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The application, safety, and challenge of nanomaterials on plant growth and stress tolerance

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ABSTRACT

Nanomaterials have been widely used due to their unique biological effects and bio-interaction properties. We will discuss the effects of nanomaterials on plant growth environment, nutrient uptake and utilization, resistance to biotic and abiotic stresses, and challenges of nanomaterials application and safety considerations. Nanomaterials can positively enhance the growth and stress resistance of plants by altering the environment, including the soil physical and chemical properties and the microbial activity in the soil. A moderate supply of nanomaterials can regulate plant metabolism and gene expression, improve antioxidant capacity and nutrient uptake, and thus enhance their adaptability to adverse conditions. However, an inappropriate concentration of nanomaterials can cause stress to plants, indicating that some controversies and potential ecological risks exist. In summary, we will delve into the potential of nanomaterials in the regulation of plant growth and stress tolerance and provide references and insights for future research and applications.

1. Introduction

In recent years, nanomaterials (nanoparticles, NPs) have been extensively studied and applied in various fields such as biology, medicine, and environment due to their nanoscale size and high specific surface area (Faria et al., 2018; Hu et al., 2024; Jacquot de Rouville et al., 2018; Rajput et al., 2022; Wang et al., 2023a). NPs can be classified into three categories based on the number of spatial dimensions that conform to the nanoscale: nanofilms, nanotubes, and nanoparticles (Shin et al., 2023). According to the chemical composition, they can be divided into nano-metals, nano-crystals, nano-ceramics, nano-composites, and so on (Lead et al., 2018). When it comes to their applications, NPs can be divided into nano-pesticides, nano-carriers, nano-biomedical materials, and so on. Due to their special nanoscale effects, NPs have unique biological effects and bio-interaction properties (Hu and Xianyu, 2021), which make them play essential roles in the above applications (Jin et al., 2018; Lal et al., 2020; Rahman et al., 2018; Wang et al., 2022b).

In agriculture, as a new type of functional material, NPs have attracted more and more attention in plant biology research. The rapid development of nanotechnology has provided a new approach to improving the growth and resistance of plants. It has been shown that NPs can be used as the carriers of pesticides, which can increase the adhesion and permeability of pesticides on the surface of plants, improve the efficiency of pesticides, and reduce the application amount (Ale et al., 2023; Huang et al., 2024; Sushil et al., 2021). When NPs carry fertilizers, they can realize precise fertilization, which can reduce the waste of nutrients, improve the efficiency of plant absorption, and reduce the pollution of the environment (Wang et al., 2023b; Zhao et al., 2018). At the same time, NPs themselves can be prepared as nano-fungicides and nano-pesticides to control crop diseases and pests (Ale et al., 2023). Moreover, the plant growth promoters with NPs can facilitate plant growth and development and improve yield and quality (Saberi Riseh et al., 2022; Zhao et al., 2020). Besides, NPs are also widely used in water management and soil remediation, where they can be used to improve and purify water quality and soil, removing harmful pollutants from them (Gibert et al., 2022; Sushil et al., 2021).

In this paper, we will focus on the research progress of nanomaterials in plant growth and stress tolerance. It aims to explore the effects of NPs on the environment and plant response to adversity stress, as well as the effects on the regulation of plant nutrition and metabolism. Additionally, it will examine the challenges associated with using NPs in agriculture and consider safety concerns. Sorting out and analyzing the currently available research results both at home and abroad, will

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provide a comprehensive analysis of the potential benefits and limitations of NPs for enhancing plant growth and stress tolerance. This information can serve as a valuable resource for future research and practical application, and promote the sustainable development of agricultural production and the protection of ecological environment.

2. Effects of nanomaterials on plant growth environment

Soil plays a crucial role in plant growth by offering vital nutrients that are necessary for their development. It has been found that NPs will affect crop growth and development by altering the soil environment in which the plants live, such as soil pH, structure, porosity, bulk density, water, particle properties, organic matter content, and composition (Fig. 1) (Iqbal et al., 2024; Wang et al., 2022a). Meanwhile, as shown in Fig. 1, NPs can also influence microbial activity in the soil (Huang et al., 2022; Yang et al., 2018), which is expected to alleviate soil macronutrient and micronutrient deficiencies (Hussain et al., 2023). For example, the porous nanomaterial oblique zeolite can absorb enriched NH_4^+ in the soil and release it slowly to regulate the soil nitrogen content, thus increasing the utilization of nitrogen fertilizer, and leading to a significant increase in ryegrass yield (Millán et al., 2008). The future of selenium nano fertilizers in agriculture is promising, as evidenced by studies indicating that novel Se-doped carbon quantum dots (Se-CQDs) can markedly enhance the diversity and relative abundance of bacterial communities in soil, particularly the *Actinobacteria* phylum. This is attributed to their high hydrophilicity and selenium-rich nature, which results in an increase in the quantity of plant growth-promoting substances present in the soil (Yin et al., 2024). Similarly, nano zero-valent iron (nZVI) can remediate the heavy metal-contaminated soil by interacting with heavy metals through adsorption, reduction, co-precipitation, and complexation to immobilize the heavy metals in the soil, thereby increasing the bacterial abundance and diversity in the soil and increasing the enzymatic activity, ultimately enhances the metabolic function of the soil and remediates the soil (Jin et al., 2023). The new polyacrylamide dispersed magnetite (PAM-MAG) NPs, which immobilize 82.5 % of the water-leachable arsenate, significantly control the metal release from the soil (Zheng et al., 2020). In addition, crops are also susceptible to trace elements such as boron, copper, zinc, iron, manganese, etc., and it is theoretically feasible to use nanomaterials to regulate the control of trace elements, but there are still vacancies in the relevant research (Shang et al., 2019).

3. Effects of nanomaterials on plant nutrient uptake and utilization

Plant growth and development require a variety of nutrients, such as nitrogen, phosphorus, and potassium, which are absorbed through the root system and transported within the plant to participate in various biochemical processes and maintain the normal physiological functions of the plant (Oldroyd and Leyser, 2020). However, the effectiveness and supply levels of these nutrients in the soil are often limited, which adversely affects plant growth (Liu et al., 2022b; Sun et al., 2022). In recent years, NPs have been introduced as a new type of functional material for plant growth and agricultural production due to their unique properties and functions, which have the potential to regulate plant nutrition and metabolism by improving nutrient uptake, enhancing nutrient use efficiency, and modulating hormonal signaling pathways in plants.

3.1. Regulation of the substances uptake and transport in plant by nanomaterials

Due to their nanoscale size and high specific surface area, nanomaterials have higher reactivity and solubility, which help to improve the effectiveness of nutrients in soil (Juárez-Maldonado et al., 2019). It has been found that some nanomaterials, like zinc oxide nanoparticles and iron oxide nanomaterials, have the ability to create stable complexes with nutrients in the soil. This process enhances the water solubility of nutrients, facilitating their absorption by plant roots (Elshayb et al., 2021; Wang et al., 2014). The application of composite nanomaterials comprising calcium phosphate nanoparticles and zinc ions to tomato leaves elicited a pronounced pH response, rendering calcium, phosphorus, and zinc more soluble within the fruits and markedly elevating their concentration (Parra-Torrejón et al., 2023). As a result, essential nutrients like nitrogen, phosphorus, and potassium are more readily taken up by crops, leading to improved growth rates and higher yields in plants (Fig. 1).

After absorbing external material components, plants need to transport and distribute them among different tissues and organs to meet the needs of growth, development, and metabolism (Oldroyd and Leyser, 2020; Xu, 2018). Nanomaterials can serve as carriers to enhance the targeted delivery of materials within plants. Research indicates that nanocellulose has the ability to chelate with iron, forming nanocellulose-iron chelates that are more efficiently absorbed by the leaves of iron-deficient pear trees compared to traditional chelates. This process helps in addressing iron-deficiency yellowing in pear trees,

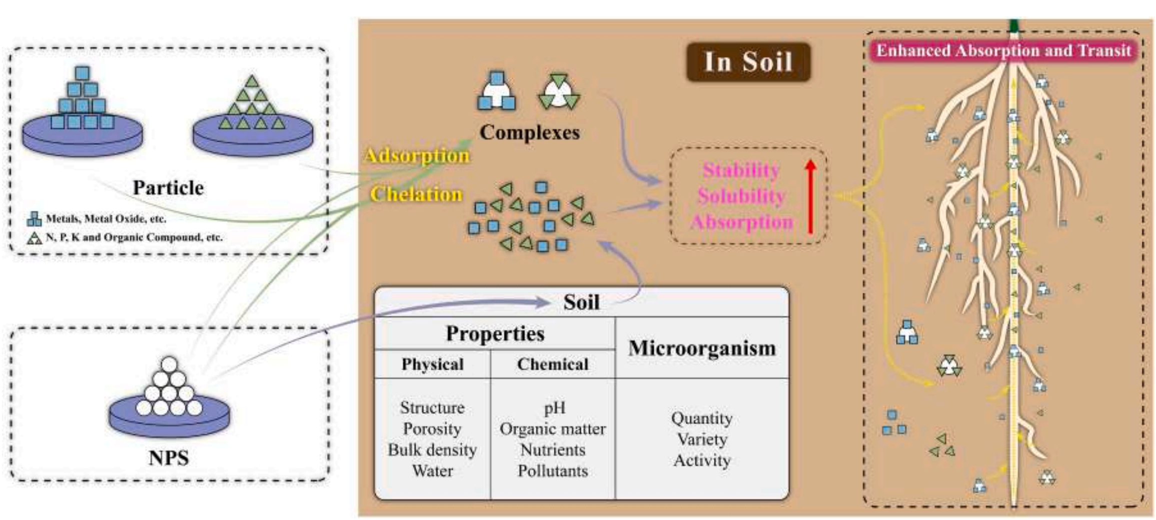

Fig. 1. Effects of nanomaterials in the soil on plant growth environment. Nanomaterials have the potential to enhance plant growth by modifying soil characteristics and increasing the stability of nutrient complexes, which in turn promotes the absorption of essential elements by plants.

while also enhancing nutrient uptake efficiency and minimizing wastage (Bian, 2022). Two nanomaterials, nano-silica and nano-selenium dioxide, can work together to regulate the uptake of polycyclic aromatic hydrocarbons (PAHs) in the ornamental plant *Sedum spectabile*, which provides a new approach for regulating the translocation of the plant (Liu et al., 2023b). Furthermore, the nanomaterials are more readily absorbed by the plant, nanosized selenium is rapidly converted to selenium (IV) when sprayed on plant leaves, binds to a variety of selenium-binding proteins (SBPs), and translocases within the plant body, thereby providing a novel solution to selenium deficiency in plants (Wang et al., 2023b).

3.2. Regulation of plant growth and metabolism by nanomaterials

Recent studies have demonstrated that nanomaterials can regulate plant metabolic activity, which refers to various biochemical reactions and material transformation processes in plants, including photosynthesis and material synthesis. Photosynthesis is a fundamental process of plant growth, which involveing the conversion of carbon dioxide and water into organic matter and oxygen through light energy. Lu (2021) found that the Mn_3O_4 enzyme can significantly increase the photosynthetic pigment content of cucumber seedlings, enhance the photosynthetic rate, and improve the biomass of cucumber. Silver nanoparticles have also been shown to increase chlorophyll and carotenoid content in plants (Gupta et al., 2018). Xiong et al. (2017) demonstrated that nanomaterials can also regulate the activity of critical enzymes in the dark reactions of photosynthesis, thereby controlling carbon fixation and modulating plant photosynthesis. In addition, nanomaterials can also restrict the essential genes involved in photosynthesis and control the related photosynthetic pigments or enzyme activities to regulate plant photosynthesis (Mohammad et al., 2013). In contrast, polystyrene nanoparticles have been demonstrated to facilitate enhanced photosynthesis in tobacco plants. This is achieved by increasing the synthesis of light and pigment, regulating the expression of photosystem I and photosynthesis chain-related genes, thereby improving the efficiency of light energy capture and electron transfer (Tian et al., 2024). For instance, nano-manganese affects the activity of the CP43 protein in the Mn_4Ca complex in plant photosystem II, improves the activity of the electron transport chain, and enhances the hydrolysis of oxygen-dissolving complexes in chloroplasts (Pradhan et al., 2013). Cerium dioxide nanoparticles can increase the intensity of plant photosynthesis by increasing the above-ground Ce^{3+} content of plants and participating in photosynthesis as a substitute for Mg^{2+} (Zhang et al., 2021). These effects contribute to increasing the production of photosynthetic products and biomass accumulation, and promote plant growth and development.

Substance synthesis is a critical process that occurs in plants, including protein synthesis, lipid synthesis, and hormone synthesis, etc., and these processes are necessary to maintain plant growth and development. It has been found that some nanomaterials can increase the yield of synthesized products by increasing the synthetic enzyme activity and promoting catalytic reactions, for examle, nano-Cu-chitosan improves the activity of α-amylase to increase the starch content in maize (Pramod et al., 2011). Meanwhile, manganese nanoparticles can regulate the nitrate reductase and nitrite reduction pathway in non-nodulated plants to increase the level of nitrogen assimilation in plants (Pradhan et al., 2014). The utilization of reactive oxygen species-generating nanomaterials (e.g., nano silver) for "stress training" in rice can facilitate the production of anti-ROS-related enzymes, hormones, and specialized metabolites (Chen et al., 2023c). In addition, Se-CQDs markedly enhanced the expression of genes encoding tomato aquaporin gene (*PIP*), growth hormone synthesis gene (*NIT*), Se methyltransferase gene (*SMT*), and methionine methyltransferase gene (*MMT*) (Yin et al., 2024). These effects help to increase the metabolic level of plants and enhance their adaptability to environmental changes and adversity.

In summary, nanomaterials have a regulatory effect on plant growth and metabolism. By increasing the efficiency of plant nutrient absorption and utilization, regulating plant physiological, and metabolic activity, as well as the process of substance synthesis and degradation to achieve the purpose of increasing yield, nanomaterials are expected to become a new type of synergist in agricultural production.

4. Effect of nanomaterials on plant resistance to biotic and abiotic stresses

4.1. Effect of nanomaterials on plant resistance to biotic stresses

Biotic stresses such as viral, bacterial, and fungal infections can pose severe threats to plant growth and yield. As a result, there has been a growing interest in utilizing nanomaterials to enhance plant resistance to these threats. In this part, we will explore the application of nanomaterials in plant defense against biotic stresses and their potential implications.

4.1.1. Effect of nanomaterials on plant resistance to microorganisms

Plant viruses are one of the critical limiting factors for crop growth, causing symptoms such as spots, shriveling, and necrosis, and reducing yield and quality (Masood et al., 2024; Scholthof et al., 2011). Nanomaterials show potential applications in inhibiting plant virus infection. Studies have shown that metal NPs can disrupt the assembly and spread of virus particles (Elmer and White, 2018), and zinc NPs can regulate phytohormone content and activate plant resistance genes (Bhattacharjee et al., 2022), thereby increasing the plant's immunity to viruses (Fig. 2). Nanomaterials provide a promising avenue for the development of novel virus-antiviral agents in agriculture.

Most plants are susceptible to bacterial and fungal infections that cause a variety of diseases. The antimicrobial properties of nanomaterials have been widely studied, and some nanoparticles have been shown to have an excellent inhibitory effect on plant pathogens. Both nano-SiO_2 and $Si(OH)_2$ can enhance the antimicrobial capacity for *Arabidopsis thaliana* by modulating the salicylic acid pathway, although nano-SiO_2 has a lower fully effective dose compared to $Si(OH)_2$, and it does not cause phytotoxicity at ten-fold higher concentrations (Du et al., 2022; El-Shetehy et al., 2021). Cai (2021) found that g-C_3N_4 nanosheets bind to bacterial cell membranes and produce a large amount of reactive oxygen species (ROS) in the presence of light, which breaks the bacterial cell membranes and leads to cytoplasmic leakage and DNA damage, thus causing bacterial death to achieve the effect of antimicrobial activity (Fig. 2). Nano-metals, on the other hand, can inhibit the growth of a variety of plant pathogens, for example, nano-silver significantly inhibits the germination of pathogenic fungal conidia, wheat root rot flat umbilical helminths (*Bipolaris sorokiniana*) (Mishra et al., 2014). Moreover, nano-silver has broad-spectrum antimicrobial activity, which can improve plant resistance to pathogenic microorganisms such as *Fusarium oxysporum* (Zhao et al., 2020) and *Gloeophyllum abietinum* (Narayanan and Park, 2014). Qiu et al. (2023) showed that nano ZnO can increase ROS content and decrease abscisic acid content, thereby enhancing the plant resistance to rice blast (*Magnaporthe oryzae*). Ma et al. (2019) showed that nano-copper phosphate can regulate the time-dependent expression of plant defense-related genes in tomatoes to enhance their resistance to *F. acnes* by transcriptomics, as shown in Fig. 2. Nano-graphene oxide, on the other hand, can be entangled with bacterial and fungal spores to locally perturb their cell membranes and lead to a decrease in bacterial membrane potential and electrolyte leakage from fungal spores, which ultimately leads to cell lysis for antimicrobial purposes (Chen et al., 2014).

4.1.2. Effect of nanomaterials on plant resistance to pests

In addition, NPs have shown promise for plant-insect resistance performance. Xiao et al. (2021) found that cerium oxide nanoparticles can significantly promote plant growth, and increase plant-insect

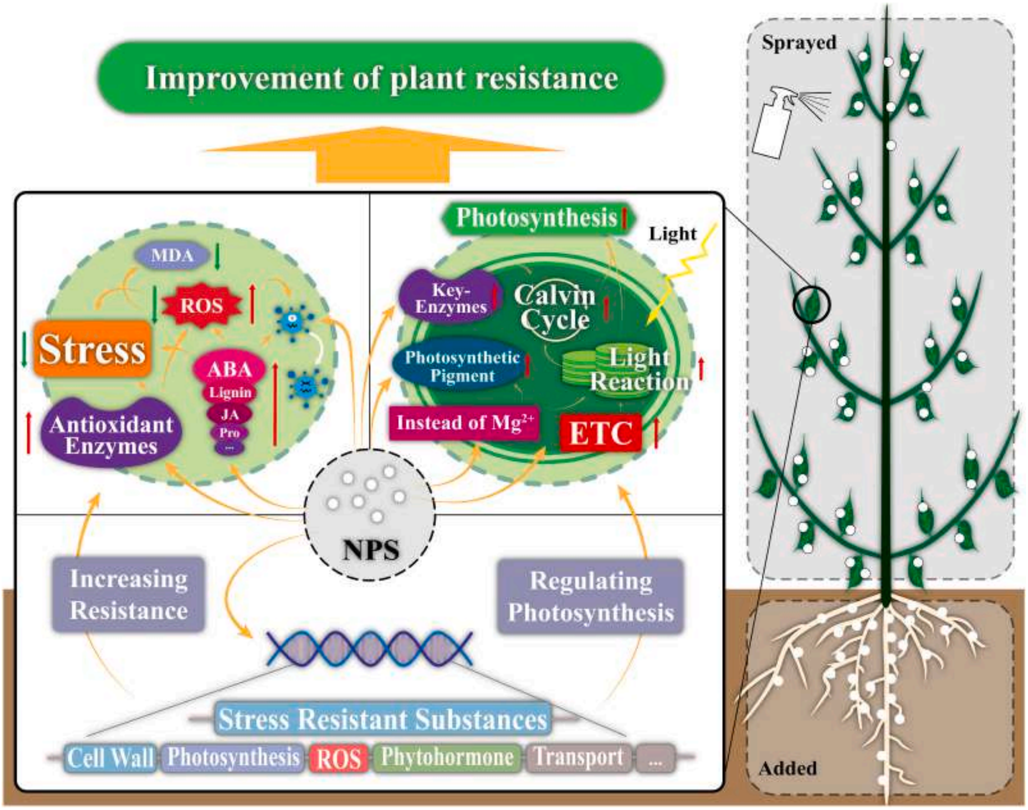

Fig. 2. Nanomaterials enhance plant resistance to adversity through multiple pathways. Nanomaterials can enhance plant resistance by regulating gene expression and increasing the levels of antiviral substances whether they are sprayed on the plant above-ground tissues or added to the growing environment. They can also directly regulate the production of reactive oxygen species (ROS) in plants to induce a response to adversity to improve resistance. In addition, nanomaterials can also participate in photosynthesis through multiple pathways to enhance the photosynthetic efficiency of plants, making them stronger and improving their level of resilience.

resistance with a dose-dependent effect. However, when the green peach aphid (*Myzus persicae)* was directly fed with cerium oxide nanoparticles treated plant leaves, its survival and reproduction were not affected (Marucci et al., 2019). These results suggest that the effect of nanomaterials on plant-insect resistance may be through the modulation of the plant's defense mechanisms. Some studies have shown that nanomaterials such as nano-silica sprayed on the surface of rice leaves can increase the lignin content of plants to enhance physical defenses against rice planthoppers (*Nilaparvata lugens*) (Cheng et al., 2021). Nanosilica can also activate multiple defense pathways in plants, leading to varying increases in the content of insect-resistant substances such as jasmonic acid, butyric acid, and chlorogenic acid to enhance insect resistance (Saw et al., 2023). Based on the transcriptomic analysis, Zhang et al. (2023) demonstrated that nano-selenium enhances tanshinone and salvinorin by activating salicylic acid and jasmonic acid signaling pathways in *Salvia miltiorrhiza*, as well as the downstream ethylene-responsive element binding factors and WRKY transcription factors, which presented a high resistance to aphids ultimately. Nanosilicon, on the other hand, upregulates the expression of maize chlorogenic acid synthesis genes and increases chlorogenic acid levels in leaves to enhance resistance to oriental armyworms (*Mythimna separata*) (Wang et al., 2021). Moreover, Nano copper can significantly increase the expression of Bt toxin-encoding genes in transgenic cotton, which also improves insect resistance (Borgatta et al., 2018). Overall, these findings suggest that nanomaterials can be a valuable tool for improving plant-insect resistance and potentially reducing the need for chemical pesticides, as shown in Fig. 2. However, further research is needed to fully understand the mechanisms underlying these effects and to optimize the use of nanomaterials in agriculture.

4.2. Effect of nanomaterials on plant resistance to abiotic stresses

Besides the biotic stress, plants often suffer various abiotic stresses in nature, such as salt stress, heavy metal pollution, climate change, chemical pollution, and so on (Waadt et al., 2022). Abiotic stresses mainly cause oxidative stress on plants due to the excessive production of reactive oxides by plant cells in adversity, which can cause oxidative damage to biomolecules such as cell membranes, proteins, and nucleic acids (Apel and Hirt, 2004; Debona et al., 2017). Studies have shown that nanomaterials can act as antioxidants to mitigate the damage caused by oxidative stress in plants, thus improving their resistance to abiotic stress (Fig. 2) (Cui et al., 2024; Najafi Vafa et al., 2021). For example, zinc oxide nanomaterials have been observed to relieve the symptoms of oxidative stress induced by various kinds of stresses in the plant body (Liu et al., 2022a). Rico et al. (2011) discovered that zinc oxide nanoparticles can induce proline synthesis in bananas and enhance the activity of the antioxidant enzyme system to improve the antioxidant performance of plants. Hu (2022) reported that iron nano fertilizer can enhance the catalase (CAT) activity and reduce the malondialdehyde (MDA) content of peanuts to attenuate oxidative damage and enhance antioxidant performance. Similarly, it has also been demonstrated that cerium oxide nanoparticles can mimic the activities of CAT and superoxide dismutase (SOD) and reduce the content of ROS in *A. thaliana* leaves (Wu et al., 2018). Chitosan-selenium-engineered nanomaterials, on the other hand, can improve plant tolerance to abiotic stresses by scavenging reactive oxygen species (Fang et al., 2024). In contrast, the application of nanomaterials at the germination stage of plants can promote ROS production and similarly improve plant tolerance to multiple abiotic stresses (Chen et al., 2023a). However, the plant response to nanoparticles varied in different species, for example, the attachment accumulation of NPs does not significantly affect the inter-root growth in duckweed (Dovidat et al., 2020).

4.2.1. Effect of nanomaterials on plant resistance to salt stress

When exposed to high salt environments, plants experience changes in their cellular osmotic pressure and ionic toxicity, resulting in compromised growth and development (Deinlein et al., 2014; Shalaby et al., 2021). Several studies have shown that nanomaterials can affect plant salt resistance. It was found that nano-Fe_3O_4 can enhance plant resistance to salt stress through multiple pathways. Nano-Fe_3O_4-soaked tomato seeds showed significantly higher germination potential than the salt-stressed control, suggesting that nano-Fe_3O_4 can alleviate the inhibition of seed germination by salt stress (Chen et al., 2023b; Liu et al., 2023a). An et al. (2020) found that suitable concentrations of cerium oxide NPs can regulate the expression of salt tolerance genes in plant cells, thereby enhancing their salt stress resistance. Cerium oxide nanoparticles can reduce the ROS content in plant leaves, thus reducing the activity of non-selective cation channels in leaf mesenchymal cells. Consequently, the intracellular concentration of potassium ions is elevated, which in turn enhances the plant's photosynthetic efficiency and its overall stress tolerance (Wu et al., 2018). In addition, cerium oxide nanoparticles can alter the root structure of plants and reduce the plasmalemma barrier in the roots, allowing more Na^+ to be transported to the above-ground part of the plant, thus improving the salt tolerance of the plant (Rossi et al., 2017).

4.2.2. Effect of nanomaterials on plant resistance to heavy metal stress

The application of nanomaterials for heavy metal stress has attracted much attention. Heavy metal pollution is a global problem that seriously affects soil quality and plant growth. Rizwan et al. (2019) found that ZnO nanomaterials, either applied alone or mixed with biochar, significantly improved maize growth under cadmium stress. This beneficial effect was attributed to the reduction of electrolyte leakage, malondialdehyde, and hydrogen peroxide content in maize leaves and roots. Concurrently, it increased the activity of antioxidant enzymes and the concentration of chlorophyll, thereby substantially improving the maize's resistance to cadmium toxicity. Also, nanomaterial SAMMNS has excellent adsorption capacity, which can adsorb and immobilize cadmium heavy metal ions in the soil and effectively reduce the content of cadmium heavy metal ions, thus reducing their toxicity effects for plants (Fang et al., 2020). Foliar spraying of titanium dioxide NPs on cowpeas has been shown to enhance the activity of proteins responsive to heavy metal stress in both roots and leaves. It also promotes the levels of essential micronutrients, such as zinc, manganese, and cobalt, in seeds, thereby augmenting the plant's tolerance to cadmium metal (Ogunkunle et al., 2020). Jin et al. (2016) found that nano-hydroxyapatite can significantly increase soil pH and reduce the solubility and mobility of Pb metals, thus increasing the resistance of ryegrass to Pb metals. In contrast, MnO nanoparticles facilitate the ability of plants to withstand Pb stress by enhancing their inherent resilience (Tahir et al., 2024). Furthermore, nanomaterials have the capacity to form stable complexes in the soil, effectively hindering the further migration of heavy metals. This action contributes to mitigating the ecological risks posed by heavy metal contamination (Feizi et al., 2018). Carboxymethyl cellulose (CMC) was used to form compounds with nano-metals to stabilize the metal materials, and the CMC-stabilized nanoFe_0 can significantly reduce the accumulation of Cr in the body of the plant (Bian, 2022).

4.2.3. Effect of nanomaterials on plant resistance to drought and high-temperature stress

Climate change has triggered many extreme weather events, such as drought and high temperatures. Nanomaterials can be used to improve plant adaptation under these extreme conditions. Sun et al. (2020) showed that zinc oxide NPs can modulate the metabolic pathway of endogenous melatonin in maize and activate the plant's antioxidant system, or enhance the level of photosynthetic carbon assimilation by regulating photosynthesis, thereby improving drought tolerance. Meanwhile, the application of nano-nutrients to tomatoes can increase plant drought tolerance by modulating the antioxidant enzyme activities, secondary metabolites, and osmotic substances (Mubashir et al., 2023). Akhtar et al. (2021) demonstrated that silica, in association with plant growth-promoting rhizobacteria (PGPR), significantly increases plant hormone levels and nutrient uptake and enhances the production rate of antioxidants, thus significantly improving the drought tolerance of wheat. Similarly, spraying nano-silica on strawberries can increase the soluble sugar content and regulate osmotic resistance to high temperatures, and also nano-silica exhibits antioxidant-like enzyme activity, which can increase the plant's tolerance to high temperatures (Yang et al., 2023). The study of Qi et al. (2013) showed that nano-titanium dioxide can increase photosynthetic efficiency by modulating photosystem II (PS II) in cucumber leaves and thus improving the level of high-temperature tolerance. Nano-selenium can be transferred from below ground to above ground in sorghum and can promote higher levels of unsaturated phospholipids under high-temperature stress, improve pollen germination, and significantly increase plant seed yield (Djanaguiraman et al., 2018). These studies provide new insights for the development of nanomaterials with the ability to modulate plant climate adaptation.

5. Challenges and safety considerations for nanomaterials applications

5.1. The role of nanomaterials themselves in stressing plants

Although many studies have reported that nanomaterials have a positive effect on plant resistance to adversity, nanomaterials themselves possess a certain degree of toxicity, and their stressful effects on plants should not be ignored. As shown in Fig. 3, the ability of plants to absorb nanomaterials is related to the size of their particles, small particles of nanomaterials can enter the plant cells to change the cell structure, which in turn affects the regulation of the cells. In contrast, nanomaterials with large particles that cannot enter the plant cell will accumulate on the cell surface, weakening the cell's ability to exchange substances (Atha et al., 2012; Parkinson et al., 2022). Stampoulis et al. (2009) discovered that pumpkins treated with nano-silver exhibited a silver content in their aboveground parts that was 4.7 times higher compared to those treated with silver powder. This finding underscores the ability of nano-silver to infiltrate the plant system and accumulate in various parts, including roots, stems, and leaves. However, this accumulation can have a detrimental impact on plant growth. For instance, it can obstruct the root system's cell walls, impeding the uptake of water and inorganic salts. Additionally, it can induce oxidative stress and alter gene expression patterns, thereby affecting the plant's overall health and development (Hossain et al., 2016; Li et al., 2022b).

In addition to the direct effects of nanomaterials on plants, nanomaterials can release ions in different media, and these ions, whether they work in the soil or are absorbed by plants, accumulate to a certain extent and adversely affect the environment and plant growth (Fig. 3). When soybeans were treated with nano-MoS_2, Mo would be released. Low concentrations of nano-MoS_2 enhanced the activity of soybean nitrogenase and improving the functionality of soybean rhizomes. However, an excessively high concentration of nano-MoS_2 resulted in the release of an excessive amount of Mo and the accumulation of sulfate in the plant, which significantly reduced the yield of soybeans (Li et al., 2024). Heavy metal ions can denature proteins, damage cell membranes, cause damage to cellular organelles, and induce chromosomal aberrations, which in turn inhibit root hair elongation, germination, biomass accumulation, and chlorophyll production in plants (Apte et al., 2009). Nano-Al_2O_3 can release aluminum ions, which will make soil acidification and inhibit the growth of plant roots. Besides this,

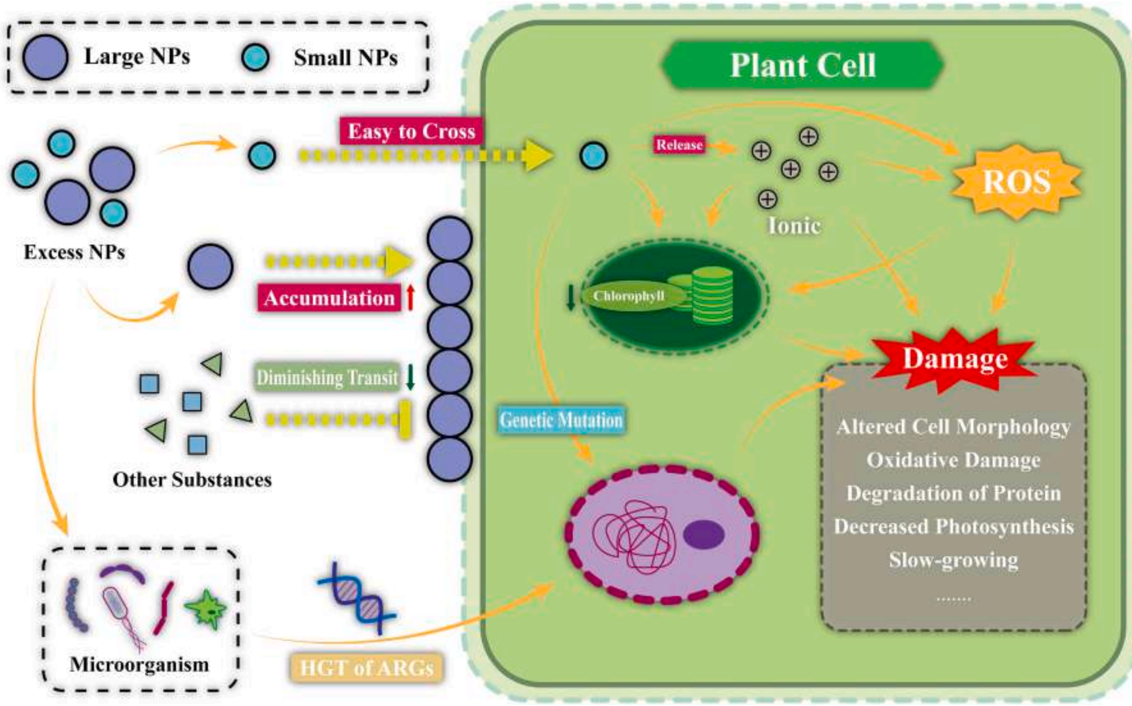

Fig. 3. Inappropriate concentrations of nanomaterials can damage plant cells. Nanomaterials themselves exhibit inherent toxicity. Large particles of nanomaterials tend to attach to the surface of plant cells, changing cell morphology and interfering with the cell's material exchange function, thereby affecting plant growth. Small particles of nanomaterials are more likely to cross the cell barrier. Due to their high surface activity, nanomaterials can release ions or generate ROS within the cell, leading to cellular toxicity and disrupting various physiological processes, including photosynthesis. In addition, nanomaterials also affect microorganisms, potentially enhancing the horizontal gene transfer (HGT) of antibiotic resistance genes (ARGs).

nano-Al_2O_3 will also make the plant excessive accumulation of ROS, resulting in membrane lipid peroxidation (Kochian, 1995; Tahara et al., 2008). Dimkpa et al. (2013) found that the Cu^{2+} released from nano-CuO not only denatures the proteins but also inhibits the uptake of Fe^{3+} and Ca^{2+} by plants, thereby impeding chlorophyll synthesis and consequently, root growth. In addition, nano-CuO was able to influence maize cell morphology by affecting the expression of maize cell wall-related genes, which led to cell wall relaxation and thus cell deformation and enlargement (Yang, 2016). The combined effects of the ion release from nanometer CuO and the activation of stress-regulated genes create a challenging environment for plant growth and development, as depicted in Fig. 3.

However, the impact of nanomaterials on plants varies significantly. Although all are nano-metal oxides, nano ZnO has been observed to release only a minimal amount of ions into the solution, thus avoiding the ionic toxicity that can be detrimental to experimental plants. Lin and Xing (2008) found that Zn^{2+} released from ZnO nano-suspension did not exhibit toxic effects on the growth of radish, oilseed rape and ryegrass. Nevertheless, even in the absence of ionic toxicity, nano-ZnO has been identified as potentially genotoxic to plants. It can inhibit seed germination, photosynthesis, and overall plant growth (Azarin et al., 2023; Dimkpa et al., 2012; Lin and Xing, 2008; Lv et al., 2022; Salah et al., 2015). Nano zinc oxide can lead to excessive accumulation of ROS in barley seedlings, thereby damaging leaves and inhibiting root growth (Dong et al., 2021). The lack of systematic research methods and evaluation frameworks often results in inconsistent conclusions across studies, highlighting the need for a more unified and rigorous approach to understanding the complex interactions between nanomaterials and plant systems.

In addition, the application of nanomaterials may have an impact on gene expression and genetic stability in plants. Some nanomaterials pose transgenic risks by interacting with microorganisms, plant, and animal cells, potentially triggering gene mutations or altering expression levels. For example (Fig. 3), nanomaterials may promote horizontal gene transfer (HGT) of antibiotic resistance genes (ARGs) by facilitating the development of microorganisms, leading to their rapid dissemination in the soil-plant system and then entering the food chain to threaten human health (Chen et al., 2022; Luo et al., 2022; Wang et al., 2024).

5.2. Soil and environmental pollution

The application of nanomaterials may have potential risks to the environment, primarily reflected in the following aspects: 1. Toxicity of nanomaterials: certain nanomaterials, such as nano plastics and nano silver, are known to possess significant toxicity, posing a direct threat to the environment (Kumar et al., 2022; Zhang et al., 2022). 2. Environmental release and contamination: nanomaterials may be released into the soil and the environment during the process of their use, which leads to the pollution of the soil and the water, causes adverse impacts on the environment and the ecosystem, and may be absorbed by the organisms in the ecological environment, enter the food chain and accumulate (Li et al., 2022a; Liu et al., 2023c; Yan et al., 2024). For instance, in agricultural settings, the accumulation of nanomaterials can degrade soil quality, suppress soil microbial activity, diminish soil fertility, and exert lasting effects on soil ecosystems (Xu et al., 2020). 3. Functional alteration through interactions with other compounds: NPs may undergo functional changes when interacting with other compounds. For example, the binding of natural organic matter to NPs can promote aggregation, thereby reducing their bioavailability and reactivity (Silva et al., 2023). In light of these potential risks, it is imperative to establish a perfect environmental risk assessment system to ensure that the application of nanomaterials does not cause irreversible effects on the ecological environment.

5.3. Food safety issues

If nanomaterials are used in food crops, their impact on food safety needs to be considered. Several studies have indicated that nanomaterials may enter the human body through the food chain and have potential health effects (Yan and Chen, 2019). For example, NPs may penetrate alveolar and cellular membranes, directly affecting the respiratory and immune systems of animal bodies, and inhalation of carbon nanotubes can lead to lung tissue damage and fibrosis of the lungs. It may lead to lung cancer in the same way that inhalation of asbestos fibers does (Bengalli et al., 2023). Additionally, The study of Lett et al. (2021) suggests that nano-plastics can lead to the disruption of endostasis in human beings, leading to blood clots or cardiovascular disease. Given these findings, it is imperative to conduct adequate risk assessments when using nanomaterials in food crops to ensure their safety for human consumption.

5.4. Safety issues of nanomaterials applications

Nanomaterials have superior physical and chemical properties compared to other materials. In comparison to the insecticide TMX (thiamethoxam) suspension, the TMX insecticide formulated with nanocarriers demonstrated a markedly enhanced efficacy in controlling *Diaphorina citri*. Furthermore, the toxicity of the two formulations to beneficial pollinator *Apis cerana* exhibited no notable discrepancy (Liu et al., 2024). Numerous studies conducted in recent years have improved our understanding of the toxicity of nanomaterials. The application of nanomaterials also faces potential challenges and risks, and their biosafety must be fully considered (White and Gardea-Torresdey, 2018). Although nanomaterials have specific growth-regulating effects in plants, their long-term effects on plants and soil ecosystems are not apparent. Further in-depth studies on their mechanisms of action and biosafety are needed to provide a scientific basis for their application and ensure safety and sustainability through appropriate measures.

Although there is still no complete set of programmatic strategies to make a unified ecological risk assessment of the toxicity of nanomaterials (Allouzi et al., 2021; Lombi et al., 2019), researchers have made significant progress in related innovations, which provide more scientific guidance for subsequent unified assessment strategies. For example, the GRACIOUS (Grouping, read-across and classification framework for regulatory risk assessment of manufactured nanomaterials and safe (r) design (SbD) of nano-enabled products (NEPs); https://www.h2020gracious.eu/) framework is currently proposed to fill the data gaps in the hazard assessment of nanomaterials, simplify the grouping of nanomaterials, and apply it to substance risk assessment. Researchers can use the framework to make a efficient, precise, and targeted risk assessment of their research subjects (Stone et al., 2020). The safety concerns surrounding the application of nanomaterials can be effectively mitigated through rigorous scientific research and prudent management practices. This will bring new possibilities for agricultural production and food security and promote the development of agriculture in a more efficient, green, and sustainable direction.

6. Conclusions and outlook

6.1. Conclusions of potential impacts of nanomaterials on plant growth and stress tolerance

Nanomaterials, as a new type of functional material, hold the potential to significantly influence plant growth and stress tolerance. These advanced materials can refine soil structure, increase soil porosity, and improve the soil's capacity to retain water and nutrients. This, in turn, expands the nutrient uptake area and absorption efficiency of the plant root system. Nanomaterials can also form stable complexes with soil nutrients, increasing their water solubility and thus facilitating nutrient absorption by the roots. Additionally, nanomaterials can stimulate the activity of root-associated microorganisms, improve the soil environment, boost the number and activity of beneficial micro-organisms in the soil, and inhibit the growth of harmful micro-organisms, thus improving the resistance of plants to pests and diseases.

Furthermore, nanomaterials can regulate nutrient transport and distribution in plants and improve the efficiency of nutrient utilization. Nanomaterials can improve the aeration and gas exchange capabilities of plant cells. Simultaneously, nanomaterials, functioning as analogs of photosynthetic pigments, can absorb and transmit energy from sunlight, regulate the process of photosynthesis and respiration in plants, increase the accumulation of photosynthetically active products, improve the carbon fixation capacity of crops, and increase the supply of oxygen and the emission of carbon dioxide, which in turn increase the respiration rate and metabolic level of plants, and this helps to increase plant biomass and yield and improve crop quality. Additionally, the nanomaterials may affect the synthesis and transport of phytohormones, thereby regulate plant growth and development and have an impact on plant growth and resistance.

Moreover, nanomaterials can enhance the adaptability of plants to various adversities, such as drought, salinity, heavy metals, pests, and diseases. By regulating the physiological metabolism of plants, nanomaterials can promote the self-repairing ability of plants and reduce the damage caused by adversity. This helps to increase the survival rate and yield of crops in unfavorable environments. Nanomaterials can stimulate plants to produce more secondary metabolites, such as antioxidant substances and secondary metabolites. These substances can enhance the chemical defenses of crops against pathogenic micro-organisms and pests, thus reducing the incidence of plant pests and diseases.

Despite the promising potential of nanomaterials to enhance plant growth and resistance, they present certain safety challenges. Research on the application of nanomaterials is still incomplete, and their practical application needs to be fully considered to avoid adverse effects on plants and soil ecosystems. In addition, the dosage and mode of application of nanomaterials need to be scientifically planned and rationally controlled to avoid adverse effects caused by overuse. Further in-depth studies on the long-term effects of nanomaterials in plants are needed. Therefore, during the application of nanomaterials, research and monitoring must be strengthened, and a scientific evaluation framework must be established to ensure their sustainable application and safety in agricultural production. By rationally utilizing the promotional effects of nanomaterials, the growth and development of plants can be improved, and the resistance of crops can be enhanced, bringing new possibilities for agricultural production and food security.

6.2. Directions for future research and prospects for development

The research direction and development prospects of nanomaterials on plant growth and stress tolerance is comprehensive, and future research can delve deeper into the intricate mechanisms by which nanomaterials influence these aspects of plant biology. By examining the uptake, transport, metabolism, and regulation of signaling pathways of nanomaterials within plants, researchers can elucidate their impact on the physiological and biochemical processes of plants. This will lay a solid scientific foundation for their practical applications. It is essential to recognize that nanomaterials vary in type, size, and shape, each potentially exerting distinct effects on plant growth and stress tolerance. Comparative studies among different nanomaterials will help to identify the most suitable nanomaterials for specific crops and environmental conditions, and more precise agricultural efficiency research on nanomaterials combined with plant genomics can explore their effects on plant gene expression and genetic stability. An in-depth study of the role of nanomaterials at the level of plant genes can lead to a better understanding of the mechanisms of nanomaterials in plant growth and stress tolerance.

In the realm of nanomaterial research, there is a pressing need to enhance the biosafety assessment of these materials within plants. It is crucial to establish an environmental monitoring system for the application of nanomaterials. This will enable early detection of potential risks and issues and ensure the safety and sustainability of nanomaterials in agricultural production. Future research needs to focus more on validating the application of nanomaterials in actual agricultural production. Through field trials and other approaches, the actual effects and economic benefits of nanomaterials in different agricultural systems can be evaluated, which will provide practical data to support their promotion in agricultural production. Overall, future research on nanomaterials on plant growth and resistance has excellent prospects for development. Research on the mechanisms of action of nanomaterials, comprehensive assessment of biosafety, and gradual advancement of practical applications will be explored in greater depth. With these continued innovations, nanomaterials can pave the way for a new era of agricultural advancement that balances productivity with ecological integrity.

CRediT authorship contribution statement

Dawei Xue: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Cong Dang:** Writing – review & editing, Visualization. **Yuchen Ping:** Writing – original draft, Visualization, Data curation. **Danyun Cao:** Writing – original draft. **Jinyan Hu:** Writing – original draft. **Yiru Lin:** Writing – original draft.

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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

Akhtar, N., Ilyas, N., Mashwani, Z.-R., Hayat, R., Yasmin, H., Noureldeen, A., Ahmad, P., 2021. Synergistic effects of plant growth promoting rhizobacteria and silicon dioxide nano-particles for amelioration of drought stress in wheat. Plant Physiol. Biochem. 166, 160–176. https://doi.org/10.1016/j.plaphy.2021.05.039.

Ale, A., Andrade, V.S., Gutierrez, M.F., Bacchetta, C., Rossi, A.S., Orihuela, P.S., Desimone, M.F., Cazenave, J., 2023. Nanotechnology-based pesticides: environmental fate and ecotoxicity. Toxicol. Appl. Pharm. 471, 116560. https://doi.org/10.1016/j.taap.2023.116560.

Allouzi, M.M.A., Tang, D.Y.Y., Chew, K.W., Rinklebe, J., Bolan, N., Allouzi, S.M.A., Show, P.L., 2021. Micro (nano) plastic pollution: the ecological influence on soil-plant system and human health. Sci. Total Environ. 788, 147815. https://doi.org/10.1016/j.scitotenv.2021.147815.

An, J., Hu, P., Li, F., Wu, H., Shen, Y., White, J.C., Tian, X., Li, Z., Giraldo, J.P., 2020. Emerging investigator series: molecular mechanisms of plant salinity stress tolerance improvement by seed priming with cerium oxide nanoparticles. Environ. Sci.: Nano 7, 2214–2228. https://doi.org/10.1039/D0EN00387E.

Apel, K., Hirt, H., 2004. Reactive oxygen species: metabolism, oxidative stress, and signal transduction. Annu. Rev. Plant Biol. 55, 373–399. https://doi.org/10.1146/annurev.arplant.55.031903.141701.

Apte, S., Rogers, N., Batley, G., 2009. Ecotoxicology of Manufactured Nanoparticles, pp. 267–305. https://doi.org/10.1002/9781444307504.ch7.

Atha, D.H., Wang, H., Petersen, E.J., Cleveland, D., Holbrook, R.D., Jaruga, P., Dizdaroglu, M., Xing, B., Nelson, B.C., 2012. Copper oxide nanoparticle mediated DNA damage in terrestrial plant models. Environ. Sci. Technol. 46, 1819–1827. https://doi.org/10.1021/es202660k.

Azarin, K., Usatov, A., Minkina, T., Duplii, N., Kasyanova, A., Fedorenko, A., Khachumov, V., Mandzhieva, S., Rajput, V.D., 2023. Effects of bulk and nano-ZnO particles on functioning of photosynthetic apparatus in barley (*Hordeum vulgare* L.). Environ. Res. 216, 114748. https://doi.org/10.1016/j.envres.2022.114748.

Bengalli, R.D., Zerbi, G., Lucotti, A., Catelani, T., Mantecca, P., 2023. Carbon nanotubes: structural defects as stressors inducing lung cell toxicity. Chem.-Biol. Interact. 382, 110613. https://doi.org/10.1016/j.cbi.2023.110613.

Bhattacharjee, R., Kumar, L., Mukerjee, N., Anand, U., Dhasmana, A., Preetam, S., Bhaumik, S., Sihi, S., Pal, S., Khare, T., Chattopadhyay, S., El-Zahaby, S.A., Alexiou, A., Koshy, E.P., Kumar, V., Malik, S., Dey, A., Prockow, J., 2022. The emergence of metal oxide nanoparticles (NPs) as a phytomedicine: a two-facet role in plant growth, nano-toxicity and anti-phyto-microbial activity. Biomed. Pharmacother. 155, 113658. https://doi.org/10.1016/j.biopha.2022.113658.

Bian, Y., 2022. Underlying Mechanism and Application of Nanocellulose-Iron Chelation for Remediationof Pear Iron Deficiency Chlorosis (M.D). Henan Agricultural University. ⟨https://doi.org/10.27117/d.cnki.ghenu.2022.000615⟩.

Borgatta, J., Ma, C., Hudson-Smith, N., Elmer, W., Plaza Pérez, C.D., De, La, Torre-Roche, R., Zuverza-Mena, N., Haynes, C.L., White, J.C., Hamers, R.J., 2018. Copper based nanomaterials suppress root fungal disease in watermelon (*Citrullus lanatus*): role of particle morphology, composition and dissolution behavior. ACS Sustain. Chem. Eng. 6, 14847–14856. https://doi.org/10.1021/acssuschemeng.8b03379.

Cai, L., 2021. Antimicrobial Bioactivities and Plant Immunity Mechanism Triggered of g-C3N4 Nanosheets and g-C3N4 @ZnONPs (Ph.D). Southwest University. ⟨https://doi.org/10.27684/d.cnki.gxndx.2021.000019⟩.

Chen, S., Liu, H., Yangzong, Z., Gardea-Torresdey, J.L., White, J.C., Zhao, L., 2023a. Seed priming with reactive oxygen species-generating nanoparticles enhanced maize tolerance to multiple abiotic stresses. Environ. Sci. Technol. 57, 19932–19941. https://doi.org/10.1021/acs.est.3c07339.

Chen, S., Lu, Y., Qi, Y., Zheng, Q., Zhang, X., Zhao, W., Chen, J., 2023b. Effects of seed soaking in Fe_3O_4 nanoparticle on tomato seed germination and seedling protective enzyme system under saline stress. Acta Pedol. Sin. 61, 1–12. https://doi.org/10.11766/trxb202302090055.

Chen, S., Pan, Z., Zhao, W., Zhou, Y., Rui, Y., Jiang, C., Wang, Y., White, J.C., Zhao, L., 2023c. Engineering climate-resilient rice using a nanobiostimulant-based "Stress Training" strategy. ACS Nano 17, 10760–10773. https://doi.org/10.1021/acsnano.3c02215.

Chen, J., Peng, H., Wang, X., Shao, F., Yuan, Z., Han, H., 2014. Graphene oxide exhibits broad-spectrum antimicrobial activity against bacterial phytopathogens and fungal conidia by intertwining and membrane perturbation. Nanoscale 6, 1879–1889. https://doi.org/10.1039/C3NR04941H.

Chen, F., Xu, Y., Du, H., Wu, H., Wang, X., Zeng, J., Wang, Z., 2022. Nanomaterials and environmental antimicrobial resistance: propagation and inhibition of antibiotic resistance gene flow in the soil-plant system (in Chinese). Chin. Sci. Bull. 67, 4206–4223.

Cheng, B., Chen, F., Wang, C., Liu, X., Yue, L., Cao, X., Wang, Z., Xing, B., 2021. The molecular mechanisms of silica nanomaterials enhancing the rice (*Oryza sativa* L.) resistance to planthoppers (*Nilaparvata lugens* Stal). Sci. Total Environ. 767, 144967. https://doi.org/10.1016/j.scitotenv.2021.144967.

Cui, B., Luo, H., Yao, X., Xing, P., Deng, S., Zhang, Q., Yi, W., Gu, Q., Peng, L., Yu, X., Zuo, C., Wang, J., Wang, Y., Tang, X., 2024. Nanosized-selenium-application-mediated cadmium toxicity in aromatic rice at different stages. Plants 13, 2253. https://doi.org/10.3390/plants13162253.

Debona, D., Rodrigues, F.A., Datnoff, L.E., 2017. Silicon's role in abiotic and biotic plant stresses. Annu. Rev. Phytopathol. 55, 85–107. https://doi.org/10.1146/annurev-phyto-080516-035312.

Deinlein, U., Stephan, A.B., Horie, T., Luo, W., Xu, G., Schroeder, J.I., 2014. Plant salt-tolerance mechanisms. Trends Plant Sci. 19, 371–379. https://doi.org/10.1016/j.tplants.2014.02.001.

Dimkpa, C.O., Latta, D.E., McLean, J.E., Britt, D.W., Boyanov, M.I., Anderson, A.J., 2013. Fate of CuO and ZnO nano- and microparticles in the plant environment. Environ. Sci. Technol. 47, 4734–4742. https://doi.org/10.1021/es304736y.

Dimkpa, C.O., McLean, J.E., Latta, D.E., Manangón, E., Britt, D.W., Johnson, W.P., Boyanov, M.I., Anderson, A.J., 2012. CuO and ZnO nanoparticles: phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. J. Nanopart. Res. 14, 1125. https://doi.org/10.1007/s11051-012-1125-9.

Djanaguiraman, M., Belliraj, N., Bossmann, S.H., Prasad, P.V.V., 2018. High-temperature stress alleviation by selenium nanoparticle treatment in grain sorghum. ACS Omega 3, 2479–2491. https://doi.org/10.1021/acsomega.7b01934.

Dong, M., Sun, R., Yang, Q., Zhang, L., Yong, Y., Fang, Y., Zhang, X., Zhang, X., Xue, D., 2021. Phenotype, physiology, and gene expression of barley seedlings in response to nano zinc oxide stress. Phyton-Int. J. Exp. Bot. 90, 1589–1598. https://doi.org/10.32604/phyton.2021.017465.

Dovidat, L.C., Brinkmann, B.W., Vijver, M.G., Bosker, T., 2020. Plastic particles adsorb to the roots of freshwater vascular plant *Spirodela polyrhiza* but do not impair growth. Limnol. Oceanogr. Lett. 5, 37–45. https://doi.org/10.1002/lol2.10118.

Du, J., Liu, B., Zhao, T., Xu, X., Lin, H., Ji, Y., Li, Y., Li, Z., Lu, C., Li, P., Zhao, H., Li, Y., Yin, Z., Ding, X., 2022. Silica nanoparticles protect rice against biotic and abiotic stresses. J. Nanobiotechnol. 20, 197. https://doi.org/10.1186/s12951-022-01420-x.

Elmer, W., White, J.C., 2018. The future of nanotechnology in plant pathology. Annu. Rev. Phytopathol. 56, 111–133. https://doi.org/10.1146/annurev-phyto-080417-050108.

Elshayb, O.M., Farroh, K.Y., Amin, H.E., Atta, A.M., 2021. Green synthesis of zinc oxide nanoparticles: fortification for rice grain yield and nutrients uptake enhancement. Molecules 26, 584. https://doi.org/10.3390/molecules26030584.

El-Shetehy, M., Moradi, A., Maceroni, M., Reinhardt, D., Petri-Fink, A., Rothen-Rutishauser, B., Mauch, F., Schwab, F., 2021. Silica nanoparticles enhance disease resistance in arabidopsis plants. Nat. Nanotechnol. 16, 344–353. https://doi.org/10.1038/s41565-020-00812-0.

Fang, J., Peng, Y., Zheng, L., He, C., Peng, S., Huang, Y., Wang, L., Liu, H., Feng, G., 2024. Chitosan–se engineered nanomaterial mitigates salt stress in plants by

scavenging reactive oxygen species. J. Agric. Food Chem. 72, 176–188. https://doi.org/10.1021/acs.jafc.3c06185.
Fang, K., Xiao, X., Ye, Y., Zhong, G., Zhu, A., Zhou, L., Wang, M., Wang, F., Hong, X., 2020. Application effects of SAMMNS nanometer material in paddy fields of Cd & Cu composite pollution (in Chinese). J. Agric. 10, 46–51.
Faria, M., Björnmalm, M., Thurecht, K.J., Kent, S.J., Parton, R.G., Kavallaris, M., Johnston, A.P.R., Gooding, J.J., Corrie, S.R., Boyd, B.J., Thordarson, P., Whittaker, A.K., Stevens, M.M., Prestidge, C.A., Porter, C.J.H., Parak, W.J., Davis, T. P., Crampin, E.J., Caruso, F., 2018. Minimum information reporting in bio-nano experimental literature. Nat. Nanotechnol. 13, 777–785. https://doi.org/10.1038/s41565-018-0246-4.
Feizi, M., Jalali, M., Renella, G., 2018. Nanoparticles and modified clays influenced distribution of heavy metals fractions in a light-textured soil amended with sewage sludges. J. Hazard. Mater. 343, 208–219. https://doi.org/10.1016/j.jhazmat.2017.09.027.
Gibert, O., Sánchez, D., Cortina, J.L., 2022. Removal of nitrate and pesticides from groundwater by nano zero-valent iron injection pulses under biostimulation and bioaugmentation scenarios in continuous-flow packed soil columns. J. Environ. Manag. 321, 115965. https://doi.org/10.1016/j.jenvman.2022.115965.
Gupta, S.D., Agarwal, A., Pradhan, S., 2018. Phytostimulatory effect of silver nanoparticles (AgNPs) on rice seedling growth: an insight from antioxidative enzyme activities and gene expression patterns. Ecotoxicol. Environ. Saf. 161, 624–633. https://doi.org/10.1016/j.ecoenv.2018.06.023.
Hossain, Z., Mustafa, G., Sakata, K., Komatsu, S., 2016. Insights into the proteomic response of soybean towards Al_2O_3, ZnO, and ag nanoparticles stress. J. Hazard. Mater. 304, 291–305. https://doi.org/10.1016/j.jhazmat.2015.10.071.
Hu, Z., 2022. Effects of Foliar Spraying Nano-iron Fertilizer on Growth and Iron Nutrition of Peanut and Citrus Seedlings (M.D). Southwest University. 〈https://doi.org/10.27684/d.cnki.gxndx.2022.000736〉.
Hu, Y., Cao, Y., Ma, C., Yan, W., 2024. Nano-biochar as a potential amendment for metal (loid) remediation: implications for soil quality improvement and stress alleviation. J. Environ. Manag. 351, 119658. https://doi.org/10.1016/j.jenvman.2023.119658.
Hu, J., Xianyu, Y., 2021. When nano meets plants: a review on the interplay between nanoparticles and plants. Nano Today 38, 101143. https://doi.org/10.1016/j.nantod.2021.101143.
Huang, H., Chen, J., Liu, S., Pu, S., 2022. Impact of ZnO nanoparticles on soil lead bioavailability and microbial properties. Sci. Total Environ. 806, 150299. https://doi.org/10.1016/j.scitotenv.2021.150299.
Huang, X., Ni, X., Li, H., Wei, Y., Wang, Z., Zhen, C., Yin, M., Shen, J., Shi, W., Zhang, Y., Yan, S., 2024. Synergistic mechanism of botanical pesticide camptothecin encapsulated in a nanocarrier against fall armyworm: enhanced stability and amplified growth suppression. Ecotoxicol. Environ. Saf. 284, 116900. https://doi.org/10.1016/j.ecoenv.2024.116900.
Hussain, M., Zahra, N., Lang, T., Zain, M., Raza, M., Shakoor, N., Adeel, M., Zhou, H., 2023. Integrating nanotechnology with plant microbiome for next-generation crop health. Plant Physiol. Biochem. 196, 703–711. https://doi.org/10.1016/j.plaphy.2023.02.022.
Iqbal, S., Xu, J., Arif, M.S., Worthy, F.R., Jones, D.L., Khan, S., Alharbi, S.A., Filimonenko, E., Nadir, S., Bu, D., Shakoor, A., Gui, H., Schaefer, D.A., Kuzyakov, Y., 2024. Do added microplastics, native soil properties, and prevailing climatic conditions have consequences for carbon and nitrogen contents in soil? A global data synthesis of pot and greenhouse studies. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.3c10247.
Jacquot de Rouville, H.P., Kammerer, C., Rapenne, G., 2018. From the synthesis of nanovehicles to participation in the first nanocar race-view from the french team. Molecules 23, 612. https://doi.org/10.3390/molecules23030612.
Jin, Y., Liu, W., Li, X., Shen, S., Liang, S., Liu, C., Shan, L., 2016. Nano-hydroxyapatite immobilized lead and enhanced plant growth of ryegrass in a contaminated soil. Ecol. Eng. 95, 25–29. https://doi.org/10.1016/j.ecoleng.2016.06.071.
Jin, S., Oh, S., Brammer, K., 2018. Articles comprising nano-materials for geometry-guided stem cell differentiation and enhanced bone growth. US20180297839A1.
Jin, Y., Wang, Y., Li, X., Luo, T., Ma, Y., Wang, B., Liang, H., 2023. Remediation and its biological responses to Cd(II)-Cr(VI)-Pb(II) multi-contaminated soil by supported nano zero-valent iron composites. Sci. Total Environ. 867, 161344. https://doi.org/10.1016/j.scitotenv.2022.161344.
Juárez-Maldonado, A., Ortega-Ortíz, H., Morales-Díaz, A.B., González-Morales, S., Morelos-Moreno, Á., Cabrera-De la Fuente, M., Sandoval-Rangel, A., Cadenas-Pliego, G., Benavides-Mendoza, A., 2019. Nanoparticles and nanomaterials as plant biostimulants. Int. J. Mol. Sci. 20, 162. https://doi.org/10.3390/ijms20010162.
Kochian, L.V., 1995. Cellular mechanisms of aluminum toxicity and resistance in plants. Annu. Rev. Plant Biol. 46, 237–260. https://doi.org/10.1146/annurev.pp.46.060195.001321.
Kumar, R., Manna, C., Padha, S., Verma, A., Sharma, P., Dhar, A., Ghosh, A., Bhattacharya, P., 2022. Micro(nano)plastics pollution and human health: how plastics can induce carcinogenesis to humans? Chemosphere 298, 134267. https://doi.org/10.1016/j.chemosphere.2022.134267.
Lal, R., Hwang, M.T., Landon, P.B., Glinskii, G.V., Mo, A., Ramachandran, S., Lee, J., Meckes, B., 2020. Nano-sensors for nucleic acid detection and discrimination. US10793898B2.
Lead, J.R., Batley, G.E., Alvarez, P.J.J., Croteau, M.-N., Handy, R.D., McLaughlin, M.J., Judy, J.D., Schirmer, K., 2018. Nanomaterials in the environment: behavior, fate, bioavailability, and effects–an updated review. Environ. Toxicol. Chem. 37, 2029–2063. https://doi.org/10.1002/etc.4147.
Lett, Z., Hall, A., Skidmore, S., Alves, N.J., 2021. Environmental microplastic and nanoplastic: exposure routes and effects on coagulation and the cardiovascular system. Environ. Pollut. 291, 118190. https://doi.org/10.1016/j.envpol.2021.118190.
Li, S., Chen, S., Zhang, Z., Huang, Y., Li, G., Li, Y., Deng, X., Li, J., 2022b. Short-term exposure to silver nano-particles alters the physiology and induces stress-related gene expression in *Nelumbo nucifera*. Plant Physiol. Biochem. 177, 38–45. https://doi.org/10.1016/j.plaphy.2022.02.021.
Li, M., Zhang, Y., Feng, S., Zhang, X., Xi, Y., Xiang, X., 2022a. Bioaccumulation and biomagnification effects of nano-TiO_2 in the aquatic food chain. Ecotoxicology 31, 1023–1034. https://doi.org/10.1007/s10646-022-02572-0.
Li, M., Zhang, P., Guo, Z., Zhao, W., Li, Y., Yi, T., Cao, W., Gao, L., Tian, C.F., Chen, Q., Ren, F., Rui, Y., White, J.C., Lynch, I., 2024. Dynamic transformation of nano-MoS2 in a soil-plant system empowers its multifunctionality on soybean growth. Environ. Sci. Technol. 58, 1211–1222. https://doi.org/10.1021/acs.est.3c09004.
Lin, D., Xing, B., 2008. Root uptake and phytotoxicity of ZnO nanoparticles. Environ. Sci. Technol. 42, 5580–5585. https://doi.org/10.1021/es800422x.
Liu, Y., Ben, Y., Che, R., Peng, C., Li, J., Wang, F., 2023c. Uptake, transport and accumulation of micro- and nano-plastics in terrestrial plants and health risk associated with their transfer to food chain – a mini review. Sci. Total Environ. 902, 166045. https://doi.org/10.1016/j.scitotenv.2023.166045.
Liu, S., He, F., Kuzyakov, Y., Xiao, H., Hoang, D.T.T., Pu, S., Razavi, B.S., 2022b. Nutrients in the rhizosphere: a meta-analysis of content, availability, and influencing factors. Sci. Total Environ. 826, 153908. https://doi.org/10.1016/j.scitotenv.2022.153908.
Liu, D., Iqbal, S., Gui, H., Xu, J., An, S., Xing, B., 2023a. Nano-iron oxide (Fe_3O_4) mitigates the effects of microplastics on a ryegrass soil–microbe–plant system. ACS Nano 17, 24867–24882. https://doi.org/10.1021/acsnano.3c05809.
Liu, L., Nian, H., Lian, T., 2022a. Plants and rhizospheric environment: affected by zinc oxide nanoparticles (ZnO NPs). A review. Plant Physiol. Biochem. 185, 91–100. https://doi.org/10.1016/j.plaphy.2022.05.032.
Liu, T., Qian, K., Fan, J., Qin, Z., Yi, L., Wang, J., Dou, W., 2024. Nano-based smart pesticide formulations utilizing starch nanocrystals: achieving high stability and extended effective duration. Ind. Crops Prod. 214, 118470. https://doi.org/10.1016/j.indcrop.2024.118470.
Liu, J., Wang, Y., Wang, M., Feng, X., Liu, R., Xue, Z., Zhou, Q., 2023b. Improving the uptake of PAHs by the ornamental plant *Sedum spectabile* using nano-SiO_2 and nano-CeO_2. Sci. Total Environ. 870, 161808. https://doi.org/10.1016/j.scitotenv.2023.161808.
Lombi, E., Donner, E., Dusinska, M., Wickson, F., 2019. A One Health approach to managing the applications and implications of nanotechnologies in agriculture. Nat. Nanotechnol. 14, 523–531. https://doi.org/10.1038/s41565-019-0460-8.
Lu, L., 2021. Utilizing Mn3O4 Nanozyme to Promote Plant Growth and Enhance Stress Tolerance (M.D). Nanjing University. 〈https://doi.org/10.27235/d.cnki.gnjiu.2021.002556〉.
Luo, L., Deng, D., Zhao, X., Hu, H., Li, X., Gu, J., He, Y., Yang, G., Deng, O., Xiao, Y., 2022. The dual roles of nano zero-valent iron and zinc oxide in antibiotics resistance genes (ARGs) spread in sediment. Int. J. Environ. Res. Public. Health 19, 9405. https://doi.org/10.3390/ijerph19159405.
Lv, W., Geng, H., Zhou, B., Chen, H., Yuan, R., Ma, C., Liu, R., Xing, B., Wang, F., 2022. The behavior, transport, and positive regulation mechanism of ZnO nanoparticles in a plant-soil-microbe environment. Environ. Pollut. 315, 120368. https://doi.org/10.1016/j.envpol.2022.120368.
Ma, C., Borgatta, J., De, La, Torre-Roche, R., Zuverza-Mena, N., White, J.C., Hamers, R.J., Elmer, W.H., 2019. Time-dependent transcriptional response of tomato (*Solanum lycopersicum* L.) to cu nanoparticle exposure upon infection with fusarium oxysporum f. sp. lycopersici. ACS Sustain. Chem. Eng. 7, 10064–10074. https://doi.org/10.1021/acssuschemeng.9b01433.
Marucci, R.C., Freitas, L.M., Santos-Rasera, J.R., Alves, D.S., Carvalho, G.A., Carvalho, H. W.P. de, 2019. Are cerium oxide nanoparticles transferred from plants to the aphid *Myzus persicae* (Hemiptera: Aphididae)? Fla. Entomol. 102, 555–561. https://doi.org/10.1653/024.102.0338.
Masood, H.A., Qi, Y., Zahid, M.K., Li, Z., Ahmad, S., Lv, J.-M., Shahid, M.S., Ali, H.E., Ondrasek, G., Qi, X., 2024. Recent advances in nano-enabled immunomodulation for enhancing plant resilience against phytopathogens. Front. Plant Sci. 15, 1445786. https://doi.org/10.3389/fpls.2024.1445786.
Millán, G., Agosto, F., Vázquez, M., Botto, L., Lombardi, L., Juan, L., 2008. Use of clinoptilolite as a carrier for nitrogen fertilizers in soils of the Pampean regions of Argentina. Cienc. Invest. Agrar. 35, 293–302. https://doi.org/10.4067/S0718-16202008000300007.
Mishra, S., Singh, B.R., Singh, A., Keswani, C., Naqvi, A.H., Singh, H.B., 2014. Biofabricated silver nanoparticles act as a strong fungicide against bipolaris sorokiniana causing spot blotch disease in wheat. PLoS One 9, e97881. https://doi.org/10.1371/journal.pone.0097881.
Mohammad, H., Ghafariyan, Mohammad, Malakouti, J., Mohammad, R., Dadpour, 2013. Effects of magnetite nanoparticles on soybean chlorophyll. Environ. Sci. Technol. 47, 10645–10652.
Mubashir, A., Nisa, Z.-, Shah, A.A., Kiran, M., Hussain, I., Ali, N., Zhang, L., Madnay, M. M.Y., Alsiary, W.A., Korany, S.M., Ashraf, M., Al-Mur, B.A., AbdElgawad, H., 2023. Effect of foliar application of nano-nutrients solution on growth and biochemical attributes of tomato (*Solanum lycopersicum*) under drought stress. Front. Plant Sci. 13, 1066790. https://doi.org/10.3389/fpls.2022.1066790.
Najafi Vafa, Z., Sirousmehr, A., Bijani, M., 2021. Effect of different levels of humic acid and nano-zinc fertilizer on the antioxidant enzyme activities and essential oil of Savory (*Satureja hortensis* L.). Hortic. Plants Nutr. 3, 43–58. https://doi.org/10.22070/hpn.2020.4876.1050.

Narayanan, K.B., Park, H.H., 2014. Antifungal activity of silver nanoparticles synthesized using turnip leaf extract (*Brassica rapa* L.) against wood rotting pathogens. Eur. J. Plant Pathol. 140, 185–192. https://doi.org/10.1007/s10658-014-0399-4.

Ogunkunle, C.O., Odulaja, D.A., Akande, F.O., Varun, M., Vishwakarma, V., Fatoba, P.O., 2020. Cadmium toxicity in cowpea plant: effect of foliar intervention of nano-TiO_2 on tissue Cd bioaccumulation, stress enzymes and potential dietary health risk. J. Biotechnol. 310, 54–61. https://doi.org/10.1016/j.jbiotec.2020.01.009.

Oldroyd, G.E.D., Leyser, O., 2020. A plant's diet, surviving in a variable nutrient environment. Science 368, eaba0196. https://doi.org/10.1126/science.aba0196.

Parkinson, S.J., Tungsirisurp, S., Joshi, C., Richmond, B.L., Gifford, M.L., Sikder, A., Lynch, I., O'Reilly, R.K., Napier, R.M., 2022. Polymer nanoparticles pass the plant interface. Nat. Commun. 13, 7385. https://doi.org/10.1038/s41467-022-35066-y.

Parra-Torrejón, B., Cáceres, A., Sánchez, M., Sainz, L., Guzmán, M., Bermúdez-Perez, F. J., Ramírez-Rodríguez, G.B., Delgado-López, J.M., 2023. Multifunctional nanomaterials for biofortification and protection of tomato plants. Environ. Sci. Technol. 57, 14950–14960. https://doi.org/10.1021/acs.est.3c02559.

Pradhan, S., Patra, P., Das, S., Chandra, S., Mitra, S., Dey, K.K., Akbar, S., Palit, P., Goswami, A., 2013. Photochemical modulation of biosafe manganese nanoparticles on *Vigna radiata*: a detailed molecular, biochemical, and biophysical study. Environ. Sci. Technol. 47, 13122–13131. https://doi.org/10.1021/es402659t.

Pradhan, S., Patra, P., Mitra, S., Dey, K.K., Jain, S., Sarkar, S., Roy, S., Palit, P., Goswami, A., 2014. Manganese nanoparticles: impact on non-nodulated plant as a potent enhancer in nitrogen metabolism and toxicity study both in vivo and in vitro. J. Agric. Food Chem. 62, 8777–8785. https://doi.org/10.1021/jf502716c.

Pramod, M., Dhoke, S.K., Khanna, A.S., 2011. Effect of nano-ZnO particle suspension on growth of mung (*Vigna radiata*) and gram (*Cicer arietinum*) seedlings using plant agar method. J. Nanosci. Nanotechnol. 2011, 696535. https://doi.org/10.1155/2011/696535.

Qi, M., Liu, Y., Li, T., 2013. Nano-TiO_2 improve the photosynthesis of tomato leaves under mild heat stress. Biol. Trace Elem. Res. 156, 323–328. https://doi.org/10.1007/s12011-013-9833-2.

Qiu, J., Chen, Y., Liu, Z., Wen, H., Jiang, N., Shi, H., Kou, Y., 2023. The application of zinc oxide nanoparticles: an effective strategy to protect rice from rice blast and abiotic stresses. Environ. Pollut. 331, 121925. https://doi.org/10.1016/j.envpol.2023.121925.

Rahman, M.K., Baig, M.T., Al-Majed, A., 2018. Nano zeolite cement additive and methods of use. US10150904B1.

Rajput, V.D., Minkina, T., Ahmed, B., Singh, V.K., Mandzhieva, S., Sushkova, S., Bauer, T., Verma, K.K., Shan, S., van Hullebusch, E.D., Wang, B., 2022. Nano-biochar: a novel solution for sustainable agriculture and environmental remediation. Environ. Res. 210, 112891. https://doi.org/10.1016/j.envres.2022.112891.

Rico, C.M., Majumdar, S., Duarte-Gardea, M., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2011. Interaction of nanoparticles with edible plants and their possible implications in the food chain. J. Agric. Food Chem. 59, 3485–3498. https://doi.org/10.1021/jf104517j.

Rizwan, M., Ali, S., Zia Ur Rehman, M., Adrees, M., Arshad, M., Qayyum, M.F., Ali, L., Hussain, A., Chatha, S.A.S., Imran, M., 2019. Alleviation of cadmium accumulation in maize (*Zea mays* L.) by foliar spray of zinc oxide nanoparticles and biochar to contaminated soil. Environ. Pollut. 248, 358–367. https://doi.org/10.1016/j.envpol.2019.02.031.

Rossi, L., Zhang, W., Ma, X., 2017. Cerium oxide nanoparticles alter the salt stress tolerance of *Brassica napus* L. by modifying the formation of root apoplastic barriers. Environ. Pollut. 229, 132–138. https://doi.org/10.1016/j.envpol.2017.05.083.

Saberi Riseh, R., Hassanisaadi, M., Vatankhah, M., Soroush, F., Varma, R.S., 2022. Nano/microencapsulation of plant biocontrol agents by chitosan, alginate, and other important biopolymers as a novel strategy for alleviating plant biotic stresses. Int. J. Biol. Macromol. 222, 1589–1604. https://doi.org/10.1016/j.ijbiomac.2022.09.278.

Salah, S.M., Yajing, G., Dongdong, C., Jie, L., Aamir, N., Qijuan, H., Weimin, H., Mingyu, N., Jin, H., 2015. Seed priming with polyethylene glycol regulating the physiological and molecular mechanism in rice (*Oryza sativa* L.) under nano-ZnO stress. Sci. Rep. 5, 14278. https://doi.org/10.1038/srep14278.

Saw, G., Nagdev, P., Jeer, M., Murali-Baskaran, R.K., 2023. Silica nanoparticles mediated insect pest management. Pestic. Biochem. Physiol. 194, 105524. https://doi.org/10.1016/j.pestbp.2023.105524.

Scholthof, K.-B.G., Adkins, S., Czosnek, H., Palukaitis, P., Jacquot, E., Hohn, T., Hohn, B., Saunders, K., Candresse, T., Ahlquist, P., Hemenway, C., Foster, G.D., 2011. Top 10 plant viruses in molecular plant pathology. Mol. Plant Pathol. 12, 938–954. https://doi.org/10.1111/j.1364-3703.2011.00752.x.

Shalaby, T.A., Abd-Alkarim, E., El-Aidy, F., Hamed, E.-S., Sharaf-Eldin, M., Taha, N., El-Ramady, H., Bayoumi, Y., Dos Reis, A.R., 2021. Nano-selenium, silicon and H_2O_2 boost growth and productivity of cucumber under combined salinity and heat stress. Ecotoxicol. Environ. Saf. 212, 111962. https://doi.org/10.1016/j.ecoenv.2021.111962.

Shang, Y., Hasan, Md.K., Ahammed, G.J., Li, M., Yin, H., Zhou, J., 2019. Applications of nanotechnology in plant growth and crop protection: a review. Molecules 24, 2558. https://doi.org/10.3390/molecules24142558.

Shin, J., Kang, N., Kim, B., Hong, H., Yu, L., Kim, J., Kang, H., Kim, J.S., 2023. One-dimensional nanomaterials for cancer therapy and diagnosis. Chem. Soc. Rev. 52, 4488–4514. https://doi.org/10.1039/D2CS00840H.

Silva, M.M. da, Wasserman, M.A.V., Wasserman, J.C., de, F.A., Pérez, D.V., Pereira, T.R., Barreto, M.B., Santos-Oliveira, R., 2023. Effect of nanomaterials on the bioavailability of metals in sediments from a highly impacted tropical coastal environment. Environ. Nanotechnol. Monit. Manag. 20, 100799. https://doi.org/10.1016/j.enmm.2023.100799.

Stampoulis, D., Sinha, S.K., White, J.C., 2009. Assay-dependent phytotoxicity of nanoparticles to plants. Environ. Sci. Technol. 43, 9473–9479. https://doi.org/10.1021/es901695c.

Stone, V., Gottardo, S., Bleeker, E.A.J., Braakhuis, H., Dekkers, S., Fernandes, T., Haase, A., Hunt, N., Hristozov, D., Jantunen, P., Jeliazkova, N., Johnston, H., Lamon, L., Murphy, F., Rasmussen, K., Rauscher, H., Jiménez, A.S., Svendsen, C., Spurgeon, D., Vázquez-Campos, S., Wohlleben, W., Oomen, A.G., 2020. A framework for grouping and read-across of nanomaterials-supporting innovation and risk assessment. Nano Today 35, 100941. https://doi.org/10.1016/j.nantod.2020.100941.

Sun, L., Song, F., Guo, J., Zhu, X., Liu, S., Liu, F., Li, X., 2020. Nano-ZnO-induced drought tolerance is associated with melatonin synthesis and metabolism in maize. Int. J. Mol. Sci. 21, 782. https://doi.org/10.3390/ijms21030782.

Sun, C., Sun, N., Ou, Y., Gong, B., Jin, C., Shi, Q., Lin, X., 2022. Phytomelatonin and plant mineral nutrition. J. Exp. Bot. 73, 5903–5917. https://doi.org/10.1093/jxb/erac289.

Sushil, A., Kamla, M., Nisha, K., Karmal, M., Sandeep, A., 2021. Nano-enabled pesticides in agriculture: budding opportunities and challenges. J. Nanosci. Nanotechnol. 21, 3337–3350. https://doi.org/10.1166/jnn.2021.19018.

Tahara, K., Yamanoshita, T., Norisada, M., Hasegawa, I., Kashima, H., Sasaki, S., Kojima, K., 2008. Aluminum distribution and reactive oxygen species accumulation in root tips of two Melaleuca trees differing in aluminum resistance. Plant Soil 307, 167–178. https://doi.org/10.1007/s11104-008-9593-5.

Tahir, K., Haroon, U., Akbar, M., Elahi, M., Quraishi, U.M., 2024. Tetragonal crystalline MnO nanoparticles alleviate Pb stress in wheat by modulating antioxidant enzymes in leaves. Physiol. Mol. Biol. Plants 30, 1401–1411. https://doi.org/10.1007/s12298-024-01488-9.

Tian, J., Xu, Z., Huang, W., Han, D., Dang, B., Xu, J., Jia, W., 2024. Physiobiochemical and transcriptional responses of tobacco plants (*Nicotiana tabacum* L.) to different doses of polystyrene nanoplastics. Ind. Crops Prod. 220, 119218. https://doi.org/10.1016/j.indcrop.2024.119218.

Waadt, R., Seller, C.A., Hsu, P.-K., Takahashi, Y., Munemasa, S., Schroeder, J.I., 2022. Plant hormone regulation of abiotic stress responses. Nat. Rev. Mol. Cell Biol. 23, 680–694. https://doi.org/10.1038/s41580-022-00479-6.

Wang, X., Chen, Q., Pang, R., Zhang, C., Huang, G., Han, Z., Su, Y., 2024. Exposure modes determined the effects of nanomaterials on antibiotic resistance genes: the different roles of oxidative stress and quorum sensing. Environ. Pollut. 360, 124772. https://doi.org/10.1016/j.envpol.2024.124772.

Wang, Y., Fang, Z., Kang, Y., Tsang, E.P., 2014. Immobilization and phytotoxicity of chromium in contaminated soil remediated by CMC-stabilized nZVI. J. Hazard. Mater. 275, 230–237. https://doi.org/10.1016/j.jhazmat.2014.04.056.

Wang, Y., Feng, L.J., Sun, X.D., Zhang, M., Duan, J.L., Xiao, F., Lin, Y., Zhu, F.P., Kong, X. P., Ding, Z., Yuan, X.Z., 2023b. Incorporation of selenium derived from nanoparticles into plant proteins in vivo. ACS Nano 17, 15847–15856. https://doi.org/10.1021/acsnano.3c03739.

Wang, F., Wang, Q., Adams, C.A., Sun, Y., Zhang, S., 2022a. Effects of microplastics on soil properties: current knowledge and future perspectives. J. Hazard. Mater. 424, 127531. https://doi.org/10.1016/j.jhazmat.2021.127531.

Wang, Z., Xiao, Z., Wang, C., Yue, L., 2022b. Application method of silicon quantum dots for controlling corn armyworm. US20220104499A1.

Wang, Q., Zhang, Y., Ma, Y., Wang, M., Pan, G., 2023a. Nano-crosslinked dynamic hydrogels for biomedical applications. Mater. Today Bio 20, 100640. https://doi.org/10.1016/j.mtbio.2023.100640.

Wang, Z., Zhu, W., Chen, F., Yue, L., Ding, Y., Xu, H., Rasmann, S., Xiao, Z., 2021. Nanosilicon enhances maize resistance against oriental armyworm (*Mythimna separata*) by activating the biosynthesis of chemical defenses. Sci. Total Environ. 778, 146378. https://doi.org/10.1016/j.scitotenv.2021.146378.

White, J.C., Gardea-Torresdey, J., 2018. Achieving food security through the very small. Nat. Nanotechnol. 13, 627–629. https://doi.org/10.1038/s41565-018-0223-y.

Wu, H., Shabala, L., Shabala, S., Giraldo, J.P., 2018. Hydroxyl radical scavenging by cerium oxide nanoparticles improves Arabidopsis salinity tolerance by enhancing leaf mesophyll potassium retention. Environ. Sci.: Nano 5, 1567–1583. https://doi.org/10.1039/C8EN00323H.

Xiao, Z., Fan, N., Yue, L., Chen, F., Ji, H., Shu, Y., Rasmann, S., Wang, Z., 2021. Dose-dependent effects of CeO_2 nanomaterials on tomato plant chemistry and insect herbivore resistance. Environ. Sci.: Nano 8, 3577–3589. https://doi.org/10.1039/D1EN00837D.

Xiong, T., Dumat, C., Dappe, V., Vezin, H., Schreck, E., Shahid, M., Pierart, A., Sobanska, S., 2017. Copper oxide nanoparticle foliar uptake, phytotoxicity, and consequences for sustainable urban agriculture. Environ. Sci. Technol. 51, 5242–5251. https://doi.org/10.1021/acs.est.6b05546.

Xu, G., 2018. Sensing and transport of nutrients in plants. Semin. Cell Dev. Biol. 74, 78–79. https://doi.org/10.1016/j.semcdb.2017.09.020.

Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., Wang, H., Lu, Z., Brookes, P.C., Tang, C., Gan, J., Xu, J., 2020. Microplastics in the soil environment: occurrence, risks, interactions and fate – a review. Crit. Rev. Environ. Sci. Technol. 50, 2175–2222. https://doi.org/10.1080/10643389.2019.1694822.

Yan, A., Chen, Z., 2019. Impacts of silver nanoparticles on plants: a focus on the phytotoxicity and underlying mechanism. Int. J. Mol. Sci. 20, 1003. https://doi.org/10.3390/ijms20051003.

Yan, X., White, J.C., He, E., Peijnenburg, W.J.G.M., Zhang, P., Qiu, H., 2024. Temporal dynamics of copper-based nanopesticide transfer and subsequent modulation of the interplay between host and microbiota across trophic levels. ACS Nano. https://doi.org/10.1021/acsnano.4c06047.

Yang, Z., 2016. The Phytotoxicity Assessment of Metal Oxide Nanoparticles on Maize (*Zea mays* L.) and Rice (*Oryza sativa* L.) (M.D). Northeast Normal University.

Yang, X., Bento, C.P.M., Chen, H., Zhang, H., Xue, S., Lwanga, E.H., Zomer, P., Ritsema, C.J., Geissen, V., 2018. Influence of microplastic addition on glyphosate decay and soil microbial activities in Chinese loess soil. Environ. Pollut. 242, 338–347. https://doi.org/10.1016/j.envpol.2018.07.006.

Yang, S., Huang, Y., Guo, Y., Zhao, L., Niu, X., Wang, J., Zhang, Y., 2023. The effect of SiO_2 NPs nanomaterials on strawberry growth and high temperature stress (in Chinese). South China Fruits 52, 181–185. https://doi.org/10.13938/j.issn.1007-1431.20220539.

Yin, K., Bao, Q., Li, J., Wang, M., Wang, F., Sun, B., Gong, Y., Lian, F., 2024. Molecular mechanisms of growth promotion and selenium enrichment in tomato plants by novel selenium-doped carbon quantum dots. Chemosphere 364, 143175. https://doi.org/10.1016/j.chemosphere.2024.143175.

Zhang, P., Guo, Z., Monikh, F.A., Lynch, I., Valsami-Jones, E., Zhang, Z., 2021. Growing rice (*Oryza sativa*) aerobically reduces phytotoxicity, uptake, and transformation of CeO_2 nanoparticles. Environ. Sci. Technol. 55, 8654–8664. https://doi.org/10.1021/acs.est.0c08813.

Zhang, J., Wang, F., Yalamarty, S.S.K., Filipczak, N., Jin, Y., Li, X., 2022. Nano silver-induced toxicity and associated mechanisms. Int. J. Nanomed. 17, 1851–1864. https://doi.org/10.2147/IJN.S355131.

Zhang, Y., Zhang, T., Pan, Y., Ma, L., Fang, Y., Pan, C., Qiang, Y., Cao, X., Xu, H., 2023. Nano-selenium promotes the product quality and plant defense of *Salvia miltiorrhiza* by inducing tanshinones and salvianolic acids accumulation. Ind. Crops Prod. 195, 116436. https://doi.org/10.1016/j.indcrop.2023.116436.

Zhao, X., Cui, H., Wang, Y., Sun, C., Cui, B., Zeng, Z., 2018. Development strategies and prospects of nano-based smart pesticide formulation. J. Agric. Food Chem. 66, 6504–6512. https://doi.org/10.1021/acs.jafc.7b02004.

Zhao, L., Lu, L., Wang, A., Zhang, H., Huang, M., Wu, H., Xing, B., Wang, Z., Ji, R., 2020. Nano-biotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance. J. Agric. Food Chem. 68, 1935–1947. https://doi.org/10.1021/acs.jafc.9b06615.

Zheng, M., Huang, Z., Ji, H., Qiu, F., Zhao, D., Bredar, A.R.C., Farnum, B.H., 2020. Simultaneous control of soil erosion and arsenic leaching at disturbed land using polyacrylamide modified magnetite nanoparticles. Sci. Total Environ. 702, 134997. https://doi.org/10.1016/j.scitotenv.2019.134997.