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REVIEW

Enhancing Plant Resilience to Biotic and Abiotic Stresses through Exogenously Applied Nanoparticles: A Comprehensive Review of Effects and Mechanism

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ABSTRACT: A steady rise in the overall population is creating an overburden on crops due to their global demand. On the other hand, given the current climate change and population growth, agricultural practices established during the Green Revolution are no longer viable. Consequently, innovative practices are the prerequisite of the time struggle with the rising global food demand. The potential of nanotechnology to reduce the phytotoxic effects of these ecological restrictions has shown significant promise. Nanoparticles (NPs) typically enhance plant resilience to stressors by fortifying the physical barrier, optimizing photosynthesis, stimulating enzymatic activity for defense, elevating the concentration of stress-resistant compounds, and activating the expression of genes associated with defense mechanisms. In this review, we thoroughly cover the uptake and translocations of NPs crops and their potential valuable functions in enhancing plant growth and development at different growth stages. Additionally, we addressed how NPs improve plant resistance to biotic and abiotic stress. Generally, this review presents a thorough understanding of the significance of NPs in plants and their prospective value for plant antioxidant and crop development.

KEYWORDS: Crop; abiotic stress; antioxidant; biotic stress; nanoparticles

1 Introduction

The detrimental impacts of non-living environmental variables on species within a particular ecosystem are called abiotic stress. Significant worldwide concerns include environmental stressors like severe temperature, drought, salinity, and heavy metal contamination. Abiotic stress is more likely to affect plants in the setting of a changing global climate. As a result of global warming, climate change is linked to a marked rise in the frequency and severity of heat waves, droughts, and other abiotic stressors such as flooding, salinity, and freezing temperatures [1]. Likewise, biotic stresses such as viruses, fungus, bacteria, insects, and nematodes can markedly affect the vigor and productivity of crops [2,3].

The use of exogenous compounds is one of the most efficient and environmentally friendly strategies devised to lessen the negative effect of abiotic stress on plants [4]. Nanotechnology is a significant and quickly progressing field of research that has produced numerous innovations [5]. Agriculture's future needs to be secure and sustainable, and nanotechnology has the potential to help achieve this [6]. Nanotechnology is primarily used in agriculture to monitor product and nutrient levels and apply nano pesticides and fertilizers, strengthen plant resistance to microbial disease and insect pests, and promote growth and productivity [7]. Nanoparticles (NPs) are becoming increasingly important in molecular biology studies because of their special physicochemical qualities. These include extraordinary intracellular stability, nanoscale dimensions (1–100 nm), increased surface area, and enhanced reactivity [8]. NPs made of metals and metal-based compounds have a wide range of physicochemical characteristics and are extensively used in many different sectors. These include agricultural and other industries such as textiles, food preparation, biomedicine, chemical processing, optics, and pharmaceuticals [9,10].

Moreover, metal-based NPs directly affect plant transcriptional regulation and transcript processing [11]. These compounds can bind to specific regions of promoters to alter gene expression, or they can interact with DNA molecules to change the structure of chromatin. Additionally, metal NPs can affect transcript processing via their interactions with RNA-binding proteins and splicing factors. Growth and development of plants are affected by gene expression patterns [12,13]. Metal NPs have a substantial effect on proteins both during and after translation. During protein synthesis, these NPs can affect ribosomal activity, affecting protein quantity and efficiency. They possess the capacity to modify ribosome activity, which affects the synthesis of particular proteins as well as the manner in which protein synthesis proceeds. Furthermore, it has been demonstrated that metal NPs can alter the stability, function, and localization of protein by causing post-translational changes such as phosphorylation, acetylation, and ubiquitination. These alternations are required for controlling a variety of biological functions, such as responses to stress, hormone signaling, and plant growth regulation [14,15]. The lower concentration of NPs caused superoxide dismutase (SOD) and peroxidase (POD) bursts, whereas these enzymes were inhibited at greater doses. Low concentrations of some chemical have harmful effects, but greater concentration have an adverse effect. This phenomenon is called a hormesis effect [16].

This study focuses on understanding how NPs affect plants to improve abiotic and biotic stress tolerance and contribute to sustainable agricultural operations. It summarizes the current understanding and potential applications of NPs in crop plants.

2 Mechanism of Abiotic and Biotic Stress Tolerance by Nanoparticles

To achieve sustainability in agriculture, technologies must be developed to increase food output and reduce crop yield loss. Numerous forms of abiotic stress on plants, such as salt drought, waterlogging, submersion, heavy metal stressors, and mineral and metal toxicity that reduce crop development and yield, are regarded as a significant rising issue in the field of agriculture [17,18]. These variables are primarily responsible for a decline in production. Throughout their lives, plants must deal with a variety of abiotic stressors and develop strong defense mechanisms to withstand them. Research on NPs has reported that they help plants to overcome abiotic stress by their concentration-dependent impact on plant growth and development [18–20]. Additionally, it has been reported that NPs have been found to increase the action of several antioxidant enzymes, including catalase (CAT), POD, and SOD [21]. In order to improve crop plants, NPs cooperate with plants in a variety of ways that result in numerous morphological and physiological changes depending on their chemical composition, size surface coverage, and reactivity. NPs affect plant growth and development in both favorable and harmful ways [22].

NPs represent a viable method for enhancing biotic stress tolerance across different species. This cutting-edge field combines nanotechnology and biological system to develop strategies that strengthen resistance against non-living environmental [23]. Apart from the biosynthesis process, precise and continuous post-synthetic remodeling can regulate the composition and structure of the cell wall during biotic interactions [24]. Their interaction with cell wall material such as cellulose, hemicellulose, and lignin strengthens plant defenses against pathogens [25]. Through adsorption or surface deposition, NPs interact with the plant cell wall to create a barrier that prevents diseases or pests from directly contacting the cell wall, protecting plants from biotic stress [26,27]. NPs can activate defensive responses in plants by interacting with the cell wall, triggering genes relevant to defense, and promoting the production of antimicrobial substances such as protein and phytoalexins that inhibit the development of pathogens [27,28]. Plants produce reactive oxygen species (ROS), trigger phytohormone pathways, and release secondary metabolites in response to biotic stress that inhibit herbivores or prevent the growth of pathogens [29]. NPs, including ZnO and TiO_2 have been found to produce ROS upon light exposure [30]. NPs improve biotic stress defense by generating ROS directly within the cell wall. Additionally, by binding to cell wall proteins, they improve their stability and provide improved cell wall defense. The attachment of NPs to cell wall protein provides an added line of resistance in contrast to environmental stresses, with infections [31]. By upregulating genes involved in lignin production and improving the mechanical strength of the cell wall, NPs may affect the metabolic process involved in cell wall biosynthesis [32]. Most defense-related genes are produced by plants exposed to metallic NPs strengthening their cell wall barriers and generating antimicrobial compounds. Through epigenetic processes including DNA methylation and histone acetylation, metal oxide NPs can change gene expression without changing the DNA sequence [33]. This mechanism may result in the activation or suppression of genes essential for cell growth, division, and stress responses. More study is necessary for the best use of metallic NPs since their effects on gene expression differ depending on their characteristics, concentration, exposure time, and plant species [34].

3 Alleviation of Biotic and Abiotic Stress in Crop by Using Nanoparticles

In response to unfavorable environmental conditions, plants initiate biochemical, physiological and transcriptomic changes to alleviate stress [35,36]. These circumstances primarily inhibit their development by generating reactive oxygen species (ROS), which then acts as signal molecules to initiate stress resistance mechanisms.

In agriculture, NPs can be applied in the form of nanosensors, nanofertilizers, nanoherbicides/ nanopesticides/ nanopesticides and nanoremediators [5,37]. However, the mechanism underlying how NPs interact with plants has not been completely elucidated [38,39]. The types of NPs and application of NPs improve growth traits under abiotic and biotic stress (Figs. 1 and 2 and Table 1).

Figure 1: Types of NPs and their function

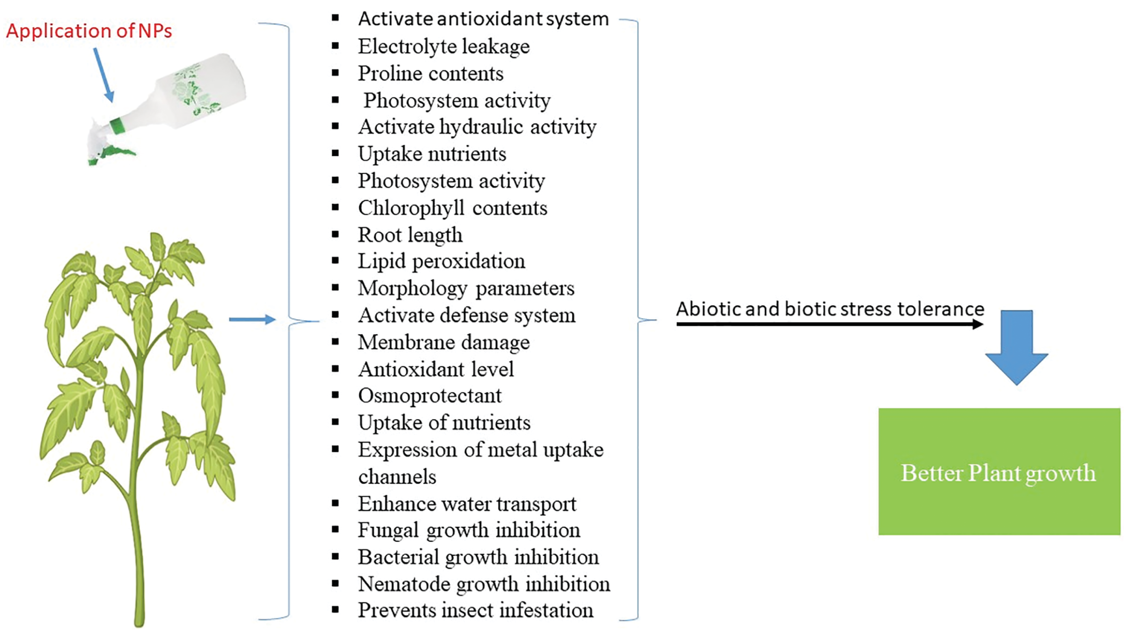

Figure 2: The application of NPs develops growth traits under abiotic and biotic stress

3.1 Nanoparticle Application to Lessen the Effects of Salt Stress

Salt is a significant abiotic stressor that lowers crop quality and productivity on about 45 million hectares of irrigated land [40]. Salinity stress modifies the intake of nutrients, reduces the uptake of water, and causes indirect drought stress through osmotic stress. The buildup of sodium and chloride ions in the cytoplasm cell sources ionic toxicity [41]. The metabolic processes in plant cells are interfered with under such circumstances, which lowers plant development as well as crop efficiency and features overall [42,43]. Agricultural land salinization is primarily driven by two key factors: Overuse of chemicals and climate change.

An alternate strategy to counteract salt stress is to apply various NPs, which lessens the toxicity effects that come with it. Applying FeO-NPs mitigated NaCl stress by enhancing growth, green photosynthetic pigment, and antioxidant enzyme activity in wheat plants. These NPs exhibited the resources to protect cells against ionic stress and reduce the accumulation of sodium ions within cells [44]. Applying ZnO-NPs (0.12 g pot^{-1}) to wheat under salt stress resulted in increased plant height during the vegetative and mature stages longer shoots and spikes, improved fresh and dry weights, and higher levels of chlorophyll A and B, all of which improved grain output [45]. Ye et al. [46] discovered manganese seed priming nanoparticle control the molecular response of pepper plants, shielding them against saline stress. Nanotubes with multi-walled surfaces lessen the development of ROS, thiobarbituric acid, and the Na^+/K^+ ratio, enhances rapeseed (*Brassica napus* L.) salt tolerance. However, additional study on both physiochemical and molecular levels is required to clarify how NPs work to improve a plant's ability to withstand salinity [47]. Hernández-Fuentes et al. [48] revealed that applying Cu-NPs (250 mg L^{-1}) to tomato plant leaves stressed by salt affected the fruit's antioxidant activity as well as the buildup and disintegration of bioactive compounds. Applying $nSiO_2$ seems to alleviate the deleterious effect of salt by enhancing the epicuticular wax layer [49]. Faiz et al. [50] demonstrated that ZnO-NPs treatment effectively alleviated salt stress in tomato seedlings, boosting antioxidant defenses protein content, catalase (CAT), superoxide dismutase (SOD), and peroxidase (POD). Application of ZnO-NPs to rice not only prevents Na^+ from being absorbed, lessening the negative consequences of saline-sodic stress on the grain, but it also makes Zn easier to absorb, increasing rice's chloroplast pigment content and facilitating effective photosynthesis. Additionally, improves the electron acceptor side of the electron transport chain, which makes it easier for electrons to move between PSII and PSI [51]. The combination of copper oxide and zinc oxide NPs applied topically for nutrient absorption, photosynthesis, and reducing antioxidant activity lowering excess Na^+ in radish plants. However, both the metal oxide NPs showed differential responses [52]. The application of SiO_2-NPs (30 ± 5 nm) boosted salt-tolerant rice yield by increasing panicle size and grain filling rate. Chlorophyll levels, leaf area index, potassium ion content, dry matter, root system growth, and antioxidant activities were all improved by SiO_2 NPs which also reduced malondialdehyde content [53].

3.2 Nanoparticle Application to Lessen the Effects of Drought Stress

Plants normally encounter fluctuating environmental conditions that may be suboptimal for their emergence and development. In the context of ongoing environmental changes and anthropogenic activities, drought and other extreme weather disasters are likely to happen more frequently in the future [54–56]. Crop yields can be severely affected by global warming and drought. It is crucial for the life cycle of plants to have access to water. In general, drought conditions result in reduced water availability for plants; however, a number of variables, such as the length and intensity of the drought, the stage at which develops when it is under water stress, and certain plant characteristics like root architecture, the makeup of the epicuticular wax, and the integrity of cell wall, all affect crop productivity [56,57]. As a result, signal perception and transduction play a complicated and multifaceted role in plants' response to drought.

Different drought-coping mechanisms have evolved in plants, such as tolerance, avoidance, and escape. The application of nSe alleviated drought stress (DS) adverse effects by boosting photosynthetic pigment production, dry biomass accumulation, RWC, and antioxidant defenses [58]. Applying Se-NPs to leaves at a concentration of 10 ppm substantially improves drought resistance in grapevine saplings. This enhancement is achieved through strengthening antioxidant defense, increasing proline and protein production, and promoting overall plant development. However, Se-NPs concentration below 10 ppm are less effective, while those above this level may result in toxic effects on the plants [59]. Similarly, Javan et al. [60] revealed that fruit firmness in sustained deficit irrigation (SDI) plants decreased by 25.2%, 25.2%, and 21.5% at TiO_2-NPs concentrations of 10, 20, and 30 mg L^{-1}, respectively, compared to full irrigation (FI). Cu-NPs application alleviated DS adverse effects, improving wheat growth and yield parameters such as plant height, spike length, 1000 grain weight, stomatal conductance, leaf chlorophyll content, water use efficiency, leaf turgor potential, relative water content, and grain yield [61]. Water-stressed maize seedlings treated with O-CMC NPs showed a considerable increase in chlorophyll content as well as the activity of many antioxidant enzymes, including polyphenol oxidase (PPO), catalase (CAT), Peroxidase (POD), and superoxide dismutase (SOD) [62]. According to Asghari et al. [63], basil under drought stress exhibited improved physiological and phytochemical features when exposed to Se-NPs at concentrations of 50 and 100 ppm. The foliar spray of 10, 20, 30, and 40 Se-NPs to wheat under drought stress conditions improved various growth signs. This improvement were observed in multiple aspects of plant development, including overall plant height, shoot dimensions and mass (both fresh and dry), root characteristics (length and weight in fresh and dry), as well as leaf metrics [64]. Additionally, ZnO-NPs can reduce the buildup of ROS and lipid peroxidation, as well as increase antioxidant activity, in cucumber (*Cucumis sativus*) seedlings under moderate oxidative stress [65]. Similarly, El-Zohri et al. [66] revealed that tomato plants' ability to withstand drought stress can be enhanced successfully by tropically applying green ZnO-NPs at lower concentrations. Bisht et al. [67] reported that hematite-NPs decreased ammonia and proline nitrate levels by 22.4%, 25%, and 37%, respectively. Also, 50 mg/L of hematite NPs worked best to control nitrogen and osmolyte breakdown during water stress. Under drought conditions, the combination of Chitosan-Coated Iron Oxide NPs and Kitoplus® advanced stimulant led to an increase in oil yield in a mint plant [68]. Nano-silicon (nSi) application on Kalamata olive tree leaves in a semi-arid environment specifies that treating with 200 mg L^{-1} notably enhances mechanical strength, growth, and productivity in trees facing moderate stress on physiological and biochemical characteristics under deficit irrigation conditions [69]. In conclusion, prior research has demonstrated promising outcomes after applying NPs to mitigate the negative effects of scarcity stress on plant development and output.

3.3 Nanoparticle Application to Lessen the Effects of Temperature Stress

Among the dynamic environmental elements, one of the most harmful stresses is thought to be the constant rise in temperature [70]. Elevated temperature increases the generation of ROS and triggers oxidative stress in crop plants. This leads to the degradation of membrane lipids, disruption of cellular balance, and impairment of various metabolic functions. Ultimately, these effects result in cell death within the plant [71]. Furthermore, heat stress inhibits carbon fixation, increases the breakdown of chlorophyll, and inhibits photosystem II and electron flow. These results interfere with the photosynthesis process, resulting in diminished plant growth [72]. On the contrary, these plants' defense mechanisms, secondary metabolism, respiration, and the synthesis of proteins and nucleic acids are all impacted by low temperatures [73,74]. Recent advancements in nanotechnology have improved the efficiency of the agriculture sector with prospective applications to expand plant emergence and change under demanding conditions [75]. In wheat plants, the application of GS-Ag-NPs reduces the effect of heat stress by increasing the flux of carbohydrates metabolism, SOD, and protein, including HSPs, crude fibers, and minerals [76]. The ZnO-NPs application boosted the root dry weight, root–shoot ratio, total dry weight, and chlorophyll a/b ratio in Xiangyaxiangzhan by 10.48%–18.10%, 1.96%–20.31%, 3.25%–6.02%, and 3.70%–6.11% at low temperature, respectively [77]. Wang et al. [78] reported that the application of CH-NPs exposed efficacy in lessening the harmful influences of low-temperature pressure on (*Musa acuminate* var Baxi) plants through the decline of ROS buildup. Similarly, Djanaguiraman et al. [79] discovered application of Se-NPs in sorghum subjected to elevated temperatures demonstrated efficacy in mitigating adverse effects including membrane degradation, reduced pollen viability, and diminished crop yields, through the initiation of the wheat antioxidant defense system. ZnO-NPs treatment of alfalfa seedlings prior to heat stress changed the ultrastructure of mitochondria, cell walls, and chloroplasts, minimizing heat-induced damage and improving plant growth. Likewise, ZnO-NPs dramatically reduced the decrease in TGS-GUS gene expression that heat caused in *Arabidopsis thaliana* seedlings that were subjected to 37°C of heat stress [80]. Younis et al. [81] results show that applying Si or Si-NPs to cellular organelles, particularly the nucleus and chloroplasts, successfully repaired the structural harm brought on by heat stress. Furthermore, as demonstrated by higher levels of photosynthetic pigments, improved performance index, and increased photochemical efficiency of photosystem II, both Si and Si-NPs increased photosynthetic capacity. The foliar treatment of nano-ZnO is an effective method to defend mung bean crop from heat stress-induced damage with the minor risk of NPs release into the environment compared to soil application [82]. Similarly, Plaksenkova et al. [83] showed the study concentration of Fe_3O_4 may positively affect the yield and quality of rocket seedlings, and possibly these NPs could expand the ability of plants to stand against environmental stresses.

3.4 Nanoparticle Application to Lessen the Effect of Heavy Metals

A variety of life forms, including plants, are at risk due to heavy metals (HMs). Crop yields are severely affected by HMs because they disrupt imperative cellular biomolecules severely hampering plant metabolism. NPs are one of the most recent, efficient, and promising strategies for alleviating HMs [84,85].

Faizan et al. [86] revealed that foliar use of ZnO-NPs shortens the negative influence of Cd on tomato plants by increasing the creation of chloroplast pigments, regulating osmoregulation and diminishing the content of O^{2-}, MDA, and H_2O_2. Likewise, Alomrani et al. [87] revealed that low concentration of Cu-NPs efficiently threatened *Solanum melogena* from the opposing outcome of heavy metal stress. Cu-NPs showed a key role in plant physiology by stimulating enzyme activity and resistance mechanisms. Similarly, Ahmad et al.'s [88] research showed that applying Si-NPs reduces the amount of Cd adsorbed by tomato roots, reducing heavy metal's effects. Moreover, it enhances tomato plants under Cd stress regarding growth, yield, and biomolecule indicators. The application of ZnO-NPs initiated efficient heavy metal tolerance mechanisms by triggering multiple biochemical pathways in a coordinated manner to avoid cellular damage from heavy metal oxidative stress-caused toxicity in *Leucaena leucocephala* [89]. Additionally, Samani et al. [90] revealed that nano silica acts as a beneficial soil amendment, improving nutrient availability and mitigating the harmful impacts of heavy metals on *Calendula officinalis*. Applying FeO and Se-NPs to wheat reduced oxidative stress and Cd absorption while improving ($p < 0.05$). gas exchange properties, synthetic and non-synthetic, gene expression, and plant evolution and biomass [91]. Coriander plants exhibited enhanced resistance to Cd stress when titanium dioxide NPs were utilized in seed priming. Similarly, Sardar et al. [92] concluded that TiO_2-NP treatment of coriander plants under Cd stress, positively influenced photosynthetic content, total soluble sugar concentration, growth, and yield parameters. Likewise, the application of Ag-NPs might reduce aluminum's harmful impact on pineapple growth and nutrition at specific concentrations. This is vital for maintaining adequate photosynthetic pigments and a balanced mineral intake during *in vitro* pineapple cultivation [93]. In lettuce, ZnO-NPs significantly reduced cadmium uptake, with a maximum reduction noticed at a concentration of 100 mg/L of G-ZnO-NPs. The concentrations of zinc (Zn) and cadmium (Cd) were inversely correlated in lettuce shoots [94]. Nevertheless, it is crucial to create innovative nano-remediation techniques to mitigate the detrimental effects of HMs on plant growth and development.

4 Biotic Stress

A major contributor to crop losses in agriculture is biotic stress [95]. Living organisms, such as fungi, viruses, bacteria, insect pests, and herbivores, are responsible for causing biotic stress in plants. Unlike abiotic stress, biotic stress severely impedes plant growth through nutritional deficiency, potentially leading to the death of the plant [96,97]. Nanotechnology offers diverse applications for enhancing agricultural productivity, safeguarding crops, and improving the storage, packaging, and transportation of farm products.

Additionally, it provides eco-friendly, effective, and secure approaches to control the transmission of plant-based biotic stress [98].

4.1 Disease Stress

Kaur et al. [99] demonstrated that biosynthesized Ag-NPs exhibit a 46% increase in efficacy and reduced chickpea *Fusarium wilt* incidence by 73.33% compared to CuOCl. Also, Ag-NPs showed non-toxic properties to chickpea seed germination and the soil microbial community. The application of ZnO-NPs to the artificially inoculated tomato plants with the pathogen *Ralstonia. solanacearum* significantly enhances plant growth by reducing bacterial soil population and disease severity as compared with the untreated control [100]. The application of CeO_2-NPs exhibited significant antifungal activity against *Ustilago tritici*, the fungal pathogen affecting wheat crops, across all concentrations tested [101]. Similarly, Satti et al. [102] revealed that applying varying concentrations of NPs externally to wheat plants led to decreased disease occurrence and severity index. The most effective suppression of pathogens was achieved when using TiO_2 NPS at a concentration of 40 mg L^{-1}. The exogenous treatment of apples (cv.Anna) with chitosan nanoparticles or bulk chitosan significantly enhanced systemic acquired resistance (SAR) against *Penicillium expansum* infection by enhancing the expression of crucial defense-related genes [103]. The application of ZnO-NPs considerably prevents blast development and improves blast resistance in rice by prompting ROS accumulation and expression of defense-related genes *OsNAC4, OsPR10, OsKSL4, and OsPR1b* [104]. Additionally, Ghareeb et al. [105] concluded that using ZnONPs improved the quality and quantity of sweet pepper crops while dramatically lowering the severity of *Fusarium oxysporum* disease. Furthermore, the application of ZnO-NPs to *M. incognita* resulted in a substantial reduction in the number of nematode galls, egg masses per root, eggs/egg mass, and females by 98%, 99%, 99.9%, and 95.5%, respectively. Foliar application of 0.10 g L^{-1} MnO_2-NPs in conjunction with *Pseudomonas putida* yielded the most significant reduction in wilt disease indices, galling, and *Meloidogyne incognita* population, while simultaneously promoting the greatest increase in plant growth parameters. Application of ZnO-NPs using *Azadirachta indica* leaf extract for biocontrol of diseased lychee fruits [106]. In banana leaves, CS-NP spraying significantly decreased BSV replication by elevating plant defense mechanisms and growth responses. An 18.20-fold increase in expression was achieved with CS-NPs at 400 mg L^{-1} [107].

4.2 Pest Stress

Pests pose a significant challenge in agriculture as they have the potential to cause harm to crops and contaminate stored food, resulting in a decline in food quality and the spread of plant diseases [108,109]. The application of silver NPs at low doses could effectively reduce the population of phytophagous mites on tomato plants while minimizing harmful effects on non-target mite species [110]. Additionally, peach tree leaf extracts treated with Ag-NPs and Zn-NPs demonstrated complete rice weevil mortality (*Sitophilus oryza* L.) and less *Rhyzopertha dominica* via the fumigation method [111]. Similarly, Al-Azzazy et al. [112] application of ZnO-NPs at varying concentrations ((200, 400, 600, 1000, 1250, and 1500 ppm) against all stages of the date palm mites. As zinc oxide nanoparticle concentrations increased, both tetranychid and phyttoseiid mite mortality rates increased. With minimal effects on *Amblyseius swirskii*, ZnO-NPs were shown to be highly effective in killing *Oligonychus afrasiaticus* and *Eutetranychus palmatus*. Bapat et al. [113] concluded that a higher concentration of Si-NPs in tomatoes inhibited the larval growth of *Helicoverpa armigera*. Application of Silicon NPs (0.5 and 1 mg L^{-1}) on tomato plants reduced their susceptibility to the Root-knot nematode (*Meloidogyne incognita*). SiO_2-NPs demonstrated a significant protective effect against *Caryedon serratus* in groundnuts at concentrations of 0.67 and 1.7 mg/kg, and mortality rose with exposure duration [114]. Similarly, Al-Azzazy et al. [115] reported that higher concentrations of Cu-NPs correlated with increased mortality rates in both phytophagous and predatory mites. Cu-NPs demonstrated significant efficacy in eliminating *Phyllocoptruta oleivora*, *Eutetranychus orientalis*, and *Brevipalpus obovatus* while exhibiting minimal effects on *Amblyseius swirskii* and *Euseius scutalis*. Nanosilica, with a 30 nm particle size at 0.5 g/kg rice, showed 80% and 97.4% mortality rates against *Sitophilus oryzae* after 7 and 14 days, respectively [116]. SiO_2-NP fumigation of maize grains proved highly active against four common pests: *Sitophilus oryzae*, *Rhizopertha dominica*, *Tribolium castaneum*, and *Orizaephilus surinamenisis* [117].

Table 1: Effect of NPs on crop plants under abiotic and biotic stress

Plant species	NPs	Key findings	References
Salt stress			
Wheat *Triticum aestivum*	FeO-NPs	A FeO-NPs-based treatment might serve as a viable approach for mitigating the adverse effects of Cd on saline soils polluted with Cd, thus promoting safe agriculture.	[44]
Wheat *Triticum aestivum*	ZnO-NPs	ZnO-NPs outperform traditional zinc fertilizers in saline conditions and could replace them to enhance crop yields in such soils.	[45]
Pepper *Capsicum annuum*	Manganese-NPs	Manganese-NPs Control Salinity-Modulated Molecular Responses in *Capsicum annuum* L. through Priming: A Sustainable Approach for Agriculture.	[46]
Rapeseed *Brassica napus*	Carbonaceous nanomaterials (CNMs)	NR-dependent NO functions downstream of MWCNTs in salinity tolerance, which necessitates the re-establishment of redox and ion homeostasis.	[47]
Tomato *Solanum lycopersicum*	Cu-NPs	Cu-NPs foliar application demonstrates potential in mitigating the adverse effects of sodium chloride (NaCl) exposure on fruit quality.	[48]
Strawberry *Fragaria ananassa*	$nSiO_2$	Applying $nSiO_2$ can alleviate salinity stress in strawberry plants by improving the epicuticular wax layer (EWL) and sustaining photosynthesis and relative moisture content.	[49]
Carrot *Daucus carota*	MgO-NPs	The potential of magnesium oxide NPs to enhance nutritional content in *Daucus carota* through modulation of the antioxidant system and polyamines.	[50]

(Continued)

Table 1 (continued)

Plant species	NPs	Key findings	References
Rice *Oryza sativa*	ZnO-NPs	ZnO-NPs are improving the growth and photosynthetic efficiency of rice in saline, sodic soils.	[51]
Raddish *Raphanus sativus*	CuO and ZnO-NPs	ZnO-NPs exhibit superior efficacy and demonstrate more favorable effects compared to CuO NPs in enhancing vigor and mitigating the detrimental impacts of NaCl stress in radish plants.	[52]
Rice *Oryza sativa*	Silica-NPs	SiO_2 NPs demonstrate significant potential for mitigating salt stress and enhancing rice quality and growth.	[53]
Drought stress			
Soybean *Glycine max*	nSe	Enhanced soybean tolerance and potentially improve crop yields under drought conditions	[58]
Grapevine *Vitis vinifera*	Se-NPs	Grapevine seedlings' capacity to withstand drought was improved by foliar application of Se-NPs, which balanced the antioxidant defense system and increased proline and protein accumulation.	[59]
Strawberry *Fragaria ananassa*	TiO_2	To enhance physicochemical features under drought stress, foliar treatment of TiO_2 under partial root-zone drying (PRD) is recommended.	[60]
Wheat *Triticum aestivum*	Cu-NPs	Cu-NP application increased wheat production, WUE, physiological indices, and water-related traits.	[61]
Maize *Zea mays*	*O*-Carboxymethyl chitosan	Their potential role in assisting with the recovery from oxidative damage and protecting maize seedlings from water stress.	[62]
Basil (*Ocimum basilicum* L.)	Se-NPs	Low-concentration Se-NPs improve plant tolerance and the quantity and quality of EO in basil under drought conditions.	[63]
Wheat *Triticum aestivum*	Se-NPs	Improving drought tolerance by promoting the development and growth of wheat plants under severe drought stress	[64]

(Continued)

Table 1 (continued)

Plant species	NPs	Key findings	References
Cucumber *Cucumis sativus*	ZnO-NPs	ZnO-NPs could be a useful strategy for treating drought stress in cucumber seedlings.	[65]
Tomato *Solanum lycopersicum*	ZnO-NPs	Applying zinc oxide NPs by foliar spray—which is made from *Coleus forskohlii* leaf extract—improves tomato growth and antioxidant system performance under various drought circumstances.	[66]
Peppermint *Mentha piperita*	Fe-CTs-NPS	The development and production of peppermint plants are significantly increased by applying Kitoplus and Fe-CTs NPS to their leaves, particularly when the plants are experiencing water scarcity.	[68]
Olive *Olea europea*	nSi	The vigor, yield, and mechanical resilience of "Kalamata" olive trees can be efficiently enhanced under stress by applying 200 $mg \cdot L^{-1}$ nSi	[69]
Temperature stress			
Wheat *Triticum aestivum*	GS-AgNPs	An anticipatory model using GS-AgNPs, focuses on the genes and variables that respond to heat stress and their possible ability to ameliorate its effects.	[76]
Rice *Oryza sativa*	ZnO-NPs	The harmful effects of cold stress on fragrant rice in its infancy by applying them to the leaves at the appropriate concentration (100 mg/L^{-1}).	[77]
Banana *Musa paradisiaca*	Chitosan-NPs	In banana plants, Chitosan-NPs treated mitigated chilling stress.	[78]
Sorghum *sorghum bicolor*	Se-NPs	Se-NPs enhance the antioxidative defense systems of sorghum plants, protecting them from heat stress.	[79]
Thale cress *Arabidopsis thaliana*	ZnO-NPs	The synergistic effect may be influenced by factors such as the plant developmental stage, duration of heat exposure, temperature, and heat shock-related genes.	[80]

(Continued)

Table 1 (continued)

Plant species	NPs	Key findings	References
Wheat *Triticum aestivum*	Si or Si-NPs.	Certain heat stress-related damage may be lessened by soaking wheat grains in solutions containing Si or Si-NPs.	[81]
Mungbean *Vigna radiata*	ZnO-NPs	A concentration of 30 mgl^{-1} nano-ZnO showed superior performance across all sowing dates and effectively mitigated the negative effect of heat stress	[82]
Heavy metals stress			
Tomato *Solanum lycopersicum*	ZnO–NPs	ZnO-NPs mitigated Cd's effects, enhancing gene expression in stressed and non-stressed plants.	[86]
Carrot *Daucus carota*	MgO-NPs	By increasing the activity of antioxidant enzymes, MgO-NPs can neutralize ROS, reducing lead (Pb) toxicity and enhancing plant growth.	[50]
Brinjal *Solanum melongena*	Cu-NPs	Cu-NPs stimulated the synthesis of osmo-regulators and antioxidants under Cd-stress	[87]
Tomato *Solanum lycopersicum*	Se-NPs	Under cadmium stress conditions, Se-NPs enhanced the levels of ascorbic acid, protein, carboxylic acid, flavonoids, and proline in tomato plants. Additionally, the activity of stress enzymes was increased in the presence of cadmium stress.	[88]
Leucaena *Leucaena leucocephala*	ZnO-NPs	MDA concentration in leaves significantly decreased when ZnO-NPs were added, although photosynthetic pigment and total soluble protein levels increased.	[89]
Marigold *Calendula officinalis*	Nano silica	By improving soil nutrient availability and lessening the harmful effects of heavy metals on *Calendula officinalis*, nano silica is an efficient soil modifier.	[90]
Wheat *Triticum aestivum*	FeO and Se NPs	FeO and Se-NPs increased cellular fractionation and reduced proline metabolism and the AsA-GSH cycle in *Triticum aestivum*.	[91]

(Continued)

Table 1 (continued)

Plant species	NPs	Key findings	References
Coriander *Coriandrum sativum*	TiO_2-NPs	It improved plant growth, photosynthesis, and antioxidant potential with TiO_2-NPs and decreased Cd uptake and translocation in plants.	[92]
Pineapple *Ananas comosus*	Ag-NP	Application of Ag-NP increased proline synthesis in response to stress, enhanced shoot growth, and raised the ratios of chlorophyll a/b and total/carotenoid.	[93]
Lettuce *Lactuca sativa*	ZnO-NPS	With regard to improving crop development under stress and their function in regulating plant absorption of Cd, this work provides insights into the effects of chemical and green-produced ZnO-NPs. These findings may have consequences for sustainable agricultural methods.	[94]
Disease stress			
Chickpea *Cicer arietinum*	Ag-NPs	*In vitro*, Ag-NPs demonstrated a very high antifungal efficacy of 95% against FOC. The incidence of wilt was reduced by 73.33% in pot tests.	[99]
Tomato *Solanum lycopersicum*	ZnO-NPs	A biosynthesized ZnO-NP could be an effective approach for controlling *Ralstonia. Solanacearum*.	[100]
Wheat *Triticum aestivum*	CeO_2-NPs	The use of CeO_2-NPs could be a promising way to combat fungal diseases affecting wheat	[101]
Wheat *Triticum aestivum*	TiO_2-NPs	Wheat plants were treated with TiO_2 NPs to combat fungal diseases and gain insight into how plants respond to biotic stress.	[102]
Apple *Malus domestica*	Chitosan-NPs	Chitosan NPs offer an environmentally sustainable and effective solution against blue mold in apples.	[103]
Rice *Oryza sativa*	ZnO-NPs	ZnO-NPs caused the level of ABA to drop, which probably caused the increased production of genes linked to defense.	[104]

(Continued)

Table 1 (continued)

Plant species	NPs	Key findings	References
Pepper *Capsicum annuum*	ZnO-NPs	Comparing ZnO-NPs to commercial nematipides and fungicides, it was discovered that they were more effective against sweet pepper infected with *Fusarium oxysporum* and *Meloidogyne. Incognita*.	[105]
Lychee *Litchi chinensis*	ZnO-NPs	ZnO-NPs can considerably prevent the growth of lychee fruit disease at a dose of 1.0 mg/mL.	[106]
Banana *Musa paradisiaca*	CS-NPs	ROS (PR1 and PR2), catalase activity, and peroxidase activity were all higher in plants treated with Cs-NP.	[107]
Pest stress			
Tomato *Solanum lycopersicum*	Ag-NPs	A strategy using Ag-NPs for mite control would be eco-friendly.	[110]
Tomato *Solanum lycopersicum*	Si-NPs	Si-NPs conjugates can be improved through the optimization and use of different biomolecules in terms of shelf life, stability in planta, and insect growth retardation.	[113]
Peach *Prunus persica*	Ag-NPs and Zn-NPs	The concentration of nanomaterials increased, and there was a corresponding rise in the mortality rate of rice weevils, specifically *S.oryzae* and *R.domonic*a.	[111]
Groundnut *Arachis hypogaea*	Silica-NPs	Silica-NPs offer a promising approach for controlling *Caryedon serratus* in stored groundnuts (*Arachis hypogaea* L.).	[114]
Date Palm *Phoenix dactylifera* L	ZnO-NPs	Zinc oxide -NPs are an effective control agent for *Oligonychus afrasiaticus* and *Eutetranychus palmatus* control.	[112]
Orange *Citrus sinensis*	Cu-NPs	In orange trees, Cu-NPs reduce phytophagous mite populations significantly while exhibiting minimal damaging effects on predatory mites.	[115]
Rice *Oryza sativa*	Silica-NPs	The optimum dose of Silica-NPs was found to be 0. 5g/kg for the protection of stored rice against rice weevil.	[116]

(Continued)

Table 1 (continued)

Plant species	NPs	Key findings	References
Maize *Zea mays*	SiO_2-NPs	Small and safe doses of SiO_2-NPs can be applied as growth promoters, as well as strong unconventional pesticides for crops during storage.	[117]

5 Conclusion

Plants rely on NPs to mitigate the adverse effects of environmental stress. NPs may improve plant growth and development by increasing photosynthesis and improving nutrient absorption, even in adverse environments. Nanoparticles have been found to stimulate the production of a range of defensive compounds in plants, which in turn alter the plant's internal environment and enable it to better withstand various stressors. The utilization of NPs has been shown to improve the ability of plants to endure adverse conditions by activating the antioxidant mechanisms within the plant, thereby minimizing the accumulation of ROS during stress and promoting the expression of genes that provide protection. Abiotic and biotic stress tolerance with NPs is well documented; however, the majority of studies are still in the laboratory. Several concerns have been raised about the potential adverse effects of NPs on the environment and the possibility that NPs could accumulate in edible plant parts due to their extensive usage. Therefore, it is necessary to develop appropriate evaluation methodologies to assess the effects of NPs and nano fertilizers on both biotic and abiotic ecosystem components. It is essential to conduct further research on the development of nanomaterials with low cost, low toxicity, hormesis, ecological safety, and self-degradation properties to commercialize nanotechnology.

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