity (Iqbal *et al*.,2010) [21], converting ROS into harmless end products by behaving as a reducing agent (Abbas *et al*.,2015) [1]

Effect on Enzymatic Activity-

Cadmium has an inhibitory effect on the function of many principal enzymes in plants. Cd competeswith essential enzyme-activating cations like zinc, magnesium and calcium to replace them. (Gupta *et al*., 2019; Cuypers *et al*.,2011; Pourrut *et al*.,2011) [9]. Due to Cd stress, seedling facilitating enzymes are inactive (Yan *et al*.,2014) [46]. In barley seeds, remarkable inhibition of acid phosphatases α-amylases, and proteaseswas observed, which catalyze the mobilization of stored sugar inside the endosperm (Kalai *et al*., 2014) [24]. According to Salas *et al*. (2018) [35], in rice changes in proteolytic enzyme activity occurs due to Cd stress which contributes to the cellular metabolism. Cd is reported to inhibit the activity of enzymes participating in the nitrogen metabolism (Chang *et al*., 2013) [8] Cd is reported to to decrease the activity of nitrogenase in several plant species likechickpea (Hasan *et al*.,2008) [16], and mung bean (Wahid *et al*.,2007) [45].

Plant water relations and nutrient uptake-

Haung *et al.* (2017) suggested that cadmium stress adversely affects plant root characteristics andit play a role in water and nutrient uptake. According to Redjala *et al.* (2011)

plantroots primarily mediate the uptake of water and nutrient from the soil, and this leads to several physiological changes by providing an entry site for cadmium (Khan *et al*., 2007; Feng *et al*.,2010) [13]. Cd interferes in the uptake of essential nutrients. Cd adversely impacts water relation in plant and interferes with metabolic processes. Cd uptake via calcium channels in leaves of plant disruptswater relation, leading to stomatal closure resulting in decreased transpirationand inhibition of photosynthesis. Because of decreased photosynthesis nutrient imbalance and inhibition in growth occurs in plants (Uneo *et al.*,2009b). Khan *et al*. (2016) suggested that Cd stress has been reported to significantly decrease the concentrations of essential nutrients like nitrogen, phosphorus, and sulphur in the above-ground parts of plant.

Role of nanoparticles in heavy metal stress management in plants-

Several traditional methods including, soil treatment additive, chemical chelators, and phytoremediation methods, have been employed to alleviate heavy metal toxicity in plants. However, these strategies often face some limitations, such as high economic cost, potential secondary environmental risks, and inconsistent efficacy across varying soil conditions (Jiang *et al*., 2022), In contrast, NPs have developed into potential alternative for mitigating heavy metal stress due to their high reactivity, and enhanced capacity for metal adsorption and detoxification. Studies have reported that researchers have used Iron oxide nanoparticles (IONPs) with silicon nanoparticles to ameliorate Cd (Koleva *et al*., 2022), As (Rai *et al*., 2022, and Pb toxicity (Ghouri*et al*., 2024) [14]. In rice, iron oxide nanoparticles have been reported to decrease heavy metal stress by stimulating the antioxidant defense system, improving iron uptake, and reducing the toxic metal accumulation.

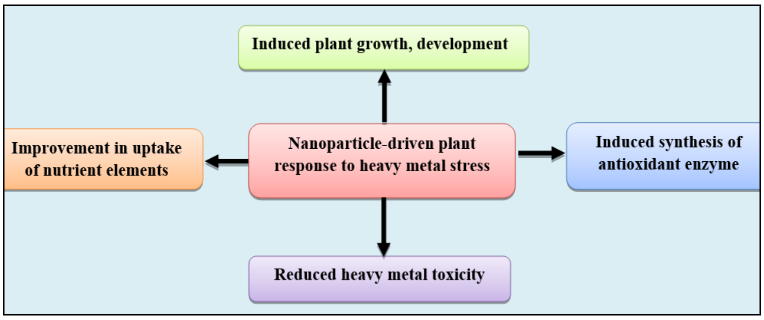

Fig 2: Impact of nanoparticles on plants

Recent research has demonstrated that nanoparticles (NPs) play a significant role in enhancing plant tolerance to heavy metal stress, particularly cadmium (Cd) toxicity. For example, titanium dioxide (TiO_2) nanoparticles have been reported to reduce Cd uptake in rice (*Oryza sativa* L.) and alleviate Cd-induced toxicity by enhancing the plant's antioxidant defense system. These nanoparticles improve the activities of key antioxidant enzymes, reduce oxidative damage, and help maintain cellular homeostasis, thereby mitigating the adverse effects of Cd stress on plant growth and physiology (Zhou *et al*., 2017; Rizwan *et al*., 2019) [34, 50]. Likewise, the research conducted on *Brassica juncea* L. revealed that TiO_2 NPs increased chlorophyll and carotenoids content while reducing MDA, which indicates oxidative damage (Deepak *et al*., 2021) [10].
Furthermore, ZnO NPs have exhibited excellent potential for mitigation of heavy metal toxicity. ZnO NPs not only restricts the entry of Cd but also increases chlorophyll content along with the activities of antioxidants enzymes such as CAT and SOD (Timilsina *et al*., 2023) [41], *In* a similar way, ZnO NPs helped in the increased grain and straw production together with enhanced photosynthetic pigments and antioxidants in *Triticum aestivum* (Hussain *et al*., 2021) [20]. In spinach, ZnO NPs helped increase plant biomass, with a balance in metal accumulation, favoring Cu and Fe while lowering Cd content (Sharifan *et al*., 2020) [38].
In addition to all this, iron oxide (Fe_3O_4) nanoparticles have also been seen to enhance plant development in cases of Cd pollution. According to Ahmad *et al*,(2026) [3], Fe_3O_4 NPs helped in lowering down the level of Cd uptake and promoted antioxidative system and photosynthesis of the plants *Glycine max* L. (Ahmad *et al*., 2026) [3]. Similarly, in Taraxacum plants, the use of Fe_3O_4 NPs enhanced photosynthetic pigments, enzyme activities, and metal ion uptake (Xingfan Li *et al*., 2025). Another useful nanoparticle is selenium nanoparticles (SeNPs). According to Wang *et al*., these nanoparticles lower down Cd concentration within the cells and even help in trapping the metal within the cell wall, hence minimizing toxic effects of Cd on the plants (Wang *et al*., 2023b) [44]. Similarly, in *Vignaradiata* L., the application of SeNPs improved overall growth and biomass production under Cd stress (Fatima *et al*., 2025) [12].
From all the above observations, it is very clear that TiO_2, ZnO, Fe_3O_4, and SeNPs nanoparticles can successfuly inhibit heavy metal toxicity. These particles work by inhibiting metal uptake, enhancing antioxidant systems, promoting photosynthesis, and regulating metal availability within plant cells.

Conclusion

Cadmium proved to be significant issue for food safety and human health. The contamination ofheavy metals and methods for their remediation have received considerable attention globally due to their persistent nature. To overcome the hazardous effects of heavy metals like Cd, nanotechnology has emerged as an essential component for sustainable development. The use of nanoparticles in plants to enhance tolerance to Cd toxicity and to remediate this toxic element is one of the most promising and cost-effective approaches recently developed. Due to the ability of nanoparticlesto penetrate plants over a large surface area, facilitate more efficient adsorption, and targeted delivery. NPs play an important role in regulating photosynthesis and detoxifying ROS, thus improvingseed germination, growth, and yield of crops. NPsmodulate the mobile or immobile forms of heavy metals, thereby helping plants to grow well. The application of NPsexhibited positive resultsby increasing heavy metal tolerance in plants and increasing the plant growth, indicating that the application of NPsfor the remediation of metal-polluted soils might have remarkable potential in the near future.

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References

1. Abbas G, Saqib M, Akhtar J, Murtaza G, Shahid M. Effect of salinity on rhizosphere acidification and antioxidant activity of two acacia species. Can J for Res,2015:45:124–129. https://doi.org/10.1139/cjfr-2014-0354
2. Abbas T, Rizwan M, Ali S, Adrees M, Zia-ur-Rehman M, Qayyum MF, *et al*. Effect of biochar on alleviation of cadmium toxicity in wheat (*Triticum aestivum* L.) grown on Cd-contaminated saline soil. Environ Sci Pollut Res,2017:25:25668–25680. https://doi.org/10.1007/s11356-017-8987-4
3. Ahmad P, Alyemeni MN, Wijaya L, Alam P, Ahanger MA, Ashraf M. Iron oxide nanoparticles improve photosynthesis and antioxidant defense under cadmium stress in *Glycine max*. Journal of Hazardous Materials,2026:450:131-234. https://doi.org/10.1016/j.jhazmat.2023.131234
4. Athar R, Ahmad M. Heavy metal toxicity in legume–microsymbiont system. Journal of Plant Nutrition,2002:25(2):369–386. https://doi.org/10.1081/PLN-100108842
5. Ali H, Khan E, Ilahi I. Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. J Chem, 2019, 1–14. https://doi.org/10. 1155/2019/6730305
6. Andresen E, Peiter E, Küpper H. Trace metal metabolismin plants. J Exp Bot,2018:69:909–954. https://doi.org/10.1093/jxb/erx465
7. Baruah N, Subham CM, Farooq M, Gogoi N. Influence of heavy metals on seed germination and seedling growth of wheat, pea, and tomato. Water Air Soil Pollut.,2019:230:273-288. https://doi.org/10.1007/s11270-019-4329-0.
8. Chang YS, Chang YJ, Lin CT, Lee MC, Wu CW, Lai YH. Nitrogen fertilization promotes the phytoremediation of cadmium in *Pentas lanceolata*. Int Biodeter Blodegr,2013:85:709–714. https://doi.org/10.1016/j.ibiod.2013.05.021
9. Cuypers A, Karen S, Jos R, Kelly O, Els K, Tony R, *et al*. The cellular redox state as a modulator in cadmium and copper responses in *Arabidopsis thaliana* seedlings. J Plant Physiology,2011:168:309–316. https://doi.org/10.1016/j.jplph.2010.07.010
10. Deepak M, Kumar A, Singh R. Titanium dioxide nanoparticles alleviate cadmium toxicity in *Brassica juncea* by modulating antioxidant defense and photosynthetic performance. Journal of Plant Growth Regulation,2021:40:1234–1245. https://doi.org/10.1007/s00344-020-10173-5
11. Du X, Li X, Yang M, Wang T, Du Q, Gao Y, *et al*. Foliar nanoparticles alleviated cadmium-induced phytotoxicity in dandelion via regulation of ionomics, metabolomics, and rhizobacterial networks. Journal of Hazardous Materials,2025:496:139357. https://doi.org/10.1016/j.jhazmat.2025.139357
12. Fatima S, Iqbal N, Khan NA, Masood A. Selenium nanoparticles enhance growth and biomass of *Vigna radiata* under heavy metal stress. Plant Physiology and Biochemistry,2025:198:107689. https://doi.org/10.1016/j.plaphy.2023.107689
13. Feng Y, Yang Y, Zhang Y, Kang Y, Zhang H. Cadmium uptake, translocation and physiological responses in plants: A review. Environmental and Experimental Botany,2010:67(1):1–8. https://doi.org/10.1016/j.envexpbot.2009.06.005
14. Ghouri F, Shahid M, Niazi NK, Bibi I. Role of nanoparticles in alleviating lead toxicity in plants: Mechanistic insights and future perspectives. Journal of Hazardous Materials,2024:454:131364. https://doi.org/10.1016/j.jhazmat.2023.131364
15. Greger M, Johansson M, Stihl A, Hamza K. Foliar uptake of Cd by pea (*Pisum sativum*) and sugar beet (*Beta vulgaris*). Physiol Plant,1993 Aug:88(4):563-570. doi: 10.1111/j.1399-3054.1993.tb01372.x. PMID: 28741769.
16. Hasan SA, Hayat S, Ali B, Ahmad A. 28-Homobrassinolide protects chickpea (*Cicer arietinum*) from cadmium toxicity by stimulating antioxidants. Environ Pollut,2008:151:60–66. https://doi.org/10.1016/j.envpol.2007.03.006
17. Horvath E, Pal M, Szalai G, Paldi E, Janda T. Exogenous4-hydroxybenzoic acid and salicylic acid modulate the effect of short-term drought and freezing stress on wheat plants. Biologia Plantarum,2007:51:480–487. https://doi.org/10.1007/s10535-007-0101-1
18. Hsu YT, Kao CH. Toxicity in leaves of rice exposed to cadmium is due to hydrogen peroxide accumulation. Plant Soil,2007:298:231–241.
19. Huang D, Gong X, Liu Y, Zeng G, Lai C, Bashir H, *et al*. Effects of calcium at toxic concentrations of cadmium in plants. Planta,2017:245(5):863–873.

20. Hussain A, Ali S, Rizwan M, Rehman MZ, Javed MR. Zinc oxide nanoparticles improve growth and antioxidant system in wheat under cadmium stress. Chemosphere,2021:273:129687. https://doi.org/10.1016/j.chemosphere.2021.129687
21. Iqbal N, Masood A, Nazar R, Syeed S, Khan NA. Photosynthesis, growth and antioxidant metabolism in mustard (*Brassica juncea* L.) cultivars differing in cadmium tolerance. Agric Sci China,2010:9:519–527. https://doi.org/10.1016/S1671-2927(09)60125-5
22. Ismael MA, Elyamine AM, Moussa MG, Cai M, Zhao X, Hu C. Cadmium in plants: Uptake, toxicity, and its interactions with selenium fertilizers. Metallomics, 2019. https://doi.org/10.1039/c8mt00247a
23. Iannone MF, Rosales EP, Groppa MD, Benavides MP. Reactive oxygen species formation andcel death in catalase-deficient tobacco leaf disks exposed to cadmium. Protoplasma,2010:245:15–27. https://doi.org/10.1007/s00709-009-0097-9
24. Kalai T, Sgherri C, Tekaya M, Radyukina N, Karmous I, Abdelly C, *et al*. Cadmium effects on seed germination and seedling growth of barley (*Hordeum vulgare* L.): Proteolytic and amylolytic enzyme activities. Acta Physiologiae Plantarum,2014:36:1403–1411. https://doi.org/10.1007/s11738-014-1524-1
25. Khan NA, Singh S, Nazar R, Iqbal N. Cadmium-induced alterations in growth and metabolism of plants. Journal of Plant Biology,2007:50(6):679–686. https://doi.org/10.1007/BF03030606
26. Khan MIR, Nazir F, Asgher M, Per TS, Khan NA. Selenium and sulfur influence ethylene formation and alleviate cadmium-induced oxidative stress by improving proline and glutathione production in wheat (*Triticum aestivum* L.). Journal of Plant Physiology,2016:200:61–69. https://doi.org/10.1016/j.jplph.2016.05.010
27. Koleva L, Petrov P, Georgieva K, Stoyanova Z. Combined application of iron oxide and silicon nanoparticles mitigates cadmium toxicity in plants by improving physiological and biochemical traits. Environmental Science and Pollution Research,2022:29:56789–56802. https://doi.org/10.1007/s11356-022-19645-3
28. Matayoshi CL, Pena LB, Arbona V, Gómez-Cadenas A, Gallego SM. Biochemical and hormonal changes associated with root growth restriction under cadmium stress during maize (*Zea mays* L.) pre-emergence. Plant Growth Regul,2022:96(2):269–281. https://doi.org/10.1007/s10725-021-00774
29. Miller G, Suzuki N, Ciftci-Yilmaz S, Mittler R. Reactive oxygen species homeostasis and signalling during drought and salinity stresses. Plant Cell Environ,2010:33(4):453–467.
30. Pandey N, Pathak GC, Pandey DK, Pandey R. Heavy metals, Co, Ni, Cu, Zn and Cd, produce oxidative damage and evoke differential antioxidant responses in spinach. Brazilian Journal of Plant Physiology,2009:21(2):103-111.
31. Pourrut B, Pohu AL, Pruvot C, Garçon G, Verdin A, Waterlot C, *et al*. Assessment of fly ash-aided phytostabilisation of highly contaminated soils after an 8-year field trial Part 2. Influence on Plants. Sci Total Environ,2011:409:4504–4510. https://doi.org/10.1016/j.scitotenv. 2011.07.047
32. Rai PK, Lee SS, Zhang M, Tsang YF, Kim KH. Nanoparticles in the remediation of arsenic-contaminated soils: Mechanisms and applications. Environmental Research,2022:204:112156. https://doi.org/10.1016/j.envres.2021.112156
33. Redjala T, Sterckeman T, Skiker M, Echevarria G. Contribution of apoplast and symplast to short-term nickel uptake by maize and *Leptoplax emarginata* roots. Environmental and Experimental Botany,2011:72(1):99–106. https://doi.org/10.1016/j.envexpbot.2010.12.007
34. Rizwan M, Ali S, Qayyum MF, Ok YS, Adrees M, Ibrahim M, *et al*. Effect of metal and metal oxide nanoparticles on growth and physiology of plants: A review. Environmental Science and Pollution Research,2019:26:17271–17287. https://doi.org/10.1007/s11356-019-04803-y
35. Salas P, López-Gómez M, Sandalio LM, del Río LA. Cadmium stress modifies proteolytic activities and protein turnover in rice (*Oryza sativa* L.). Plant Physiology and Biochemistry,2018:127:146–155. https://doi.org/10.1016/j.plaphy.2018.03.015
36. Shanmugaraj BM, Malla A, Ramalingam S. Cadmium Stress and Toxicity in Plants: An Overview. Cadmium Toxicity and Tolerance in Plants, 2019, 1–17. https://doi.org/10.1016/b978-0-12-814864-8.00001-2
37. Shanthala L, Venkatesh B, Lokesha AN, Prasad TG, Sashidhar VR. Glutathione depletion due to heavy metal-induced phytochelatin synthesis caused oxidative stress damage: Beneficial adaptation to one abiotic stress in linked to vulnerability to a second abiotic stress. J Plant Biol,2006:33:209–214.
38. Sharifan H, Ma X, Moore KL, Habib MR, Evans C. Zinc oxide nanoparticles mitigate cadmium toxicity and enhance nutrient accumulation in *Spinacia oleracea*. Environmental Science Nano,2020:7:142–156. https://doi.org/10.1039/C9EN00965A
39. Shen H, Christie P, Li X. Uptake of zinc, cadmium and phosphorus by arbuscular mycorrhizal maize (*Zea mays* L.) from a low available phosphorus calcareous soil spiked with zinc and cadmium. Environ Geochem Health,2006:28:111–119.
40. Srivastava V, Gusain D, Sharma YC. A critical review on the toxicity of some widely engineered nanoparticles. Ind., Eng., Chem. Res,2015:54:6209–6233.
41. Timilsina A, Adhikari T, Bhattarai S. Zinc oxide nanoparticles reduce cadmium toxicity and enhance antioxidant defense in *Lactuca sativa*. Environmental Nanotechnology, Monitoring & Management,2023:19:100789. https://doi.org/10.1016/j.enmm.2022.100789
42. Tyler G, Balsberg Påhlsson AM, Bengtsson G, Baath E, Tranvik L. Heavy-metal ecology of terrestrial plants, microorganisms and invertebrates. Water, Air, and Soil Pollution,1989:47:189–215. https://doi.org/10.1007/BF00279329
43. Ueno D, Koyama E, Kono I, Ando T, Yano M, Ma JF. Identification of a novel major quantitative trait locus controlling distribution of Cd between roots and shoots in rice. Plant Cell Physiol,2009(b):50(12):2223–2233.

44. Wang Y, Chen X, Huang Z, Li T. Selenium nanoparticles reduce cadmium accumulation and improve antioxidant defense in maize (*Zea mays* L.). Science of the Total Environment,2023:857:159321. https://doi.org/10.1016/j.scitotenv.2022.159321
45. Wahid A, Ghani A, Ali I, Ashraf MY. Effects of cadmium on carbon and nitrogen assimilation in shoots of mungbean (*Vigna radiate* L., Wilczek) seedlings. J Agron Crop Sci,2007:194:357–365. https://doi.org/10.1111/j.1439-037X.2007.00270
46. Yan H, Filardo F, Hu X, Zhao X, Fu D. Cadmium stress alters the redox reaction and enzyme activities in plants. Environmental Science and Pollution Research,2014:21:5951–5961. https://doi.org/10.1007/s11356-014-2541-3
47. Younis U, Malik SA, Rizwan M, Qayyum MF, OkYS, Shah MHR, *et al*. Biochar enhances the cadmium tolerance in spinach (*Spinacia oleracea*) through modification of Cd uptake and physiological and biochemical attributes. Environ. Sci. Pollut. Res.,2016:23:21385–21394. https://doi.org/10.1007/s11356-016-7344-3.
48. Zhang GP, Fukami M, Sekimoto H. Genotypic differences in effects of cadmium on growth and nutrient compositions in wheat. J. Plant Nutr.,2000:23:1337–1350.
49. Zhao FJ, Ma Y, Zhu YG, Tang Z, McGrath SP. Soil contamination in China : current status and mitigation strategies. Environ Sci Technol,2015:49:750–759. https://doiorg/10.1021/es5047099
50. Zhou Q, Zhang J, Fu J, Shi J, Jiang G. Biomonitoring: An appealing tool for assessment of metal pollution in the aquatic ecosystem. Environmental Pollution,2017:219:713–721. https://doi.org/10.1016/j.envpol.2016.06.035