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APPLICATION OF NANOTECHNOLOGY FOR PLANTS IN RESPONSE TO ENVIRONMENTAL STRESSES

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Abstract

This study provides a comprehensive overview of nanotechnology in plant science, addressing its classification, preparation methods, physicochemical properties, and application prospects. Particular attention is given to recent research progress and the potential safety risks associated with plant responses to environmental stresses. Furthermore, the study outlines key problems and challenges that nanotechnology is expected to face in the future. The primary objective is to offer theoretical guidance and strategic insights that can inform and inspire deeper investigations in these related fields.

Key words: Nanotechnology; Plant; Environmental stress; Safety risks

Introduction

Due to the detrimental effects from global climate changes and human activities, more and more plants are facing increasingly severe environmental stress challenges, such as drought, saline-alkali soil, higher levels of UV-B radiation and heavy metal pollution ect., (Safshekan *et al.*, 2025; Li *et al.*, 2025). Against this backdrop, it is very crucial to seek innovative and effective methods to enhance the adaptability and resistance of plants against various adverse external factors. Recent years, nanotechnology, as a new type of cutting-edge technology, has been widely explored for their potential applications in helping plants cope with environmental stresses (Dong *et al.*, 2026; Hussian *et al.*, 2026). Especially, due to the unique properties and structures of nanomaterials, nanotechnology will probably supply some new strategies for plant cultivation (Dong *et al.*, 2026).

This article primarily focuses on summarizing the current research progress of nanotechnology in plants' responses to diverse environmental stressors, and looks forward to the problems and challenges that nanotechnology will probably face in the future, aiming to provide theoretical references and strategic inspirations for deep development in these related research fields.

Overview of nanomaterials

Nanomaterials' classification: Nanomaterials usually refer to ultra-fine materials with particle sizes at the nanometer level, which possess unique structures and physicochemical properties. According to different characteristics of the nanoscale in space, they can be classified into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) nanomaterials (Nikam *et al.*, 2018). Based on material properties, they can be categorized into metallic nanomaterials, oxide nanomaterials, nanocomposites, etc (Nikam *et al.*, 2018). Depending to nanomaterial morphology, they can be classified as nanoparticles, nanowires, nanofibers, etc. Based on functional characteristics, they can also be classified as semiconductor nanomaterials, magnetic nanomaterials, nonlinear optical nanomaterials, nanoferroelectric materials, nanosuperconducting materials, and nanothermoelectric materials, etc (Nikam *et al.*, 2018; Fan *et al.*, 2020; Yang *et al.*, 2023).

Special effects of nanomaterials: Nanomaterials exhibit various special effects due to their small size and unique structure. The size effect of nanomaterials is manifested in their small volume and few atoms. The surface effect is explained to the fact that nanomaterials have a relatively large surface area, which leads to significant influences of the interactions between surface atoms and molecules on materials' properties. The macroscopic quantum tunneling effect enables microscopic particles to pass through potential barriers (Zhang *et al.*, 2023). When the particle size of materials is reduced to nanometer scale, their physical and chemical properties change, a phenomenon known as the quantum size effects (Yang *et al.*, 2023). The special effects of nanomaterials have enabled them being widely applied in many fields such as optics, medicine and electromagnetics. For instance, oxide nanoparticles can rapidly change color under the influence of an electric field or light (Fan *et al.*, 2020), semiconductor nanomaterials can be used for light source excitation and photoelectric conversion, as well as the preparation of optical tweezers and photothermal agents (Yu *et al.*, 2020; Zhang *et al.*, 2023). Additionally, due to their unique mechanical properties, nanomaterials are also often used in high-strength metallic materials preparation (Shang *et al.*, 2013; Zheng *et al.*, 2017; Hong *et al.*, 2023).

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Preparation and characterization of nanomaterials: The preparation methods of nanomaterials mainly include physical methods, chemical methods, and physicochemical methods. Chemical methods provide multiple pathways for nanomaterial synthesis, such as emulsion method, precipitation method, vapor deposition, hydrothermal synthesis, and sol-gel method, etc (Judran *et al.*, 2021; Liu *et al.*, 2022a; Wang *et al.*, 2022a; Xu *et al.*, 2022; Li *et al.*, 2023a; Li *et al.*, 2023b; Zeng *et al.*, 2023). Physicochemical methods greatly enrich nanomaterials' preparations and provide more possibilities for their applications (Wang *et al.*, 2018; Shen *et al.*, 2021; Wen *et al.*, 2022; Zhang *et al.*, 2022; Chen *et al.*, 2023). The characterization of nanomaterials is of great significance for revealing their structure, morphology, composition, interface, function, and dynamic characteristics, and it will provide important theoretical supports and reference values for the preparation and performance optimization of nanomaterials (Fig. 1).

Absorption and transport pathways of nanomaterials in plants

The main absorption mechanisms of nanomaterials in plants include transmembrane transport, endocytosis pathway, and cell wall penetration. The absorption efficiency of nanomaterials is closely related to their size, shape, and surface modification. Previous researches have shown that smaller-sized nanomaterials are more easily absorbed by plant roots, and surface modification can enhance hydrophilicity and lipophilicity, thereby increasing the bioavailability of nanomaterials in plants (Parkinson *et al.*, 2022; Wang *et al.*, 2023). The transport pathways of nanomaterials within plants have a significant impact on their absorption efficiency. Once being absorbed, nanomaterials can be transported between plant cells through symplastic and apoplastic pathways. The symplastic pathway mainly involves plasmodesmata between cells, while the apoplastic pathway involves nanomaterials entering through stomata or the epidermis and then passing through the intercellular spaces and cell walls (Hu *et al.*, 2020; Wang *et al.*, 2021a). Nanomaterials transport not only affects their distribution within plants but also controls plants' responses to environmental stresses.

Impact of nanomaterials on plants

When plants are exposed to unfavorable environmental conditions, their interaction with nanomaterials might be beneficial to enhance their adaptability and resistance (Wang *et al.*, 2021a). Nanomaterials can affect plants' growth and development in various ways, as shown in Fig. 2. (1) Nanomaterials can regulate soil conditions, maintain soil moisture and ion balance in order to help plants grow healthily under drought or saline-alkali stress. (2) Nanomaterials with high specific surface area and active surface can absorb heavy metal pollutants in soil to play a detoxification role. (3) Nanomaterials can act as carriers for fertilizers or nutrients to improve the absorption and utilization efficiency of nutrients through plant root systems, and promote plant growth and development. (4) Nanomaterials can interact with plant cells, activating or inhibiting signaling molecules within plants, such as hormones, calcium ions, and reactive oxygen species, thereby influencing signal transduction in plants. (5) Nanomaterials can regulate plant hormone levels to affect plant growth and development, and stress response mechanisms. (6) Nanomaterials can also enhance plant stress resistance by regulating some key gene expression. For example, specific nanoparticles can act as signaling molecules, triggering signal transduction pathways within plant cells and thereby activating or inhibiting the expression of genes related to stress responses. These gene expression changes might enhance plants' tolerance to environmental stress, helping plants survive and grow under various adverse conditions.

However, most of previous studies regarding the impacts of nanomaterials on plant growth, development, and stress resistance, are still at laboratory exploration stages (Hu *et al.*, 2020; Wang *et al.*, 2021a; Sun *et al.*, 2021; Manzoor *et al.*, 2023). The large-scale application in field environments or crop breeding has not yet been carried out. Therefore, the promotion and application of nanomaterials and their reproducibility need to be urgently broken through in the future.

Application of nanotechnology in plants' responses to environmental stresses

Application of nanotechnology in plant against abiotic stresses: A large number of studies have found that some nanomaterials can precisely regulate plant physiology processes and biochemical metabolisms at the cellular and molecular levels, thereby they could probably improve plants' abilities to cope with various abiotic stresses.

Nanomaterials' role in regulating plants' responses to drought stress: With continuous abnormal changes in global climate, drought phenomenon is becoming increasingly severe, threatening the development of industry, agriculture, and human society. The usage of nanotechnology has brought significant effects on improving crops drought resistance and other climatic problems on agricultural production. Its molecular mechanisms maybe involve the following two aspects. Firstly, nanomaterials can reduce oxidative damage caused by abiotic stress to plant cells. Secondly, the photo-sensitivity of nanomaterials optimizes photosynthesis, further enhancing plants' adaptability to drought environments. Manzoor's research pointed out that iron oxide nanoparticles (FeO NPs) and silicon oxide nanoparticles (SiO NPs) application can promote wheat growth by increasing antioxidant enzyme contents in soil to effectively reduce reactive oxygen species (ROS) acceleration (Manzoor *et al.*, 2023). Sun *et al.*, (2021) indicated that Mn_3O_4 NPs can degrade hydrogen peroxide (H_2O_2) in root tips of corn under drought stress to maintain intracellular ROS stability, and enhance cell mitotic ability of root tips, thereby improving corn drought resistance. Chen *et al.*, (2021) found that alfalfa leaves with nano-graphene can rapidly change expression activities of specific genes relating to antioxidant defense and photosynthesis, finally enhancing alfalfa drought tolerance. Ghani *et al.*, (2022) proposed that when cucumber seedlings are exposed to 100 mg/L zinc oxide nanoparticles (ZnO NPs), photosynthetic pigment synthesis and PSII photochemical activity would be increased, while cucumber seedlings had faced less drought stress. Meanwhile, other studies have shown that soybean plants with 50μM chitosan-GSNONPs treatment significantly reduced electrolyte leakage, and catalase and ascorbate peroxidase enzymatic activities, but decreased malondialdehyde (MDA) contents and H_2O_2 levels. NPs application also regulated the expression levels of drought stress-related marker genes such as GmDREB1a, GmP5CS, GmDEFENSIN, and NO-related genes including GmGSNOR1 and GmNOX1, to enhance soybean plants drought tolerance (Methela *et al.*, 2023). Additionally, nanoparticle treatment could up-regulate water channel protein-encoding genes TaPIP1 and TaNIP2, as well as drought resistance marker genes NAC11, WRKY27, RD20A, DREB2, ERD1, FDL19, DREB2, MYB118, and MYB174, to improve plants' water absorption and utilization (Zhao *et al.*, 2023).

Nanomaterials' role in regulating plants' responses to salt stress: Salt stress is a common problem in agriculture, which can limit plant growth and reduce crop yields. Liu *et al*. (2023) synthesized Mn_3O_4 NPs with antioxidant enzyme mimetic activity, which can remove ROS in mesophyll cells and alleviate the harmful impacts of salt stress on cotton, thereby enhancing its salt tolerance. They also found that nanoparticles such as cerium oxide, silver oxide, nano-selenium, or nano-silicon application under salt stress could regulate the expression of genes related to Na^+ and K^+ transport in crops, reduce the intracellular Na^+ or increase K^+ concentrations, and maintain cellular ion balance. Moreover, nanoparticles would enhance plants' salt tolerance by regulating the expression of genes related to plant hormones synthesis such as abscisic acid, gibberellin, auxin, cytokinin, and ethylene, and promoting polyamines biosynthesis and gas signal molecules production such as NO, CO, H_2, H_2S, and ethylene (Khan *et al.*, 2021). Gong *et al.*, (2023) treated peas and *Eucommia ulmoides* with carbon dot nanocatalysts, and found that carbon dot nanocatalysts could act as antioxidants to regulate oxidative stress in plant via removing reactive oxygen species, reactive nitrogen species and stabilize free radicals, thus alleviated oxidative damages to biological components caused by salt stress, and repaired redox enzymes function in plants. In addition, other studies have also shown that cerium oxide nanoparticles (CeO_2 NPs) can improve salt tolerance of cucumber seedlings by inducing CsAKT1-mediated K^+ absorption (Peng *et al.*, 2022).

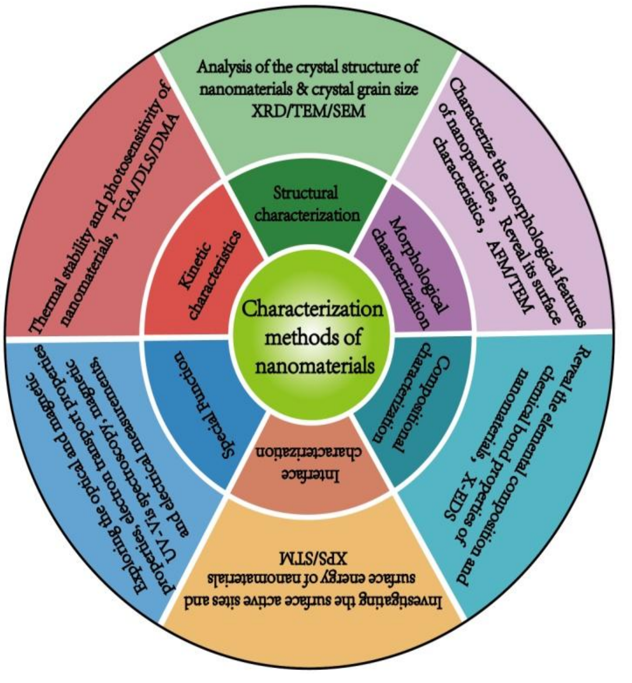

Fig. 1. Characterization methods for nanomaterials.

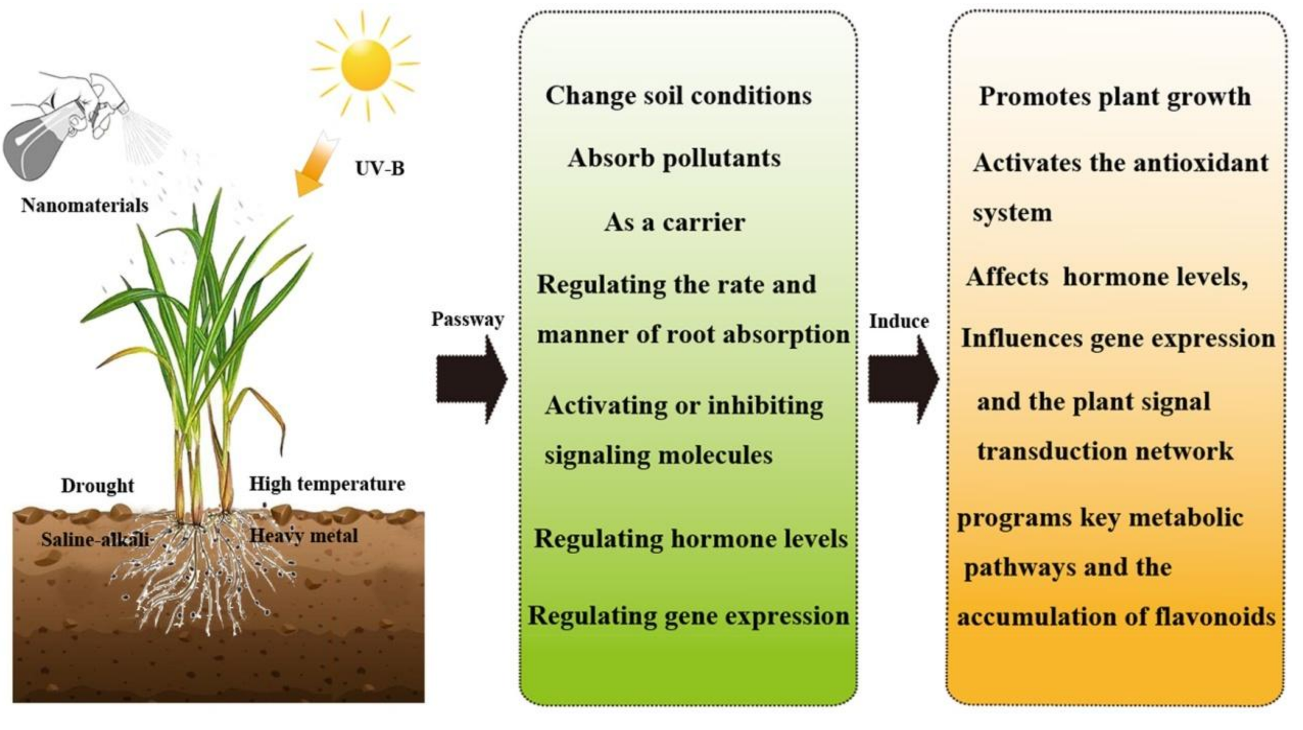

Fig. 2. Effects of nanomaterials' application for plants under abiotic stress conditions.

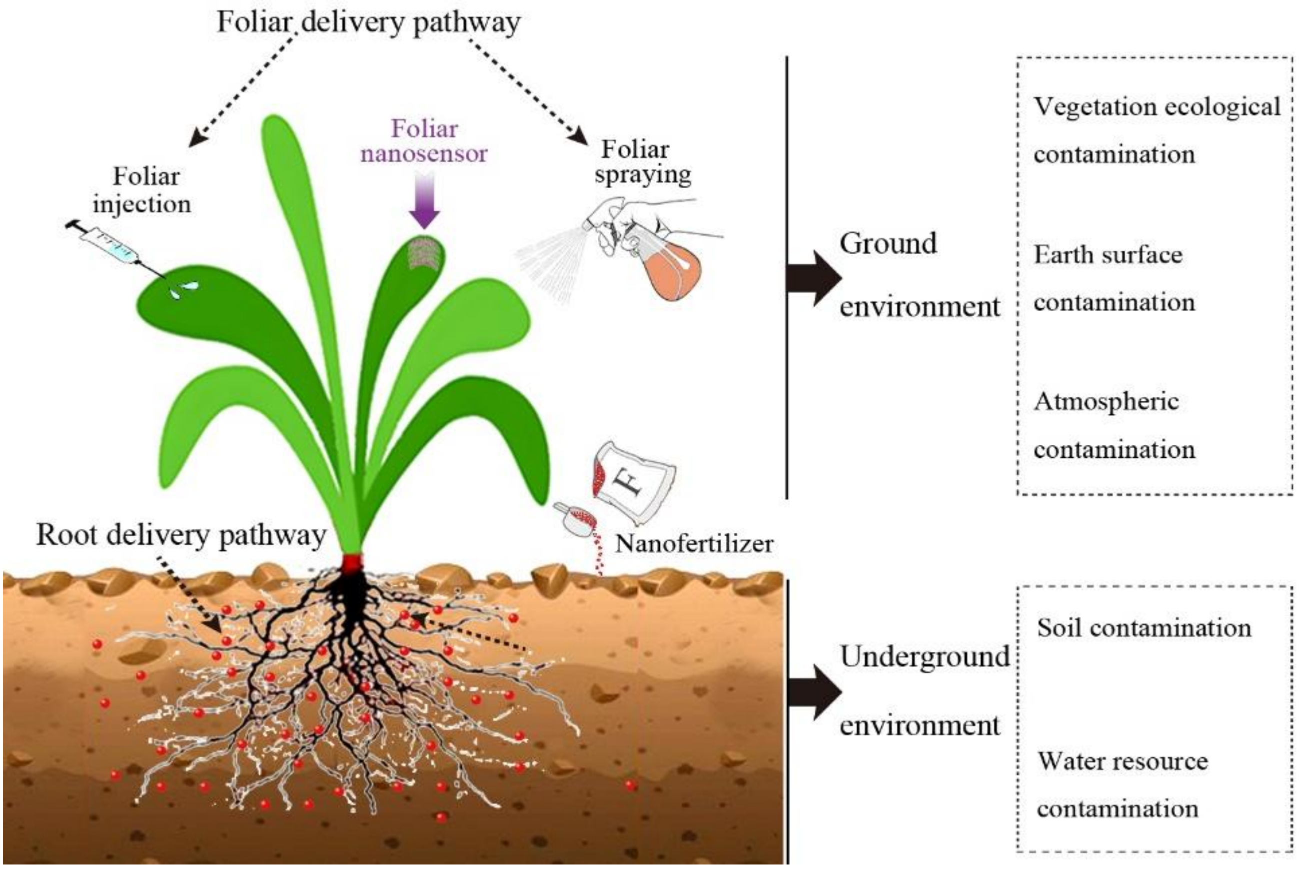

Fig. 3. The pathways of nanoparticles for entering plants and its potential safety risks during application.

Nanomaterials participate in regulating plants' responses to temperature stress: Nanomaterials can effectively cope with temperature stress on plants by multiple ways. Firstly, nanomaterials can be used to design nanotransport systems, which help plants more effectively eliminate harmful substances, in order to improve the stability of cell membrane, and reduce the damages of temperature on plant cells. Through precise material transfer, nanoparticles help cells better cope with external temperature stress. Some studies have shown that when being sprayed on tomato leaves, nano-carriers can accelerate spermidine release from nano-carriers as temperature rises, and then promote photosynthesis efficiency of tomato plants under heat and light stress. Secondly, nanomaterials can activate antioxidant enzymes to enhance plants' adaptability to high or low temperatures. Others' studies found that spraying 20mg/L silica nanoparticles (SiO_2NPs) on plant leaves before high temperature could significantly increase the values of Fv/Fm, net photosynthetic rate, soluble sugar content, peroxidase and catalase activity of strawberries, whereas reduce MDA content, finally alleviate physiological damages caused by high temperature. Besides, nanomaterials can also regulate the signal transduction pathways mediated by plant hormones. When corn was subjected to high temperature stress, the cis-regulatory elements in the promoter region of Zm CDPK7 gene responded rapidly to high temperature, and abscisic acid positively regulated Zm CDPK7 expression, which in turn positively regulated the accumulation of key enzymes RBOHs, CAT1 and APX1 involved in ROS accumulation or clearance and of molecular chaperones HSPs expression (Zhao *et al.*, 2020).

Nanomaterials participate in regulating plants' responses to heavy metal stress: The accumulation and diffusion of heavy metals such as cadmium and mercury in natural environments could cause severe toxic effects on plants in many aspects. Heavy metals can hinder photosynthesis and respiration of plants, disturb nutrient absorption and material metabolism, that will inhibit growth and development of plants (Li *et al.*, 2014). Secondly, heavy metals can induce damages on cell membrane and degradation of proteins, and inhibition of physiological metabolism in plants (Figlioli *et al.*, 2019). In addition, heavy metals can also cause oxidative stress to cell or organelle structures, thus destroying their biological functions (Yadav, 2010). Recent studies found that Fe_3O_4 NPs and ZnO NPs could program key metabolic pathways such as alkaloids, amino acids, and flavonoids, alleviating Cd stress for plants. Fe_3O_4 NPs can alter amino acid sugar and nucleotide sugar metabolism, flavonoid and phenylalanine metabolism, thereby alleviating the toxicity of cadmium and arsenic in seedlings (Zou *et al.*, 2022; Lu *et al.*, 2023). Multi-walled carbon nanotubes can promote *Solanum nigrum* growth under heavy metal stress by up-regulating specific gene expression, and reprogramming metabolic processes being related with defense mechanism (Chen *et al.*, 2022). Kareem *et al*., (2022) observed that the ultrastructure of alfalfa roots and leaves could be protected, and Cd toxicity had been relieved through adding biochar to Cd-contaminated soil and spraying ZnO NPs on the leaves. Under As stress, the addition of NPs significantly increased plant height, root length and biomass, and also improved As transfer coefficient and tolerance index of rape, thereby alleviating As toxicity to rape. Hao *et al*., (2023) reported that 250mg/kg of graphite carbon-nitrogen compounds could control plant nutrient assimilation, alleviate the toxicity induced by As/Cd, as well as promote the growth and development of rice seedlings. Kumar *et al*., (2023) demonstrated that foliar application of titanium dioxide nanoparticles (TiO_2 NPs) improved photosynthetic properties, DNA damage, antioxidant defense and phytochelatin biosynthesis of sunflowers, thus alleviating the $Cr6^+$ toxicity.

Nanomaterials' role in regulating plant responses to ultraviolet stress: In recent years, the increment of greenhouse gases and chlorofluorocarbons has sharply depleted the ozone layer. Ozone can absorb ultraviolet radiation from the solar spectrum. The sharply depletion of ozone resulted in an increase of ultraviolet radiation reaching the Earth's surface, with UV-B being the main source of enhanced ultraviolet radiation (Rodríguez-Calzada, *et al.*, 2019). The higher intensity of UV-B radiation has adverse effects on plant growth and development. Previous reports indicated that nanomaterials mitigated the unfavorable effects by UV-B stress on plants. Tripathi *et al*., (2017) found that silicon nanoparticles (Si NPs) could effectively reduce the inhibitory effects of UV-B on fresh weight, dry weight and area of leaves, and protect wheat seedlings from the damage of ROS by UV-B stress possibly through activating NO-mediated defense mechanisms. Foliar spraying of TiO_2 NPs provided UV-B protection for photosynthetic organisms due to the maintenance of cell wall and chloroplast structure, and ROS scavenging (Sicard *et al.*, 2011; Jurkow *et al.*, 2020). The application of TiO_2 NPs enhanced the antioxidant activity of saffron via increasing the concentration of flavonoids and phenolic, and help plants resist UV-B stress (Rikabad *et al.*, 2019). Nano-TiO_2 application to spinach significantly reduced the accumulation of superoxide anion radicals (O_2^-), H_2O_2 and malondialdehyde, and enhanced the activities of CAT, glutathione peroxidase (GPX), superoxide dismutase (SOD) and ascorbate peroxidase (APX). Wang *et al.* (2021b) also found that TiO_2 NPs treatment up-regulated F3H and CHS expression to stimulate flavonoid synthesis and effectively shield UV-B. TiO_2 NPs also induced the expression of UV-B stress response genes MPK6 and MPK3, as well as DNA damage repair genes SOG1, RAD51 and BRCA1, preventing microtubule depolymerization in plants. These studies have indicated that nanomaterials have significant improvements on the stress damage by UV-B in plants.

Altogether, we have found that the optimal dosage of different nanoparticles when applied to the certain crop may greatly vary, and the most suitable dosage of the same nanoparticle when applied to different crops may also be different (Sicard *et al.*, 2011; Rikabad *et al.*, 2019; Wang *et al.*, 2021b; Wang *et al.*, 2022b; Ahmed *et al.*, 2022; Qiu *et al.*, 2023). These data indicate that the growth and development of crops have a specific concentration dependence on nanoparticles. When the dosage of nanoparticle exceeds the optimal application amount, it is instead detrimental to crops growth. This phenomenon also reflects the potential chemical toxic effects of nanomaterials on crops and other organisms, which is one of the primary reasons restricting the promotion and application of nanotechnology. In addition, during the application of nanomaterials in the farmland, they will inevitably spread to the surrounding ecological environment such as soil, water bodies, and other crops, which will unavoidably cause secondary pollution to the environment (Fig. 3). This is also a severe threatening that needs to be considered for the large-scale application of nanotechnology.

Application of nanotechnology in plant against biotic stresses: Biotic stresses are also the common factors affecting plant growth and development, which mainly caused by pathogens, insects, and parasitic plants. Biotic stressors have tremendous threats various plants and crops. Nanomaterials can improve plant growth conditions and its immune system, then strengthen their resistance to pathogenic microorganisms, finally enabling plants to acquire the better ability to resist biotic stress. Ahmed *et al*., (2022) have studied the effect of chitosan-iron nanocomposites on rice resistance to bacterial blight and other stresses, and proposed a mechanism to weaken the harmful effects of bacterial blight to plants. Qiu *et al*., (2023) found that zinc oxide NPs reduced the occurrence of rice blast. Wang *et al*., (2022b) discovered that nano-sulfur could be used as an agricultural amendment to inhibit plant diseases. Carbon dots and graphene oxide have also played significant roles in the prevention of plant pathogens (Azizi-Lalabadi *et al.*, 2020). The possible mechanisms by which plants respond to biotic stresses might mainly include the following two aspects. (1) Activation of plant immune system. When exposed to biotic stresses, nanomaterials probably trigger a series of immune responses, including the activation of disease-resistant genes and the production of antibacterial proteins, which help plants more rapidly and effectively respond to pathogen invasion. (2) Strengthening of cell wall. Nanomaterials play a role in the formation and strengthening of cell wall. The strengthening of cell wall helps improve the mechanical strength and disease resistance of plants, slows down the speed of pathogen invasion into cells, and thereby enhances plants' resistance to biotic stresses. The application of nanomaterials provides new strategies and technical support for improving or enhancing plants' stress resistance. The innovative development of nanomaterials is expected to bring new vitality for the stability and sustainability development of agriculture in the future.

Applications in environmental protection: Although the application of nano-biotechnology may cause secondary pollution to ecological environment, some specific nanomaterials can also be used for environmental pollution monitoring, playing a safeguarding role in ecological and environmental protection (Shen *et al.*, 2022). Due to their ability of absorption tiny substances, many nanomaterials can be used as adsorbents to remove harmful substances from water sources, soil, and atmosphere, thereby improving water quality, soil quality, and achieving the goal of air pollution control. Nano-photocatalytic materials can effectively utilize light energy to degrade pollutants, achieving the purpose of environmental governance (Shen *et al.*, 2022; Liu *et al.*, 2022b; Atkinson *et al.*, 2022). As well as, nanomaterials can be used for efficient monitoring and treatment of environmental pollutants as biochemical sensors. At present, the application of nanotechnology in environmental protection has become another important supplement and research hotspot in plant science field.

Challenges and prospects: Many nanomaterials have been reported that can enhance plants' tolerance to stresses, but their effectiveness and reproducibility in field applications still require systematic evaluation in the future (Liu *et al.*, 2022b; Atkinson *et al.*, 2022). Additionally, the potential environmental risks posed due to the use of nanomaterials must be considered. Preliminary experimental data indicate that the negative impacts of nanomaterials on ecosystems exhibit high dependence on application dosage, material type, and plant characteristics. Some nanomaterials can cause phytotoxic effects on crops themselves at high concentrations, while others may harm the certain sensitive plants even at low concentrations.

In conclusion, while nanotechnology has shown great potential in numerous fields, they still face challenges. The large-scale production of nanomaterials remains technically difficult due to high costs, poor stability, and environmental impact, which greatly restrict the feasibility and economy of their widespread application. Application within living cells has extremely high requirements for long-term stability and biocompatibility of nanomaterials to ensure their stable performance and normal function in bodies and avoiding biological toxicity reactions (Li *et al.*, 2023c). The large-scale production, standardized application, and cost-effectiveness of nanomaterials in plants still require in-depth research. In environmental protection field, nanomaterials may also bring new challenges, especially in water treatment and waste management, where long-term impact of their potential toxicity needs to be evaluated to ensure safe use and avoid secondary environmental pollution (Majeed *et al.*, 2023; Majumderv *et al.*, 2024). Moreover, attention should be paid to the impact of nanomaterials on food safety and production environments to ensure they do not negatively affect food quality and human health. Therefore, future research should focus on a deeper understanding of nanomaterial properties and exploring solutions to achieve nano-biotechnology sustainable development and application in pant science fields.

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References

Ahmed, T., M. Noman, H. Jiang, M. Shahid, C. Ma, Z. Wu, M.M. Nazir, M.A. Ali and J.C. White. 2022. Bioengineered chitosan-iron nanocomposite controls bacterial leaf blight disease by modulating plant defense response and nutritional status of rice (*Oryza sativa* L.). *Nano Today*, 45: 101547-101563.

Atkinson, J.T., L. Su, X. Zhang, G.N. Bennett, J.J. Silberg, C.M. Ajo-Franklin. 2022. Real-time bioelectronic sensing of environmental contaminants. *Nat.*, 611 (7936): 548-553.

Azizi-Lalabadi, M., H. Hashemi, J. Feng, and S.M. Jafari. 2020. Carbon nanomaterials against pathogens; the antimicrobial activity of carbon nanotubes, graphene/graphene oxide, fullerenes, and their nanocomposites. *Adv. Coll. Interf. Sci.*, 284: 102250.

Chen, X., J. Wang, R. Wang, D. Zhang, S. Chu, X. Yang, T. Hayat, Z. Fan, X. Cao, Y.S. Ok, and P. Zhou. 2022. Insights into growth-promoting effect of nanomaterials: Using transcriptmics and metabolomics to reveal the molecular mechanisms of MWCNTs in enhancing hyperaccumulator under heavy metal (loid)s stress. *J. Hazard. Mater.*, 439: 129640-129652.

Chen, Z., J. Niu, Z. Guo, X. Sui, N. Xu, H.A. Kareem, M.U. Hassan, M. Yan, Q. Zhang, J. Cui, J. Kang, Z. Wang, F. Mi, D. Karagić, and Q. Wang. 2021. Graphene enhances photosynthesis and the antioxidative defense system and alleviates salinity and alkalinity stresses in alfalfa (*Medicago sativa* L.) by regulating gene expression. *Environ. Sci. Nano.*, 8: 2731-2748.

Chen, Z., W. Wang, J. Duan, F. Qian, Y. Cao, J. He, D. Wang, P. Dong and Y. Zhang. 2023. Highly efficient synthesis of nano $LiMn_{0.90}Fe_{0.10}PO_4/C$ composite via mechanochemical activation assisted calcination. *Ceram. Int.*, 49: 18483-18490.

Dong, Q., T. Huang, C. Zhou, X. Wan, X. He, P. Miao, H. Cheng, X. Wang, H. Yu, M. Hu, D. Li, B. Qu, Y. Wu, J. Li and C. Pan. 2026. Nano-priming with selenium nanoparticles reprograms seed germination, antioxidant defense, and phenylpropanoid metabolism to enhance *Fusarium graminearum* resistance in maize seedlings. *J. Adv. Res.*, 81: 13-25.

Fan, Z., S. Zhang, J. Tang and P. Fan. 2020. Structure, preparation and application of graded nanomaterials. *Chin. J. Appl. Chem.*, 37(5): 489-501.

Figlioli, F., M.C. Sorrentino, V. Memoli, C. Arena, G. Maisto, S. Giordano, F. Capozzi and V. Spagnuolo. 2019. Overall plant responses to Cd and Pb metal stress in maize: Growth pattern, ultrastructure, and photosynthetic activity. *Environ. Sci. Poll. Res.*, 26(2): 1781-1790.

Ghani, M. I., S. Saleem, S. Rather, M.S. Rehmani, S. Alamri, V.D. Rajput, H.M. Kalaja, N. Saleem, T.A. Sial and M. Liu. 2022. Foliar application of zinc oxide nanoparticles: An effective strategy to mitigate drought stress in cucumber seedling by modulating antioxidant defense system and osmolytes accumulation. *Chemosphere.*, 289: 133202-133215.

Gong, J., Q. Liu, L. Cai, Q. Yang, Y. Tong, X. Chen, S. Kotha, X. Mao and W. He. 2023. Multimechanism collaborative superior antioxidant enzymes to alleviate salt stress-induced oxidative damage in plant growth. *ACS Sustain. Chem. Eng.*, 11(10): 4237-4247.

Hao, Y., Z. Cai, C. Ma, J.C. White, Y. Cao, Z. Chang, X. Xu, L. Han, W. Jia, J. Zhao and B. Xing. 2023. Root Exposure of graphitic Carbon Nitride (g-C3N4) modulates metabolite profile and endophytic bacterial community to alleviate cadmium- and arsenate-induced phytotoxicity to rice (*Oryza sativa* L.). *ACS Nano.*, 17 (20): 19724-19739.

Hong, Q., Y. Wang, R. Wang, Z. Chen, H. Yang, K. Yu, Y. Liu, H. Huang, Z. Kang and P.W. Menezes. 2023. In situ coupling of carbon dots with co-ZIF nanoarrays enabling highly efficient oxygen evolution electrocatalysis. *Small.*, 19(31): 2206723.

Hu, P., J. An, M.M. Faulkner, H. Wu, Z. Li, X. Tian and J.P. Giraldo. 2020. Nanoparticle charge and size control foliar delivery efficiency to plant cells and organelles. *ACS Nano.*, 14(7): 7970-7986.

Hussain, S., Z. Younas, F. Abasi, M. Nazik, F. Ahmad, N.I. Raja, T. Mukhtar, Z. Manzoor, R. Khan and Z.U.R. Mashwani. 2026. Deciphering the potential of silver-selenium nanocomposites on growth metrics, physiological attributes, and antioxidant proffles in cotton (*Gossypium hirsutum* L.). *Plant Nano Biol.*, 16: 100271.

Judran, H.K., N.A. Yousif and S.M.H. Aljawad. 2021. Preparation and characterization of CdS prepared by hydrothermal method. *J. Sol-gel. Sci. Tech*., 97(1): 48-62.

Jurkow, R., R. Pokluda, A. Sękara and A. Kalisz. 2020. Impact of foliar application of some metal nanoparticles on antioxidant system in oakleaf lettuce seedlings. *BMC Plant Biol.*, 20(1): 290-302.

Kareem, H., M. Adeel, M. Azeem, M.A. Ahmad, N. Shakoor, M.U. Hassan, S. Saleem, A. Irshad, J. Niu, Z. Guo, C. Branko, R. Hołubowicz and Q. Wang. 2022. Antagonistic impact on cadmium stress in alfalfa supplemented with nano-zinc oxide and biochar via upregulating metal detoxification. *J. Hazard. Mater.*, 443: 130309-130321.

Khan, M. N., Y. Li, Z. Khan, L. Chen, J. Liu, J. Hu, H. Wu and Z. Li. 2021. Nanoceria seed priming enhanced salt tolerance in rapeseed through modulating ROS homeostasis and α-amylase activities. *J. Nanobiotechnol.*, 19(1): 276-295.

Kumar, D., O.P. Dhankher, R.D. Tripathi and C.S. Seth. 2023. Titanium dioxide nanoparticles potentially regulate the mechanism(s) for photosynthetic attributes, genotoxicity, antioxidants defense machinery, and phytochelatins synthesis in relation to hexavalent chromium toxicity in *Helianthus annuus L. J. Hazard. Mater.*, 454: 131418-131434.

Li, C., W. Xie, X. Zhang, J. Liu, M. Zhang and J. Shao. 2023c. Pickering emulsion stabilized by modified pea protein-chitosan composite particles as a new fat substitute improves the quality of pork sausages. *Meat Sci.*, 197: 109086-109095.

Li, H., S. Zhao, Z. Wang and F. Li. 2023b. Controllable preparation of 2D V_2O_5 peroxidase-mimetic nanozyme to develop portable paper-based analytical device for intelligent pesticide assay. *Small.*, 19 (14): 2206465.

Li, S., P. Keoingthong, J. Xu, Y. Yan, J. Shen, Y. Xu, L. Zhang, X. Xia, X. Cao, S. Wang and Z. Chen. 2023a. Highly efficient carbon supported Co-Ir nanozyme for the determination of total antioxidant capacity in foods. *Biosens. Bioelectron.*, 236: 115416-115424.

Li, Y., H. Men, J. Li, W. Cao, Y. Pan and L. Gao. 2025. Repair effects of melatonin application on physiological damages induced by UV-B radiation in alfalfa seedlings. *Protoplasma*, 262: 1309-1318.

Li, Z., Z. Ma, T.J. Kuijp, Z. Yuan and L. Huang. 2014. A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Sci. Total Environ.*, 468-469: 843-853.

Liu, C., B. Xu, D. J. McClements, X. Xu, S. Cui, L. Gao, L. Zhou, L. Xiong, Q. Sun and L. Dai. 2022a. Properties of curcumin-loaded zein-tea saponin nanoparticles prepared by antisolvent co-precipitation and precipitation. *Food Chem.*, 391: 133224.

Liu, J., J. Gu, J. Hu, H. Ma, Y. Tao, G. Li, L. Yue, Y. Li, L. Chen, F. Cao, H. Wu and Z. Li. 2023. Use of Mn_3O_4 nanozyme to improve cotton salt tolerance. *Plant Biotechnol. J.*, 21: 1935-1937.

Liu, S., J. Sun, G. Ren and X. Meng. 2022b. Vacancy-engineered bismuth-based semiconductor with enhanced photocatalytic activity: A review. *Mat. Sci. Semicon. Proc.*, 137: 106230-106243.

Lu, T., X. Wang, X. Cui, J. Li, J. Xu, P. Xu and J. Wan. 2023. Physiological and metabolomic analyses reveal that Fe_3O_4 nanoparticles ameliorate cadmium and arsenic toxicity in Panax notoginseng. *Environ. Pollut.*, 337: 122578-122594.

Majeed, U., H. Majeed, A. Shafi, X. Liu, J. Ye, Y. Wang, W. Xue, Y. Luo and T. Yue. 2023. DNA binding peptide CF-14 enhances bactericidal efficacy of eugenol/carvacrol nanoparticles to Escherichia coli. *Food Chem.*, 429: 136861-136870.

Majumderv, S., S. Moharana and K.H. Kim. 2024. Cellulose nano-papers: A comprehensive review of their synthesis methods, applications, and influence on the circular economy. *J. Clean. Prod.*, 451: 142045.

Manzoor, N., L. Ali, A.A. AL-Huqail, S.M.S. Alghanem, H.A.S. Al-Haithloul, T. Abbas, G.W. Chen, L. Huan, Y. Liu and G. Wang. 2023. Comparative efficacy of silicon and iron oxide nanoparticles towards improving the plant growth and mitigating arsenic toxicity in wheat (*Triticum aestivum* L.). *Ecotox. Environ. Safe.*, 264: 115382-115391.

Methela, N.J., A. Pande, M.S. Islam, W. Rahim, A. Hussain, D. Lee, B. Mun, N.P.M.J. Raj, S. Kim, Y. Kim and B. Yun. 2023. Chitosan-GSNO nanoparticles: a positive modulator of drought stress tolerance in soybean. *BMC Plant Biol.*, 23(1): 639-654.

Nikam, A.V., B.L.V. Prasad and A.A. Kulkarni. 2018. Wet chemical synthesis of metal oxide nanoparticles: a review. *Cryst. Eng. Comm.*, 20(35): 5091-5107.

Parkinson, S.J., S. Tungsirisurp, C. Joshi, B.L. Richmond, M.L. Gifford, A. Sikder, I. Lynch, R.K. O'Reilly and R.M. Napier. 2022. Polymer nanoparticles pass the plant interface. *Nat. Comm.*, 13(1): 7385.

Peng, Y., L. Chen, L. Zhu, L. Cui, L. Yang, H. Wu and Z. Bie. 2022. CsAKT1 is a key gene for the CeO_2 nanoparticle's improved cucumber salt tolerance: A validation from CRISPR-Cas9 lines. *Environ. Sci. Nano.*, 9: 4367-4381.

Qiu, J., Y. Chen, Z. Liu, H. Wen, N. Jiang, H. Shi and Y. Kou. 2023. The application of zinc oxide nanoparticles: An effective strategy to protect rice from rice blast and abiotic stresses. *Environ. Pollut.*, 331: 121925-121935.

Rikabad, M.M., L. Pourakbar, S.S. Moghaddam and J. Popović-Djordjević. 2019. Agrobiological, chemical and antioxidant properties of saffron (*Crocus sativus* L.) exposed to TiO_2 nanoparticles and ultraviolet-B stress. *Ind. Crop. Prod.*, 37: 137-143.

Rodríguez-Calzada, T., M. Qian, Å. Strid, S. Neugart, M. Schreiner, T. Torres-Pacheco and R.G. Guevara-González. 2019. Effect of UV-B radiation on morphology, phenolic compound production, gene expression, and subsequent drought stress responses in chili pepper (*Capsicum annuum* L.). *Plant Physiol. Biochem.*, 134: 94-102.

Safshekan, S., L. Pourakbar and F. Rahmani. 2025. The effect of Zn NPs on some growth, biochemical and anatomical factors of chickpea plant stem under UVB irradiation. *Plant Nano Bio*., 12: 100154.

Shang, W., X. Kang, H. Ning, J. Zhang, X. Zhang, Z. Wu, G. Mo, X. Xing and B. Han. 2013. Shape and size controlled synthesis of MOF nanocrystals with the assistance of ionic liquid mirco emulsions. *Langmuir.*, 29(43): 13168-13174.

Shen, X., Q. Zhou, M. Han, X. Qi, B. Li, Q. Zhang, J. Zhao, C. Yang, H. Liu and Y. Hu. 2021. Rapid mechanochemical synthesis of polyanionic cathode with improved electrochemical performance for Na-ion batteries. *Nat. Commun.*, 12(1): 2848-2858.

Shen, Y., J. Li, S. Zhang, X. Jiang, J. Liang, T. Li, R. Guo, W. Guan and L. Yang. 2022. Cd stress alleviation in mung-bean seedlings with biogenic hydroxyapatite nanoparticles as ecofriendly remediation agents. *Environ. Sci. Nano*, 9: 3844-3858.

Sicard, C., M. Perullini, C. Spedalieri, T. Coradin, R. Brayner, J. Livage, M. Jobbágy and S.A. Bilmes. 2011. CeO_2 Nanoparticles for the protection of photosynthetic organisms immobilized in Silica Gels. *Chem. Mater.*, 23(6): 1374-1378.

Sun, G., Z. Dong, G. Li, H. Yuan, J. Liu, X. Yao, J. Gu, H. Wu and Z. Li. 2021. Mn_3O_4 nanoparticles alleviate ROS-Inhibited root apex mitosis activities to improve maize drought tolerance. *Saudi J. Biol. Sci.*, 28: 1196-1202.

Tripathi, D.K., S. Singh, V.P. Singh, S.M. Prasad, N.K. Dubey and D.K. Chauhan. 2017. Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (*Triticum aestivum*) seedlings. *Plant Physiol. Biochem.*, 110: 70-81.

Wang, H., J. DeLisio, T. Wu, X. Wang and M.R. Zacharia. 2018. One-step solvent-free mechanochemical synthesis of metal iodate fine powders. *Powder Technol.*, 324: 62-68.

Wang, J., H. Wu, Y. Wang, W. Ye, X. Kong and Z. Yin. 2021a. Small particles, big effects: How nanoparticles can enhance plant growth in favorable and harsh conditions. *J. Integr. Plant Biol.*, 2326: 217-224.

Wang, J., M. Li, J. Feng, X. Yan, H. Chen and R. Han. 2021b. Effects of TiO_2-NPs pretreatment on UV-B stress tolerance in *Arabidopsis thaliana*. *Chemosphere*, 281: 130809-130822.

Wang, N., Z. Li, G. Zhu, Z. Yu, R. Qin, J. Zhou and N. Lin. 2023. Chemical modifications on cellulose nanocrystals for composites surface chemistry to tailored compatibility and mechanical enhancement. *Macromolecules*, 56(18): 7505-7519.

Wang, S., K. Cao, L. Xu and Y. Tong. 2022a. Improving electrochemical properties of carbon nanotubes/reduced graphene oxide composite fibers by chemical modification. *Appl. Physiol.*, 129(1): 56-67.

Wang, Y., C. Deng, W.H. Elmer, C.O. Dimkpa, S. Sharma, G. Navarro, Z. Wang, J. LaReau, B.T. Steven, Z. Wang, L. Zhao, C. Li, O.P. Dhankher, J.L. Gardea-Torresdey, B. Xing and J.C. White. 2022b. Therapeutic delivery of nanoscale sulfur to suppress disease in tomatoes: in vitro imaging and orthogonal mechanistic investigation. *ACS Nano*, 16(7): 11204-11217.

Wen, Y., Q. Fu, A. Soliwoda, S. Zhang, M. Zheng, W. Mao and Y. Wang. 2022. Cell-derived nanovesicles prepared by membrane extrusion are good substitutes for natural extracellular vesicles. *J. Extracell. Vesicles.*, 1: 100004-100013.

Xu, X., T. Zhong, N. Zuo, Z. Li, D. Li, L. Pi, P. Chen, M. Wu, T. Zhai and X. Zhou. 2022. High-T_C two-dimensional ferroelectric $CuCrS_2$ grown via chemical vapor deposition. *ACS Nano.*, 16(5): 8141-8149.

Yadav, S.K. 2010. Heavy metals toxicity in plants: An overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. *S. Afr. J. Bot.*, 76(2): 167-179.

Yang, M., S. Wang, J. Fu, Y. Zhu, J. Liang, S. Chen, S. Hu, J. Hu, J. He and Q. Li. 2023. Quantum size effect to induce colossal high-temperature energy storage density and efficiency in polymer/inorganic cluster composites. *Adv. Mater.*, 35(30): e2301936.

Yu, Y., M. Song, C. Chen, Y. Du, C. Li, Y. Han, F. Yan, Z. Shi and S. Feng. 2020. Bortezomib-Encapsulated CuS/Carbon Dot nanocomposites for enhanced photothermal therapy via stabilization of polyubiquitinated substrates in the proteasomal degradation pathway. *ACS. Nano.*, 14(8): 10688-10703.

Zeng, H., Y. Wen, L. Yin, R. Cheng, H. Wang, G. Liu and J. He. 2023. Recent developments in CVD growth and applications of 2D transition metal dichalcogenides. *Front. Physiol.*, 18(5): 53603.

Zhang, F., P. Camarero, P. Haro-González, L. Labrador-Páez and D. Jaque. 2023. Optical trapping of optical nanoparticles: Fundamentals and applications. *O. E. Sci.*, 2(9): 15-38.

Zhang, Z., C. Gómez-García, Q. Wu, J. Xin, H. Pang, H. Ma, D. Chai, S. Li and C. Zhao. 2022. Synthesis of a polyoxometalate-Encapsulated Metal-Organic framework via in ditu ligand transformation showing highly catalytic activity in both hydrogen evolution and dye degradation. *Inorg. Chem.*, 61(30): 11830-11836.

Zhao, W., Z. Wu, M. Made, G. Zhu, Y. Wei, P. Zhou, Q. Zhang, M. Song, Z. Tan, P. Zhang, Y. Rui and I. Lynch. 2023. Nanoenabled enhancement of plant tolerance to heat and drought stress on molecular response. *J. Agric. Food Chem.*, 71(51): 20405-20418.

Zhao, Y., H. Du, Y. Wang, H. Wang, S. Yang, C. Li, N. Chen, H. Yang, Y. Zhang, Y. Zhu, L. Yang and X. Hu. 2020. The calcium-dependent protein kinase ZmCDPK7 functions in heat-stress tolerance in maize. *J. Integr. Plant Biol.*, 63(3): 510-527.

Zheng, W., X. Hao, L. Zhao and W. Sun. 2017. Controllable preparation of nanoscale metal-organic frameworks by ionic liquid microemulsions. *Ind. Eng. Chem. Res.*, 56(20): 5899-5905.

Zou, C., T. Lu, R. Wang, P. Xu, Y. Jing, R. Wang, J. Xu and J. Wan. 2022. Comparative physiological and metabolomic analyses reveal that Fe_3O_4 and ZnO nanoparticles alleviate Cd toxicity in tobacco. *J. Nanobiotechn.*, 20(1): 302-324.