Zinc Oxide Nanoparticles in Enhancing Plant Stress Resistance

Subjects: Materials Science, Biomaterials

Contributor: Zijun Wang, Sijin Wang, Tingting Ma, You Liang, Zhongyang Huo, Fengping Yang

Zinc oxide nanoparticles (ZnO nanoparticles) have gained substantial attention from researchers worldwide for their capacity to alleviate the detrimental impacts of both biotic and abiotic stress on plants, concurrently reducing dependence on environmentally harmful chemicals.

Keywords: zinc oxide ; nanoparticles ; agriculture ; plants ; biotic stress ; abiotic stress

1. Introduction

With the continuous changes in the global climate and the increasing impact of human activities, agriculture is facing unprecedented challenges [1][2][3][4]. Climate change and global warming have led to an increase in extreme weather events, posing threats to crop yields and soil fertility [5][6]. Simultaneously, biotic stresses such as viruses, bacteria, fungi, and parasites, as well as abiotic stresses including drought, salinity, high and low temperatures, and heavy metal toxicity, have severely compromised the health and productivity of crops [7][8][9][10][11]. In order to overcome these challenges, the agricultural sector has been actively exploring innovative methods to bolster crop resilience, increase yields, and decrease dependence on chemical pesticides and fertilizers [12][13][14][15][16][17][18].

In recent years, the emergence of nanotechnology has opened up new possibilities for addressing these challenges [19][20][21][22]. Specifically, zinc oxide nanoparticles (ZnO nanoparticles) have garnered considerable attention as a promising tool, demonstrating significant potential in effectively addressing both biotic and abiotic stresses [23]. The preparation methods for ZnO nanoparticles encompass various approaches, incorporating physical techniques such as vapor deposition and ball milling [24]. Chemical methods include solvothermal, hydrothermal, precipitation, and microwave procedures [25].

Biotic and abiotic stresses stand as two primary limiting factors for crop growth and yield in agricultural production [26][27][28][29][30]. Biotic stresses encompass various invasions by viruses, bacteria, fungi, and pests, posing significant threats to crop growth [31][32][33][34][35]. Simultaneously, abiotic stresses primarily arise from environmental factors such as drought, high temperatures, low temperatures, salinity, and others, severely impacting plant growth and yield [36][37][38][39][40]. Recent research has underscored the significant potential of ZnO nanoparticles in mitigating biotic and abiotic stress in agriculture [41][42][43][44]. These nanoparticles have displayed the capacity to hinder the growth of different pathogenic microorganisms, such as bacteria, fungi, pests, and viruses [45][46][47][48][49][50][51].

2. Preparation of ZnO Nanoparticles

The methods employed for synthesizing ZnO nanoparticles encompass physical, chemical, and biological approaches, as depicted in **Figure 1**. During the synthesis process, ZnO nanoparticles may undergo contamination, such as the introduction of iron ions, resulting in a notable change in the solubility of ZnO nanoparticles. Impurities in ZnO nanoparticles can arise from factors like the purity of reactants or the type of reaction vessel utilized in the synthesis process. Utilizing diverse synthesis methods and reactants enables the production of nano zinc oxide with varying impacts on plants, even while maintaining consistent particle sizes and shapes [52].

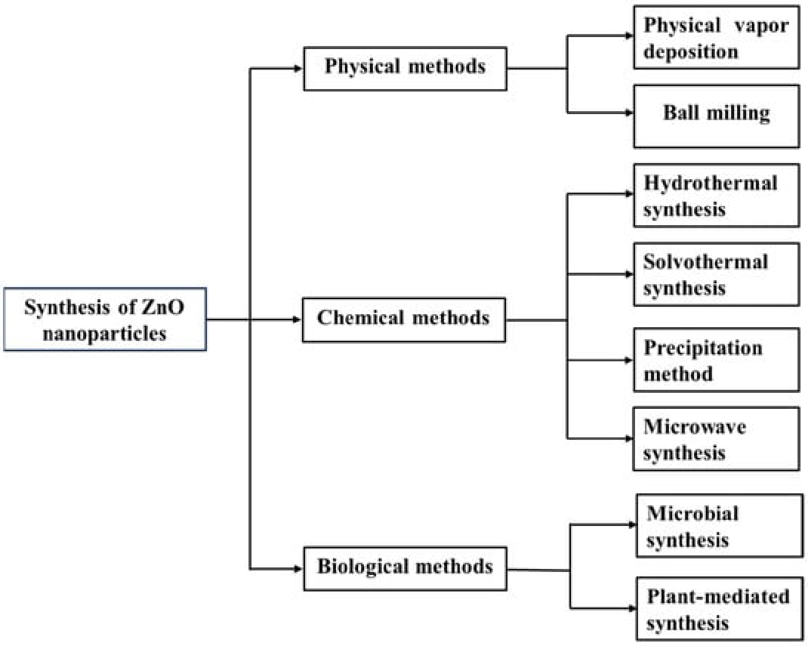

Figure 1. Various strategies for the fabrication of ZnO nanoparticles.

3. Absorption and Transfer of ZnO Nanoparticles in the Plant

Nanoparticles, particularly those composed of ZnO, possess an array of diverse characteristics, including particle size, shape, and surface area, that render them highly significant in their interactions with plant tissues [53][54][55]. These interactions are influenced by the plant cell walls, which serve as natural barriers with pores spanning a size range of 3 to 8 nm and a thickness of 5 to 20 nm [56][57][58]. The size of nanoparticles is of paramount importance, as those smaller than the pore size can efficiently penetrate plant tissues. In the case of larger nanoparticles, there are two possible mechanisms through which they can enter plants. Firstly, the nanoparticles may induce the formation of new pores, which could be slightly larger than the usual ones [59][60][61]. Secondly, the loosening of cell walls induced by reactive oxygen species (ROS) may enable larger nanoparticles to pass through [62].

Root application and foliar application are the most commonly employed methods for delivering ZnO nanoparticles to plants [63][64][65][66]. For root application, Arruda et al. reviewed research indicating several possible mechanisms [67]. ZnO nanoparticles may decompose directly in the soil, releasing ions that can be taken up by plants. Larger ZnO nanoparticles may decompose in the soil, forming smaller nanoparticles that can be incorporated into plant tissues. Alternatively, these smaller ZnO nanoparticles may further decompose, releasing ions that can be incorporated into plant tissues [68]. Upon exposure to plant tissues, nanoparticles can penetrate the cell wall and cell membrane of the root epidermis and cortex, undergoing a series of complex events to enter the plant's vascular bundle (xylem) and move towards the stele (**Figure 2**) [69][70][71][72][73].

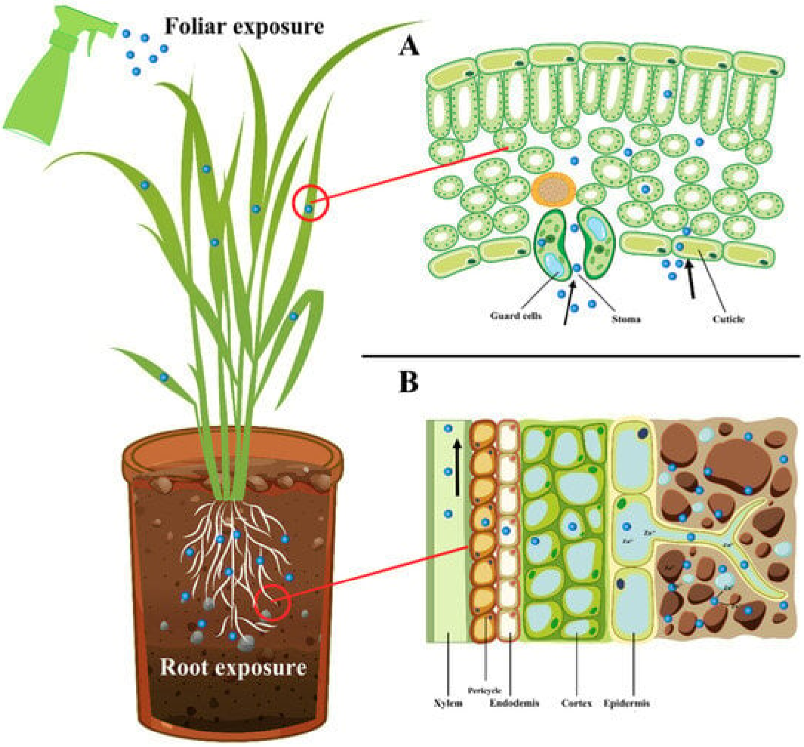

Figure 2. Mechanisms of ZnO nanoparticles uptake and transport in plant tissues. Transverse cross-section of the leaf showing entry of nanoparticles through stomata, cuticle penetration (**A**). Transverse cross-section of the root showing entry of nanoparticles through the root epidermis and cortex or biotransformation into zinc ions (**B**).

In the case of foliar application, ZnO nanoparticles are sprayed onto the leaf surface and can be absorbed through the stomata and cuticle (**Figure 2**A). Subsequently, they are further transported within the plant through phloem sieve tubes, facilitating their whole-plant conduction [74].

For ZnO nanoparticles, the particles undergo two primary transformations in the environment: dissolution and chemical modifications [75]. Dissolution involves the release of ions and chelation with organic matter, while chemical modifications encompass processes such as reduction, oxidation, and sulfidation [76][77].

4. Impact of ZnO Nanoparticles against Biotic and Abiotic Stress

Plants are consistently exposed to challenging environmental conditions from the moment of emergence. Various unfavorable factors impede the normal growth, development, and reproduction of plants, encompassing both biotic stress (diseases, pests, and weeds) and abiotic stress (high temperature, drought, salinity, low temperature, heavy metals, etc.) [78]. These adverse elements can result in considerable losses in crop yield and quality. Nanotechnology emerges as a powerful tool to counteract the detrimental effects of both biotic and abiotic stress on plants. In particular, ZnO nanoparticles exhibit considerable promise owing to their low cost, simple preparation methods, and environmental friendliness [79]. They hold substantial potential for mitigating the impact of both biotic and abiotic stress, offering a diverse range of applications and the prospect of addressing significant challenges in plant cultivation (**Figure 3**).

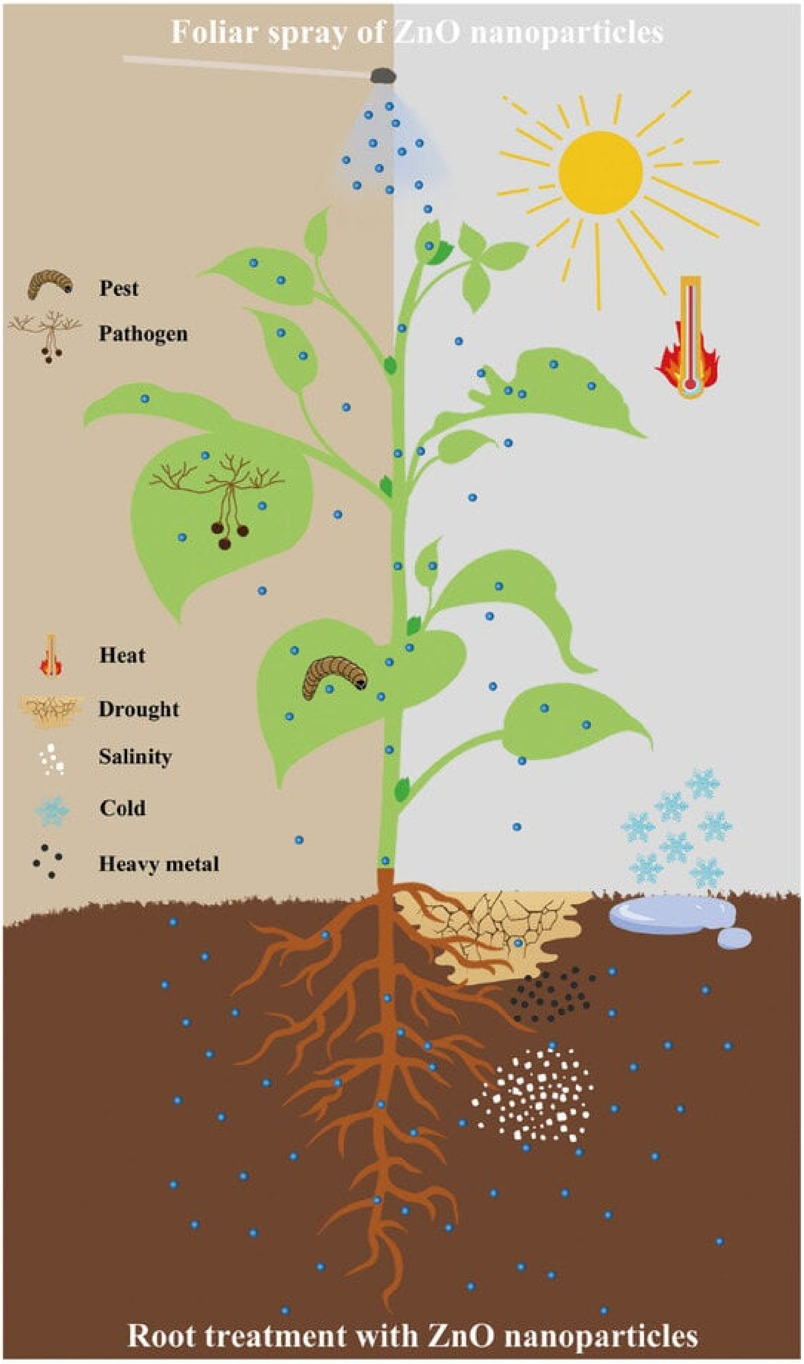

Figure 3. Effects of ZnO nanoparticles reducing abiotic and biotic stress in plants.

4.1. Impact of ZnO Nanoparticles against Biotic Stress

4.1.1. Pests

In recent years, nanotechnology has garnered considerable attention as biological pesticides for pest control to promote sustainable agriculture and delay the emergence of resistance. The fall armyworm (*Spodoptera frugiperda*) is an immensely devastating pest that inflicts substantial harm to crops globally, particularly maize and rice. Previous research has reported that the application of ZnO nanoparticles not only possesses the capacity to manage *Spodoptera frugiperda* but also can significantly reduce its abundance in ecosystems through various mechanisms, including physical distortion, diminished fertility, decreased egg deposition, and viability [80][81].

4.1.2. Plant Pathogens

The antimicrobial properties of ZnO nanoparticles have been extensively studied and well documented, and they play a vital role in the management of plant pathogenic microorganisms. Keerthana et al. reported that ZnO nanoparticles synthesized using aqueous peel extract of *Citrus medica* have excellent antimicrobial potential against plant pathogenic organisms (including *Streptomyces sannanesis*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Salmonella enterica*, *Candida albicans*, and *Aspergillus niger*) [82]. Green tomato, as a substance rich in alkaloids and ascorbic acid, has been employed for the synthesis of ZnO nanoparticles and used for the control of bacterial leaf blight in rice. ZnO nanoparticles exhibited effective antibacterial activity against *Xanthomonas oryzae* pv. *oryzae* [83]. Soliman et al. utilized a one-pot wet synthesis technique to fabricate sub-5 nm ZnO-based nanoparticles, which showed excellent dispersibility and remarkable antibacterial activity against citrus huanglongbing (HLB) disease. The nanoparticles were capable of translocating within the phloem and xylem of citrus trees. Treatment with 400 mg/L of ZnO nanoparticles markedly decreased the severity of the disease in infected citrus plants, leading to an estimated 60% reduction in disease occurrence [84].

Several mechanisms have been postulated to elucidate their capacity to hinder the growth of fungi and bacteria and mitigate the intensity of infections and diseases. One proposed mechanism is the disruption of cell membranes and interference with metabolic processes in the pathogens. ZnO nanoparticles have the ability to penetrate bacterial cells and release Zn^{2+}. These ions can exert toxic effects by inhibiting active transport, bacterial metabolic processes, and enzyme functionality. The toxicity of Zn^{2+} on bacterial cellular biomolecules ultimately leads to cell death [85][86]. Another mechanism entails the production of reactive oxygen species (ROS) upon UV irradiation. ZnO nanoparticles possess the ability to generate ROS, such as superoxide anion (O^{2-}), hydroxyl ion (OH^-), and hydrogen peroxide (H_2O_2). These active species interact with cellular constituents like lipids, proteins, and DNA, resulting in cell impairment or mortality. The entry of ZnO nanoparticles into bacterial cells triggers oxidative stress and the generation of ROS, resulting in the disruption of the bacterial cell membrane and suppression of cellular proliferation [87][88][89][90][91].

4.2. Impact of ZnO Nanoparticles against Abiotic Stress

4.2.1. Drought Stress

Drought, a prevalent abiotic stress, can considerably diminish crop yields by inducing prolonged water scarcity. Water, functioning as a medium for plant survival and nutrient transportation, is pivotal for the robust growth of crops. Drought stress influences diverse physiological and biochemical processes in plants, thus jeopardizing their typical survival capabilities. The quest for innovative approaches to tackle drought stress has become significantly crucial. Previous research has reported that ZnO nanoparticles can enhance drought-stress tolerance in plants, mitigating the negative impacts of drought on crop yield and biomass accumulation. Sun et al. investigated the effect of ZnO nanoparticles on drought tolerance in plants and revealed their ability to stimulate the synthesis of the endogenous hormone melatonin. Alterations in the activity of antioxidant enzymes were also noted, including malondialdehyde, catalase, and ascorbate peroxidase, thus activating the plant's internal antioxidant system [92][93].

4.2.2. Heat Stress

In recent years, the increasing levels of carbon dioxide emissions have intensified the greenhouse effect, resulting in severe high-temperature weather conditions. When temperatures exceed the optimal range for specific time periods or when plants are exposed to prolonged high-intensity light, they undergo heat stress, which adversely affects the normal growth and yield of crops. The application of ZnO nanoparticles has been observed to effectively enhance the heat stress tolerance in a few plant species (alfalfa, mungbean, chickpea, and wheat). A sufficient supply of zinc under heat stress can regulate the PSII efficiency of plants, improve water relations, increase free proline in leaves, enhance antioxidant enzyme activities (SOD, MDA, H_2O_2, and APX), and elevate the concentration of zinc ions in leaves. This can help mitigate the detrimental impacts of heat stress on plants, leading to improved plant growth and photosynthesis [94][95].

4.2.3. Salinity Stress

Salt stress, as one of the most prevalent abiotic stresses globally, is exacerbated by various factors such as climate change, irrigation water contamination, and improper fertilizer application, resulting in soil salinization and subsequent crop yield reduction. Soil salinization typically disrupts plant osmotic balance, induces ion toxicity, and diminishes water availability, leading to disturbances in plant physiological and biochemical processes and causing structural damage to plant morphology. ZnO nanoparticles can enhance plant salt tolerance by improving membrane integrity, scavenging reactive oxygen species generated by stress, regulating cell division, nutrient and water transport, and modulating levels of carbohydrates, amino acids, protein metabolism, photosynthetic pigments, and osmoregulators. Extensive research has reported the potential of ZnO nanoparticles in mitigating the adverse impacts of salinity stress on various crops, such as safflower, wheat, tomato, pea, rice, rapeseed, and so on [96][97][98][99][100][101][102][103].

4.2.4. Cold Stress

Cold stress hinders the growth and reduces the yield of crops by affecting their physiological, biochemical, molecular, and metabolic processes [104][105][106]. Some studies have reported that ZnO nanoparticles can alleviate the harm caused by cold stress in various plants [107][108][109]. At the physiological level, foliar application of ZnO nanoparticles can alleviate the inhibitory effect of low-temperature stress on the growth of rice seedlings (including plant height, root length, and dry biomass). At the physiological level, ZnO nanoparticles can restore rice chlorophyll accumulation under cold stress, increase the activity of antioxidant enzymes (SOD, POD, CAT), and reduce intracellular H_2O_2, MDA, and proline content.

At the molecular level, foliar application of ZnO nanoparticles can induce the expression of antioxidant systems (OsCu/ZnSOD1, OsCu/ZnSOD2, OsCu/ZnSOD3, OsPRX11, OsPRX65, OsPRX89, OsCATA, and OsCATB) and cold-responsive transcription factors (such as OsbZIP52, OsMYB4, OsMYB30, OsNAC5, OsWRKY76, and OsWRKY94) in young rice leaves under cold treatment. This leads to the restoration of the expression of all the mentioned genes to the control level after cold stress, effectively mitigating the harm of cold stress to plants [109].

4.2.5. Heavy Metal Stress

The contamination of terrestrial soil by heavy metals (arsenic (As), Pb (plumbum), Cd (cadmium), mercury (Hg), and chromium (Cr)) has become a significant global environmental issue, adversely affecting ecological integrity, soil quality, and agricultural productivity [110][111][112]. The resulting food security concerns pose a substantial risk to ecosystems and human health. Consequently, the remediation or immobilization of toxic heavy metals in contaminated farmlands has become an urgent and critical issue [113][114]. Li et al. reported that the treatment of rice seeds with ZnO nanoparticles affects the physiological, biochemical, and molecular characteristics of plants under cadmium stress. At the physiological level, ZnO nanoparticles can increase plant fresh weight and root crown length. At the biochemical level, ZnO nanoparticles can enhance the activity of antioxidant enzymes (SOD, POD) in rice, as well as the content of metallothioneins (ROS scavengers) and chlorophyll (chlorophyll a, chlorophyll b, a + b, and carotenoids). At the metabolic level, ZnO nanoparticles primarily alleviate the harm of cadmium to rice by affecting the metabolism of amino acids (alanine, aspartate, and glutamate), taurine, subtaurine, and phenylpropanoid biosynthesis. Additionally, the application of zinc oxide can effectively increase the activity of α and β-amylase (in seeds) and total amylase (in seedlings), which may be beneficial for seed germination [115]. In mung bean plants, ZnO nanoparticles reduce the harm of cadmium to plants by regulating cellular homeostasis. ZnO nanoparticles enhance the activity of ROS scavenging enzymes (such as CAT, APX, GR, glutathione peroxidase (GPX), and guaiacol peroxidase (GPOX)) to reduce plant toxicity caused by cadmium stress. ZnO nanoparticles also regulate redox enzymes (such as NADPH-dependent thioredoxin reductase (NTR), ferredoxin (Fd), ferredoxin-NADP reductase (FNR), and thioredoxin (Trx)), effectively improving plant growth under cadmium stress [115]. ZnO nanoparticles exhibit a high affinity for heavy metals, enabling them to bind and immobilize these toxic substances in the soil. This capability effectively mitigates the adverse effects of heavy metal pollution on plant growth and overall soil quality. At the molecular level, the expression levels of OsNRAMP1, OsNRAMP4, and OsNRAMP5 genes involved in cadmium transport in rice under cadmium stress decreased significantly with treatment using zinc oxide nanomaterials, while the expression of the OsZIP1 gene related to zinc transport exhibited upregulation. This suggests that zinc oxide nanomaterials can alleviate cadmium toxicity in rice by enhancing the expression levels of resistance-related genes [116].

5. Conclusions

At the physiological level, ZnO nanoparticles can enhance the agronomic traits of plants under stressful conditions, promoting increased plant growth and biomass. At the biochemical level, ZnO nanoparticles exhibit the ability to boost the activity of plant antioxidant enzymes, scavenge ROS generated under stress, regulate osmotic balance, and maintain cellular homeostasis, thereby alleviating the impact of both biotic and abiotic stress on plants. On the molecular level, ZnO nanoparticles can influence plant hormone signaling pathways, modulate stress-responsive genes, and enhance plant stress tolerance. Hence, the utilization of ZnO nanoparticles is anticipated to offer a novel, environmentally friendly, and cost-effective method to enhance agricultural productivity while mitigating the impact of various stressors on plants.

References

1. Gowdy, J. Our hunter-gatherer future: Climate change, agriculture and uncivilization. Futures 2020, 115, 102488.
2. Tian, Z.; Wang, J.-W.; Li, J.; Han, B. Designing future crops: Challenges and strategies for sustainable agriculture. Plant J. 2021, 105, 1165–1178.
3. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ. Sci. Pollut. Res. 2022, 29, 42539–42559.
4. Zsögön, A.; Peres, L.E.P.; Xiao, Y.; Yan, J.; Fernie, A.R. Enhancing crop diversity for food security in the face of climate uncertainty. Plant J. 2022, 109, 402–414.
5. Maharajan, T.; Ceasar, S.A.; Krishna, T.P.A.; Ignacimuthu, S. Management of phosphorus nutrient amid climate change for sustainable agriculture. J. Environ. Qual. 2021, 50, 1303–1324.
6. Nguyen, T.T.; Grote, U.; Neubacher, F.; Rahut, D.B.; Do, M.H.; Paudel, G.P. Security risks from climate change and environmental degradation: Implications for sustainable land use transformation in the Global South. Glob. Chang. Biol.

2023, 63, 101322.

7. Miller, R.N.G.; Costa Alves, G.S.; Van Sluys, M.-A. Plant immunity: Unravelling the complexity of plant responses to biotic stresses. Ann. Bot. 2017, 119, 681–687.
8. Gimenez, E.; Salinas, M.; Manzano-Agugliaro, F. Worldwide research on plant defense against biotic stresses as improvement for sustainable agriculture. Sustainability 2018, 10, 391.
9. Nabi, R.B.S.; Tayade, R.; Hussain, A.; Kulkarni, K.P.; Imran, Q.M.; Mun, B.-G.; Yun, B.-W.J.E. Nitric oxide regulates plant responses to drought, salinity, and heavy metal stress. Exp. Bot. 2019, 161, 120–133.
10. Zhao, K.; Yang, Y.; Zhang, L.; Zhang, J.; Zhou, Y.; Huang, H.; Luo, S.; Luo, L. Silicon-based additive on heavy metal remediation in soils: Toxicological effects, remediation techniques, and perspectives. Environ. Res. 2022, 205, 112244.
11. Islam, M.; Sandhi, A. Heavy metal and drought stress in plants: The role of microbes—A review. Gesunde Pflanz. 2023, 75, 695–708.
12. Lamichhane, J.R.; Dachbrodt-Saaydeh, S.; Kudsk, P.; Messéan, A. Toward a reduced reliance on conventional pesticides in European agriculture. Plant Dis. 2016, 100, 10–24.
13. Schröder, P.; Sauvêtre, A.; Gnädinger, F.; Pesaresi, P.; Chmeliková, L.; Doğan, N.; Gerl, G.; Gökçe, A.; Hamel, C.; Millan, R.; et al. Discussion paper: Sustainable increase of crop production through improved technical strategies, breeding and adapted management—A European perspective. Sci. Total Environ. 2019, 678, 146–161.
14. Bilal, S.; Shahzad, R.; Imran, M.; Jan, R.; Kim, K.M.; Lee, I.-J. Synergistic association of endophytic fungi enhances Glycine max L. resilience to combined abiotic stresses: Heavy metals, high temperature and drought stress. Ind. Crops Prod. 2020, 143, 111931.
15. Ramakrishna, W.; Rathore, P.; Kumari, R.; Yadav, R. Brown gold of marginal soil: Plant growth promoting bacteria to overcome plant abiotic stress for agriculture, biofuels and carbon sequestration. Sci. Total Environ. 2020, 711, 135062.
16. Ashraf, S.A.; Siddiqui, A.J.; Elkhalifa, A.E.O.; Khan, M.I.; Patel, M.; Alreshidi, M.; Moin, A.; Singh, R.; Snoussi, M.; Adnan, M. Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment. Sci. Total Environ. 2021, 768, 144990.
17. Mansoor, S.; Kour, N.; Manhas, S.; Zahid, S.; Wani, O.A.; Sharma, V.; Wijaya, L.; Alyemeni, M.N.; Alsahli, A.A.; El-Serehy, H.A.; et al. Biochar as a tool for effective management of drought and heavy metal toxicity. Chemosphere 2021, 271, 129458.
18. Wang, D.; Saleh, N.B.; Byro, A.; Zepp, R.; Sahle-Demessie, E.; Luxton, T.P.; Ho, K.T.; Burgess, R.M.; Flury, M.; White, J.C.; et al. Nano-enabled pesticides for sustainable agriculture and global food security. Nat. Nanotechnol. 2022, 17, 347–360.
19. Lowry, G.V.; Avellan, A.; Gilbertson, L.M. Opportunities and challenges for nanotechnology in the agri-tech revolution. Nat. Nanotechnol. 2019, 14, 517–522.
20. Rastogi, A.; Zivcak, M.; Tripathi, D.K.; Yadav, S.; Kalaji, H.M.; Brestic, M. Phytotoxic effect of silver nanoparticles in Triticum aestivum: Improper regulation of photosystem I activity as the reason for oxidative damage in the chloroplast. Photosynthetica 2019, 57, 209–216.
21. Arora, S.; Murmu, G.; Mukherjee, K.; Saha, S.; Maity, D. A comprehensive overview of nanotechnology in sustainable agriculture. J. Biotechnol. 2022, 355, 21–41.
22. Saritha, G.N.G.; Anju, T.; Kumar, A. Nanotechnology-big impact: How nanotechnology is changing the future of agriculture? J. Agric. Food Res. 2022, 10, 100457.
23. Prasad, A.R.; Williams, L.; Garvasis, J.; Shamsheera, K.O.; Basheer, S.M.; Kuruvilla, M.; Joseph, A. Applications of phytogenic ZnO nanoparticles: A review on recent advancements. J. Mol. Liq. 2021, 331, 115805.
24. Gomez, J.L.; Tigli, O. Zinc oxide nanostructures: From growth to application. J. Mater. Sci. 2013, 48, 612–624.
25. Uribe-López, M.C.; Hidalgo-López, M.C.; López-González, R.; Frías-Márquez, D.M.; Núñez-Nogueira, G.; Hernández-Castillo, D.; Alvarez-Lemus, M.A. Photocatalytic activity of ZnO nanoparticles and the role of the synthesis method on their physical and chemical properties. J. Photochem. Photobiol. A 2021, 404, 112866.
26. Ma, Y. Seed coating with beneficial microorganisms for precision agriculture. Biotechnol. Adv. 2019, 37, 107423.
27. Akhtar, N.; Wani, A.K.; Dhanjal, D.S.; Mukherjee, S. Insights into the beneficial roles of dark septate endophytes in plants under challenging environment: Resilience to biotic and abiotic stresses. World J. Microbiol. Biotechnol. 2022, 38, 79.
28. dos Santos, T.B.; Ribas, A.F.; de Souza, S.G.H.; Budzinski, I.G.F.; Domingues, D.S. Physiological responses to drought, salinity, and heat stress in plants: A review. Stresses 2022, 2, 113–135.

29. Moustaka, J.; Moustakas, M. Early-stage detection of biotic and abiotic stress on plants by chlorophyll fluorescence imaging analysis. Biosensors 2023, 13, 796.

30. Wahab, A.; Muhammad, M.; Munir, A.; Abdi, G.; Zaman, W.; Ayaz, A.; Khizar, C.; Reddy, S.P.P. Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. Plants 2023, 12, 3102.

31. Aslam, M.M.; Karanja, J.; Bello, S.K. Piriformospora indica colonization reprograms plants to improved P-uptake, enhanced crop performance, and biotic/abiotic stress tolerance. Physiol. Mol. Plant Pathol. 2019, 106, 232–237.

32. Hashem, A.; Tabassum, B.; Fathi Abd_Allah, E. Bacillus subtilis: A plant-growth promoting rhizobacterium that also impacts biotic stress. Saudi J. Biol. Sci. 2019, 26, 1291–1297.

33. Pandey, S.; Gupta, S. Evaluation of Pseudomonas sp. for its multifarious plant growth promoting potential and its ability to alleviate biotic and abiotic stress in tomato (Solanum lycopersicum) plants. Sci. Rep. 2020, 10, 20951.

34. Kashyap, B.; Kumar, R. Sensing methodologies in agriculture for monitoring biotic stress in plants due to pathogens and pests. Inventions 2021, 6, 29.

35. Zhao, D.; Wang, H.; Chen, S.; Yu, D.; Reiter, R.J. Phytomelatonin: An emerging regulator of plant biotic stress resistance. Trends Plant Sci. 2021, 26, 70–82.

36. Gupta, A.; Bano, A.; Rai, S.; Mishra, R.; Singh, M.; Sharma, S.; Pathak, N. Mechanistic insights of plant-microbe interaction towards drought and salinity stress in plants for enhancing the agriculture productivity. Plant Stress 2022, 4, 100073.

37. Vancostenoble, B.; Blanchet, N.; Langlade, N.B.; Bailly, C. Maternal drought stress induces abiotic stress tolerance to the progeny at the germination stage in sunflower. Environ. Exp. Bot. 2022, 201, 104939.

38. Wang, X.; Komatsu, S. The role of phytohormones in plant response to flooding. Int. J. Mol. Sci. 2022, 23, 6383.

39. Zhang, H.; Zhu, J.; Gong, Z.; Zhu, J.-K. Abiotic stress responses in plants. Nat. Rev. Genet. 2022, 23, 104–119.

40. Raza, A.; Charagh, S.; Abbas, S.; Hassan, M.U.; Saeed, F.; Haider, S.; Sharif, R.; Anand, A.; Corpas, F.J.; Jin, W.; et al. Assessment of proline function in higher plants under extreme temperatures. Plant Biol. J. 2023, 25, 379–395.

41. Reddy Pullagurala, V.L.; Adisa, I.O.; Rawat, S.; Kim, B.; Barrios, A.C.; Medina-Velo, I.A.; Hernandez-Viezcas, J.A.; Peralta-Videa, J.R.; Gardea-Torresdey, J.L. Finding the conditions for the beneficial use of ZnO nanoparticles towards plants-A review. Environ. Pollut. 2018, 241, 1175–1181.

42. Rajput, V.D.; Minkina, T.; Kumari, A.; Harish; Singh, V.K.; Verma, K.K.; Mandzhieva, S.; Sushkova, S.; Srivastava, S.; Keswani, C. Coping with the challenges of abiotic stress in plants: New dimensions in the field application of nanoparticles. Plants 2021, 10, 1221.

43. Silva, S.; Dias, M.C.; Silva, A.M.S. Titanium and zinc based nanomaterials in agriculture: A promising approach to deal with (a)biotic stresses? Toxics 2022, 10, 172.

44. Mazhar, M.W.; Ishtiaq, M.; Maqbool, M.; Hussain, S.A. Foliar application of zinc oxide nanoparticles improves rice yield under biotic stress posed by Magnaporthe oryzae. Arch. Phytopathol. Plant Prot. 2023, 56, 1093–1111.

45. Jayaseelan, C.; Rahuman, A.A.; Kirthi, A.V.; Marimuthu, S.; Santhoshkumar, T.; Bagavan, A.; Gaurav, K.; Karthik, L.; Rao, K.B. Novel microbial route to synthesize ZnO nanoparticles using Aeromonas hydrophila and their activity against pathogenic bacteria and fungi. Spectrochim. Acta Part A 2012, 90, 78–84.

46. Cai, L.; Liu, C.; Fan, G.; Liu, C.; Sun, X. Preventing viral disease by ZnONPs through directly deactivating TMV and activating plant immunity in Nicotiana benthamiana. Environ. Sci. Nano 2019, 6, 3653–3669.

47. Das, S.; Yadav, A.; Debnath, N. Entomotoxic efficacy of aluminium oxide, titanium dioxide and zinc oxide nanoparticles against Sitophilus oryzae (L.): A comparative analysis. J. Stored Prod. Res. 2019, 83, 92–96.

48. Mosquera-Sánchez, L.P.; Arciniegas-Grijalba, P.A.; Patiño-Portela, M.C.; Guerra–Sierra, B.E.; Muñoz-Florez, J.E.; Rodríguez-Páez, J.E. Antifungal effect of zinc oxide nanoparticles (ZnO-NPs) on Colletotrichum sp., causal agent of anthracnose in coffee crops. Biocatal. Agric. Biotechnol. 2020, 25, 101579.

49. Abdelaziz, A.M.; Dacrory, S.; Hashem, A.H.; Attia, M.S.; Hasanin, M.; Fouda, H.M.; Kamel, S.; ElSaied, H. Protective role of zinc oxide nanoparticles based hydrogel against wilt disease of pepper plant. Biocatal. Agric. Biotechnol. 2021, 35, 102083.

50. Zudyte, B.; Luksiene, Z. Visible light-activated ZnO nanoparticles for microbial control of wheat crop. J. Photochem. Photobiol. B 2021, 219, 112206.

51. Bouqellah, N.A.; El-Sayyad, G.S.; Attia, M.S. Induction of tomato plant biochemical immune responses by the synthesized zinc oxide nanoparticles against wilt-induced Fusarium oxysporum. Int. Microbiol. 2023.

52. Tymoszuk, A.; Wojnarowicz, J. Zinc oxide and zinc oxide nanoparticles impact on in vitro germination and seedling growth in Allium cepa L. Materials 2020, 13, 2784.
53. Khan, M.R.; Adam, V.; Rizvi, T.F.; Zhang, B.; Ahamad, F.; Jośko, I.; Zhu, Y.; Yang, M.; Mao, C. Nanoparticle–plant interactions: Two-way traffic. Small 2019, 15, 1901794.
54. Su, Y.; Ashworth, V.; Kim, C.; Adeleye, A.S.; Rolshausen, P.; Roper, C.; White, J.; Jassby, D. Delivery, uptake, fate, and transport of engineered nanoparticles in plants: A critical review and data analysis. Environ. Sci. Nano 2019, 6, 2311–2331.
55. Hong, J.; Wang, C.; Wagner, D.C.; Gardea-Torresdey, J.L.; He, F.; Rico, C.M. Foliar application of nanoparticles: Mechanisms of absorption, transfer, and multiple impacts. Environ. Sci. Nano 2021, 8, 1196–1210.
56. Paulraj, T.; Wennmalm, S.; Wieland, D.C.F.; Riazanova, A.V.; Dėdinaitė, A.; Günther Pomorski, T.; Cárdenas, M.; Svagan, A.J. Primary cell wall inspired micro containers as a step towards a synthetic plant cell. Nat. Commun. 2020, 11, 958.
57. Zhang, H.; Goh, N.S.; Wang, J.W.; Pinals, R.L.; González-Grandío, E.; Demirer, G.S.; Butrus, S.; Fakra, S.C.; Del Rio Flores, A.; Zhai, R.; et al. Nanoparticle cellular internalization is not required for RNA delivery to mature plant leaves. Nat. Nanotechnol. 2022, 17, 197–205.
58. Wu, H.; Li, Z. Nano-enabled agriculture: How do nanoparticles cross barriers in plants? Plant Commun. 2022, 3, 100346.
59. Miralles, P.; Church, T.L.; Harris, A.T. Toxicity, uptake, and translocation of engineered nanomaterials in vascular plants. Environ. Sci. Technol. 2012, 46, 9224–9239.
60. Alemzadeh, E.; Dehshahri, A.; Izadpanah, K.; Ahmadi, F. Plant virus nanoparticles: Novel and robust nanocarriers for drug delivery and imaging. Colloids Surf. B 2018, 167, 20–27.
61. Usman, M.; Farooq, M.; Wakeel, A.; Nawaz, A.; Cheema, S.A.; Rehman, H.u.; Ashraf, I.; Sanaullah, M. Nanotechnology in agriculture: Current status, challenges and future opportunities. Sci. Total Environ. 2020, 721, 137778.
62. Sun, X.; Chen, J.; Fan, W.; Liu, S.; Kamruzzaman, M. Production of reactive oxygen species via nanobubble water improves radish seed water absorption and the expression of aquaporin genes. Langmuir 2022, 38, 11724–11731.
63. Raliya, R.; Nair, R.; Chavalmane, S.; Wang, W.-N.; Biswas, P. Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (Solanum lycopersicum L.) plant. Metallomics 2015, 7, 1584–1594.
64. Yang, X.; Alidoust, D.; Wang, C. Effects of iron oxide nanoparticles on the mineral composition and growth of soybean (Glycine max L.) plants. Acta Physiol. Plant. 2020, 42, 128.
65. Gao, X.; Kundu, A.; Bueno, V.; Rahim, A.A.; Ghoshal, S. Uptake and translocation of mesoporous SiO2-coated ZnO nanoparticles to solanum lycopersicum following foliar application. Environ. Sci. Technol. 2021, 55, 13551–13560.
66. Khan, I.; Awan, S.A.; Rizwan, M.; Hassan, Z.U.; Akram, M.A.; Tariq, R.; Brestic, M.; Xie, W. Nanoparticle’s uptake and translocation mechanisms in plants via seed priming, foliar treatment, and root exposure: A review. Environ. Sci. Pollut. Res. 2022, 29, 89823–89833.
67. Capaldi Arruda, S.C.; Diniz Silva, A.L.; Moretto Galazzi, R.; Antunes Azevedo, R.; Zezzi Arruda, M.A. Nanoparticles applied to plant science: A review. Talanta 2015, 131, 693–705.
68. Rajput, V.D.; Minkina, T.M.; Behal, A.; Sushkova, S.N.; Mandzhieva, S.; Singh, R.; Gorovtsov, A.; Tsitsuashvili, V.S.; Purvis, W.O.; Ghazaryan, K.A.; et al. Effects of zinc-oxide nanoparticles on soil, plants, animals and soil organisms: A review. Environ. Nanotechnol. Monit. Manag. 2018, 9, 76–84.
69. Tripathi, D.K.; Shweta; Singh, S.; Singh, S.; Pandey, R.; Singh, V.P.; Sharma, N.C.; Prasad, S.M.; Dubey, N.K.; Chauhan, D.K. An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity. Plant Physiol. Biochem. 2017, 110, 2–12.
70. Avellan, A.; Yun, J.; Morais, B.P.; Clement, E.T.; Rodrigues, S.M.; Lowry, G.V. Critical review: Role of inorganic nanoparticle properties on their foliar uptake and in planta translocation. Environ. Sci. Technol. 2021, 55, 13417–13431.
71. Khan, M.; Khan, M.S.A.; Borah, K.K.; Goswami, Y.; Hakeem, K.R.; Chakrabartty, I. The potential exposure and hazards of metal-based nanoparticles on plants and environment, with special emphasis on ZnO NPs, TiO2 NPs, and AgNPs: A review. Environ. Adv. 2021, 6, 100128.
72. Yadav, V.; Arif, N.; Kováč, J.; Singh, V.P.; Tripathi, D.K.; Chauhan, D.K.; Vaculík, M. Structural modifications of plant organs and tissues by metals and metalloids in the environment: A review. Plant Physiol. Biochem. 2021, 159, 100–112.

73. Shi, J.; Yang, B.; Wang, H.; Wu, Y.; He, F.; Dong, J.; Qin, G. The combined contamination of nano-polystyrene and nanoAg: Uptake, translocation and ecotoxicity effects on willow saplings. Sci. Total Environ. 2023, 905, 167291.
74. Sánchez-Palacios, J.T.; Henry, D.; Penrose, B.; Bell, R. Formulation of zinc foliar sprays for wheat grain biofortification: A review of current applications and future perspectives. Front. Plant Sci. 2023, 14, 1247600.
75. Dutta, T.; Bagchi, D.; Bera, A.; Das, S.; Adhikari, T.; Pal, S.K. Surface engineered ZnO-humic/citrate interfaces: Photoinduced charge carrier dynamics and potential application for smart and sustained delivery of Zn micronutrient. ACS Sustain. Chem. Eng. 2019, 7, 10920–10930.
76. Gonzalez-Moragas, L.; Maurer, L.L.; Harms, V.M.; Meyer, J.N.; Laromaine, A.; Roig, A. Materials and toxicological approaches to study metal and metal-oxide nanoparticles in the model organism Caenorhabditis elegans. Mater. Horiz. 2017, 4, 719–746.
77. Martins, N.C.T.; Avellan, A.; Rodrigues, S.; Salvador, D.; Rodrigues, S.M.; Trindade, T. Composites of biopolymers and ZnO NPs for controlled release of zinc in agricultural soils and timed delivery for maize. ACS Appl. Nano Mater. 2020, 3, 2134–2148.
78. Zhang, Q.; Ying, Y.; Ping, J. Recent advances in plant nanoscience. Adv. Sci. 2022, 9, 2103414.
79. Mandal, A.K.; Katuwal, S.; Tettey, F.; Gupta, A.; Bhattarai, S.; Jaisi, S.; Bhandari, D.P.; Shah, A.K.; Bhattarai, N.; Parajuli, N. Current research on zinc oxide nanoparticles: Synthesis, characterization, and biomedical applications. Nanomaterials 2022, 12, 3066.
80. Pittarate, S.; Rajula, J.; Rahman, A.; Vivekanandhan, P.; Thungrabeab, M.; Mekchay, S.; Krutmuang, P. Insecticidal effect of zinc oxide nanoparticles against Spodoptera frugiperda under laboratory conditions. Insects 2021, 12, 1017.
81. Pittarate, S.; Perumal, V.; Kannan, S.; Mekchay, S.; Thungrabeab, M.; Suttiprapan, P.; Sengottayan, S.-N.; Krutmuang, P. Insecticidal efficacy of nanoparticles against Spodoptera frugiperda (J.E. Smith) larvae and their impact in the soil. Heliyon 2023, 9, e16133.
82. Keerthana, P.; Vijayakumar, S.; Vidhya EV, N.P.; Punitha, V.N.; Nilavukkarasi, M.; Praseetha, P.K. Biogenesis of ZnO nanoparticles for revolutionizing agriculture: A step towards anti -infection and growth promotion in plants. Ind. Crops Prod. 2021, 170, 113762.
83. Abdallah, Y.; Liu, M.; Ogunyemi, S.O.; Ahmed, T.; Fouad, H.; Abdelazez, A.; Yan, C.; Yang, Y.; Chen, J.; Li, B. Bioinspired green synthesis of chitosan and zinc oxide nanoparticles with strong antibacterial activity against rice pathogen Xanthomonas oryzae pv. oryzae. Molecules 2020, 25, 4795.
84. Soliman, M.; Lee, B.; Ozcan, A.; Rawal, T.B.; Young, M.; Mendis, H.C.; Rajasekaran, P.; Washington, T.; Pingali, S.V.; O'Neill, H.; et al. Engineered zinc oxide-based nanotherapeutics boost systemic antibacterial efficacy against phloem-restricted diseases. Environ. Sci. Nano 2022, 9, 2869–2886.
85. Chang, Y.-N.; Zhang, M.; Xia, L.; Zhang, J.; Xing, G. The toxic effects and mechanisms of CuO and ZnO nanoparticles. Materials 2012, 5, 2850–2871.
86. Soren, S.; Kumar, S.; Mishra, S.; Jena, P.K.; Verma, S.K.; Parhi, P. Evaluation of antibacterial and antioxidant potential of the zinc oxide nanoparticles synthesized by aqueous and polyol method. Microb. Pathog. 2018, 119, 145–151.
87. Premanathan, M.; Karthikeyan, K.; Jeyasubramanian, K.; Manivannan, G. Selective toxicity of ZnO nanoparticles toward Gram-positive bacteria and cancer cells by apoptosis through lipid peroxidation. Nanomed. Nanotechnol. Biol. Med. 2011, 7, 184–192.
88. Vani, C.; Sergin, G.; Annamalai, A. A study on the effect of zinc oxide nanoparticles in Staphylococcus aureus. Int. J. Adv. Pharm. Biol. Sci. 2011, 2, 326–335.
89. Sirelkhatim, A.; Mahmud, S.; Seeni, A.; Kaus, N.H.M.; Ann, L.C.; Bakhori, S.K.M.; Hasan, H.; Mohamad, D. Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism. Nano-Micro Lett. 2015, 7, 219–242.
90. Król, A.; Pomastowski, P.; Rafińska, K.; Railean-Plugaru, V.; Buszewski, B. Zinc oxide nanoparticles: Synthesis, antiseptic activity and toxicity mechanism. Adv. Colloid Interface Sci. 2017, 249, 37–52.
91. Agarwal, H.; Menon, S.; Kumar, S.V.; Rajeshkumar, S. Mechanistic study on antibacterial action of zinc oxide nanoparticles synthesized using green route. Chem.-Biol. Interact. 2018, 286, 60–70.
92. Sun, L.; Song, F.; Guo, J.; Zhu, X.; Liu, S.; Liu, F.; Li, X. Nano-ZnO-induced drought tolerance Is associated with melatonin synthesis and metabolism in maize. Int. J. Mol. Sci. 2020, 21, 782.
93. El-Zohri, M.; Al-Wadaani, N.A.; Bafeel, S.O. Foliar sprayed green zinc oxide nanoparticles mitigate drought-induced oxidative stress in tomato. Plants 2021, 10, 2400.
94. Ullah, A.; Romdhane, L.; Rehman, A.; Farooq, M. Adequate zinc nutrition improves the tolerance against drought and heat stresses in chickpea. Plant Physiol. Biochem. 2019, 143, 11–18.

95. Thakur, S.; Asthir, B.; Kaur, G.; Kalia, A.; Sharma, A. Zinc oxide and titanium dioxide nanoparticles influence heat stress tolerance mediated by antioxidant defense system in wheat. Cereal Res. Commun. 2022, 50, 385–396.

96. Elshoky, H.A.; Yotsova, E.; Farghali, M.A.; Farroh, K.Y.; El-Sayed, K.; Elzorkany, H.E.; Rashkov, G.; Dobrikova, A.; Borisova, P.; Stefanov, M.; et al. Impact of foliar spray of zinc oxide nanoparticles on the photosynthesis of Pisum sativum L. under salt stress. Plant Physiol. Biochem. 2021, 167, 607–618.

97. Faizan, M.; Bhat, J.A.; Chen, C.; Alyemeni, M.N.; Wijaya, L.; Ahmad, P.; Yu, F. Zinc oxide nanoparticles (ZnO-NPs) induce salt tolerance by improving the antioxidant system and photosynthetic machinery in tomato. Plant Physiol. Biochem. 2021, 161, 122–130.

98. Singh, P.; Arif, Y.; Siddiqui, H.; Sami, F.; Zaidi, R.; Azam, A.; Alam, P.; Hayat, S. Nanoparticles enhances the salinity toxicity tolerance in Linum usitatissimum L. by modulating the antioxidative enzymes, photosynthetic efficiency, redox status and cellular damage. Ecotoxicol. Environ. Saf. 2021, 213, 112020.

99. Yasmin, H.; Mazher, J.; Azmat, A.; Nosheen, A.; Naz, R.; Hassan, M.N.; Noureldeen, A.; Ahmad, P. Combined application of zinc oxide nanoparticles and biofertilizer to induce salt resistance in safflower by regulating ion homeostasis and antioxidant defence responses. Ecotoxicol. Environ. Saf. 2021, 218, 112262.

100. Adil, M.; Bashir, S.; Bashir, S.; Aslam, Z.; Ahmad, N.; Younas, T.; Asghar, R.M.A.; Alkahtani, J.; Dwiningsih, Y.; Elshikh, M.S. Zinc oxide nanoparticles improved chlorophyll contents, physical parameters, and wheat yield under salt stress. Front. Plant Sci. 2022, 13, 932861.

101. Singh, A.; Sengar, R.S.; Rajput, V.D.; Minkina, T.; Singh, R.K. Zinc oxide nanoparticles improve salt tolerance in rice seedlings by improving physiological and biochemical indices. Agriculture 2022, 12, 1014.

102. Lalarukh, I.; Zahra, N.; Al Huqail, A.A.; Amjad, S.F.; Al-Dhumri, S.A.; Ghoneim, A.M.; Alshahri, A.H.; Almutari, M.M.; Alhusayni, F.S.; Al-Shammari, W.B.; et al. Exogenously applied ZnO nanoparticles induced salt tolerance in potentially high yielding modern wheat (Triticum aestivum L.) cultivars. Environ. Technol. Innov. 2022, 27, 102799.

103. Sarkar, R.D.; Kalita, M.C. Alleviation of salt stress complications in plants by nanoparticles and the associated mechanisms: An overview. Plant Stress 2023, 7, 100134.

104. Manasa, S.L.; Panigrahy, M.; Panigrahi, K.C.S.; Rout, G.R. Overview of cold stress regulation in plants. Plants. Bot. Rev. 2022, 88, 359–387.

105. Soualiou, S.; Duan, F.; Li, X.; Zhou, W. Crop production under cold stress: An understanding of plant responses, acclimation processes, and management strategies. Plant Physiol. Biochem. 2022, 190, 47–61.

106. Raza, A.; Charagh, S.; Najafi-Kakavand, S.; Abbas, S.; Shoaib, Y.; Anwar, S.; Sharifi, S.; Lu, G.; Siddique, K.H.M. Role of phytohormones in regulating cold stress tolerance: Physiological and molecular approaches for developing cold-smart crop plants. Plant Stress 2023, 8, 100152.

107. Markarian, S.; Shariatmadari, H.; Shirvani, M.; Mirmohammady Maibody, S.A.M. Impacts of ZnO nanoparticles and dissolved zinc (ZnSO4) on low temperature induced responses of wheat. J. Plant Nutr. 2023, 46, 3435–3449.

108. Elsheery, N.I.; Sunoj, V.S.J.; Wen, Y.; Zhu, J.J.; Muralidharan, G.; Cao, K.F. Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. Plant Physiol. Biochem. 2020, 149, 50–60.

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

110. Zhang, J.; Yang, R.; Li, Y.C.; Peng, Y.; Wen, X.; Ni, X. Distribution, accumulation, and potential risks of heavy metals in soil and tea leaves from geologically different plantations. Ecotoxicol. Environ. Saf. 2020, 195, 110475.

111. Pescatore, A.; Grassi, C.; Rizzo, A.M.; Orlandini, S.; Napoli, M. Effects of biochar on berseem clover (Trifolium alexandrinum, L.) growth and heavy metal (Cd, Cr, Cu, Ni, Pb, and Zn) accumulation. Chemosphere 2022, 287, 131986.

112. Tian, W.; Zhang, M.; Zong, D.; Li, W.; Li, X.; Wang, Z.; Zhang, Y.; Niu, Y.; Xiang, P. Are high-risk heavy metal(loid)s contaminated vegetables detrimental to human health? A study of incorporating bioaccessibility and toxicity into accurate health risk assessment. Sci. Total Environ. 2023, 897, 165514.

113. Gong, Y.; Zhao, D.; Wang, Q. An overview of field-scale studies on remediation of soil contaminated with heavy metals and metalloids: Technical progress over the last decade. Water Res. 2018, 147, 440–460.

114. Chen, Y.; Liu, D.; Ma, J.; Jin, B.; Peng, J.; He, X. Assessing the influence of immobilization remediation of heavy metal contaminated farmland on the physical properties of soil. Sci. Total Environ. 2021, 781, 146773.

115. Li, Y.; Liang, L.; Li, W.; Ashraf, U.; Ma, L.; Tang, X.; Pan, S.; Tian, H.; Mo, Z. ZnO nanoparticle-based seed priming modulates early growth and enhances physio-biochemical and metabolic profiles of fragrant rice against cadmium toxicity. J. Nanobiotechnol. 2021, 19, 75.

116. Ghouri, F.; Shahid, M.J.; Liu, J.; Lai, M.; Sun, L.; Wu, J.; Liu, X.; Ali, S.; Shahid, M.Q. Polyploidy and zinc oxide nanoparticles alleviated Cd toxicity in rice by modulating oxidative stress and expression levels of sucrose and metal-transporter genes. J. Hazard. Mater. 2023, 448, 130991.