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Review Article

# Nanoparticle-mediated enhancement of plant tolerance to combined abiotic stresses: Mechanisms and applications

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ABSTRACT

Plants are exposed to an increasing number of complex abiotic stresses such as drought, salt, extreme temperatures and heavy metal contamination which often occur in combination and severely inhibit growth, development and crop yield. These stresses affect water and nutrient uptake, photosynthesis, cause oxidative damage, produce reactive oxygen species (ROS), and affect hormonal and metabolic systems. Conventional approaches such as selective breeding and agronomic manipulations do not provide significant relief under multifactorial stress conditions. Nanoparticles (NPs) have unique physicochemical properties like high surface area, reactivity and tunable surface chemistry that allow their interaction with plants at physiological, biochemical and molecular levels. Thus, nanotechnology is a promising alternative. The engineered nanoparticles can enhance water and nutrient uptake, serve as antioxidants, stabilize cellular osmotic equilibrium and modify stress-responsive gene expression. Recent studies have shown that these nanoparticles may induce tolerance to combined stress conditions, but the vast majority of studies have been limited to single-stress scenarios. This mini-review highlights the recent advances in nanoparticle-mediated plant stress tolerance and discusses the mechanisms, potential agricultural applications, and challenges and future prospects for sustainable crop production.

## 1. Introduction

Drought, salinity, extreme temperatures and heavy metal contamination are abiotic stresses that severely limit the crop productivity and food security in the global agricultural systems. Natural and agricultural ecosystems tend to experience these stresses concomitantly, which causes more extreme impacts than each of the stress conditions on its own [1–3]. Integrated water and nutrient balance of plants, compromised photosynthetic capacity, destabilized membranes and excessive production of reactive oxygen species (ROS), leading to oxidative stress of cell structures, are the results of the combined stress conditions. These perturbations do not only suppress growth and yield, but also impact metabolic homeostasis, nutrient assimilation and hormone signaling, triggering a cascade of stress-related physiological and molecular problems [4].

Conventional methods of enhancing stress tolerance, such as

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**Table 1**
Nanoparticle types, physicochemical characteristics, uptake mechanisms, and functional roles in enhancing plant tolerance to abiotic stresses.

| Nanoparticle Types | Examples | Typical Size Range (nm) | Physicochemical Characteristics | Uptake and Translocation Pathway | Physiological Effects | Biochemical and Molecular Mechanisms | Major Abiotic Stresses Mitigated | Advantages | Limitations | References |
|---|---|---|---|---|---|---|---|---|---|---|
| **Metal Oxide Nanoparticles** | $TiO_2$, ZnO, $Fe_3O_4$, $CeO_2$, CuO | 10–100 | High surface area, photocatalytic activity, variable surface charge, catalytic redox properties | Root absorption via apoplastic and symplastic pathways; foliar penetration through stomata and cuticle; translocation through xylem and phloem | Enhance photosynthetic efficiency, chlorophyll synthesis, nutrient uptake, root growth, water-use efficiency, membrane stability | Activate antioxidant enzymes (SOD, CAT, APX), regulate ROS homeostasis, stimulate stress-responsive genes, improve ion balance and osmotic adjustment | Drought, salinity, heat, heavy metal toxicity | Multifunctional stress protection, nutrient delivery, improved biomass production | Dose-dependent phytotoxicity, ROS overproduction at high concentrations | Cao et al., [15–17] |
| **Carbon-Based Nanoparticles** | Graphene Oxide (GO), Reduced Graphene Oxide (rGO), Carbon Dots (CDs), Carbon Nanotubes (CNTs), Fullerene (C60) | 1–100 | High conductivity, exceptional surface reactivity, large surface-to-volume ratio, mechanical stability | Root uptake, foliar entry through stomata, intracellular transport to chloroplasts and mitochondria | Improve hydraulic conductivity, water transport, root architecture, photosynthetic performance | Direct ROS scavenging, enhanced antioxidant activity, regulation of signaling molecules and stress-responsive pathways | Drought, oxidative stress, salinity, heat stress | Efficient water management and redox regulation | Potential accumulation in tissues and uncertain long-term environmental impacts | Alluqmani, Alabdallah [8,18,19] |
| **Silica Nanoparticles ($SiO_2$ NPs)** | Mesoporous silica nanoparticles, nano-silica | 20–200 | Porous structure, high stability, biocompatibility, large adsorption capacity | Root uptake and deposition within epidermal and vascular tissues | Enhance cell wall strength, reduce transpiration, improve water retention, maintain leaf turgor | Increase antioxidant defense, improve silicon-mediated stress signaling, regulate osmolyte accumulation | Drought, salinity, heat stress | Environmentally friendly and highly biocompatible | Excessive accumulation may interfere with nutrient dynamics | El-Beltagi et al., [20, 21] |
| **Quantum Dots (QDs)** | CdSe, ZnS, Carbon Quantum Dots, Graphene Quantum Dots | 2–20 | Fluorescent properties, tunable optical behavior, nanoscale dimensions, high sensitivity | Cellular uptake through endocytosis-like mechanisms and vascular transport | Facilitate stress detection, monitor physiological changes, improve photosynthetic electron transport | Modulate ROS generation, enable imaging of intracellular signaling and stress responses | Oxidative stress, heat stress, stress monitoring applications | Real-time tracking of plant responses | Potential heavy-metal toxicity (Cd-containing QDs) | Jiao et al., [22,23] |
| **Metal Nanoparticles** | Ag, Au, Fe, Cu | 5–100 | High reactivity, antimicrobial activity, electron transfer capability | Root and foliar uptake with systemic transport through vascular tissues | Enhance defense responses, improve nutrient mobilization, stimulate growth and stress adaptation | Modulate hormone signaling, activate antioxidant enzymes, regulate transcription factors involved in stress tolerance | Drought, salinity, oxidative stress, combined stresses | Broad-spectrum stress protection and antimicrobial activity | Bioaccumulation risk and possible phytotoxicity at elevated doses | Francis et al., [24,25] |
| **Iron Oxide Nanoparticles** | $Fe_2O_3$, $Fe_3O_4$ | 10–80 | Magnetic properties, high nutrient value, redox-active surface | Predominantly root uptake and vascular translocation | Improve chlorophyll synthesis, nutrient acquisition, photosynthesis, root development | Enhance antioxidant systems, improve iron homeostasis, regulate osmolyte biosynthesis | Drought, salinity, nutrient deficiency | Dual role as nutrient source and stress mitigator | Oxidative stress under excessive application | [26–28]) |
| **Zinc Oxide Nanoparticles** | ZnO NPs | 10–70 | High zinc availability, photocatalytic activity, antimicrobial properties | Root absorption and foliar uptake | Improve germination, root elongation, chlorophyll content, nutrient-use efficiency | Enhance proline accumulation, antioxidant defense, ion homeostasis and ABA-mediated signaling | Drought, salinity, heat stress | Effective nano-fertilizer and stress alleviator | Potential toxicity at high doses due to Zn accumulation | Jomova et al., [29–31] |
| **Cerium Oxide Nanoparticles** | $CeO_2$ NPs (Nanoceria) | 5–50 | Redox cycling between $Ce^{3+}$ and $Ce^{4+}$, strong antioxidant capacity | Root and foliar uptake with intracellular localization | Preserve chloroplast structure, stabilize photosystems, reduce oxidative damage | Mimic antioxidant enzymes and directly scavenge ROS | Heat stress, oxidative stress, drought | Exceptional antioxidant properties | Limited field-scale validation studies | Khalid et al., [32]; Kumari et a l.,2024) |
| **Nano-Fertilizer Formulations** | NPK-NPs, Zn-NPs, Fe-NPs, Cu-NPs | 20–200 | Controlled nutrient release, enhanced nutrient-use efficiency | Root uptake and targeted delivery systems | Improve nutrient uptake, biomass accumulation, yield stability under stress | Regulate metabolic pathways and nutrient signaling networks | Drought, salinity, nutrient stress | Reduced fertilizer losses and improved efficiency | Regulatory concerns and commercialization challenges | Lowry et al., [3,33,34] |

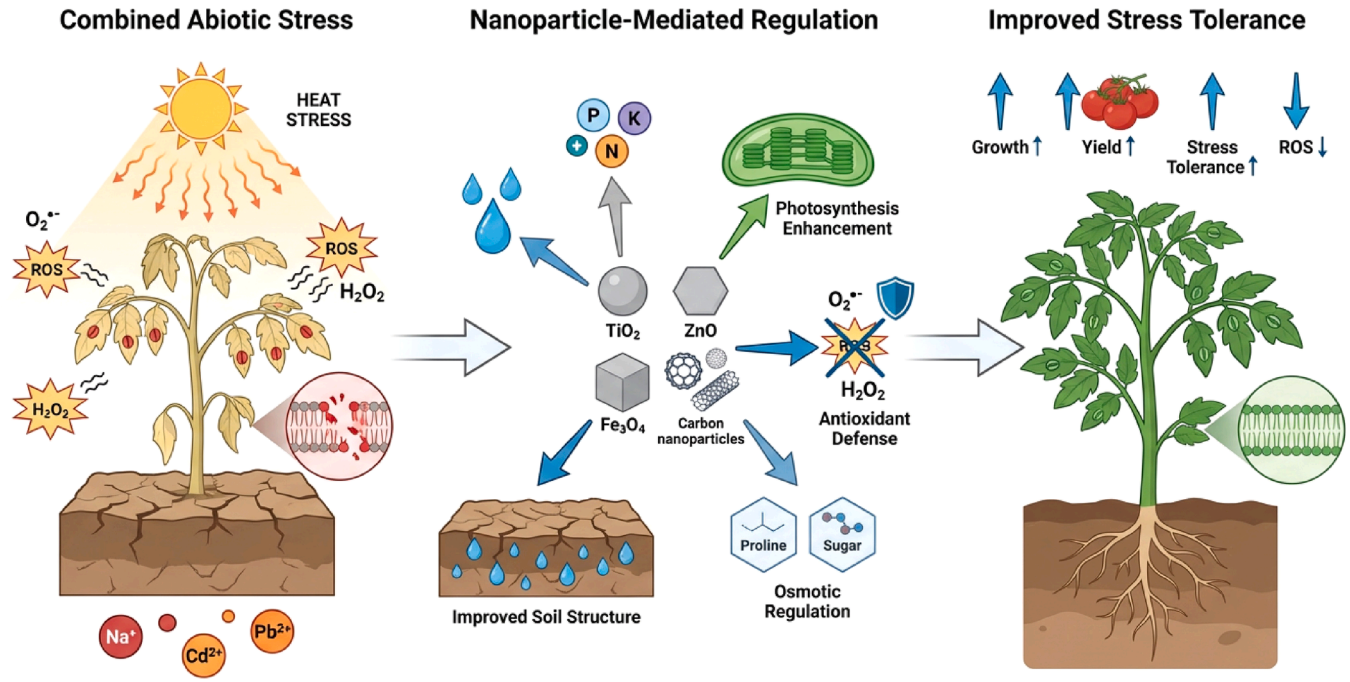



**Fig. 1.** Nanoparticle-induced mechanisms to enhance plant tolerance to combined abiotic stresses. Schematic representation of the role of nanoparticles ($TiO_2$, ZnO, $Fe_3O_4$ and carbon-based nanomaterials) in alleviating the adverse effects of heat, drought, salinity and heavy metal stress by improving photosynthesis, nutrient uptake, antioxidant defense, osmotic regulation and soil water retention, ultimately reducing oxidative damage and improving plant growth, yield and stress resilience.

selective breeding, genetic modification, and conventional agronomic methods, have limited effectiveness in the context of combined stresses [5]. Agronomic practices tend to be stress specific and rarely alleviate multiple stress interactions, and its breeding to multiple stress tolerance is difficult because interactions are complicated, and the environment is variable [6]. With the increasing incidence of climatic change, there is

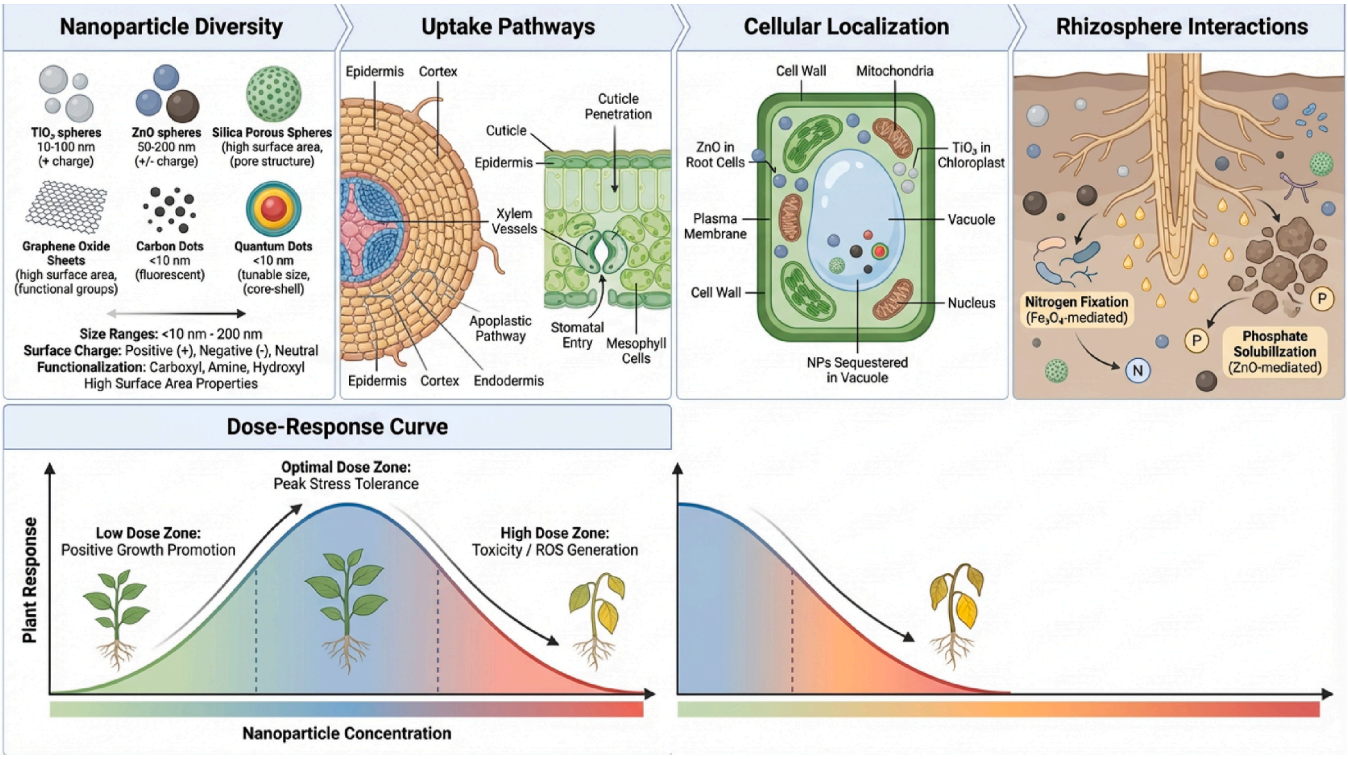



**Fig. 2.** Mechanistic basis of plant-nanoparticle interactions. Summary of NP properties, transport routes, intracellular destinations, and interactions in the rhizosphere (top panel) and the related dose-response relationships in plants (bottom panel). Processes: Apoplastic and stomatal uptake, Subcellular targeting ($TiO_2$ in chloroplasts, ZnO in root cells, vacuolar sequestration), Symbiotic nutrient cycling (nitrogen fixation and phosphate solubilization) The biphasic dose-response curves show the shift from positive growth promotion at low concentrations to ROS-mediated toxicity at high concentrations.

the increasing need to find new approaches to managing various abiotic stresses in crops, which can be done at the same time and provide a lasting solution to resilient agriculture [7].

Nanotechnology has proved to be a useful technology in improving the ability of plants to resist adverse conditions. Nanoparticles (NPs) are engineered materials, often smaller than 100 nanometers in diameter, with a large surface-to-volume ratio, surface properties that can be modified, and distinct chemical reactivity, which allows them to interact with plant cells where bulk materials cannot [8]. The NPs have the ability to modify the physiology of plants over a range of levels, such as water and nutrient uptake, photosynthesis, osmotic regulation, and hormonal signaling. Moreover, nanoparticles may serve as a carrier of nutrients, antioxidants or bioactive molecules, where they have multifunctional value to stressed plants [9].

Recent experiments have shown that nanoparticles may be used to increase the tolerance to personal stresses, e.g. drought or salinity, by the means of physiological, biochemical and molecular changes [10]. Even though the studies on mixed stress situations are not numerous, the identified mechanisms indicate that nanoparticles can have the synergistic effect under the conditions of multi-factors [11]. This mini-review is a synthesis of current information on nanoparticle-based improvement of plant stress tolerance along with a focus on the physiological, biochemical and molecular processes occurring, practical aspects in agricultural applications and the future research directions to create sustainable nano-enabled approaches in enhancing crops.

## 2. Nanoparticles properties and plant interactions

The wide variety of nanoparticles employed to study plant stresses include metal and metal oxide nanoparticles (e.g., TiO2, ZnO, Fe3O4) and carbon-based nanomaterials (e.g., graphene oxide and carbon dots), silica nanoparticles, and quantum dots, (Table 1) [12,13]. These nanoparticles have distinct physicochemical characteristics such as high surface area, tunable surface chemistry and enhanced reactivity, all of which allow interactions with plant tissues on the cellular and subcellular scales, (Fig. 1). The nature, size, shape and surface functionalization of nanoparticles play a leading role in their uptake, translocation and biological action. Indicatively, smaller nanoparticles tend to be more effective in making infiltrations to plant cell walls whereas surface coats may be used to increase the stability, reduce aggregation, and improve interaction with plant tissues [14].

Nanoparticles translocation and uptake takes place via various pathways (Fig. 2). The most prevalent way is root absorption, according to which nanoparticles are absorbed through apoplastic and symplastic routes and transported through xylem and phloem to aerial tissues [35]. By foliar application, nanoparticles can get into stomata or cuticular layer, which directly interacts with mesophyll cells and chloroplasts. Nanoparticles can be localized in cell walls, vacuoles, chloroplasts, mitochondria, and nuclei once internalized and have an impact on metabolic processes and signaling pathways [36]. Research has indicated that TiO2 nanoparticles are found to be accumulating in the leaves and chloroplasts, increasing their photosynthetic efficiency, whereas ZnO nanoparticles in roots enhance the ion transfer and nutrient uptake during salinity and drought conditions [37,38].

The rhizosphere environment is also in contact with nanoparticles. Nanoparticles applied on soils can alter water microbial composition, affect root exudates, and alter nutrient availability, which indirectly affects plant growth and stress resilience [39]. As an example, iron oxide nanoparticles have been demonstrated to enhance the nitrogen fixation of legume crops and zinc oxide nanoparticles enhance phosphate solubilization by rhizosphere microbes. These interactions highlight the complex nature of nanoparticles in direct interactions with plants and the interactions in the soil ecosystem [40,41].

Nanoparticles have a dose-dependent and property-dependent biological activity. Low levels of NPs tend to favor plant development and resistance to stress, but the extreme level may result in phytotoxicity, the formation of ROS, and the damage of membranes [42]. The key to safe and effective application of nanoparticles is, therefore, learning about

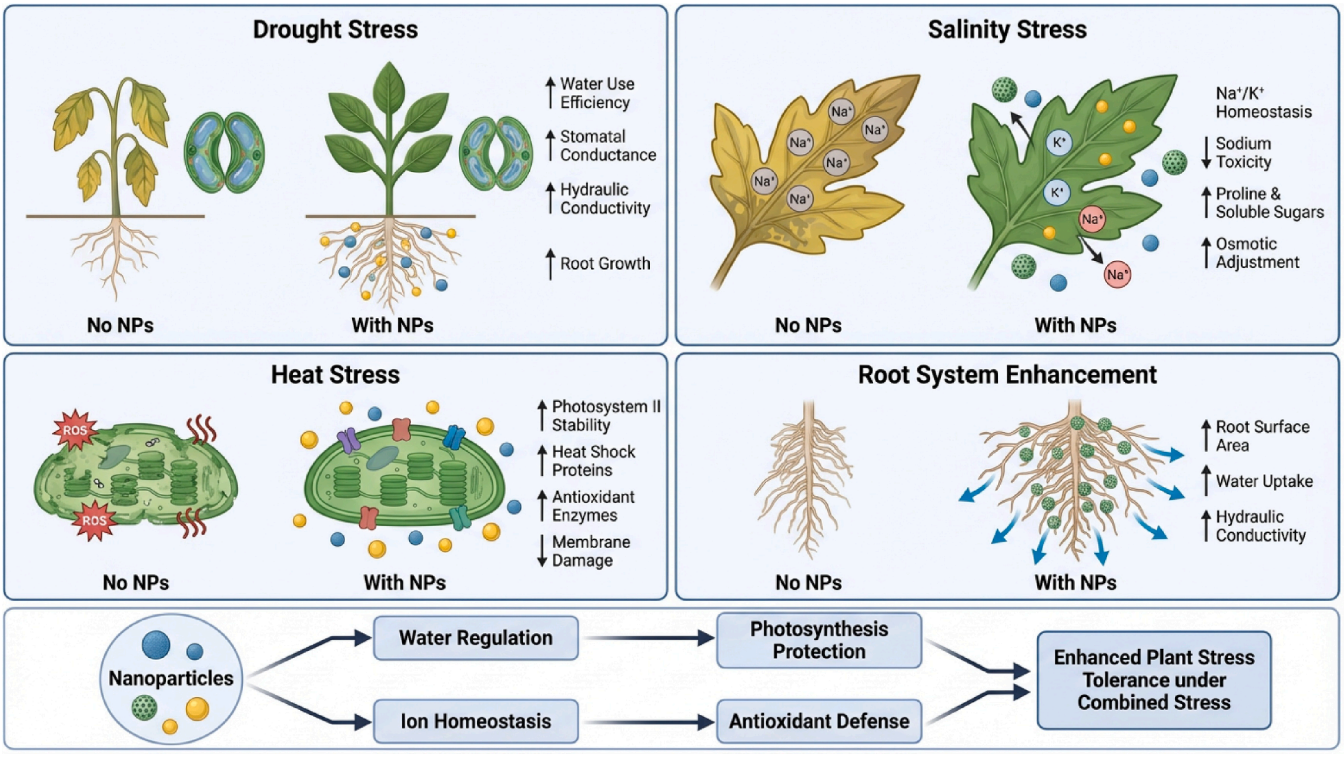



**Fig. 3.** Mechanisms of tolerance of NP against abiotic stresses and enhancement of root system. Comparison of plant physiological and molecular responses with and without NP application under drought, salinity and heat stress. The panels depict how NPs decrease cell damage (e.g., ROS, sodium poisoning) and improve adaptive features (e.g., water regulation, photosystem II stability, root surface area) leading to an overall increase in plant stress tolerance.

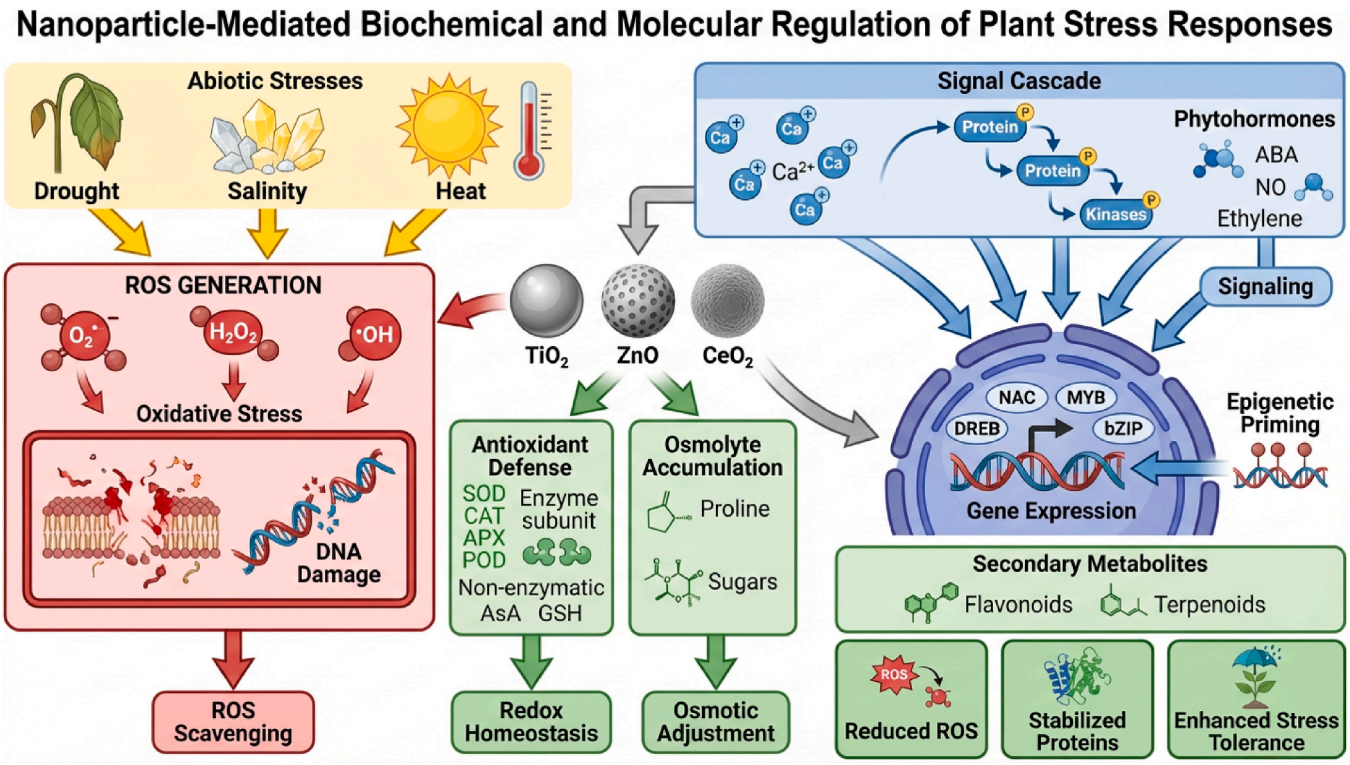



**Fig. 4.** Schematic representation of the biochemical and molecular pathways involved in nanoparticle-induced plant stress tolerance. The left panel shows the induction of oxidative stress (ROS generation and subsequent cellular damage) by the abiotic factors (drought, salinity, heat). Center and right panels show therapeutic roles of nanoparticles ($TiO_2$, ZnO and $CeO_2$) in scavenging ROS through antioxidant up-regulation and osmolyte accumulation. The diagram also specifies the activation of signal cascades ($Ca^{2+}$, kinases and phytohormones) and epigenetic modifications which trigger transcription factor-mediated gene expression, leading to the accumulation of secondary metabolites and increased stress tolerance.

the best nanoparticle characteristics, which are particle size, surface charge and concentration. The combination of these distinct characteristics and diverse interactions of nanoparticles makes them potent controllers of plant stress responses, (Table 1) and they could be used to help alleviate complicated abiotic stress events [43,44].

## 3. Physiological effects under stress

Nanoparticles have been reported to enhance significantly the physiological functions of plants in the abiotic stresses, (Fig. 3). In the drought, a lack of water decreases the turgor pressure, distorts stomatal control and inhibits photosynthesis [45]. Some of the studies indicate that TiO2 and ZnO nanoparticle increase stomatal conductance and water use efficiency, turgor of leaves, and photosynthetic rates during water deficit. Nanoparticles associated with roots have the ability to induce root growth, lateral root growth and the total root surface area that enhances uptake of water by roots in dry soils. It has been reported that carbon-based nanomaterials including the carbon dots and graphene oxide have the capacity to enhance hydraulic conductivity, which allows water to be transported throughout the plant during drought stress [46]. Salinity stress causes osmotic and ionic imbalances, which result in low photosynthesis, ion toxicity, and low growth. According to the literature, Na + /K + homeostasis, chlorophyll stability, and metabolic functioning of salt-stressed plants are preserved by selenium, zinc oxide, and iron nanoparticles [28]. Nanoparticles enhance the ability to use nutrients more effectively as they increase ion selectivity and limit sodium concentrations in shoots, thereby preventing salt-related toxicity. Moreover, nanoparticle facilitates osmotic adjustment through the accumulation of the compatible solutes (proline and soluble sugars) that maintain the cellular hydration and turgor [26].

Protein denaturation, destabilization of membranes, and build-up of ROS are caused by heat stress which eventually decreases photosynthetic efficiency and yield. It has also been reported that nanoparticles, such as TiO2 and cerium oxide, preserve chlorophyll content, stabilize photosystem II activity, and preserve cell membranes under stressful conditions of high temperature [47]. Also, nanoparticles have the ability to activate heat shock protein and antioxidant enzyme synthesis which are protective against thermal damage [48]. Though the majority of studies are based on single stressors, physiological data points to the idea that, in the case of combinations of stress, the improvements that have been mediated by nanoparticles may provide the resilience [4]. As an example, drought and heat are usually co-occurring conditions, and research has shown that nanoparticles have the ability to yield both beneficial effects on the state of water relations and the safety of the machine of photosynthesis, which may be beneficial in the conditions of multidimensional stress [25]. Nanoparticles offer physiological basis of increased plant tolerance to the complexes of environmental stresses, by sustaining turgor, improving nutrient uptake and preservation of photosynthetic apparatus.

## 4. Biochemical mechanisms and antioxidant regulation

Among the first actions that nanoparticles promote in plants to increase their tolerance to stresses are the biochemical pathways, especially the antioxidant defense. Abiotic stresses such as drought, salinity, and heat cause excessive synthesis of reactive oxygen species (ROS) of superoxide radicals, hydrogen peroxide and hydroxyl radicals [49,50]. High concentration of ROS leads to oxidative stress on proteins, lipids and nucleic acids, impairing cell integrity and functions. It has been demonstrated that nanoparticles can boost enzymatic and non-enzymatic antioxidant defense systems, decrease the build-up of ROS, and preserve redox homeostasis [51].

The enzymatic antioxidants; superoxide dismutase (SOD), catalase (CAT), peroxidases, and ascorbate peroxidase are increased due to the

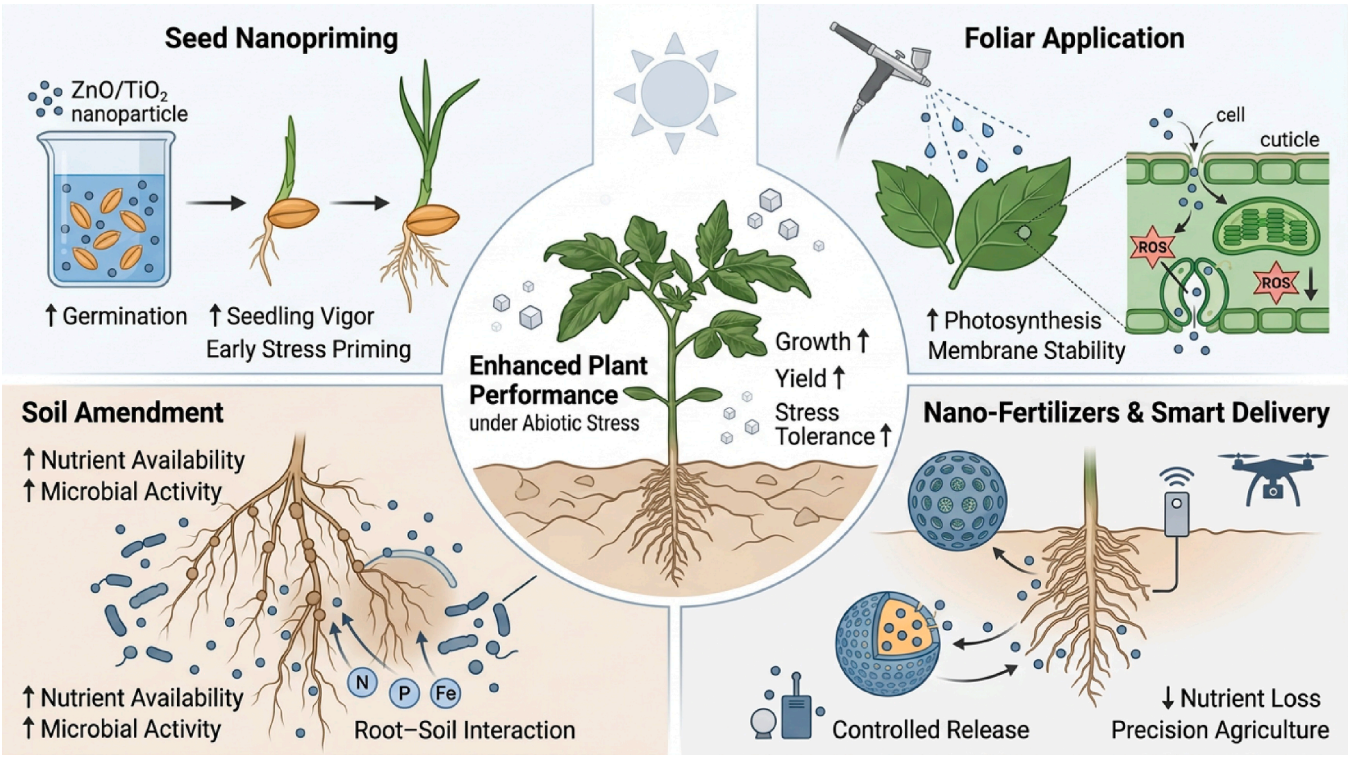



**Fig. 5.** Multifunctional aspects of nanotechnology for amelioration of plant performance under abiotic stress. The figure illustrates the main application of agricultural nanoparticles including seed nanopriming, foliar spraying, soil amendment and smart nano-fertilizers. Each pathway contributes towards physiological, biochemical and rhizospheric improvements which ultimately lead to better plant growth, higher crop yield and increased stress tolerance.

treatment with nanoparticles. These enzymes effectively counteract the ROS and hence protect the components of cells against oxidative damage [52]. The application of nanoparticles also increases the non-enzymatic antioxidants, such as ascorbate, glutathione, flavonoids, and phenolic compounds, which act as an added protection against oxidative stress. Some nanoparticles, like cerium oxide and carbon based nanomaterials, have intrinsic ROS-scavenging properties, which directly neutralize free radicals and decreases oxidative liability [32].

The osmolyte accumulation (proline, glycine betaine, soluble sugars etc) is also affected by nanoparticles. These osmolytes can stabilize proteins, membranes, ensure cellular osmotic balance, and help to globally resist stress. Indicatively, ZnO nanoparticles have been demonstrated to boost proline concentration at the time of integrated drought and salinity stress, improve osmotic adjustment and enzyme enclosures [30,53]. Also, nanoparticles affect the phytohormone signaling of abscisic acid (ABA), nitric oxide (NO), and ethylene that regulate stomatal closure, antioxidant enzyme activity, and expression of stress-responsive genes [54]. Nanoparticles present a biochemical approach to stress tolerance through a combination of ROS scavenging, osmolyte accumulation and hormonal regulation [55]. Moreover, nanoparticles may serve as induces of secondary metabolism, (Fig. 4). Research has indicated increased production of flavonoids, phenolic acids and terpenoids in reaction to exposure to nanoparticles, which helps in improving antioxidant capacity and defense signaling [56]. The overall effects of these biochemical address the reinforcement of the capacity of the plant to resist any individual or combination of abiotic stresses which is why nanoparticles play a multifunctional role in the process of cellular and molecular regulation of stress responses [57].

## 5. Molecular and genetic modulation

Nanoparticles are found to affect plant responses on both the molecular-genetic levels to regulate the expression of stress-responsive genes, transcription factors and major signaling pathways [16]. Abiotic stresses initiate a complex of molecular responses, which include engaged perception of stress receptors, calcium signaling, mitogen-activated protein kinase (MAPK) cascades and transcriptional reprogramming. These pathways can be improved with the help of nanoparticles, which results in a higher level of stress tolerance and cell adaptation [58]. An example is that zinc oxide nanoparticles have been shown to induce genes that relate to osmolyte biosynthesis, antioxidant enzyme synthesis and ion translocation, which overall increase plant resilience to drought and salinity stress [29].

DREB, NAC, MYB and bZIP families' transcription factors are stress-responsive transcription factors that are important in the regulation of stress tolerance downstream processes [59]. It has been reported that nanoparticles have the capability to regulate the activity of these transcription factors and lead to the activation of various protective pathways. It involves increased production of antioxidant enzymes, osmolytes, heat shock proteins and secondary metabolites which help in terms of improved tolerance to oxidative, osmotic and thermal stress [60]. Moreover, nanoparticles can also affect epigenetic changes, including DNA methylation and histone acetylation, that can precondition plants to endure stress events in the future and leave some sort of a stress memory [22].

Nanoparticles have an influence on the hormonal signaling pathways at the molecular level as well. They are able to regulate abscisic acid (ABA) biosynthesis and signaling that is important in stomatal closure and drought adaptation, and nitric oxide (NO) and ethylene pathways that play a role in ROS scavenging and stress adaptation [61]. This molecular process helps in the immediate and long-term physiological adaptation to enable plants to survive unfavorable conditions [62]. In addition, transcriptomic and proteomic evaluations show that exposure to nanoparticles has the potential to modulate several stress-responsive pathways in parallel, which is indicated that they may be useful in combination stress conditions, despite the scarcity of direct investigations [63].

The observed physiological and biochemical improvement has a

**Table 2**
Major challenges, research gaps, future directions, and expected outcomes of nanoparticle-based abiotic stress management in plants.

| Challenge/Research Area | Specific Issue | Scientific Basis and Implications | Future Research Direction | Expected Agricultural Outcome | References |
|---|---|---|---|---|---|
| **Phyto-toxicity of Nanoparticles** | Excessive nanoparticle accumulation can cause toxicity | High concentrations of NPs may induce ROS overproduction, membrane damage, protein denaturation, DNA damage, and metabolic disruption, leading to reduced growth and yield | Establish crop-specific toxicity thresholds; optimize particle size, coating materials, concentration, and exposure duration | Safe nanoparticle application with maximum stress-mitigation efficiency and minimal crop damage | [42,80,81]) |
| **Dose Optimization** | Lack of standardized dosage recommendations | Beneficial effects vary with NP type, plant species, growth stage, and environmental conditions | Develop dose-response models across crops and stress combinations | Improved reproducibility and field-scale adoption | Battula et al., [43,47] |
| **Environmental Persistence** | Long-term accumulation in soil and water | Metal-based NPs may persist for years, potentially altering ecosystem functions and biogeochemical cycles | Investigate degradation kinetics, transformation pathways, and environmental fate | Reduced ecological risks and improved sustainability | Devasena et al., [83, 84] |
| **Impact on Soil Microbiome** | Alteration of beneficial microbial communities | Nanoparticles may affect microbial diversity, nutrient cycling, and symbiotic relationships | Long-term rhizosphere studies integrating microbiome analyses | Preservation of soil health and ecosystem services | Mohil et al., [39,82] |
| **Food Chain Bioaccumulation** | Transfer of nanoparticles into edible plant tissues | Potential human and animal exposure through consumption of NP-treated crops remains poorly understood | Food safety assessments and trophic transfer studies | Improved consumer safety and regulatory confidence | Devasena et al., [3,83] |
| **Regulatory Uncertainty** | Lack of globally accepted standards | Absence of unified guidelines for production, application, monitoring, and disposal hinders commercialization | Development of international regulatory frameworks and risk assessment protocols | Faster commercialization and public acceptance | Batool et al., [3,85,86] |
| **Limited Understanding of Combined Stress Responses** | Most studies focus on individual stress factors | Plants in field conditions frequently encounter simultaneous drought, salinity, heat, and heavy metal stress | Conduct studies under multiple concurrent stress scenarios | More realistic recommendations for climate-resilient agriculture | Thabet, Alqudah [4, 25] |
| **Mechanistic Knowledge Gap** | Molecular mechanisms remain incompletely understood | Complex interactions occur among signaling pathways, hormones, ROS networks, and transcription factors | Integrate transcriptomics, proteomics, metabolomics, and epigenomics | Comprehensive understanding of NP-mediated stress adaptation | Mir et al., [22,63,87] |
| **Field Validation Deficiency** | Most evidence originates from laboratory and greenhouse studies | Controlled conditions do not fully represent variable field environments | Multi-location, multi-season field trials across agroecological zones | Enhanced reliability and practical applicability | Alam et al., [10,69] |
| **Economic Feasibility** | Production and application costs remain uncertain | Large-scale nanoparticle synthesis may increase production costs for farmers | Cost-benefit analyses and development of green synthesis methods | Affordable nano-enabled agriculture technologies | Hemalatha et al., [5,69] |
| **Precision Delivery Systems** | Inefficient delivery can reduce nanoparticle effectiveness | Conventional spraying often results in losses due to drift, runoff, and uneven distribution | Smart delivery systems, nano-carriers, and controlled-release formulations | Enhanced resource-use efficiency and reduced environmental contamination | Lowry et al., [34,88] |
| **Integration with Precision Agriculture** | Limited integration with digital farming technologies | Current NP applications are largely disconnected from real-time crop monitoring systems | Combine NPs with sensors, UAVs, GIS, IoT, and remote sensing platforms | Site-specific stress management and optimized resource allocation | [50,78]) |
| **Synergy with Biofertilizers and PGPR** | Interactions remain poorly characterized | Nanoparticles may enhance microbial colonization, nutrient availability, and stress signaling | Investigate NP–microbe–plant interactions under abiotic stress | Multifunctional sustainable stress-management systems | Verma et al., [40,89] |
| **Development of Nano-enabled Climate-Smart Agriculture** | Need for integrated solutions under climate change | Increasing frequency of combined stresses requires multifunctional technologies | Design integrated systems combining NPs, biochar, beneficial microbes, and precision agriculture tools | Improved resilience, productivity, and sustainability under climate variability | [15,84]) |
| **Long-Term Sustainability Assessment** | Lack of lifecycle evaluation studies | Environmental and socioeconomic impacts over multiple years remain unknown | Conduct life-cycle assessments (LCA) and sustainability analyses | Evidence-based deployment of nanotechnology in agriculture | Govindaraj et al., [3,47, 84] |

mechanistic basis of the molecular and genetic modulation evoked by nanoparticles. Nanoparticles are multi-signaling pathway and transcriptional network regulators of plant responses to stress [64]. Such multi-level modulation is especially important when the stress is combined, and the multiple protective mechanisms should be activated at the same time to enable tolerance. Altogether, molecular impacts of nanoparticles are additional to their physiological and biochemical ones, which make them a flexible instrument to improve plant resiliency [15].

## 6. Application in agriculture

Nanoparticles have a wide range of usages in the agricultural sector with the intention of augmenting plant resistance to abiotic stress and increasing the overall output. Seed nano-priming is one of the common methods of studying and seeds are primed with nanoparticles prior to being sown [65,66]. It can increase the rate of germination, seedling vigor, and initiate early defense responses that hardens plants to stressful environments [31,67,68]. Indicatively, seed treatment with ZnO and TiO2 nanoparticles has been observed to promote germination and root development under drought and salinity conditions which allows the seedlings to build a better platform to support further growth [31,68].

Another effective approach to provide a protective advantage to the photosynthetic tissues is foliar application of nanoparticles. Nanoparticles placed on the leaves may enter through the stomata or the cuticular layer and engage with chloroplasts and other organelles to promote photosynthesis and ROS levels and increase the use of nutrients [69,70]. Nanoparticles that have been used as foliar applications have been shown to protect against heat, drought and combined stress

conditions by preserving chlorophyll, minimizing oxidative damage and stabilizing membranes [19]. This technique offers a quick reaction system, especially when one is faced with an acute stressor in the field [69].

Nanoparticles can be used to improve soil amendments in terms of root growth, nutrient uptake and interactions between soil and plants [34]. In iron oxide and zinc oxide, metal oxide nanoparticles have been also reported to augment the availability of necessary nutrients, promote beneficial microbial activity, and root exudation patterns, which indirectly promote stress tolerance [27,71]. An example of this is the use of iron oxide nanoparticles in enhancing nitrogen fixation in legumes and zinc oxide nanoparticles in enhancing phosphate solubilization, which facilitates growth under conditions of nutrient limitation and stress prone conditions [27,69,72].

The nano-based fertilizers and delivery systems have multitrack potential as these systems can be used to address nutrient deficiency, stress suppression in crops and nutrient supplementation [73–75]. Nanoparticles with controlled release can offer sustained nutrient provision, lessen loss through leaching and increase the ability of plants to survive in drought, salinity or heat stress [76]. These nano-enabled systems can be integrated using precision agriculture technologies such as soil moisture sensors, remote sensing, and targeted delivery and used in an optimized manner to achieve improved resource efficiency [20]. Although these tests have shown promising results in the laboratory, there are limited field-scale studies, and a massive trial is done to determine the long-term efficacy, environmental impact and the economic feasibility [10].

Altogether, nanoparticles offer a toolkit that can be effectively applied in performance improvement of plants under stress, germination, plant growth and yield [77]. Nano-enabled agriculture has provided an opportunity to achieve sustainable crop management amid the growing complexities in the environment by integrating the concept of seed priming, foliar sprays, soil amendments and precision application strategies [78] (Fig. 5).

## 7. Challenges and future directions

Although it has been seen that nanoparticles have potential of improving abiotic stress tolerance in plants, there are a number of problems that may continue to hamper their general usage in agriculture [79]. A significant issue is phytotoxicity that might be experienced at both high levels or because of improper nanoparticle characteristics. The severe build-up of nanoparticles might result in the overproduction of reactive oxygen species, membrane integrity disruption, and the inhibition of the major metabolic pathways, which will eventually slow down the growth and yield of plants [80]. Particle size, surface charge, coating and application rate must, therefore, be optimized with the aim of maximizing the benefits and minimizing risks [81].

The other issue of concern is the environmental effect of nanoparticles. The buildup in the soil and water can impact the micro communities, the nutrient cycles, and the ecosystems [82]. Nanoparticles made of metal, especially, may not break down in the environment and this casts doubts on the toxicity and bioaccumulation of these nanoparticles over time in the food chain. It is essential to have a thorough evaluation of the environmental fate, degradation, and the possible environmental risks, prior to the large-scale application [83,84]. The regulatory processes on safe use of nanoparticles on agriculture are still developing and the formal standard operating procedures of the use, monitoring and disposal of these nanoparticles are not well established which makes a barrier in commercialization [85,86].

The study needs to be followed up by systematic analysis in nanoparticles type, size, coating and concentration in a variety of crops and stress conditions. Multi-omics, such as transcriptomics, proteomics and metabolomics, will be necessary in order to describe the molecular processes involved in the interactions between nanoparticles and plants subjected to joint stress conditions [87]. Laboratory results should be supported with field-scale experiments and prolonged trials that will help to understand the practical effectiveness of the results in real-life conditions in agriculture. Combination with accuracy farming technologies, including targeted delivery systems and remote sensing, can help to increase the efficiency and sustainability of nanoparticles [88]. The synergistic approach, which involves the use of nanoparticles with other stress reduction methods, including biofertilizers, plant growth promoting microbes, or other eco-friendly agrochemicals [89]. The knowledge of how these systems interact would potentially make it possible to develop multifunctional solutions to resilient agriculture. With these challenges overcome and progress made in understanding of the mechanistic knowledge, nanoparticle based solutions can play a significant role in sustainable crop production in an environment that is increasingly complex and variable, (Table 2) [33].

## 8. Conclusion

Engineered nanoparticles enhance plant tolerance to abiotic stress via physiological, biochemical and molecular mechanisms including water and nutrient uptake, photosynthetic stability and antioxidant defense. Although research usually focuses on single stressors, the mechanisms of nanoparticle action are also relevant for combined stress situations, especially in multifactorial conditions. The type, size and concentration of nanoparticles and the environmental impacts should be considered for successful use in agriculture. The strategies include seed priming and precision agriculture techniques but there are challenges such as phytotoxicity and regulatory issues. Future work should be directed to mechanistic studies and multi-year field trials with the nanomaterials to establish their role as an important tool in sustainable agriculture to improve crop resilience and productivity under stressful environments.

## CRediT authorship contribution statement

**Isbor Noble Eromosele:** Writing – review & editing, Software. **Abdullah Al Kafi:** Formal analysis, Data curation. **Muhammad Ishfaq:** Visualization, Validation. **Md. Nahid Mahmud:** Visualization. **Muhammad Qasim:** Visualization. **Antwi Edmond Owusu:** Writing – review & editing, Data curation. **Nilotpal Das:** Writing – review & editing, Visualization. **Muhammad Khizar Hayat:** Writing – review & editing, Writing – original draft. **Hazib Ali:** Writing – review & editing. **Rida Batool:** Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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