



Review Article

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

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Received 24 August 2023; Accepted 13 February 2024; Published 18 March 2024

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. © 2024 Friends Science Publishers

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

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

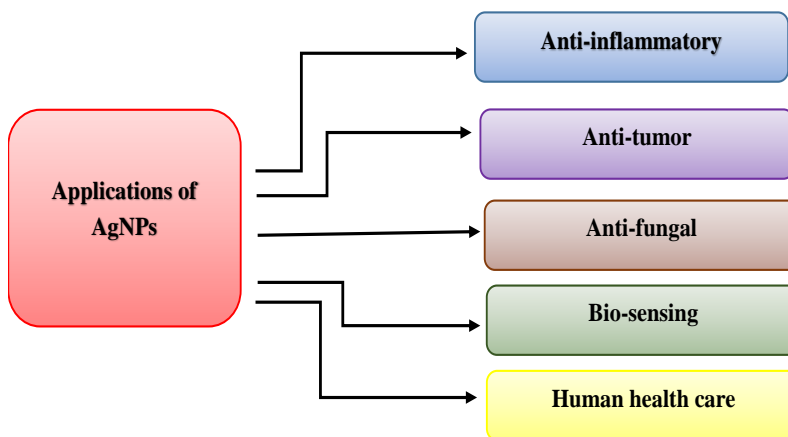


Fig. 1: Biological role of AgNPs in different fields

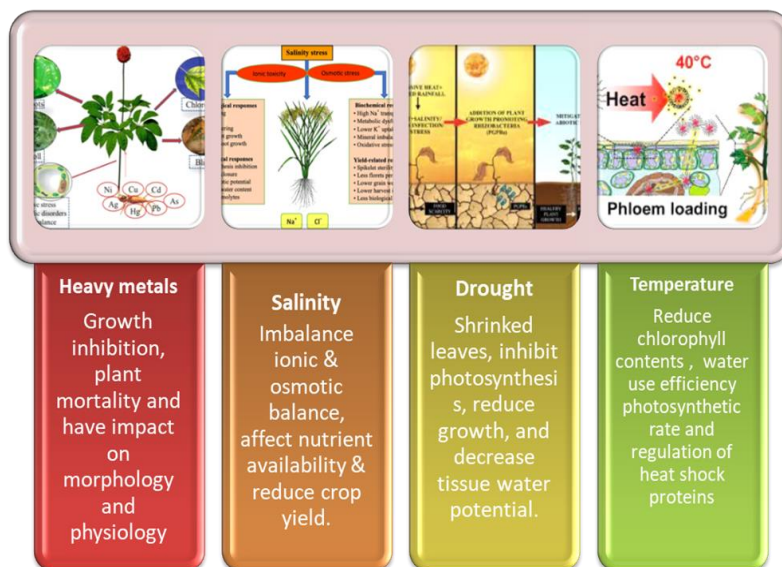


Fig. 2: Growth, physio-morphological and enzymatic changes in agricultural crops under different abiotic stresses on agriculture

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,

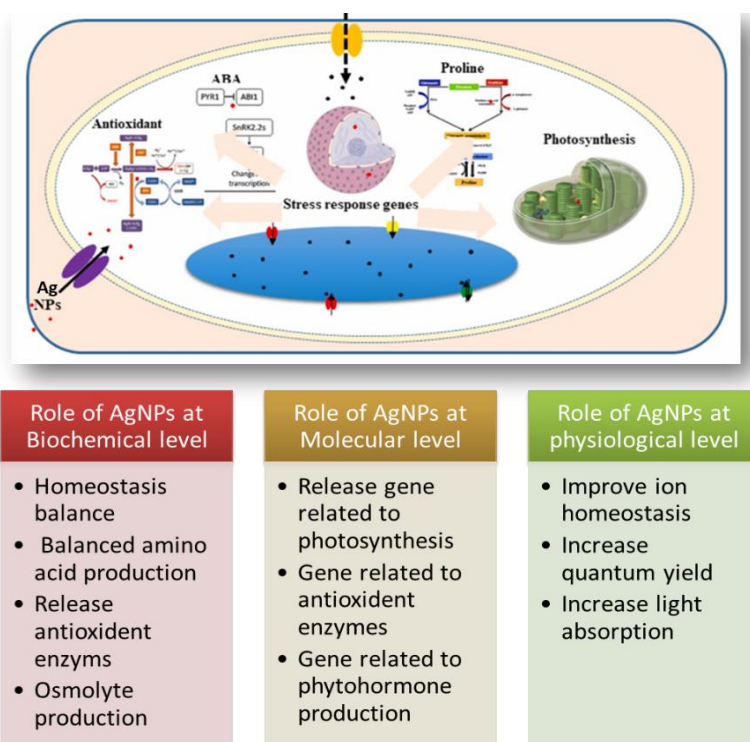
potentially disrupting local metabolic activities (Rajput *et al.* 2020a, b). In addition, NPs may directly absorb into seeds by diffusing through the cotyledon and into the coat through parenchymatic intercellular gaps (Tripathi *et al.* 2017).

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
<i>Triticum aestivum</i>	Salt stress	10 mM/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 <i>et al.</i> (2017)
<i>Lycopersicon esculentum</i>	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)
<i>Thymus vulgaris</i> and <i>T. daenensis</i>	Salt stress	0–10 mM/L	Ag-NPs increase germination percentage, shoot and root length, and seed vigor in under salinity stress	Ghavam (2018)
<i>Lycopersicon esculentum</i>	Salt stress	20 mg/L	Ag-NPs increase percentage plant survival at different levels of salinity.	Younes and Nassef (2015)
<i>Ocimum basilicum</i>	Salt stress	40 mg/L	Ag-NPs enhance germination percentage and improved resistance to salinity	Darvishzadeh (2015)
<i>Ricinus communis</i>	Salt stress	100 mg/L	Ag-NPs promoted the activities of SOD and POX under salt stress	Yasur and Rani (2013)
<i>Cuminum cyminum</i> L.	Salt stress	100 mg/L	Enhanced germination percentage, germination speed and vigor	Ekhtiyari <i>et al.</i> (2011)
<i>Lathyrus Sativus</i> L.	Salt stress	5, 10 ppm	Improve shoot and root length, germination percentage, seedling fresh and dry weight	Hojjat and Ganjali (2017)
<i>Triticum aestivum</i> 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 <i>et al.</i> (2017)
<i>Lens esculenta</i>	Drought stress	10, 20 40 µg/L	Improved germination percentage, root & shoot length.	Hojjat and Kamyab (2016)
<i>Lupinus luteus</i> L.	Heavy metal stress	25 mg/kg	Improve GPX activity and metallothioneins expression	Jaskulak <i>et al.</i> (2019)
<i>Triticum aestivum</i>	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 <i>et al.</i> (2022)
<i>Hordeum vulgare</i>	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)
<i>Oryza sativa</i>	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)
<i>Spinacia oleracea</i>	Heavy metal stress	0-50 mg/L	AgNPs reduce Cd uptake in spinach, lowering Cd-induced toxicity and improving overall plant health	Bisi-Johnson <i>et al.</i> (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 mM 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).

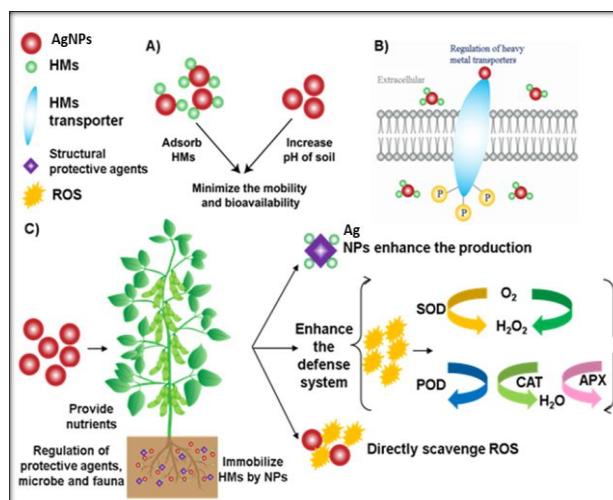


Fig. 4: Schematic role of AgNPs in reducing heavy metals stress in plants

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

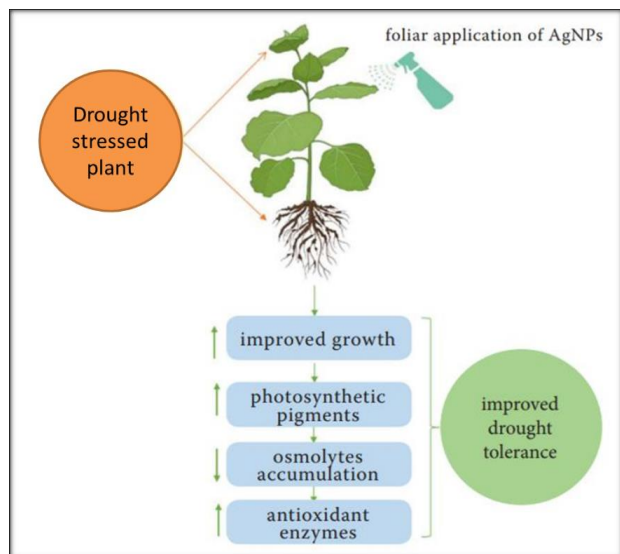


Fig. 5: Drought stress management in plants by AgNPs (Alabdallah *et al.* 2021)

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,

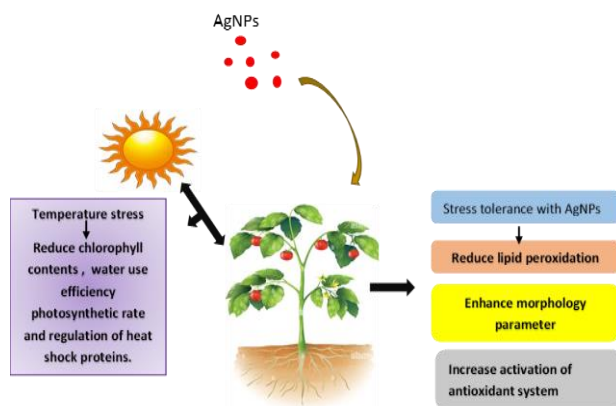


Fig. 6: Effects of temperature stress in plants and management through AgNPs

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.

Acknowledgements

All the authors are highly acknowledged for their valuable contribution in framing and sorting the existing literature for writing this review paper about the significance of AgNPs for their mitigating role towards abiotic stress management.

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.

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