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Harnessing nanotechnology to alleviate abiotic stresses in agricultural plants

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The projected doubling in world population over the next 30 years presents a formidable challenge to current systems of food production and sustainability. The esclating global demands necessitate that food systems effectively address issues of equity, advanced productivity and ensured environment sustainability (White and Gardea-Torresdey, 2018). The productivity from agriculture is highly endangered by abiotic stresses such as drought, salinity or salt stress, temperature and heavy metal contamination because of the prevailed climate conditions. These permeant challenges threatened the global food security and severely compromised the crop yield and quality (IPCC, 2023; Kaleem et al., 2025; Riyazuddin et al., 2025; Ulhassan et al., 2025). Therefore, it is prerequisite to integrate technology with resilient strategies that could help in overcoming environmental constraints and attaining sustainable crop production. The inefficient conventional agrochemical delivery contribute to wastage of resources (White and Gardea-Torresdey, 2018). Crucially, nanotechnology supports sustainable crop production, particularly when crops encounter environmental stressors.

This special issue “Harnessing Nanotechnology to Alleviate Abiotic Stresses in Agricultural Plants” focuses on the utilization of nanotechnological approaches to address environmental challenges, improve crop productivity and impart abiotic stress resilience. The featured studies included in this special issue address a diverse range of topics such as the application of nanofertilizer for improving cluster bean (*Cyamopsis tetragonoloba*) tolerance to drought stress, protective roles of magnesium oxide nanoparticles (MgO-NPs) mediated salt stress tolerance in radish (*Raphanus sativus*), and protective roles of silicon oxide nanoparticles (SiO_2-NPs) in mitigating salt stress in tomato (*Solanum lycopersicum*). Additionally, several review articles were included to highlight the involved mechanisms of targeted delivery, uptake and transport pathways of NPs within plants. These reviews also focused on the factors influencing these processes and their protective roles against abiotic and biotic stresses. Munir et al. (2025) performed a field-experiment using a split-plot design to evaluate the effectiveness of foliar-applied nanofertilizers in improving drought tolerance in two different genotypes (BR-2017 and BR-2021) of *C. tetragonoloba* under varying irrigation conditions. Relative to water-deficient conditions, the application of nano-potassium, nano-boron and nano-zinc (particularly in combination) notably enhanced the plant growth ($\geq$ 60 %), dry biomass production, pods per plant, pod yield, 100-seed weight (by up to 10 %), photosynthetic efficiency, nutrient-use efficiency, water-retention, and protein levels, with the most pronounced effects observed in BR-2021. The findings establish that these nanofertilizers possessed the capacity to markedly elevate agricultural output and improve plant physiological responses across varied irrigation conditions. These findings demonstrate that nanofertilizers represent a promising alternative to conventional fertilizers and offer a sustainable strategy for enhancing crop yields under diverse water regimes. Gautam et al. (2025) addressed that priming *R. sativus* seeds with biologically synthesized MgO-NPs at 150 μg/ml mitigated the salt stress as evidenced by enhanced shoot length, root length, total chlorophyll content, and carbohydrate levels, alongside a concurrent reduction in the concentration of protein-precipitable tannins within the tissues. MgO-NPs seed priming significantly enhanced protein bio-availability and free radical scavenging activity under saline stress. The improvement could be attributed to an elevation of antioxidant enzymes and accumulation of total phenolic and flavonoid contents. The study findings demonstrate that MgO-NP priming is a potential sustainable method for *R. sativus* cultivation in high-salt environments. A concentration-dependent attenuation of salt-mediated oxidative damage *via* induction of enzymatic and nonenzymatic antioxidant mechanism, which were effectively monitored as biomarkers.

Alam et al. (2025) investigated the mechanistic approaches by which SiO_2-NPs could alleviate 50 mM salt stress in *S. lycopersicum* and focused on the particular physiological and metabolic attributes. It was obvious that SiO_2-NPs applied to leaves significantly enhanced growth and biomass, photosynthesis, and the levels of protein and sugar contents, and total alkaloids under salt stress. The enhancement was also associated with the increase in antioxidant enzymes activity, reduction in the overproduction of lipid peroxidation and hydrogen peroxide content, and stabilization in the cellular structures. The speculated mechanism is that Si ions can cause the Na^+ efflux from cells and stimulate H^+-ATPase. These collective actions facilitate the cellular compartmentation and enhance Na^+ vacuolar sequestration for salt stress tolerance. Multiple mechanisms may involve in promoting salt stress tolerance. For instance, membrane stability, protection to cellular organalles and chloroplasts, boost antioxidant activity, and optimize carbohydrate

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metabolism. This study reveals the potency of SiO_2-NPs in alleviating salt stress tolerance of *S. lycopersicum*. This method provides a sustainable strategy for the cultivation of agricultural plants in saline-affected soils. Manzoor et al. (2025) focused on the utilization of *Artemisia annua* for zinc oxide nanoparticles (ZnO-NPs) synthesis to manage the fungal disease in sweet cherry (*Prunus avium*). The antifungal activity of ZnO-NPs against *Fusarium equiseti* was demonstrated through *in vitro* and *in vivo* investigations. Particularly, the application of 100 mg/L ZnO-NP significantly restricted the mycelial growth by 88 % and disease severity by 77 %. These evidences strongly reinforce the utilization of ZnO-NPs as environmentally friendly and biocompatible substitute of chemical fungicides for sustainable agriculture.

Razzaq and Zhou (2025) discussed the role of iron nanoparticles (Fe-NPs) in targeted delivery of plant growth regulators such as cytokinins, auxins, and gibberellins). The study highlighted how this approach can boost crop tolerance to drought and salinity. Moreover, the authors reported recent advancements for nano-delivery and underlying mechanisms for imparting abiotic stress tolerance in plants by Fe-NPs, and future perspectives for sustainable agriculture. Afzal et al. (2024) reviewed the economically feasible designs of nanostructures to escalate the efficacy of agrochemicals. The designed proposed strategy maximizes the bioavailability and mitigates the environmental contamination. In addition, the authors highlighted the mechanisms and factors influencing the properties and translocation of nanomaterials. They concluded the discussion by emphasizing the need to fill the knowledge gaps in the rational design and efficient nano-delivery to specific plant tissues. Liu et al. (2024) reviewed how nanomaterials interact with plants and specifically consider the physicochemical properties such as catalytic activity, and photoluminescence. They anticipate that technological advancements will unlock novel avenues for nanomaterials in agriculture. The review by Rehman et al. (2025) detailed the key functions of titanium dioxide nanoparticles (TiO_2-NPs), especially their biosynthesis methods, effectiveness as plant growth promoter, and protective mechanisms to enable abiotic stress tolerance. The authors also discussed how TiO_2-NPs alone or their synergistically interaction with biochar and/or phytohormones enhance their potential to manage the abiotic stressors *via* multiple mechanisms. Although these integrative strategies can effectively boost plant growth and yield quality, reduce the impact of environmental stress factors, and support safe and sustainable crop production. However, the practical application of TiO_2-NPs is hindered by dose-dependent toxicity, inconsistent formulations of product, environmental safety concerns and constraints in field applications at large-scale.

The application of NPs-based seed priming has proven emerging technique for improving plant growth and environmental stress tolerance. The review by Faizan et al. (2024) highlighted how nano-priming can alleviate heavy metals toxicity in plants by regulating physiobiochemical, metabolic and molecular responses. However, the practical implementation of nano-priming in agricultural systems necessitates first address existing knowledge gaps in research and environmental safety concerns. This special issue is dedicated to provide foundation for future research on nanoparticle-plant interactions, which is crucial for safe and sustainable agriculture amid unfavorable environmental conditions.

CRediT authorship contribution statement

Weijun Zhou: Writing – review & editing, Conceptualization. **Mohamed Salay Sheteiwy:** Writing – review & editing, Writing – original draft, Conceptualization. **Mohammad Nauman Khan:** Writing – review & editing, Writing – original draft, Conceptualization. **Xinghong Yang:** Writing – review & editing, Conceptualization. **Zaid Ulhassan:** Writing – review & editing, Writing – original draft, Conceptualization. **Renato Grillo:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Afzal, S., Singh, N.K., Lal, A.F., Sohrab, S., Singh, N., Gupta, P.S., Mishra, S.K., Adeel, M., Faizan, M., 2024. Nanostructure and plant uptake: assessing the ecological footprint and root-to-leaf dynamics. Plant Nano Biol. 10, 100122. https://doi.org/10.1016/j.plana.2024.100122.

Alam, P., Yalcin, M., Faizan, M., Albalawi, T., 2025. Response of tomato to silicon dioxide nanoparticles under salinity: impact on photosynthesis, antioxidant enzymes activity, stress biomarkers and osmoregulatory substances. Plant Nano Biol. 13, 100171. https://doi.org/10.1016/j.plana.2025.100171.

Faizan, M., Sharma, P., Sultan, H., Alam, P., Sehar, S., Rajput, V.D., Hayat, S., 2024. Nano-priming: improving plant nutrition to support the establishment of sustainable agriculture under heavy metal stress. Plant Nano Biol. 10, 100096. https://doi.org/10.1016/j.plana.2024.100096.

Gautam, A., Kumar, V., Guleria, P., 2025. Magnesium oxide nanoparticles improved biochemical and antioxidant parameters of radish to induce salt stress tolerance. Plant Nano Biol. 13, 100176. https://doi.org/10.1016/j.plana.2025.100176.

IPCC, 2023. Summary for policymakers. In: Core Writing Team, Lee, H., Romero, J. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

Kaleem, Z., Shahbaz, H., Ali, S., Albert, A., He, D., Gulzar, R.M.A., Asad, M.A.U., Zhou, W., Zhang, K., Ulhassan, Z., 2025. Melatonin and nanocopper synergistically regulate cadmium toxicity in brassica napus: evidences from photosynthesis phenomics, oxidative metabolism, and multiple defense responses. Environ. Sci. Nano 12, 3714–3730.

Liu, J., Zhou, H., Yue, L., Bao, L., Wang, D., Mao, T., Cui, Z., Wu, H., Zhai, Y., 2024. Designing nanomaterials for sustainable agriculture: introducing largely overlooked physicochemical properties. Plant Nano Biol. 10, 100121. https://doi.org/10.1016/j.plana.2024.100121.

Manzoor, M.A., Liu, X., Xu, Y., Sabir, I.A., Shah, I.H., Ashraf, G.A., Azam, M., Gulzar, S., Jiu, S., Zhang, C., 2025. Nano-scale defenders tackling sweet cherry (*Prunus avium*) fungal threats with eco-friendly zinc oxide nanoparticles. Plant Nano Biol. https://doi.org/10.1016/j.plana.2025.100198.

Munir, J., Nazim, M., Jabeen, N., Ali, M., Shah, A.A., Sultan, H., 2025. Synergistic role of foliar-applied nano-fertilizers enhances drought tolerance in cluster bean (Cyamopsis tetragonoloba L.). Plant Nano Biol. 13, 100185. https://doi.org/10.1016/j.plana.2025.100185.

Razzaq, S., Zhou, B., 2025. Revolutionizing crop production with iron nanoparticles for controlled release of plant growth regulators and abiotic stress resistance. Plant Nano Biol. 13, 100172. https://doi.org/10.1016/j.plana.2025.100172.

Rehman, M., Abdul Salam, A., Ulhassan, Z., Ali, B., Haider, Z., Ahmad, I., Yasin, M.U., Javaid, M.H., Yang, C., Fayyaz, M., Gan, Y., 2025. Titanium dioxide nanoparticles in crop stress management: mechanisms, applications, and abiotic stress mitigation. Plant Nano Biol. https://doi.org/10.1016/j.plana.2025.100207.

Riyazuddin, R., Nisha, N., Gupta, R., 2025. Phytonanotechnology in the mitigation of biotic and abiotic stresses in plants. Plant Nano Biol. 13, 100173. https://doi.org/10.1016/j.plana.2025.100173.

Ulhassan, Z., Ali, S., Kaleem, Z., Shahbaz, H., He, D., Khan, A.R., Salam, A., Hamid, Y., Sheteiwy, M.S., Zhou, W., Huang, Q., 2025. Effects of nanosilica priming on rapeseed (*Brassica napus*) tolerance to cadmium and arsenic stress by regulating cellular metabolism and antioxidant defense. J. Agric. Food Chem. 73 (8), 4518–4533.

White, J.C., Gardea-Torresdey, J., 2018. Achieving food security through the very small. Nat. Nanotechnol. 13 (8), 627–629.

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