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REVIEW

Nanoparticles and Phytohormonal Synergy in Plants: Sustainable Agriculture Approach

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ABSTRACT: The production of crops is badly affected by climate change globally. Mitigation of adverse effects of climate change is in need of time through different management practices such as developing tolerant genetic resources, hormonal applications to boost defense systems, nanoparticles, and balanced fertilization. The nano-hormonal synergy had the potential to mitigate the adverse effects of climate change by modulation of morpho-physiological and biochemical activities. Plant growth, yield, and quality can be enhanced with the supplementation of nano-hormonal interactions. Therefore, the current study explores the synergy between nanoparticles and phytohormonal use. The nanoparticles, even in low concentrations, had an excellent capability to improve the endogenous hormones contributing to the regulation of plant responses under stress conditions. Nano-hormonal interaction improved the plant tolerance against climate change by activation of signaling molecules and the plant defense system. Nano-hormonal contact triggers several enzymic and non-enzymatic activities that can scavenge toxic substances generated within the plants. The reduction in electrolyte leakage, malondialdehyde (MDA), and hydrogen peroxide (H_2O_2) was due to the supplementation of nano-hormonal exchange. The optimum production of reactive oxygen species (ROS) is necessary for normal plant growth and various developmental processes. However, the overproduction of ROS can be eliminated with nano-hormonal synergy. However, inappropriate applications can cause phytotoxicity such as germination inhibition, root malformation, and chlorosis. The optimum doses can vary depending on the kind of crop and stress conditions. The nano-hormonal interface is beneficial for crop growth, yield, and quality. Moreover, these are also effective in repairing plants damaged from adverse climatic conditions. Hence, these are effective for sustainable agriculture production.

KEYWORDS: Antioxidants; growth characters; metabolites; transcriptomics; yield

1 Introduction

Climate change is drastically reducing the productivity of crops. Biotic and abiotic stressors occur from variation in climate change. The variation in climate change may occur due to abrupt changes in temperature, irregular rainfall, nutrient deficiency, and drought conditions. Urbanization, industrialization, extensive mining, rapid population growth, and bombardment of chemicals in farming are also causes of global warming and further climate change [1]. Plants are more sensitive to abiotic stresses (salinity, temperature extremes, drought, and heavy metals), which adversely affect the productivity of crops [2]. Plant stress reactions are very complicated when subjected to adverse climatic conditions [3]. However, several pathways contribute to the tolerance of plants by signaling molecules coordination and cellular compartments [4]. The plant's reaction is based on the kind, duration, and severity of occurred stress [5]. To counteract stress reactions and enhance tolerance, plants respond to abiotic challenges by activating early stress-signaling systems [6,7]. Calcium, phospholipids, reactive oxygen species (ROS), nitric oxide (NO), and several protein kinases, spread signals when a plant is subjected to adverse conditions [8]. Plant stress tolerance improved by inhibition of energy-intensive activities. Moreover, SnRk1 kinases alter the expression of about 1000 stress-responsive genes, aiding in the restoration of homeostasis. This makes it possible for plants to tolerate abiotic stressors [9]. Moreover, plant defensive responses comprising the stomata closure during drought stress are primarily signaled by plant hormones, i.e., abscisic acid (ABA) and ethylene [5]. These stress-signaling pathways trigger transcription factors, which in turn trigger various stress-response genes to combat the severity of stress conditions in plants [5].

The optimum ROS generation in plants is necessary for sufficient plant growth and various developmental processes. Irregular and higher ROS generation greater than optimum need may injure the plants by causing oxidative injury. Oxidative stress occurs in plants due to the overproduction of ROS within the cell compartments. Moreover, physiological impairments in plants are also due to oxidative damage [10]. Regardless of the stress, damage to photosynthetic systems and membrane peroxidation have been recognized in many plants. Therefore, scavenging ROS through the activation of antioxidant molecules is the primary focus of plant defense systems [11]. The numerous plants have been shown to exhibit decreased phenol and flavonoid synthesis under abiotic stress conditions. Significant levels of phytochelatin were mostly found in response to metal toxicity. The regulation of osmolyte generation is also supportive of improving plant tolerance against adverse conditions [12]. Hence, regulation of proline activation in plants can be effective to mitigate the adverse climatic conditions. The activation of antioxidant enzymes to eliminate the ROS molecules is another significant metabolic alteration. Antioxidant enzymes aid plants in surviving oxidative stress by scavenging of ROS in excess. Abiotic stress mitigation is essential for excellent crop production [12].

Abiotic stress tolerance in crops is effectively boosted with various management techniques comprising the use of nanotechnology, organic amendments, microorganisms, and phytohormone supplements [13,14]. The capability of plants to withstand abiotic stress may be enhanced by all of these management techniques. Crop yield can be increased by cultivating resistant germplasm [15]. Thus, one of the essential strategies for the production of tolerant germplasm with an emphasis on increased yield and superior quality is the selection, assessment, and detection of tolerant genetic resources. Agricultural farming has become more sustainable with the advancements of nanotechnology [16]. Because of their reduced size, larger surface area, improved mobility, and increased porosity, nanoparticles have made remarkable contributions to agriculture farming [17–19]. These nanoparticles could increase plant growth and yield because of their small size [20]. Nanoparticles (NPs) are gaining more attention from plant researchers because of their notable performance, affordability, and climate-friendly features [21]. Higher concentrations beyond the threshold had negative impacts on growth and yield because of toxicity, but the best usage of nanoparticles is for adequate growth and yield [22]. However, several factors, including crop variety, stress level, cultural customs, and climate in the growing locations, influence the selection of nanoparticles [23]. The higher tolerance level to abiotic stress conditions is important for plants to be productive with appropriate fruit quality. Plant productivity is being disrupted by the impairment of physiological and biochemical processes due to unfavorable climatic circumstances. The regulation of morpho-physiological and biochemical processes is necessary for sufficient plant growth and yield. The interactive findings of nanoparticles and phytohormones are necessary for sustainable agriculture. Therefore, the present work aims to explore the interaction of nanoparticles and phytohormones and their impact on plant growth, yield, and quality.

2 Impact of Nanoparticles on Plant Health and Production

Nanotechnology is an emerging way to mitigate the adverse effects of climate change [24]. The plants might strengthen tolerance against abiotic stress conditions through the interaction of nanoparticles. Enhancing plant tolerance mechanisms to abiotic stress is one way that nanotechnology promises to boost crop productivity. Nanotechnology is an effective way to develop and produce crops in modern agriculture. Nanoparticles can be applied to organic agriculture, postharvest management, agri-food production, nano-agrochemicals, plant genetic advancement through nanoparticles-mediated gene transfer, and organic agriculture [25]. Nanotechnology has become more and more reliant in several sectors recently because of its many potential uses, cost-effectiveness, environmental benefits, and durability. The application of nano-pesticides and nano-fertilizers has increased the agricultural output. The commercial crops have benefited from the efficient uptake of nutrients from the soil, particularly nano fertilizers (urea-doped calcium phosphate), which have also helped to maintain crop growth and productivity and promote sustainable agriculture [26]. Madanayake et al. [27] used a urea-hydroxyapatite-montmorillonite nanohybrid composite to observe the gradual release of nitrogen. The use of hydroxyapatite nanoparticles had a major impact on radish plant germination characteristics and crop yield [28]. Many uses for nanotechnology in soil and water remediation have improved food output and quality. Furthermore, because nanotechnology is environmentally friendly, its application greatly lessens the negative impacts of chemicals on crops and the environmental damage that agriculture causes [29]. NPs have had a positive impact on the metabolism of seeds and plants, along with growth promotion. The beneficial properties of NPs' tiny size enable them to more effectively penetrate biological barriers in plants and treat plant stressors such as heat and salt stress, as well as stress brought on by heavy metals [30]. Nanoparticles had excellent potential to modulate physiological activities in plants that occur due to stress conditions.

The distinctive shape, adjustable pore size, and strong reactivity with increased surface area of nanoparticles improved their efficacy when supplemented on plants under either normal or stress conditions [31]. NPs are thought to be a useful and promising technique for controlling crop productivity and overcoming present and upcoming constraints on agricultural production by strengthening plant tolerance against abiotic stresses. Moreover, NPs have a moderating influence on drought stress by triggering physiological and biochemical regulation and controlling the expression of genes linked to plant response and tolerance. The primary mechanisms by which NPs reduce osmotic stress brought on by water scarcity are improved root growth, upregulation of aquaporins, altered intracellular water metabolism, accumulation of compatible solutes, and ionic homeostasis. NPs also increase the photosynthetic activity of drought-induced plants. NPs mitigate oxidative stress and lessen leaf water loss brought on by ABA buildup through stomatal closure by lowering ROS and triggering the antioxidant defense system [31].

Temperature extremes (heat and cold) occur because climate change has disturbed the productivity of crops. Nanoparticles are effective for the mitigation of temperature stress [32]. Plant growth can be improved with the supplementation of nanoparticles. Nanoparticle in varying quantities to mitigate the adverse effects occurring from heat stress can enhance plant growth even under drought stress [33]. Plants may experience oxidative harm due to nanoparticles' phytotoxicity. Hence, the optimum dose of nanoparticles is effective, which may vary from one crop to another and also depends on duration and types of stress. The optimum dose of nanoparticles improved the plant defense system against temperature stress by activation of the antioxidant defense system. NPs repaired the membrane leakage by reducing the overgeneration of ROS, MDA, and H_2O_2 within the cell compartments. Heat shock proteins (HSP70 and HSP90) are regulated by supplementation of NPs [34]. Heat stress can be regulated with nanoparticles by regulating of stomata mechanism in plants [33].

Salt toxicity drastically reduced the plant growth and production. NPs can mitigate the adverse effects of salt toxicity by altering physiological and biochemical activities in millet [35]. Nanoparticles and plant interaction showed a significant impact on crop productivity [36]. NPs have been shown by Zulfiqar and Ashraf [37] to support plant growth and development under salt stress. Enhancing plant nutrition may be significantly impacted by NPs' effects on nutrient absorption, transport, and ultimate allocation [38]. One of the most important elements for plant resistance to salt stress has been identified as the high K^+/Na^+ ratio, which is disturbed by salt toxicity. However, an ionic imbalance disturbed the plant growth and development. The osmotic potential of the plant is regulated, which in turn improves plant development under salt stress by supplementation of NPs [39]. Farhangi-Abriz and Torabian [40] privilege that raising the concentration of K^+ in the leaves and nano-SiO_2 improved the growth of soybean seedlings under salt stress. Moreover, a reduction in the uptake of Na^+ in excess was also recorded with NPs application.

Metal toxicity is dangerous for plants and human health. Urbanization and industrial effluents are major causes of metal toxicity in soil and plants. The optimum dose of metals is necessary for sufficient plant growth, while their excess causes toxicity because it increases oxidative harm in cell compartments. Nanoparticles are an emerging technology to cope with metal toxicity in plants. Nanoparticle remediation is extremely effective, environmentally benign, and free of hazardous byproducts as compared to chemical remediation, which relies on the kinetic pace of the reaction, and bioremediation, which is more time-consuming and microbe-dependent. Nanotechnology is becoming more and more attractive across a range of industries because of its capacity for coping and sustainable competitiveness. The application of nano-pesticides and nano-fertilizers has led to a rise in the use of nanotechnology in agriculture [41]. Zinc oxide nanoparticles (Zn-NPs) were applied to lessen phytotoxicity in rice. There were notable reductions in the rates of arsenic (As) and cadmium (Cd) accumulation [42]. The application of Iron nanoparticles (Fe-NPs) to rice plants was studied by Bidi et al. [12] because immobilization of As in the cell walls and vacuoles improved the accumulation of the chelating agents and strengthened the glyoxalase system and antioxidant enzymes. Moreover, Fe-NPs inhibited the uptake of As in radish by activation of antioxidant capacity with a decrease in guaiacol peroxidase [43]. When copper nanoparticles (Cu-NPs) were applied to lettuce, Wang et al. [44] found a significant decrease in As along with a rise in plant biomass and antioxidant activity. Mitigation of metal toxicity with different nanoparticles is an effective strategy for sustainable agriculture practices (Fig. 1).

It is predicted that more than 200 million tons of commercial fertilizer are used annually to meet 3 billion tons of crop production. The need for agricultural output cannot be met sustainably by relying solely on commercial fertilizers [45]. Numerous efficient methods are being used to lessen nutrient loss and degradation of soil and groundwater including nano-fertilizers (NFs) supplementation. NFs are covered in nanoparticles that improve the efficiency of nutrient usage by regulating nutrient release based on plant needs [31]. Nanotechnology is widely applied in agricultural activities with the use of either nanoparticles or nano-capsules in slow-release fertilizers (SRFs). Although the rate of release is regulated, the nutrient release in SRFs is slower than usual. SRFs are only marginally soluble in water and can be broken down by microbial activity. A greater nutrient utilization efficiency is indicated by enhanced plant nutrient uptake and decreased nutrient loss [46].

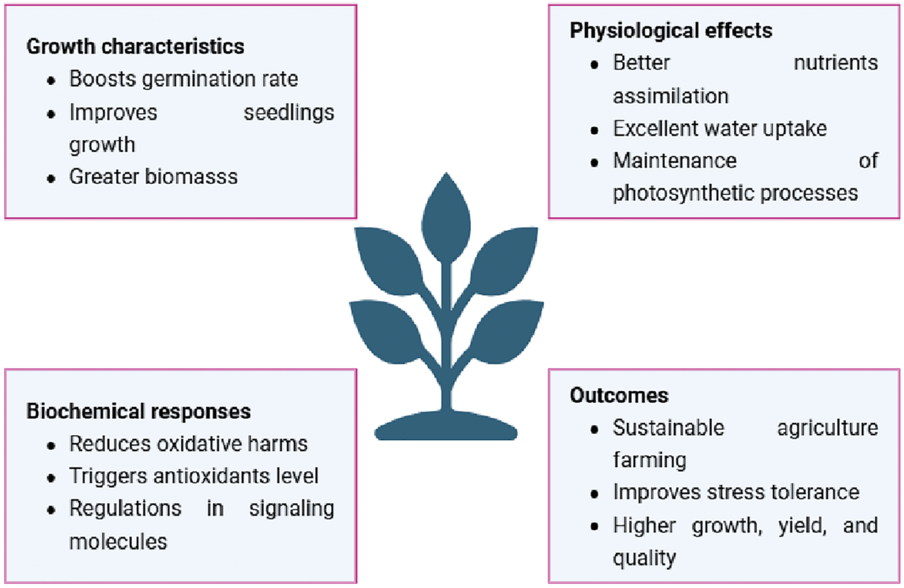

Figure 1: Impact of nanoparticles on plant growth, yield, and quality

3 Contribution of Phytohormones in Plant Stress Reactions

Phytohormones are effective tactics to enhance the climate-resilience in plants, focusing on growth and yield attributes [47]. Moreover, phytohormones are a novel and environmentally friendly way to increase plants' resistance to abiotic stress in vegetables [48]. Similarly, Saini et al. [49] privilege that phytohormones are chemical mediators that plants make and that regulate environmental stressors by growing, maturing, and responding. Phytohormones are essential for the abiotic stress response by managing several signaling pathways [50]. Furthermore, they contribute to the neglect of numerous internal and external signals, which results in notable changes in seed germination rate and plant growth. The role of phytohormones as signaling molecules in abiotic stress tolerance has been studied by several plant researchers [48,50]. Horticultural crops use jasmonates as a defense against environmental stressors. These are especially helpful for horticultural crops that can tolerate harsh climatic conditions (Fig. 2).

Jasmonates can be used to lessen environmental risks [51]. Plant defense mechanisms have evolved to accommodate environmental challenges, such as flooding in peppers [52]. Jasmonates offer an excellent crop defense mechanism in farming under harsh climatic regions [53]. Jasmonic acid regulates the defense system in melons subjected to abiotic stress conditions [54]. Different concentrations of phytohormones regulate the gene expression under normal and stress conditions for sufficient plant growth and many developmental processes [48]. Jasmonic acid foliar spraying improved crops' tolerance to salt stress [55]. Jasmonic acid has the potential to reduce oxidative harm in plants caused by abiotic stress. Jasmonic acid had the potential to reduce the movement of salts from roots to other plant parts. Hence, jasmonic acid is an excellent treatment for the reduction of oxidative harm in stressed plants [56].

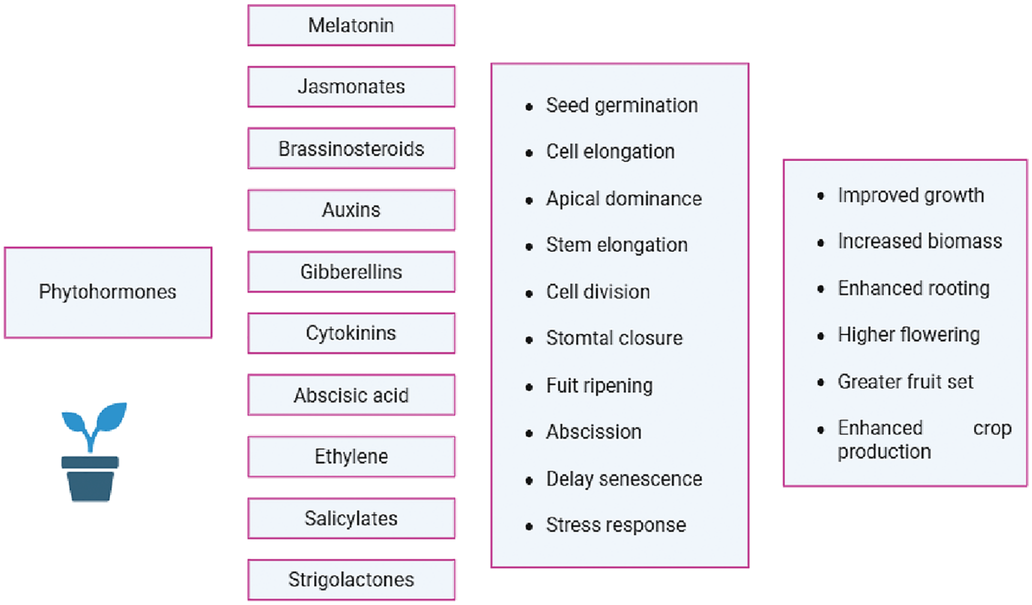

Figure 2: Impact of various phytohormones on crop growth and production

Nitric oxide (NO) is an important phytohormone and signaling molecule contributing to the tolerance of plants subjected to adverse climatic conditions. It is contributing to improving several plant traits such as flowering, fruiting, stomatal regulation, seed dormancy, seed germination, and seedling growth under normal and stressed conditions [57]. Sodium nitroprusside (SNP) is an excellent NO contributor for plants that can decrease the detrimental effects of ROS on plant growth by increasing the activity of antioxidant enzymes [58]. NO spraying is important for the enhancement of plants' resistance to salt toxicity in various crops, i.e., tomato [59], pepper [60], and eggplant [61]. Furthermore, it was found to help tolerance mechanisms in higher-growing plants grown in harsh environments [62].

Abiotic stress tolerance can be enhanced with brassinosteroid supplementation [47]. Brassinosteroid application may increase ABA levels and lessen the negative consequences that occur in plants subjected to water deficit conditions [63]. Drought stress can be mitigated with the supplementation of brassinosteroids by reducing toxic substances generated within the cell compartments. Activation of the plant defense system was also noted by application of brassinosteroids, which further scavenges toxic and over-generated ROS in peppers [64]. Moreover, a study on tomatoes demonstrates that increasing endogenous brassinosteroids enhances drought resistance while reducing oxidative harm and lipid peroxidation. The study also found that tomato drought resistance was negatively impacted by BRI1 upregulation, indicating that variations in the brassinosteroid pathway may either boost or decrease stress tolerance and emphasizing the complex interactions between brassinosteroids and stressors [65]. Hence, BRs are necessary phytohormones to combat the adverse effects of abiotic stress conditions. The nanoparticles improve plant growth, yield, and antioxidants defense system subjected to salinity stress (Table 1), drought stress (Table 2), and metal stress (Table 3).

Table 1: Impact of nanoparticles on plants' performance subjected to salinity stress

Crop names	Salinity levels	Nanoparticles type	Nanoparticles concentration	Outcomes with nanoparticles	References
Peppers	25 and 50 mM NaCl	Se-NPs	10 and 50 mg L^{-1}	Heightened chlorophylls and β-carotene	[66]
Tomato	50 mM NaCl	Cu-NPs	250 mg L^{-1}	Enhanced ascorbic acid, polyphenols, and glutathione	[67]
Pistachio	0, 100, and 200 mM NaCl	Fe-NPs	2.9 mg L^{-1}	Fe-NPs improved chlorophyll content and reduced MDA	[68]
Tomato	250 mM NaCl	ZnO-NPs	0, 20, and 40 mg L^{-1}	Enzymatic activities and cytosine methylation boosted	[69]
Peppers	25 and 50 mM NaCl	Cu-NPs	100 and 500 mg L^{-1}	Maintenance of electrolyte leakage and improvement of membrane stability	[66]
Eggplant	150 mM NaCl	TiO_2-NPs	200 and 400 ppm	Plant growth was improved by biochemical changes	[70]
Ajwain	4, 8, and 12 dS m^{-1}	Fe-NPs	3 mM	Improved Fe content, antioxidant activities, and enhanced K^+ uptake	[71]
Peppers	25 and 50 mM NaCl	Si-NPs	200 and 1000 mg L^{-1}	Activation of the defense system with strong antioxidant activities	[66]
Strawberry	0, 35, and 70 mM	ZnO-NPs	0, 15, and 30 mg L^{-1}	Elimination of toxic ions and improved Na^+/K^+ ratio	[72]
Grapes	50 and 100 mM NaCl	GO-Pro NPs	50 and 100 mg L^{-1}	Oxidative harms were controlled by activating the plant defense system	[73]

Note: Selenium nanoparticles (Se-NPs), copper nanoparticles (Cu-NPs), iron nanoparticles (Fe-NPs), zinc oxide nanoparticles (ZnO-NPs), titanium dioxide nanoparticles (TiO_2-NPs), silicon (Si-NPs), and graphene oxide nanoparticles (GO-Pro NPs).

Table 2: Impact of nanoparticles on plants' performance subjected to drought conditions

Crop names	Nanoparticles type	Nanoparticles concentration	Outcomes with nanoparticles	References
Strawberry	Fe-NPs	0, 0.01, 0.1 and 1.0 mg L^{-1}	Positive impact on relative water content and chlorophyll stability	[74]

(Continued)

Table 2 (continued)

Crop names	Nanoparticles type	Nanoparticles concentration	Outcomes with nanoparticles	References
Peppers	CNPs	6 and 12 mg L^{-1}	Improved photosynthetic processes and reduced electrolyte leakage	[75]
Cucumber	CeO_2 and ZnO-NPs	400 and 800 mg kg^{-1}	Mitigates drought stress with the enhancement of antioxidant defense and osmolyte buildup	[76]
Tomato	FCN	1.0 g L^{-1}	Nanodots regulated physiological developments and the soil atmosphere	[77]
Okra	ANPs	0, 10, 20, 50, and 70 mg kg^{-1}	Promote growth and photosynthesis in okra plants under drought stress, while titanium dioxide nanoparticles have a harmful effect	[78]
Cucumber	Si-NPs	0, 100, 200, 300, and 400 mg kg^{-1}	Boost the growth and productivity of under by improving nutrient uptake	[79]
Pomegranate	Se-NPs	10 and 50 nm	Mitigate the negative effects on crop growth and yield	[73]
Mango	Se-NPs, Ti-NPs and Si-NPs	Se (5, 10, and 20 mg L^{-1}); Ti (40, 60, and 80 mg L^{-1}) and Si (50, 100, and 150 mg L^{-1})	Improve growth, yield, and fruit quality under water deficit conditions	[80]
Grapes	TiO_2-NPs	0, 1, 10, and 100 ppm	Boost tolerance in grapevine by lessening oxidative stress	[81]

Note: Iron nanoparticles (Fe-NPs), carbon nanoparticles (CNPs), cerium dioxide (CeO_2), zinc oxide nanoparticles (ZnO-NPs), functional carbon nanodots (FCN), aluminum oxide nanoparticles (ANPs), silicon (Si-NPs), selenium nanoparticles (Se-NPs), and titanium nanoparticles (TiO_2-NPs).

Table 3: Impact of nanoparticles on plant performance subjected to heavy metal toxicity

Crop names	Metals type	Nanoparticles type	Nanoparticles concentration	Outcomes with nanoparticles	References
Tomato	Chromium	ZnO-NPs	50 mg kg^{-1}	Positive repairing of plants by lessening oxidative harms	[82]
Coriander	Cadmium	Se-NPs	5, 10, and 15 mg L^{-1}	Alleviated metal toxicity in plants by improving nutrient homeostasis	[83]
Tomato	Cadmium	Fe-NPs	20 mg L^{-1}	Mitigation of cadmium toxicity in tomato plants	[84]
Lettuce	Cadmium	ZnO-NPs	15 mg L^{-1}	Greater biomass, chlorophylls, and antioxidants	[85]

(Continued)

Table 3 (continued)

Crop names	Metals type	Nanoparticles type	Nanoparticles concentration	Outcomes with nanoparticles	References
Tomato	Arsenic	Si-NPs	250 and 1000 mg L^{-1}	Reduction in metal translocation and mitigation of phytotoxicity in plants	[86]
Onion	Chromium	Cu-NPs	15 mg kg^{-1}	Elevated metal tolerance and bulb quality with posing minimal health hazards	[87]
Eggplant	Cadmium	FeO-NPs	20,40,80, and 120 ppm	Improving morpho-anatomical, physiological, and biochemical traits	[88]
Sunflower	Chromium	TiO_2-NPs	15 mg L^{-1}	Alleviation of metal toxicity in plants by regulation of photosynthesis, antioxidants, and phytochelatins	[89]

Note: Zinc oxide nanoparticles (ZnO-NPs), selenium nanoparticles (Se-NPs), iron nanoparticles (Fe-NPs), silicon nanoparticles (Si-NPs), copper nanoparticles (Cu-NPs), and titanium nanoparticles (TiO_2-NPs).

Melatonin effectively mitigates the adverse effects of abiotic stresses in plants. Melatonin improved the nutritional condition and shielded the sugar beet photosynthetic system. Furthermore, in cabbage treated with exogenous melatonin application, there was a documented downregulation of free radical formation as well as an elevation of antioxidant potential and osmotic adaptability [90]. Furthermore, Zhang et al. [91] found that the application of melatonin promoted anthocyanin production in lemons. The application of melatonin to spinach resulted in a significant delay in leaf chlorosis within a week of storage, as well as a sustained rise in soluble sugars, proteins, total flavonoids, phenols, and vitamin C [92]. Applying melatonin (100 μ mol L^{-1}) to cucumber plants has been shown to significantly increase free proline, soluble protein, and vitamin C in addition to reducing the chilling damage index, respiration intensity, MDA contents, electrolyte leakage in tissues, ROS levels, and weight loss rate [93]. Melatonin (100 μM L^{-1}) had a very effective effect on the mitigation of drought stress in tomato [94]. Exogenous melatonin reduces salt damage in rosemary plants [95].

4 Nano-Hormonal Relations toward Resilient Crops against Climate Change

Plant defense responses are controlled by the regulation of signaling molecules with supplementation of nano-hormonal relations (Fig. 3). It is necessary for the sufficient growth of plants to explore nano-hormonal relations, either antagonistic or synergistic. Nanoparticles and phytohormones interact to regulate the stress signaling molecules effectively for proper plant growth under stressed plants [96]. However, reactions mediated by nanoparticles depend on many factors such as nanoparticle type and level, the plant species, and stress type and duration [97]. The important relationships between plant growth hormones and nanoparticles were explored by some plant researchers [98]. The application of nano-selenium caused modifications in phytohormones through NO signaling [99]. They have proposed that hormonal changes, particularly ethylene and auxin, under nano-Se exposure are indicated by the inhibition of xylem tissue differentiation, stem bending, inhibition of primary root development, and appearance of adventitious roots. Further research into nanoparticle-mediated phytohormonal changes at the molecular level is advised in the future. These signaling molecules are tightly linked to the regulation of plant development under biotic and abiotic stress. Moreover, there is a clear connection between the modification of plant hormone pools and the physiological performance of the plants [100]. It is crucial to characterize the metabolism and signaling of plant hormones to fully understand the regulatory networks that function under environmental stress. Many phytohormones contribute to the activation of the defense system in stressed plants by regulating signaling molecules. Plant hormone levels and functions are thought to be a key indicator of plant tolerance against toxicity [101].

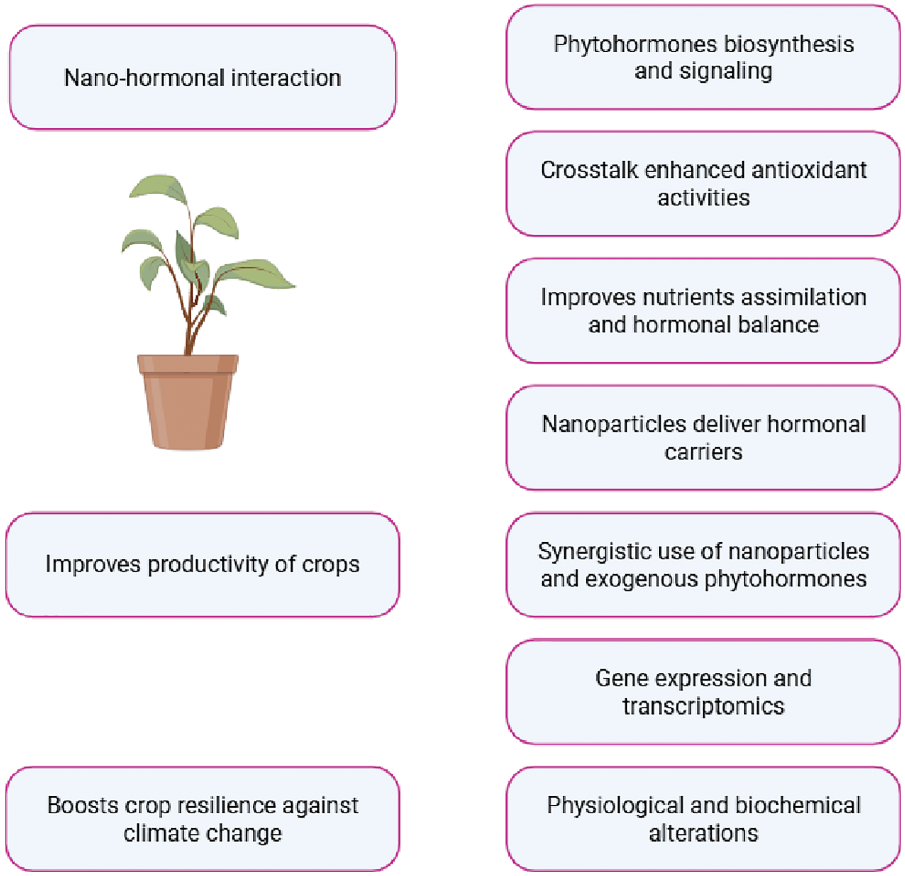

Figure 3: Interaction between nanoparticles and phytohormones improves crop production

Plant hormones and nanoparticle exposure can interact either synergistic or an antagonistic way, which is important for plants to respond to stress. Plant hormones, being adaptable regulators of plant growth and development, offer an unknown area for research on interactions between plants and nanoparticles [102]. Plant hormones auxin and cytokinin primarily control the impacts of metallic nanoparticle exposure, which can either positively or negatively impact plant growth depending on concentration. Arabidopsis is exposed to metal oxide-based nanoparticles; its hormonal profile and physiological state are connected [103]. Moreover, ZnO-NPs improve different phytohormones such as cytokinin, auxin, and ABA concentrations in plants under adverse conditions [104]. The levels of cytokinin and cytokinin phosphatase, their active precursor, were upregulated to the mild ZnO-NP concentration in Arabidopsis. The graphene oxide nanomaterial can play a part in controlling mustard root growth through interactions between several plant growth hormones [98].

Numerous studies conducted over the past few decades have demonstrated the regulatory function of nanoparticles in plants under stressed conditions. However, limited research demonstrated that employing nanomaterials to modify various phytohormone production and signaling could alleviate environmental constraints. The production of ROS is a crucial mechanism that controls plant defensive responses and development. Both biotic and abiotic stressors disrupt the equilibrium between the production and elimination of ROS in plants, which is maintained under typical metabolic circumstances. Several phytohormones, i.e., ethylene, ABA, brassinosteroids, and jasmonates, regulate ROS applied at optimal concentration [105]. ZnO-NPs treatment also had adverse effects on indole acetic acid level in root apices of Arabidopsis [102]. Similarly, Sun et al. [105] studied that Ag-NPs enter into the plant cells and tissues through plasmodesmata and disrupt auxin's and its receptor's ability to bind. However, Wei et al. [106] found that root tips of Arabidopsis treated with TiO_2 nanoparticles accumulated more auxin. Moreover, nano-titania has demonstrated the ability to regulate gibberellin production and signaling at the gene level [107]. The floral transition between the vegetative and reproductive phases of plant growth is a crucial event for controlling plant production and evasion of abiotic stress, which gibberellin regulates [108].

The effect of carbon nanoparticles on the Arabidopsis blooming and photomorphogenesis processes was examined by Kumar et al. [109]. Genes linked to the cytokinin-mediated signaling system were shown to be increased in Arabidopsis when exposed to titania and cerium nanoparticles [110]. Nanoparticles have an impact on plants' endogenous salicylic acid content. Arabidopsis leaves showed a significant increase in salicylic acid content when subjected to ZnO-NPs [103]. Jasmonic acid controls stomatal opening and shutting, the buildup of amino acids that resemble isoleucine and methionine, soluble sugars, and the activation of the antioxidant defense system [111,112]. A thin-walled carbon nanotubes (CNTs) significantly decreased the concentration of brassinosteroids in plant roots and shoots, which inhibits plant tolerance, demonstrating the phytotoxicity of CNTs in rice [112].

Nanoparticles of Fe_3O_4 and ZnO upregulated auxin and cytokinin pathways to boost plant growth [113]. Iron nanoparticles encourage drought tolerance because of drought-responsive gene expression (GmERD1) in soybean [114]. ZnO nanoparticles improve gene expression (HsfA1a and HDA3) associated with auxin and cytokinin pathways in tomato, which further improved cell division, elongation, and differentiation [115]. Generally, many plant hormones (auxins, abscisic acid, and gibberellins) were stimulated with nanoparticles by regulation of calcium ions and ROS [116–118]. Nanoparticles of zinc and silver contribute to the upregulation of genes linked with cytokinins and auxins signaling under adverse climatic conditions. Moreover, these are effective for the promotion of root and shoot growth [118–120]. Jasmonic acid transporters cleanse heavy metals through ATP-Binding Cassette-G transporter subfamily of green plant species [121,122].

5 Conclusion

Crop production drastically reduced because of fluctuations in climate change. The abrupt changes in climatic conditions, i.e., temperature extremes, irregular rainfall, water deficit conditions, water logging, nutrient deficiency, soil contamination, and wind speed are disturbing the production of crops. Therefore, management approaches are necessary to combat stress conditions for proper plant growth and development. The relation between nanoparticles and phytohormones is an effective approach to enhance tolerance in plants against adverse climatic conditions by modulation of morpho-physiological, biochemical, and molecular interventions. Joint efforts of policymakers, farmers, and researchers are required to ensure sustainable vegetable production.

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