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Review Article

Silver Nanoparticles (AgNPs) Induce Resistance in Crops against Abiotic Stress: A Review

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Abstract

Agriculture, vital for global sustenance, faces unprecedented challenges such as climate change, soil degradation and various abiotic stresses. This review explores the potential of silver nanoparticles (AgNPs) in addressing agricultural challenges, focusing on heavy metal contamination, salinity, drought and temperature stress. AgNPs, known for their unique properties, demonstrate effectiveness in adsorbing heavy metals and reducing their bioavailability in soils. Their application in nanocomposites and nano fertilizers ensures sustained remediation effects and enhanced soil microbial activity. Under heavy metal stress, AgNPs positively impact plant physiology, enhancing antioxidant enzyme activities and promoting root development, shoot biomass and overall plant growth. Additionally, AgNPs contribute to mitigating salinity stress by modulating carbohydrates and protein synthesis and improving antioxidant enzyme activity. Noteworthy is their ability to increase seed germination in salt-stress conditions. AgNPs also show promise in alleviating drought stress, preserving water balance, and enhancing growth traits. Furthermore, AgNPs exhibit effectiveness in mitigating temperature stress, and improving plant parameters in high-temperature conditions. Their versatile role in influencing plant development makes them promising tools for sustainable and resilient crop production. However, careful consideration of potential risks, including ecosystem accumulation and unintended consequences, is imperative. Ongoing research and thorough risk assessments are crucial for the safe and effective application of AgNPs in diverse environmental conditions, ensuring their contribution to sustainable agriculture and environmental remediation.

Keywords: Silver nanoparticles; Mitigation; Abiotic stress; Plants; Heavy metals

Introduction

Agriculture, the backbone of many developing economies, is facing an extraordinary challenge as the global population is projected to reach nine billion by 2050. The pressing issues of climate change, soil degradation, nutrient deficiencies, disease outbreaks, urbanization, pollution and industrialization threaten the sustainability of agricultural practices and, consequently, global food production (Godfray and Garnett 2014; Manjunatha *et al.* 2016; Fatima *et al.* 2020). Similarly, the impact of heavy metals, drought, and temperature fluctuations in agriculture disrupt plant growth, soil health, and overall crop productivity, posing significant challenges to global food security (Zulfiqar *et al.* 2019; Jalil and Ansari 2020). Meeting the demands of this growing population within the constraints of limited resources and a compromised environment requires innovative solutions. The application of nanotechnology in agriculture emerges as a promising avenue to address these challenges. Nanotechnology involves the manipulation and application of matter at the nanoscale, with nanoparticles ranging from 0.1 to 100 nm (Singh and Kumar 2023). Among these nanoparticles, silver nanoparticles (AgNPs), with their unique physical, chemical, and biological properties, have gained prominence in various industries, including medicine, food, healthcare, and consumer goods (Gurunathan *et al.* 2015). However, the synthesis of AgNPs is critical to their effectiveness in different applications. Traditional physical and chemical methods are often expensive and risky. In response, researchers have turned to biologically synthesized AgNPs, utilizing natural resources like plant leaves, stems, bark, and roots for novel metals such as platinum, gold, and silver (Vadakkan *et al.* 2024). This eco-friendly approach not only ensures excellent production, solubility, and stability but also aligns with the imperative of environmental sustainability (Gurunathan *et al.* 2015). The connection between nanotechnology and agriculture becomes particularly relevant in the face of rapidly changing

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environmental conditions and an expanding population. Abiotic stressors, intensified by climate change, pose a significant threat to global food security. These stressors encompass a range of challenges, including altered growth and development of plants, disruptions in gas exchange rates, and the exacerbation of abiotic conditions (Latef *et al.* 2017; Kim *et al.* 2019). In this context, AgNPs present themselves as potential game-changers. Not only do they possess distinctive physicochemical properties, but they also exhibit antibacterial actions, setting them apart from other nanoparticles (Mohamed *et al.* 2017). The ability of AgNPs to address multiple challenges simultaneously makes them a compelling solution for enhancing agricultural sustainability. This review delves into how abiotic stressors challenge agriculture and explores the potential of AgNPs in mitigating these challenges.

Impacts of abiotic stress on plants

Abiotic stress encompasses a range of environmental factors that can adversely affect plant growth, development, and overall well-being. These stressors include, but are not limited to, extremes in temperature, salinity, heavy metal accumulation and drought (Table 1; Fig. 1–2). Such abiotic stresses have become a focal point of research due to their substantial impacts on agricultural productivity and ecosystem health. In understanding the multifaceted impacts of abiotic stress on plants, researchers aim to develop strategies for crop improvement, environmental sustainability and resilience in the face of ongoing climate challenges. These efforts are crucial for ensuring the future health and productivity of plant ecosystems amid a changing global environment.

In recent times, the buildup of heavy metals in soil has become a serious worry, especially in developing countries experiencing rapid urbanization and industrialization (Zhao *et al.* 2015; Zhou *et al.* 2017; Yang *et al.* 2020). This concern has gained global attention due to its potential impact on the long-term health of agroecosystems, affecting around 20% of the world's land and disrupting global food productivity (Alekseenko *et al.* 2018; Wang *et al.* 2018). Heavy metal contamination affects about 2.5 billion hectares of agricultural land worldwide, with varying concentrations based on regional industrial and agricultural activities (Feng *et al.* 2019). Even trace amounts of these toxic metals can be harmful to various life forms, raising concerns about phytotoxicity (Ahlam *et al.* 2021). The accumulation of heavy metals in plant cells can result in growth inhibition, plant mortality, and the subsequent release of these metals into the environment through volatilization. This, in turn, affects various plant physiological processes, morphological characteristics, biochemical composition, and ultimately reduces crop yields (Dixit *et al.* 2015). Different crops, including rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and corn (*Zea mays* L.) are susceptible to heavy metal contamination with varying impacts on their growth due to disruptions in essential physiological processes and nutrient uptake mechanisms (Ali *et al.* 2013; Ditta *et al.* 2021). The severity of these impacts depends on factors such as the type of metal, its concentration, and the duration of exposure. For example, cadmium has been shown to stunt root and shoot growth in wheat and inhibit seed germination, while arsenic uptake in rice can affect root elongation and nutrient transport, leading to reduced grain yield (Shahid *et al.* 2016). Additionally, heavy metals induce oxidative stress in plants, damaging cellular structures, reducing chlorophyll content, and disrupting photosynthesis rates (Salam *et al.* 2024). The economic ramifications of heavy metal contamination are significant, as crops with elevated metal levels may exhibit reduced nutritional value and an increased potential for toxic effects on consumers, especially when consumed by livestock or humans (Rai *et al.* 2023).

Salt stress poses a pervasive and significant threat to plant health, impacting plant yield and survival. Soil salinity, a major environmental hazard globally, affects both flooded and dry land crops, posing a serious challenge to agriculture (Farooq *et al.* 2015; Sultan *et al.* 2023). Salinity stress arises from natural processes like rock weathering and fluctuations in the water table depth. The soluble salts released through rock weathering dissolve in water and soil solution, impacting plant growth and soil structure based on the shifting water table (Liu *et al.* 2023). Environmental factors, soil depth, temperature, light, timing, and irrigation depth influence salinity tolerance. Dry and high-temperature conditions make plants more susceptible to saline conditions due to increased evapotranspiration rates (Giordano *et al.* 2021). Elevated concentrations of salt in the soil result in metabolic and physiological issues, including cellular particle imbalance, the generation of reactive oxygen species (ROS) and damage to biomolecules, leading to programmed cell death (Tomar *et al.* 2021). The economic consequences of salt stress are substantial, with 1.5 million hectares of arable land lost each year due to salinization and sodification, affecting a staggering 1.125 billion hectares, of which 76 million are solely influenced by human activities (Abou-Zeid and Ismail 2018). Addressing and mitigating the impacts of salt stress are urgent needs to ensure sustainable food production and economic stability.

Climate change and global warming have given rise to a multifaceted challenge, with the water crisis standing out as a significant problem. Water, essential for plant health due to its role in nutrient delivery, becomes critical in the face of climate-induced water scarcity, leading to drought stress (Mujumdar 2013). Drought stress occurs when there is a reduction in the water supply to the roots or a significant increase in the rate of transpiration from the leaves, prevalent in semiarid and arid conditions. Projections by the Intergovernmental Panel on Climate Change (IPCC) paint a concerning picture, with the Earth's average temperature expected to rise between 1.8 to 4.0°C by 2100, leading to widespread drought occurrences across the globe (Ozturk *et al.* 2020).

Table 1: Effects of different abiotic stresses on some varieties of crops

Plant/crop	Abiotic stress	Impacts on plant/crop	References
Oryza sativa	Heavy metal stress	Inhibits root and shoot growth	Li *et al.* (2019a, b); Chen *et al.* (2020)
Triticum aestivum	Heavy metal stress	Reduces chlorophyll content and photosynthesis rate	Iqbal *et al.* (2017); Khan *et al.* (2020)
Solanum lycopersicum	Heavy metal stress	Disrupts root development and impairs fruit ripening	Kaur and Bakshi (2018); Bhuiyan *et al.* (2021)
Spinacia oleracea	Heavy metal stress	Accumulates in leaves and affects nutrient uptake	Sheoran and Sheoran (2017); Verma *et al.* (2021)
Zea mays	Heavy metal stress	Alters enzyme activities and hampers growth	Gupta *et al.* (2023)
Daucus carota	Heavy metal stress	It affects root development and decreases biomass	Khan *et al.* (2017)
Solanum tuberosum	Heavy metal stress	Reduces tuber yield and increases oxidative stress	Prasad *et al.* (2022)
Zea mays	Salt stress	Impaired photosynthesis and chlorophyll content, Decreased yield and kernel weight	Han *et al.* (2019)
Solanum lycopersicum	Salt stress	Decreased fruit yield and quality, Hindered nutrient uptake and assimilation	Zhang *et al.* (2021);
Cucumis sativus	Salt stress	Reduced seed germination and growth, Impaired water and nutrient transport	Zhang *et al.* (2020)
Capsicum annuum	Salt stress	Decreased fruit yield and size, altered mineral nutrient concentrations	Arrowsmith *et al.* (2012)
Lactuca sativa	Salt stress	Impaired nutrient absorption and translocation	Breś *et al.* (2022); Naz *et al.* (2024)
Secale cereal	Salt stress	Stunted growth and decreased tiller number impaired nutrient transport in roots	Moradi and Sharifi (2020)
Cotton	Drought stress	Drought causes a reduction of photosynthesis and eventually stunts plant growth	Zafar *et al.* (2023)
Brassica rapa	Drought stress	Inhibit the growth and physio-biochemical attributes	Hasnain *et al.* (2023)
Cicer arietinum L.	Drought stress	Hinder the growth and limiting the yield by impairing pistil function and reducing pollen viability	Pappula *et al.* (2024)
Vegetable plants	Heat stress	Heat stress also reduces seedling growth, root growth and causes significant yield losses	Saeed *et al.* (2023)
Solanum lycopersicum	Heat stress	affects the rate of fruit setting and production	Cappetta *et al.* (2021)
Brassica rapa	Heat stress	Reduce photosynthesis & increase respiration, which in turn reduces assimilation and causes substantial yield loss	Hassan *et al.* (2021)

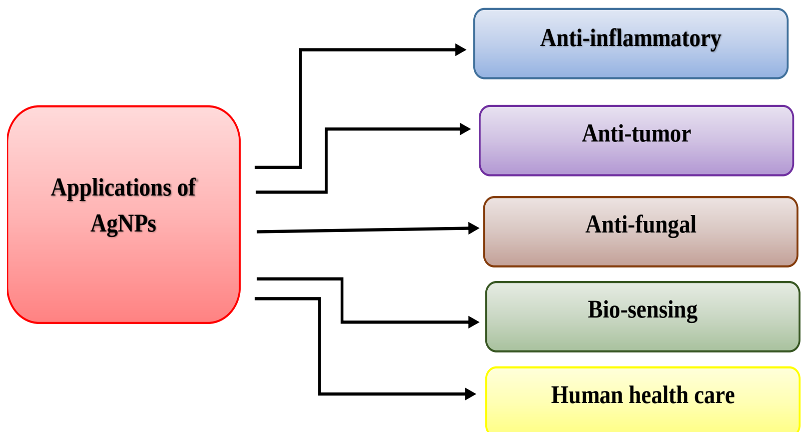

Fig. 1: Biological role of AgNPs in different fields

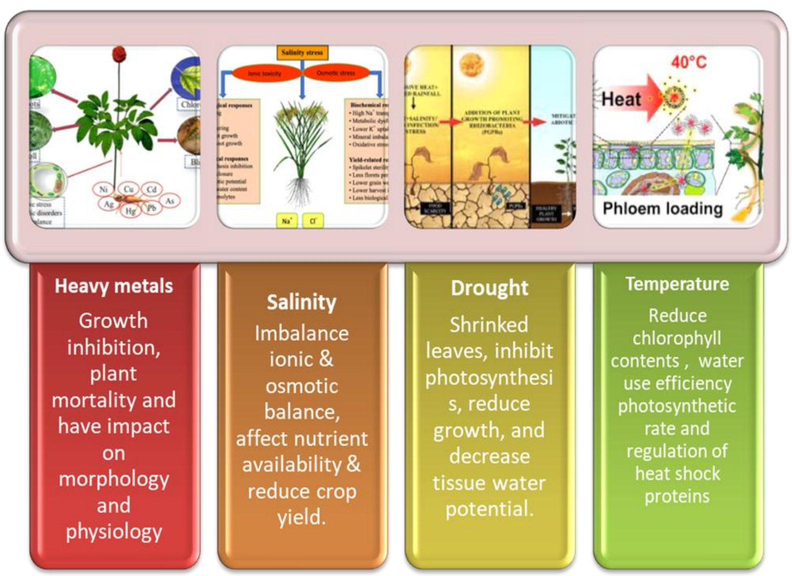

Fig. 2: Growth, physio-morphological and enzymatic changes in agricultural crops under different abiotic stresses on agriculture

The impact of drought stress on plants is evident in the wilting of plants, reduction in leaf size, increased leaf fall, and diminished transpiration, where plants lose water through their leaves (Fghire *et al.* 2015). Drought stress triggers a cascade of plant responses, involving changes in growth and yield characteristics, alterations in the levels and activities of protective antioxidants, and adjustments in the amounts of protective metabolites and proteins (Seleiman *et al.* 2021; Idrees *et al.* 2024). Aquaporins (AQPs), membrane channels activated during drought, partially control this impact by facilitating water permeability (Hasan *et al.* 2021). Developing drought-tolerant cultivars becomes imperative to ensure food security (Hasan *et al.* 2020).

Plants, being stationary, are susceptible to temperature stress that impacts both their growth and surroundings. Temperature extremes disturb the delicate balance of plant physiology, leading to substantial reductions in crop yields (Kai and Iba 2014). High-temperature stress during the reproductive stage can lead to a decrease in grain number and accelerate the time it takes for grains to fill, while frost during reproductive stages can lead to sterility and abortion of formed grains (Barlow *et al.* 2015). The intricacies of temperature stress are further accentuated under conditions of high vapor pressure deficits, affecting pollen viability crucial for successful reproduction (Lv *et al.* 2024). With increased temperature stress on major grain crops in the twenty-first century, a decline in grain yields becomes a likely trajectory (Hatfield and Prueger 2011).

The impacts of AgNPs on plants under abiotic stress

As the scientific community delves deeper into the realm of nanotechnology, the co-evolution of nanoparticles (NPs) continues to offer promising solutions for enhancing crop variety and addressing agricultural challenges. AgNPs, with their unique properties, emerge as dominant players in this field (Chouhan 2018). The non-toxic and chemically stable nature of AgNPs makes them biocompatible precursors for influencing specific traits responsible for overall plant development (Wahid *et al.* 2020a, b). Upon interacting with plants, nanoparticles (NPs) traverse the plant structure via the root junction and wound regions, penetrating both the cell wall and cell membrane of the root epidermis. This penetration is facilitated by diverse mechanisms such as carrier proteins, endocytosis, pore formation or plasmodesmata. Following this, an intricate series of events ensues, enabling the NPs to access the plant vascular bundle (xylem) through either the symplast or apoplast pathway (Pèrez-de-Luque 2017). Within the vascular bundle, NPs accumulate in cellular or subcellular organelles and undergo symplastic movement to reach the stele, ultimately being translocated to the leaves (Gohari *et al.* 2024). Furthermore, NPs possess the capability to infiltrate the cell cytoplasm by traversing through structures like cuticles, stomata, hydathodes, and trichomes on leaves. Once in the cytoplasm, these NPs may interact with various cytoplasmic organelles, potentially disrupting local metabolic activities (Rajput *et al.* 2020a, b). In addition, NPs may directly absorb into seeds by diffusing through the cotyledon and into the coat through parenchymatic intercellular gaps (Tripathi *et al.* 2017).

According to Almutairi (2016), the effects of salt stress on tomato plant seed germination and seedling growth were significantly reduced by exposure to AgNPs. After exposure to AgNPs under NaCl stress, the germination percentage, germination rate, root length, and seedling fresh and dry weight of tomato all improved. Semi-quantitative reverse transcriptase polymerase chain reaction (RT-PCR) was used to look at the expression of salt stress genes. Four of the genes for salt stress under examination—AREB, MAPK2, P5CS, and CRK1—were upregulated by AgNPs during salt stress, while three other genes—TAS14, DDF2, and ZFHD1—were down regulated. The gene expression patterns linked to exposure to AgNPs also point to the possibility that AgNPs may be involved in stress responses, suggesting that they could be effective for enhancing plant tolerance to salinity.

Salinity stress, a global issue affecting crop growth and yield, sees positive responses to AgNP application. AgNPs, when applied under salinity stress, modulate carbohydrates and protein synthesis, improve plant growth, and enhance the activity of antioxidant enzymes, contributing to the reduction of salinity impact through ROS detoxification (Ghosh *et al.* 2016; Table 2; Fig. 3) the imbalance of ions caused by salt stress disrupts the equilibrium within plant cells, resulting in the buildup of detrimental ions like sodium. AgNPs have the potential to preserve ion homeostasis by overseeing the transport of ions across cell membranes. This regulatory role contributes to mitigating the adverse impacts of salt stress on plants (Rosário *et al.* 2021). Without disrupting cellular processes and gene expression, NPs would undoubtedly be ineffective. This is because salinity stress modifies gene expression, which in turn affects plant growth by altering the expression of numerous genes involved in the various cell components and their byproducts. In order to conduct research in this field, microRNA expression in cells treated with AgNPs was analyzed (Kumar *et al.* 2013). These researchers' findings indicate that the NPs had an impact on the expression of miR398 and miR408, which control the germination of seeds, the development of roots and seedlings, and the function of antioxidants and free radical scavengers. It should be highlighted that the factors above are inhibited by increased expression of microRNA. It is widely acknowledged that plants respond to salinity stress, by generating ROS. To counteract the surplus ROS in cells subjected to salinity stress, plants deploy antioxidant enzymes (You and Chan 2015). Numerous studies have illustrated the ability of AgNPs to enhance the levels of antioxidant enzymes (Gaafar *et al.* 2020; González-García *et al.* 2021). According to these researchers, certain NPs act as specific antioxidant enzymes, assisting plants in overcoming the oxidative challenges they face.

Table 2: Role of AgNPs for alleviation of different abiotic stresses in plants

Species	Abiotic stress	Treatment of AgNPs	Effects	References
Triticum aestivum	Salt stress	10 m*M* /L	Ag-NPs increased fresh and dry weight, Improved germination and growth of wheat seedlings, total chlorophyll content, soluble sugar content and antioxidant enzymes under salt stress.	Mohamed *et al.* (2017)
Lycopersicon esculentum	Salt stress	75 mg/L	Ag-NPs enhanced CAT and POX activity under salinity stress, Ag-NPs also enhance germination under salinity stress	Almutairi (2016)
Thymus vulgaris and *T. daenensis*	Salt stress	0–10 mm/L	Ag-NPs increase germination percentage, shoot and root length, and seed vigor in under salinity stress	Ghavam (2018)
Lycopersicon esculentum	Salt stress	20 mg/L	Ag-NPs increase percentage plant survival at different levels of salinity.	Younes and Nassef (2015)
Ocimum basilicum	Salt stress	40 mg/L	Ag-NPs enhance germination percentage and improved resistance to salinity	Darvishzadeh (2015)
Riccinus communis	Salt stress	100 mg/L	Ag-NPs promoted the activities of SOD and POX under salt stress	Yasur and Rani (2013)
Cuminum cyminum L.	Salt stress	100 mg /L	Enhanced germination percentage, germination speed and vigor	Ekhtiyari *et al.* (2011)
Lathyrus Sativus L.	Salt stress	5, 10 ppm	Improve shoot and root length, germination percentage, seedling fresh and dry weight	Hojjat and Ganjali (2017)
Triticum aestivum L. At 35-40°C	Temperature stress	25, 50, 75 and 100 mg/L	Improved root length, shoot length, root number, fresh weight and dry weight	Iqbal *et al.* (2017)
Lens esculenta	Drought stress	10, 20 40 µg/L	Improved germination percentage, root & shoot length.	Hojjat and Kamyab (2016)
Lupinus luteus L.	Heavy metal stress	25 mg/kg	Improve GPX activity and metallothioneins expression	Jaskulak *et al.* (2019)
Triticum aestivum	Heavy metal stress	50 mg/kg	AgNPs can adsorb and sequester Cd ions in soil, reducing its bioavailability and uptake by wheat, thereby mitigating Cd-induced toxicity	Smith *et al.* (2022)
Hordeum vulgare	Heavy metal stress	15 mg/L	AgNPs have been shown to enhance the antioxidative defense system in barley, reducing Hg-induced oxidative stress and promoting plant growth	Johnson and Lee (2021)
Oryza sativa	Heavy metal stress	25 mg/L	Application of AgNPs leads to improved root morphology and nutrient uptake in rice, reducing Pb toxicity and enhancing overall plant biomass	Williams and Brown (2020)
Spinacia oleracea	Heavy metal stress	0-50 mh/L	AgNPs reduce Cd uptake in spinach, lowering Cd-induced toxicity and improving overall plant health	Bisi-Johnson *et al.* (2023)

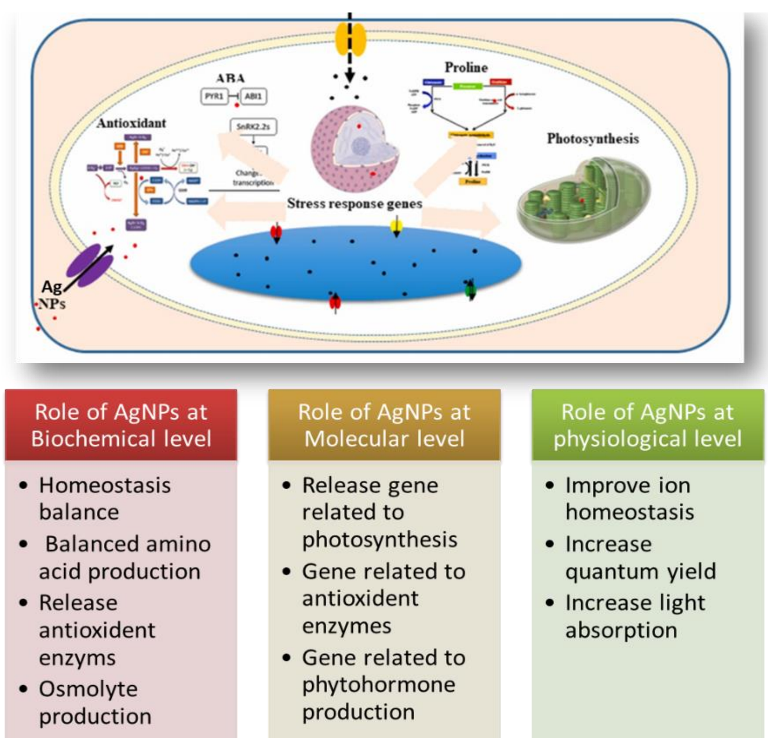

Fig. 3: Role of AgNPs at cellular, molecular and biochemical levels in crops for salt stress management

In a study conducted by Khan *et al*. (2020), the impact of seed priming with AgNPs at different concentrations was investigated on pearl millet (*Pennisetum glaucum* L.) under salinity stress conditions (0, 120 and 150 m*M* NaCl). The results indicated a substantial enhancement in the plant's developmental features due to the presence of NPs. This improvement was attributed to a decrease in the sodium-to-potassium ratio and an increase in the activity of antioxidant enzymes such as glutathione peroxidase (GPX), catalase (CAT), and superoxide dismutase (SOD). According to research conducted by Sami *et al*. (2020), one of the key mechanisms through which AgNPs at low concentrations positively influence plant growth is by enhancing antioxidant enzyme activity. According to Abou-Zeid and Ismail (2018), AgNPs were found to affect wheat germination and grain yield under salt stress by modifying photosynthetic efficiency and plant hormones as the levels of abscisic acid (ABA decreased and those of 6-benzylaminopurine, 1-naphthalene acetic acid, and indole-3-butyric acid increased.

In addressing the persistent challenge of heavy metal contamination in agriculture, the AgNPs have emerged as promising remedies. AgNPs have demonstrated effectiveness in adsorbing and sequestering heavy metals such as Pb, Cd, and Cu from soil environments (Yan *et al.* 2020; Ghafari *et al.* 2023). Their high surface area and reactivity allow the formation of stable complexes with heavy metal ions, thereby reducing their bioavailability and mobility in the soil (Li *et al.* 2019a, b). AgNPs, known for their versatility, can be incorporated into various delivery systems like nanocomposites and nano fertilizers, ensuring efficient and controlled release in soil environments (Liu *et al.* 2019). These delivery systems contribute to sustained remediation effects, providing prolonged exposure to heavy metal-contaminated soils (Ghafari *et al.* 2021). Furthermore, AgNPs enhance soil microbial activity, crucial for nutrient cycling and soil health, promoting beneficial microbial populations and mitigating the adverse effects of heavy metals on soil biodiversity (Rajput *et al.* 2020c). Under heavy metal stress, AgNPs showcase a positive impact on plant physiology by enhancing antioxidant enzyme activities, including SOD, CAT and POD (Fig. 4). These enzymes play a crucial role in mitigating oxidative stress caused by heavy metal exposure (Ma *et al.* 2013). Additionally, AgNPs improve root development, increase shoot biomass, and stimulate overall plant growth, ultimately leading to improved crop yields in metal-contaminated environments (Tripathi *et al.* 2021).

AgNPs contribute to mitigating heavy metal stress in plants by reducing oxidative stress. Heavy metals generate ROS in plant tissues, leading to oxidative damage and cell death. AgNPs, with their strong antioxidant properties, can scavenge ROS, protecting plant cells from damage and maintaining cellular homeostasis (Yadav *et al.* 2020). The positive effects of AgNPs extend beyond soil health when plants absorb them through their roots. AgNPs can undergo structural modifications within plant tissues, influencing the activity of enzymes involved in oxidative stress and activating the plant's defense system (Montes *et al.* 2017). This ability induces the generation of ROS at the cellular level, triggering secondary signaling pathways and leading to the transcriptional regulation of secondary metabolism (Marslin *et al.* 2017).

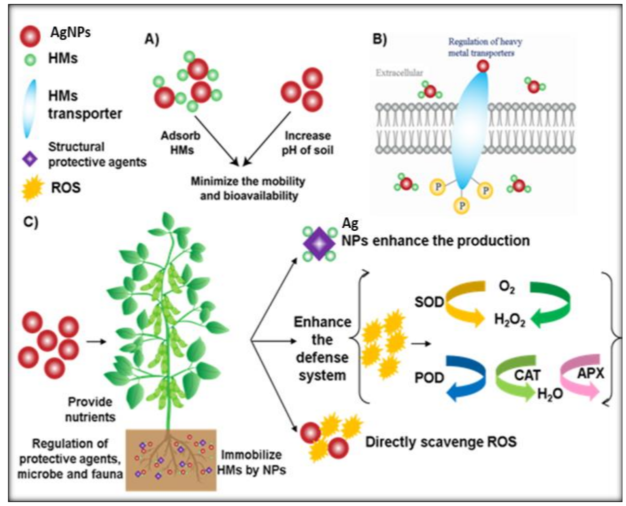

Fig. 4: Schematic role of AgNPs in reducing heavy metals stress in plants

The role of AgNPs in alleviating drought stress has also been explored (Fig. 5). The application of AgNPs shows promise in preserving water balance in plants subjected to drought stress, leading to improved growth traits, including increased germination rate and seedling biomass (Hojjat and Ganjali 2016). In wheat plants, AgNPs have been found to enhance drought tolerance by facilitating better nutrient absorption and water retention (Ahmed *et al.* 2021). Exploring the potential of AgNPs under drought stress further emphasizes their role in preserving water balance in plants and improving growth traits, including increased germination rate and seedling biomass (Hojjat and Kamyab 2017). In the realm of plant biology, the use of nanomaterials (NMs) finds diverse applications, extending from seed modification to in vitro plant tissue culture technologies (Mohamed and Kumar 2016). AgNPs emerge as significant players in alleviating drought stress, as depicted in Fig. 5, the interaction of AgNPs with cell membranes, specifically in plant roots, can lead to alterations in membrane structure and permeability. This modification facilitates a more efficient uptake of water, contributing to enhanced water absorption by plants. This improved water uptake plays a crucial role in enabling plants to sustain hydration levels and better withstand drought conditions (Ali *et al.* 2019). When plants absorb AgNPs from the soil through their roots, an active transport mechanism via the xylem comes into play (Tripathi *et al.* 2017). Within plant tissues, AgNPs may undergo structural modifications, forming complex compounds with other molecules or nutrients, or they may retain their nanomaterial properties (Dimkpa and Bindraban 2017). NPs, including AgNPs, appear to influence the activity of enzymes involved in oxidative stress, potentially activating the plant's defense system (Montes *et al.* 2017). The ability of AgNPs to induce the generation of ROS at the cellular level initiates secondary signaling pathways, leading to the transcriptional

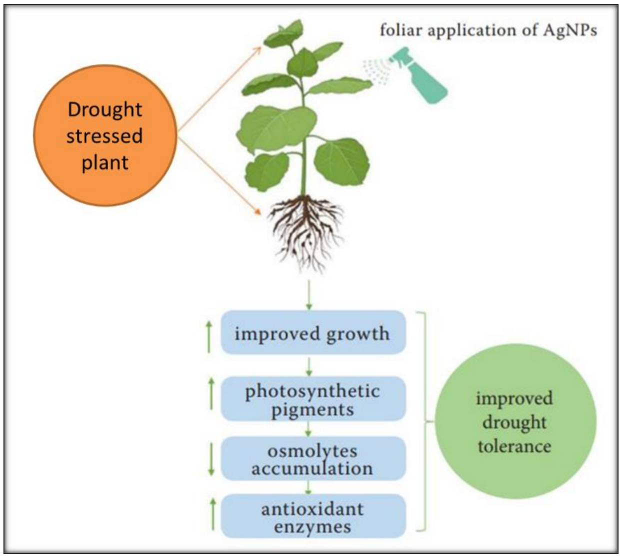

Fig. 5: Drought stress management in plants by AgNps (Alabdallah *et al.* 2021)

regulation of secondary metabolism (Marslin *et al.* 2017). Notably, the impact of NMs on plants follows a biphasic dose-response pattern termed "hormesis", where low doses stimulate plant responses, while high doses inhibit them (Agathokleous *et al.* 2019). This underscores the potential of nanotechnology to offer innovative solutions in enhancing plant resilience and mitigating the adverse effects of environmental stressors like drought.

Beyond heavy metal and salt stress, AgNPs demonstrate effectiveness in mitigating temperature stress (Fig. 6). In an experiment on wheat, AgNPs were applied to alleviate the adverse effects of high temperature. The results showed improvements in plant parameters such as shoot and root length, number of leaves and overall plant weight (Iqbal *et al.* 2017). Temperature stress can impact diverse metabolic pathways within plants. The presence of AgNPs may exert an influence on the regulation of these pathways, facilitating adaptations in plant metabolism to better align with the challenges posed by temperature stress (Khalil *et al.* 2022). Elevated temperatures, particularly during temperature stress, can cause protein denaturation in plant cells. AgNPs have the potential to trigger the expression of heat shock proteins (HSPs), serving as molecular chaperones that aid in the correct folding and stabilization of proteins when confronted with stress conditions (Magesky *et al.* 2017).

The AgNPs emerge as versatile tools with a remarkable capacity to influence plant development and alleviate various environmental stresses. Their application in agriculture holds promise for sustainable and resilient crop production. However, ongoing research is essential to delve deeper into the biochemical, molecular, and physiological mechanisms underlying their effects. As co-evolution of nanotechnology progresses, the judicious use of AgNPs has the potential to revolutionize agricultural practices,

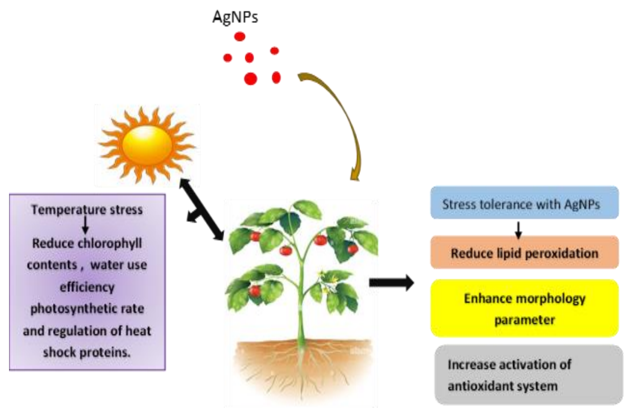

Fig. 6: Effects of temperature stress in plants and management through AgNps

contributing to low-input sustainable agriculture for both food and non-food crops (Etesami and Jeong 2018). In conclusion, the multifaceted role of AgNPs in alleviating various stresses, from heavy metal contamination to salinity and drought, underscores their potential in sustainable agriculture. These nanoparticles offer a promising avenue for enhancing plant resilience, improving crop yields, and contributing to environmental remediation. However, their use necessitates careful consideration of potential risks associated with ecosystem accumulation and unintended consequences on non-target organisms. Ongoing research and thorough risk assessments are crucial to ensuring the safe and effective application of AgNPs in diverse environmental conditions.

Conclusion

The integration of AgNPs into agriculture holds immense promise for addressing critical challenges such as heavy metal contamination, salinity stress, drought, and temperature fluctuations. AgNPs exhibit exceptional efficacy in adsorbing heavy metals from soil, enhancing soil microbial activity, and improving plant resilience. Their role in modulating carbohydrate and protein synthesis, stimulating antioxidant defense mechanisms, and promoting seed germination underscores their versatility in mitigating salinity stress. Additionally, AgNPs demonstrate significant potential in alleviating drought stress by preserving water balance in plants and enhancing nutrient absorption. When applied under temperature stress, AgNPs contribute to improved plant parameters, while AgNPs offer multifaceted benefits in sustainable agriculture; however, the careful consideration of potential ecological risks and unintended consequences is crucial. Ongoing research, coupled with comprehensive risk assessments, is imperative to ensure the safe and effective application of AgNPs, paving the way for transformative solutions in global crop production and environmental health.

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Author Contributions

SI and FZ planned the work, RH, MNK, MN and IF collected, screened and classified the literature, SP and SG completed the write up. SF and MN reviewed and handled the publication process.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

Data will be presented on due demand.

Ethics Approval

This review article needs no ethical approval.

References

Abou-Zeid H, G Ismail (2018). The role of priming with biosynthesized silver nanoparticles in the response of *Triticum aestivum* L. to salt stress. *Egypt J Bot* 58:73–85

Agathokleous E, Z Feng, I Iavicoli, EJ Calabrese (2019). The two faces of nanomaterials: A quantification of hormesis in algae and plants. *Environ Intl* 131:105044

Ahlam AAA, NAER Soheir (2021). Synthesis and characterization of zinc oxide and zinc oxide doped with chlorine nanoparticles as novel α-amylase inhibitors. *Food Nutr Sci* 12:308

Ahmed F, B Javed, A Razzaq, ZUR Mashwani (2021). Applications of copper and silver nanoparticles on wheat plants to induce drought tolerance and increase yield. *IET Nanobiotechnol* 15:68–78

Alabdallah NM, MM Hasan, AM Salih, SS Roushdy, AA Al-Shammari, SI Alsanie, M El-Zaidy (2021). Silver nanoparticles improve growth and protect against oxidative damage in eggplant seedlings under drought stress. *Plant Soil Environ* 67:617–624

Alekseenko AV, EM Antonenko, VA Alekseenko (2018). Evaluation of heavy metals pollution of soils and plants of urban territories of Donetsk region (Ukraine). *E3S Web Conf* 29:00010

Ali H, E Khan, MA Sajad (2013). Phytoremediation of heavy metals—concepts and applications. *Chemosphere* 91:869–881

Ali MA, KA Mosa, A El-Keblawy, H Alawadhi (2019). Exogenous production of silver nanoparticles by *Tephrosia apollinea* living plants under drought stress and their antimicrobial activities. *Nanomaterials* 9:1716

Almutairi ZM (2016). Influence of silver nano-particles on the salt resistance of tomato (*Solanum lycopersicum*) during germination. *Intl J Agric Biol* 18:449–457

Arrowsmith S, TP Egan, JF Meekins, D Powers, M Metcalfe (2012). Effects of salt stress on capsaicin content, growth, and fluorescence in a Jalapeño cultivar of *Capsicum annuum* (Solanaceae). *Bios* 83:1–7

Barlow KM, BP Christy, GJ O'Leary, PA Riffkin, JG Nuttall (2015). Simulating the impact of extreme heat and frost events on wheat crop production: A review. *Field Crops Res* 171:109–119

Bhuiyan MAH, SC Karmaker, M Bodrud-Doza, MA Rakib, BB Saha (2021). Enrichment, sources and ecological risk mapping of heavy metals in agricultural soils of dhaka district employing SOM, PMF and GIS methods. *Chemosphere* 263:128339

Bisi-Johnson MA, AA Adedeji, AA Sulaiman, MA Adefisoye, AI Okoh (2023). Isolation and genotypic characterization of extended-spectrum beta-lactamase-producing *Escherichia coli* O157: H7 and *Aeromonas hydrophila* from selected freshwater sources in Southwest Nigeria. *Sci Rep* 13:10746

Breś W, T Kleiber, B Markiewicz, E Mieloszyk, M Mieloch (2022). The effect of NaCl stress on the response of lettuce (*Lactuca sativa* L.). *Agronomy* 12:244

Cappetta E, G Andolfo, A Guadagno (2021). Tomato genomic prediction for good performance under high-temperature and identification of loci involved in thermotolerance response. *Hortic Res* 8:212–228

Chen XX, YM Liu, QY Zhao, WQ Cao, XP Chen, CQ Zou (2020). Health risk assessment associated with heavy metal accumulation in wheat after long-term phosphorus fertilizer application. *Environ Pollut* 262:114348

Chouhan N (2018). *Silver Nanoparticles: Synthesis, Characterization and Applications*. IntechOpen, London, UK

Darvishzadeh F (2015) Effects of silver nanoparticles on salinity tolerance in basil plant (*Ocimum basilicum* L.) during germination *in vitro*. *New Cell Mol Biotechnol J* 5:63–70

Dimkpa CO, PS Bindraban (2017). Nanofertilizers: New products for the industry. *J Agric Food Chem* 66:6462–6473

Ditta HMA, A Aziz, MK Hussain, N Mehboob, M Hussain, S Farooq, MF Azhar (2021). Exogenous application of black cumin (*Nigella sativa*) seed extract improves maize growth under chromium (Cr) stress. *Intl J Phytoremed* 23:1231–1243

Dixit R, KHW Shin, JS Choi, KR Hakeem (2015). Role of plants in remediation of environmental pollutants. *J Soil Sci Plant Nutr* 15:935–959

Ekhtiyari R, H Mohebbi, M Mansouri (2011). The study of the effects of nano silver technology on salinity tolerance of (*Foeniculum vulgare* Mill.). *Plant Ecosyst* 7:55–62

Etesami H, BR Jeong (2018). Silicon (Si): Review and future prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants. *Ecotoxicol Environ Saf* 147:881–896

Fatima Z, M Ahmed, M Hussain, G Abbas, S Ul-Allah, S Ahmad, N Ahmed, MA Ali, G Sarwar, EU Haque, P Iqbal, S Hussain (2020). The fingerprints of climate warming on cereal crops phenology and adaptation options. *Sci Rep* 10:18013

Farooq M, M Hussain, A Wakeel, KHM Siddique (2015). Salt stress in maize: Effects, resistance mechanisms, and management. A review. *Agron Sustain Dev* 35:461–481

Feng W, X Zhang, X Huang, H Yuan (2019). Ecological risk assessment and prediction of heavy metal pollution in agricultural soils in Yunnan, China. *Environ Monit Assess* 191:96–105

Fghire R, F Anaya, OI Ali, O Benlhabib, R Ragab, S Wahbi (2015). Physiological and photosynthetic response of quinoa to drought stress. *Chil J Agric Res* 75:174–183

Gaafar R, R Diab, M Halawa, A Elshanshory, A El-Shaer, M Hamouda (2020). Role of zinc oxide nanoparticles in ameliorating salt tolerance in soybean. *Egypt J Bot* 60:733–747

Ghafari HR, S Norouzi, M Heidari (2023). Different pollution levels and source profiles of heavy metals in the soil and surface dust of children's playgrounds in a coastal city; source-specific health risk assessment. *Atmos Pollut Res* 14:101869

Ghafari MD, A Malakahmad, M Soodi (2021). Silver nanoparticle-mediated toxicity to soil organisms: Effects, mechanisms, and influencing factors. *Sci Total Environ* 755:142912

Ghavam M (2018). Effect of silver nanoparticles on seed germination and seedling growth in *Thymus vulgaris* L. and *Thymus daenensis* Celak under salinity stress. *J Rangel Sci* 8:93–100

Ghosh M, A Jana, S Sinha, M Jothiramajayam, A Nag, A Chakraborty, A Mukherjee (2016). Effects of ZnO nanoparticles in plants: Cytotoxicity, genotoxicity, deregulation of antioxidant defenses, and cell-cycle arrest. *Mut Res Genet Toxicol Environ Mut* 807:25–32

Giordano M, SA Petropoulos, Y Rouphael (2021). Response and defence mechanisms of vegetable crops against drought, heat and salinity stress. *Agriculture* 11:463

Godfray HCJ, T Garnett (2014). Food security and sustainable intensification. *Philos Trans Roy Soc B Biol Sci* 369:20120273

Gohari G, M Jiang, GA Manganaris, J Zhou, V Fotopoulos (2024). Next generation chemical priming: With a little help from our nanocarrier friends. *Trends Plant Sci* 29:150–166

González-García Y, C Cárdenas-Álvarez, G Cadenas-Pliego, A Benavides-Mendoza, M Cabrera-de-la-Fuente, A Sandoval-Rangel, J Valdes-Reyna, A Juárez-Maldonado (2021). Effect of three nanoparticles (Se, Si and Cu) on the bioactive compounds of bell pepper fruits under saline stress. *Plants* 10:217

Gupta SS, D Singh, S Chandel, R Sikka, A Mukhopadhyay, SS Dhaliwal (2023). Assessment of sludge application in maize (*Zea mays* L.): Influence on crop biomass and heavy metals bioavailability. *Arch Agron Soil Sci* 69:3388–3402

Gurunathan S, E Kim, JW Han, JH Park, JH Kim (2015). Green chemistry approach for synthesis of effective anticancer palladium nanoparticles. *Molecules* 20:22476–22498

Han Q, G Kang, T Guo, Q Wang, W Xu, C Chu (2019). Maize yield and quality in response to salt stress. *Front Plant Sci* 10:1581

Hasan MM, M Skalicky, MS Jahan, MN Hossain, Z Anwar, ZF Nie, NM Alabdallah, M Brestic, V Hejnak, XW Fang (2021). Spermine: Its emerging role in regulating drought stress responses in plants. *Cells* 10:261

Hasan MM, MA Ali, MH Soliman, AA Alqarawi, EFA Allah, XW Fang (2020). Insights into 28-homobrassinolide (HBR)- mediated redox homeostasis, AsA–GSH cycle, and methylglyoxal detoxification in soybean under drought induced oxidative stress. *J Plant Intl* 15:371–385

Hasnain Z, S Zafar, S Usman, L Zhang, HO Elansary (2023). Elucidating role of melatonin foliar spray in ameliorating adverse effects of drought stress on growth and physio-biochemical attributes of *Brassica rapa* plants. *Sci Hortic* 321:112336

Hassan MU, MU Chattha, I Khan, MB Chattha, L Barbanti, M Aamer, MM Iqbal, M Nawaz, A Mahmood, A Ali (2021). Heat stress in cultivated plants: Nature, impact, mechanisms, and mitigation strategies—A review. *Plant Biosyst* 155:211–234

Hatfield JL, JH Prueger (2011). (2011). Agroecology: Implications for plant response to climate change. *In: Crop Adaptation to Climate Change*, pp:27–43. Yadav SS, RJ Redden, JL Hatfield, H Lotze-Campen, AE Hall (Eds). John Wiley & Sons, New York, USA

Hojjat SS, M Kamyab (2017). The effect of silver nanoparticle on Fenugreek seed germination under salinity levels. *Russ Agric Sci* 43:61–65

Hojjat SS, A Ganjali (2016). The effect of silver nanoparticle on lentil seed germination under drought stress. *Intl J Farm Allied Sci* 5:208–212

Idrees K, A Aziz, M Naeem, MF Azhar, S Farooq, M Hussain (2024). Combined application of zinc and silicon improved growth, gas exchange traits, and productivity of maize (*Zea mays* L.) under water stress. *Silicon* 16:831–841

Iqbal MS, MA Farooq, A Nawaz, J Akhtar, M Saqib (2017). Effect of lead toxicity on growth, chlorophyll content and mineral elements of wheat (*Triticum aestivum* L.). *Cerc Agron Mold* 50:67–75

Jalil SU, MI Ansari (2020). Stress implications and crop productivity. *In: Plant Ecophysiology and Adaptation under Climate Change: Mechanisms and Perspectives*, pp:73–86. Springer Nature, Singapore

Jaskulak M, A Rorat, A Grobelak, Z Chaabene, M Kacprzak, F Vandenbulcke (2019). Bioaccumulation, antioxidative response, and metallothionein expression in *Lupinus luteus* L. exposed to heavy metals and silver nanoparticles. *Environ Sci Pollut Res* 26:16040–16052

Johnson RA, K Lee (2021). Application of silver nanoparticles for enhancing the antioxidative defense system of barley (*Hordeum vulgare*) under mercury stress. *Ecotoxicol Environ Saf* 208:111671

Kai H, K Iba (2014). Temperature stress in plants. *In: Encyclopedia of Life Sciences*, pp:767–781. Wiley Online Library, New Jersey, USA

Kaur G, P Bakshi (2018). Physiological and biochemical responses of tomato (*Solanum lycopersicum* L.) seedlings grown under copper stress. *Phys Mol Biol Plants* 24:1019–1028

Khalil R, N ElSayed, HA Hashem (2022). Nanoparticles as a new promising tool to increase plant immunity against abiotic stress. *In: Sustainable Agriculture Reviews Nanoparticles: A New Tool to Enhance Stress Tolerance)*, Vol. 53, pp:61–91. Springer International Publishing, Cham, Switzerland

Khan M, AU Khan, MJ Alam, S Park, M Alam (2020). Biosynthesis of silver nanoparticles and its application against phytopathogenic bacterium and fungus. *Intl J Environ Anal Chem* 100:1390–1401

Khan ZI, K Ahmad, S Yasmeen, NA Akram, M Ashraf, N Mehmood (2017). Potential health risk assessment of potato (*Solanum tuberosum* L.) grown on metal contaminated soils in the central zone of Punjab, Pakistan. *Chemosphere* 166:157–162

Kim J, R Singh, J Lee (2019). AgNPs promote stomatal closure and reduce water loss in maize, enhancing its drought resistance. *Nanomaterials* 9:756

Kumar V, P Guleria, V Kumar, SK Yadav (2013). Gold nanoparticle exposure induces growth and yield enhancement in *Arabidopsis thaliana*. *Sci Total Environ* 461:462–468

Latef AAHA, AK Srivastava, H Saber, EA Alwaleed, LSP Tran (2017). *Sargassum muticum* and *Jania rubens* regulate amino acid metabolism to improve growth and alleviate salinity in chickpea. *Sci Rep* 7:10537

Li C, K Zhou, W Qin, C Tian, M Qi, X Yan, W Han (2019a). A review on heavy metals contamination in soil: Effects, sources, and remediation techniques. *Soil Sedim Contamin Intl J* 28:380–394

Li X, Z Liu, Z Hu, Y Cheng (2019b). Cadmium accumulation characteristics of different rice cultivars and screening for pollution-safe cultivars. *Ecotoxicol Environ Saf* 167:192–198

Liu H, JL Todd, H Luo (2023). Turfgrass Salinity Stress and Tolerance—A Review. *Plants* 12:925

Liu H, L Lin, J Shi, H Yang, D Chen (2019). Silver nanoparticle soil-plant transport and soil metal bioavailability: A study of agricultural field. *Environ Pollut* 246:397–404

Lv X, Q Yao, F Mao, M Liu, Y Wang, X Wang, Y Gao, Y Wang, S Liao, P Wang, S Huang (2024). Heat stress and sexual reproduction in *maize*: Unveiling the most pivotal factors and the biggest opportunities. *J Exp Bot* erad506, available online

Ma C, S Chhikara, B Xing, C Musante (2013). Whitehead, impact of cerium oxide nanoparticles on the quality of rice (*Oryza sativa* L.) grains. *Environ Sci Technol* 47:13722–13729

Magesky A, CA de Oliveira Ribeiro, L Beaulieu, É Pelletier (2017). Silver nanoparticles and dissolved silver activate contrasting immune responses and stress-induced heat shock protein expression in sea urchin. *Environ Toxicol Chem* 36:1872–1886

Manjunatha SB, DP Biradar, YR Aladakatti (2016). Nanotechnology and its applications in agriculture: A review. *J Farm Sci* 29:1–13

Marslin G, CJ Sheeba, G Franklin (2017). Nanoparticles alter secondary metabolism in plants *via* ROS burst. *Front Plant Sci* 8:832

Mohamed AKS, MF Qayyum, AM Abdel-Hadi, RA Rehman, S Ali, M Rizwan (2017). Interactive effect of salinity and silver nanoparticles on photosynthetic and biochemical parameters of wheat. *Arch Agron Soil Sci* 63:1736–1747

Mohamed MS, DS Kumar (2016). Methods of using nanoparticles. *In*: *Plant Nanotechnology*, pp:65–94. Kole C, DS Kumar, MV Khodakovskaya (Eds.). Springer International Publishing Switzerland

Montes A, MA Bisson, JA Gardella, DS Aga (2017). Uptake and transformations of engineered nanomaterials: Critical responses observed in terrestrial plants and the model plant *Arabidopsis thaliana*. *Sci Total Environ* 607:1497–1516

Moradi L, RS Sharifi (2020). Effects of salinity stress and seed inoculation with bio fertilizers on germination parameters, K and Na content of rye (*Secale cereal* L.) seedling. *Iran J Seed Sci Technol* 8:127–140

Mujumdar N (2013). Coping with water scarcity: An action framework for agriculture and food security/improving water use efficiency: New directions for water Management in India/Indian journal of agricultural economics. *Ind J Agric Econ* 68:603-603

Naz S, A Mushtaq, S Ali, HMD Muhammad, B Saddiq, R Ahmad, MA Altaf (2024). Foliar application of ascorbic acid enhances growth and yield of lettuce (*Lactuca sativa*) under saline conditions by improving antioxidant defence mechanism. *Funct Plant Biol* 51:1–15

Ozturk M, BT Unal, P García-Caparrós, A Khursheed, A Gul, M Hasanuzzaman (2020). Osmoregulation and its actions during the drought stress in plants. *Physiol Plant* 172:1321–1335

Pèrez-de-Luque A (2017). Interaction of nanomaterials with plants: What do we need for real applications in agriculture? *Environ Sci* 5:12-18

Pappula-Reddy SP, J Pang, B Chellapilla, S Kumar, BM Dissanayake, M Pal, AH Miller, KHM Siddique (2024). Insights into chickpea (*Cicer arietinum* L.) genotype adaptations to terminal drought stress: Evaluating water-use patterns, root growth, and stress-responsive proteins. *Environ Exp Bot* 218:105579

Prasad PS, T Gomathi, PN Sudha, M Deepa, K Rambabu, F Banat (2022). Biosilica/Silk Fibroin/Polyurethane biocomposite for toxic heavy metals removal from aqueous streams. *Environ Technol Innov* 28:102741

Rai PK, C Sonne, KH Kim (2023). Heavy metals and arsenic stress in food crops: Elucidating antioxidative defense mechanisms in hyper accumulators for food security, agricultural sustainability, and human health. *Sci Total Environ* 874:162327

Rajput S, D Kumar, V Agrawal (2020a). Green synthesis of silver nanoparticles using Indian Belladonna extract and their potential antioxidant, anti-inflammatory, anticancer and larvicidal activities. *Plant Cell Rep* 39:921–939

Rajput V, T Minkina, B Ahmed, S Sushkova, R Singh, M Soldatov, B Laratte, A Fedorenko, S Mandzhieva, E Blicharska, J Musarrat (2020b). Interaction of copper-based nanoparticles to soil, terrestrial, and aquatic systems: Critical review of the state of the science and future perspectives. *Rev Environ Contam Toxicol* 252:51–96

Rajput V, T Minkina, M Mazarji, S Shende, S Sushkova, S Mandzhieva, H Jatav (2020c). Accumulation of nanoparticles in the soil-plant systems and their effects on human health. *Ann Agric Sci* 65:137–143

Rosário F, IF Duarte, RJ Pinto, C Santos, PH Hoet, H Oliveira (2021). Biodistribution and pulmonary metabolic effects of silver nanoparticles in mice following acute intratracheal instillations. *Environ Sci Pollut Res* 28:2301–2314

Saeed F, UK Chaudhry, A Raza, S Charagh, A Bakhsh, A Bohra, S Ali, A Chitikineni, Y Saeed, RG Visser, KHM Siddique, RV Varsheny (2023). Developing future heat-resilient vegetable crops. *Funct Integr Genomics* 23:47

Salam A, M Rehman, J Qi, AR Khan, S Yang, M Zeeshan, Z Ulhassan, MS Afridi, C Yang, N Chen, X Fan, Y Gan (2024). Cobalt stress induces photosynthetic and ultrastructural distortion by disrupting cellular redox homeostasis in maize. *Environ Exp Bot* 217:105562

Sami F, H Siddiqui, S Hayat (2020). Impact of silver nanoparticles on plant physiology: A critical review. *In: Sustainable Agriculture Reviews: Nanotechnology for Plant Growth and Development,* Vol. 41, pp:111–127. vol 41. Springer, Cham, Switzerland

Seleiman MF, N Al-Suhaibani, N Ali, M Akmal, M Alotaibi, Y Refay, T Dindaroglu, HH Abdul-Wahid, ML Battaglia (2021). Drought stress impacts on plants and different approaches to alleviate its adverse effects. *Plants* 10:259

Shahid M, B Pourrut, C Dumat, M Nadeem, M Aslam, E Pinelli, S Rashid (2016). Heavy-metal-induced reactive oxygen species: Phytotoxicity and physicochemical changes in plants. *Rev Environ Contamin Toxicol* 232:1–44

Sheoran A, S Sheoran (2017). Phytoremediation of heavy metals contaminated soils. *J Plant Dev Sci* 9:905–915

Singh R, S Kumar (2023). *Nanotechnology Advancement in Agro-Food Industry*, pp:43–80. Springer Nature, Singapore

Smith AB, CD Johnson, MR Lee (2022). Silver nanoparticles as potential remediation agents for cadmium-contaminated soils and their effects on wheat (*Triticum aestivum*). *Environ Sci Pollut Res* 29:2707–2716

Sultan MT, U Mahmud, MZ Khan (2023). Addressing soil salinity for sustainable agriculture and food security: Innovations and challenges in coastal regions of Bangladesh. *Future Foods* 8:100260

Tomar RS, S Kataria, A Jajoo (2021). Behind the scene: Critical role of reactive oxygen species and reactive nitrogen species in salt stress tolerance. *J Agron Crop Sci* 207:577–588

Tripathi D, KK Rai, S Pandey-Rai (2021). Impact of green synthesized WcAgNPs on *in-vitro* plant regeneration and withanolides production by inducing key biosynthetic genes in *Withania coagulans. Plant Cell Rep* 40:283–299

Tripathi DK, Shweta, S Singh, R Pandey, VP Singh, NC Sharma, SM Prasad, NK Dubey, DK Chauhan (2017). An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity. *Plant Physiol Biochem* 110:2–12

Vadakkan K, NP Rumjit, AK Ngangbam, S Vijayanand, NK Nedumpillil (2024). Novel advancements in the sustainable green synthesis approach of silver nanoparticles (AgNPs) for antibacterial therapeutic applications. *Coordi Chem Rev* 499:215528

Verma S, P Bhatt, A Verma, H Mudila, P Prasher, ER Rene (2021). Microbial technologies for heavy metal remediation: Effect of process conditions and current practices. *Clean Technol Environ Policy* 25:1485–1507

Wahid F, S Fahad, S Danish, M Adnan, Z Yue, S Saud, MH Siddique, M Brtnicky, T Hammerschmiedt, R Datta (2020a). Sustainable management with mycorrhizae and phosphate solubilizing bacteria for enhanced phosphorus uptake in calcareous soils. *Agriculture* 10:334

Wahid I, S Kumari, R Ahmad, SJ Hussain, S Alamri, MH Siddiqui, MIR Khan (2020b). Silver nanoparticle regulates salt tolerance in wheat through changes in ABA concentration, ion homeostasis, and defense systems. *Biomolecules* 10:1506

Wang Y, X Xie, W Liu, C Tang, C Chen, A Yan (2018). Heavy metal pollution and health risk assessment in the Weihe River Basin, China. *Pol J Environ Stud* 27:1449–1460

Williams K, S Brown (2020). Effects of silver nanoparticles on root morphology and nutrient uptake in rice (*Oryza sativa*) under lead stress. *J Environ Sci Health* 55:215–221

Yadav A, A Yadav, V Sharma (2020). Nanotechnology in agroecosystem: Implications on plant defense mechanisms and soil health. *NS Sustain Agric* 2020:183–203

Yan Z, H Yuan, Q Zhao, L Xing, X Zheng, W Wang, W Yao (2020). Recent developments of nanoenzyme-based colorimetric sensors for heavy metal detection and the interaction mechanism. *Analyst* 145:3173–3187

Yang J, J Yu, M Li (2020). Heavy metal pollution and its potential ecological risk in surface soils of Shanghai metropolitan, China. *Environ Sci Pollut Res* 27:6755–6766

Yasur J, PU Rani (2013). Environmental effects of nanosilver: Impact on castor seed germination, seedling growth, and plant physiology. *Environ Sci Pollut Res* 20:8636–8648

You J, Z Chan (2015). ROS regulation during abiotic stress responses in crop plants. *Front Plant Sci* 6:1092

Younes NA, DM Nassef (2015). Effect of silver nanoparticles on salt tolerancy of tomato transplants (*Solanum lycopersicom* L. Mill.). *Assiut J Agric Sci* 46:76–85

Zafar S, H Afzal, A Ijaz, A Mahmood, A Ayub, A Nayab, A Moosa (2023). Cotton and drought stress: An updated overview for improving stress tolerance. *S Afr J Bot* 161:258–268

Zhang C, Y Wang, H Liu (2021). Effect of silver nanoparticles on the salt tolerance and growth of plants. *J NanoSci NanoTech* 21:3302–3312

Zhang T, Z Shi, X Zhang, S Zheng, J Wang, J Mo (2020). Alleviating effects of exogenous melatonin on salt stress in cucumber. *Sci Hortic* 262:109070

Zhao FJ, Y Ma, YG Zhu, Z Tang, SP McGrath (2015). Soil contamination in China: Current status and mitigation strategies. *Environ Sci Technol* 49:750–759

Zhou H, WT Tang, X Xu, L Liu, JF Gu, WL Wang, JL Zou, T Tian, PQ Peng, BH Liao (2017). Accumulation of heavy metals in vegetable species planted in contaminated soils and the health risk assessment. *Intl J Environ Res Publ Health* 14:289

Zulfiqar U, M Farooq, S Hussain, M Maqsood, M Hussain, M Ishfaq, M Ahmad, MZ Anjum (2019). Lead toxicity in plants: Impacts and remediation. *J Environ Manage* 250:109557