Letters in Applied NanoBioScience
Open-Access Journal (ISSN: 2284-6808)

Review
Volume 14, Issue 4, 2025, 218
https://doi.org/10.33263/LIANBS144.218

Nanotechnology for Plant Stress Tolerance under Climate Change

Naser Sabaghnia [1,*], Mohsen Janmohammadi [1]

[1] University of Maragheh, Faculty of Agriculture, Department of Plant Production and Genetics, Iran; sabaghnia@maragheh.ac.ir (N.S.); mjanmohammadi@maragheh.ac.ir (M.J.);
* Correspondence: sabaghnia@ maragheh.ac.ir;

Received: 24.12.2024; Accepted: 4.08.2025; Published: 25.11.2025

Abstract: Emerging research highlights the wide-ranging applications of nanoparticles in agriculture, showcasing their impact on plant health, nutrient delivery, environmental stress mitigation, pollutant cleanup, and food preservation. This paper reviews the applications of nanoparticles in agriculture, focusing on their roles in nutrient delivery, stress tolerance, and sustainable productivity enhancement. Nano-fertilizers were found to improve nutrient use efficiency through controlled, slow-release mechanisms, reducing environmental losses. Findings indicated that nanoparticles can enhance seed germination, boost plant metabolic activity, and improve tolerance to drought, salinity, and heat stress. Additionally, nano-formulations of bio-stimulants and plant growth regulators improved soil fertility and microbial activity, supporting resilient agroecosystems. Advanced delivery systems enabled consistent plant responses across variable field conditions, reducing reliance on chemical inputs. These results underscore the potential of nanotechnology to address key agricultural challenges, offering a pathway toward increased crop yield, environmental protection, and long-term sustainability. Continued research and appropriate regulatory oversight are essential to safely and effectively integrate nanotechnology into mainstream agricultural practices. Strategic investments in research, coupled with strong regulatory oversight, will be essential to fully unlocking nanotechnology's transformative potential and paving the way for a more sustainable agricultural future.

Keywords: nano-fertilizer; nano-particles; physiological responses; sustainable farming.

1. Introduction

Nanotechnology, by harnessing the unique physicochemical properties of nanoparticles, offers transformative opportunities to advance sustainability in agriculture. Through innovative applications in plant nutrition, growth stimulation, and crop protection, nanotechnology offers a promising framework for addressing the growing challenges of modern farming. As nonagricultural land use continues to expand and arable land remains static or declines, there is an urgent need for technologies that can enhance agricultural productivity [1]. These pressures are compounded by rising global food demand and the prevalence of malnutrition, necessitating solutions that not only increase crop yield but also improve nutritional quality. Moreover, climate change has intensified abiotic stresses, such as water scarcity, salinity, and extreme temperatures, that collectively account for up to 70% of global agricultural losses [2]. In this context, nanotechnology emerges as a powerful tool to mitigate these stresses, enhance resource efficiency, and ensure food security in a rapidly changing world. Also, biotic stresses such as diseases, pests, and weeds cause substantial agricultural losses of 20-40%. Addressing these challenges is critical to ensuring global food security and strengthening the resilience of agricultural systems. Traditional breeding methods have made limited progress in enhancing stress tolerance, largely due to the complex nature of stress-related traits and the narrow genetic variability available under adverse conditions [3]. As these approaches reach their limits and yield improvements plateau, persistent food insecurity and deepening poverty are contributing to the situation, particularly in developing regions, where agriculture remains a vital source of livelihood. In this context, identifying and implementing alternative strategies for developing stress-tolerant crops is not only necessary but imperative to meet the demands of a growing population and a changing climate.

Nanoparticles play a pivotal role in environmental remediation by removing pollutants such as heavy metals and organic toxins from soil and water, thereby restoring ecological balance and enabling the reclamation of degraded lands for agricultural use. In parallel, nano-sensors integrated into agricultural systems are transforming food quality management by detecting spoilage markers, monitoring freshness, and extending shelf life—ultimately reducing food waste and improving supply chain efficiency [4]. Additionally, nano-encapsulation technologies offer sustainable solutions for agrochemical delivery, enabling the controlled release of fertilizers and pesticides. This reduces environmental runoff and minimizes unintended impacts on non-target organisms. Despite these advances, the safe and responsible application of nanoparticles in agriculture remains a critical concern [5]. Continued research is essential to optimize nanoparticle synthesis, refine delivery methods, and evaluate potential ecological and health risks. Issues such as toxicity, bioaccumulation, and long-term environmental impacts must be thoroughly addressed to ensure safe implementation. Future innovations should emphasize sustainable, scalable approaches that prioritize affordability, accessibility, and minimal ecological disruption [6]. Nanotechnology presents a transformative frontier in agricultural and plant biotechnology. By leveraging the unique physicochemical properties of nanoparticles, such as ultra-small size, high surface area, and enhanced reactivity, this field enables interventions that are more precise, efficient, and sustainable than conventional methods [7]. In crop science, nanoparticles support a wide range of applications, including the slow and targeted release of fertilizers to enhance nutrient uptake while minimizing waste and environmental contamination [8,9]. They also improve water-use efficiency, which is vital under drought and salinity stress. Furthermore, nanoparticles bolster plant defense systems, enhancing resistance to pests and diseases. In phytoremediation, they facilitate the extraction and detoxification of pollutants from soil and water, offering a powerful tool for environmental cleanup.

Beyond mitigating abiotic and biotic stresses, nanoparticles play a vital role in advancing precision agriculture. Nano-sensors integrated into farming systems enable real-time monitoring of soil conditions, crop health, and environmental variables, facilitating data-driven decision-making processes [10]. These technologies can detect early indicators of plant stress, enabling timely, targeted interventions to help prevent yield losses. Nanotechnology also contributes to food system sustainability through smart packaging innovations that detect spoilage, extend shelf life, and improve food preservation, thereby reducing post-harvest losses. To fully harness the transformative potential of nanotechnology in agriculture, ongoing research and development are essential. Equally important is the establishment of robust frameworks to guide the safe, ethical, and equitable application of nanoparticles [11]. This includes comprehensive assessments of potential environmental and human health impacts, along with strategies to ensure that these technologies are affordable and accessible to farmers globally. Representing a paradigm shift in sustainable agriculture, nanotechnology offers innovative solutions to enhance resource efficiency, support climate adaptation, and strengthen food security, ultimately reshaping agricultural systems for a more resilient and equitable future [12]. This paper explores the multifaceted roles of nanoparticles in advancing sustainable agriculture, focusing on their capacity to optimize nutrient use, stimulate plant growth, enhance resilience to biotic and abiotic stresses, and provide environmentally friendly solutions for both productivity enhancement and ecological remediation. To ensure a comprehensive and relevant review, literature was sourced via nanoparticles in agriculture, nano-fertilizers, plant stress tolerance, precision agriculture, and nanotechnology for environmental remediation, in major scientific databases over the past five years. Papers were screened based on their relevance to the core themes of this review, and additional references were identified through cross-referencing within selected papers.

2. Nanoparticle Types

Different types of nanoparticles are being utilized in agriculture based on their size, morphology, and distinct physical and chemical properties. The following sections outline some of the most frequently used nanoparticles and their applications.

2.1. Essential metal nanoparticles.

2.1.1. Iron nanoparticles.

Iron nanoparticles, particularly iron (III) oxide (ferric oxide), are vital for various plant metabolic activities, including photosynthesis, respiration, DNA synthesis, and the production of photosynthetic pigments. These nanoparticles help reduce oxidative stress in plants by decreasing reactive oxygen species, particularly under drought conditions [13,14]. Green-synthesized iron (III) oxide nanoparticles derived from marine algae have shown potential to enhance drought-stress resilience in crops such as foxtail millet, positioning them as eco-friendly nanofertilizers [15,16]. Their application has been linked to improved plant growth under stress, increased chlorophyll content in soybeans, and enhanced photosynthesis and yield in wheat cultivated in cadmium-contaminated soils. However, more extensive field testing is necessary to confirm their broader agricultural applicability.

2.1.2. Zinc nanoparticles.

Zinc nanoparticles, notably zinc oxide, play a critical role in fostering growth and improving resilience against abiotic stresses such as salt stress, cadmium toxicity, and water scarcity [17]. Zinc is essential for the structural and functional integrity of many enzymes, directly influencing crop health. Studies have demonstrated that zinc oxide nanoparticles significantly enhance rice germination rates under saline conditions and improve drought tolerance by altering physiological and biochemical parameters [18]. Foliar application of these nano-sized particles has been shown to have a more effective impact than bulk zinc sulfate on increasing wheat yields, boosting biomass accumulation, and enhancing zinc content in grains [19].

2.1.3. Magnesium nanoparticles.

Magnesium oxide nanoparticles exhibit potent antibacterial properties, particularly against pathogens such as Staphylococcus aureus, and are effective in combating plant diseases, including tobacco bacterial wilt caused by *Ralstonia solanacearum* [20]. Research has highlighted their ability to improve plant growth and physiological attributes, including enhanced chlorophyll content, enzyme activity, and magnesium uptake, without causing phytotoxic effects. Studies in plants have shown that magnesium oxide nanoparticles positively influence growth and chlorophyll levels, although higher doses may have inhibitory effects, emphasizing the need for dose optimization [21].

2.1.4. Copper nanoparticles.

Copper nanoparticles are widely recognized for their antimicrobial properties and have been synthesized using both conventional and eco-friendly methods. They enhance the antimicrobial efficacy of agricultural practices, providing a safer alternative to traditional fungicides and pesticides. Copper (II) hydroxide and copper (II) oxide nanoparticles are incorporated into fungicides, insecticides, and nano-fertilizers to combat pathogens such as Escherichia coli and Bacillus subtilis, as well as various plant fungal diseases [22]. These nanoparticles enhance plant disease resistance by stimulating defense enzymes, such as polyphenol oxidase and phenylalanine ammonia-lyase. However, their use in hydroponic systems has shown mixed effects on plants such as lettuce and alfalfa, influencing growth, nutrient concentrations, and enzyme activity [23,24]. Potential ecological risks, including genotoxicity, oxidative stress responses, and alterations in gene expression, have been observed in crops such as cucumber, necessitating careful evaluation of their environmental impact.

2.2. Non-essential metal nanoparticles.

2.2.1. Silver nanoparticles.

Silver (Ag) nanoparticles are widely recognized for their ability to counteract the growing resistance of pests and fungi to chemical pesticides, exhibiting broad-spectrum antimicrobial activity against various phytopathogens. They are effective in addressing salt stress by restoring ionic balance and enhancing nutrient availability, making them valuable for improving crop growth in salt-affected regions [9]. Additionally, they mitigate drought stress in plants, such as eggplant seedlings, by maintaining water balance and improving growth parameters [25]. Silver nanoparticles have also been shown to enhance salinity tolerance in crops such as pearl millet, with studies reporting a near doubling of growth metrics under saline conditions [26].

2.2.2. Titanium nanoparticles.

Titanium-based nanoparticles, particularly titanium dioxide, are gaining attention for their potential to interact with plants throughout their lifecycle and aid recovery from toxicants. While lifecycle studies remain limited, early research suggests that titanium dioxide nanoparticles can influence plant growth, nutrient accumulation, and stress resilience [27]. For example, in strawberries, exposure to titanium dioxide nanoparticles increased phosphorus and potassium concentrations in fruits [28]. However, studies on sunflowers observed reductions in kernel numbers and yield when exposed to these nanoparticles [29]. Other findings include alterations in nutritional elements in crops and changes in antioxidant systems sprayed with titanium dioxide nanoparticles [30,31]. Although trends in the impacts of titanium dioxide nanoparticles on plants are not yet fully established, their presence in edible tissues and their stability raise concerns about potential human ingestion through produce grown in titanium dioxide-impacted soils.

2.3. Non-metal nanoparticles.

2.3.1. Carbon nanoparticles.

Carbon-based nanoparticles, including single-, double-, and multi-walled carbon nanotubes, as well as graphene oxide and fullerenes, play a critical role in enhancing seed germination and plant growth. These nanoparticles possess unique properties that enable them to penetrate plant cell walls and transport chemicals within cells. Single-walled carbon nanotubes were used to deliver genomes and dyes into plant cells, while multi-walled carbon nanotubes improved germination properties and growth characteristics [32]. For example, multi-walled carbon nanotubes were used for priming at 100 µg/mL for 1 day, which improved germination in barley, soybean, and maize [33]. Similarly, concentrations of 50 µg/mL enhanced germination and biomass in wheat, maize, peanut, and garlic. Carbon-based nanoparticles also exhibit antifungal properties, combating pathogens like *Fusarium graminearum* and *Fusarium poae* [34]. Moreover, they alleviate oxidative stress in plants by scavenging reactive oxygen species under abiotic stress.

2.3.2. Silicon nanoparticles.

Silicon nanoparticles enhance plant tolerance to biotic and environmental stresses. Silicon dioxide nanoparticles were beneficiated through seed priming to improve germination, photosynthetic efficiency, and crop growth in maize [35]. These nanoparticles also combat cadmium stress in wheat by increasing biomass, reducing oxidative stress, and minimizing cadmium uptake [17]. In barley, they improve grain productivity and quality by reducing lead and cadmium uptake [36]. Silicon dioxide nanoparticles have also demonstrated efficacy in increasing antioxidant defenses in rapeseed [37], mitigating copper toxicity in *Mentha arvensis* [38], and enhancing the ascorbate-glutathione cycle under cadmium tolerance in rice [39]. Furthermore, they bolster Ocimum basilicum antioxidant systems under lead-induced stress conditions, underscoring their broad utility in stress management [40].

2.4. Biologically synthesized nanoparticles.

Nanoparticles synthesized using biological methods, employing bacteria, fungi, plants, and algae, are garnering attention for their environmentally friendly and biocompatible properties. These biologically synthesized nanoparticles enhance plant growth, manage diseases, and optimize nutrient uptake, presenting a sustainable alternative to traditional chemical inputs [41]. For instance, silver nanoparticles derived from plant extracts have improved wheat germination and growth, while zinc oxide nanoparticles synthesized from algae have bolstered tomato growth under saline conditions [42]. Plant roots, rich in metabolites, are central to green nanoparticle synthesis. Ginger and cherry roots have been used to produce silver, gold, and titanium dioxide nanoparticles, showcasing their versatility, and the resulting nanoparticles, particularly those from ginger, have applications beyond agriculture, including biomedicine [43]. Plant stems are also valuable in nanoparticle biosynthesis; for example, stems from grape, lavender, Leucas grass, and the dhobi tree have been used to create silver, iron oxide, selenium, and zinc oxide nanoparticles [44]. These biologically synthesized nanoparticles possess unique properties, such as magnetic characteristics and potential applications in diabetes treatment, highlighting their multifaceted benefits. By advancing eco-friendly agricultural practices, these nanoparticles represent a significant step toward sustainable, innovative solutions to global challenges.

3. Application Types

3.1. Shoot application.

Nanoparticles can enter plant cells via foliar application through the stomatal and cuticular pathways; smaller nanoparticles enter directly through the cuticle, whereas larger nanoparticles enter through stomata (Figure 1). Foliar application of nanoparticles delivers herbicides, fertilizers, and nutritional supplements directly to leaves, bypassing soil and preventing nutrient loss, offering advantages over soil-applied fertilizers, which have low utilization rates due to leaching and adsorption, leading to environmental issues such as eutrophication [45]. Slow-release nanofertilizers from biodegradable polymers such as chitosan and mesoporous silica have been developed to enhance nutrient availability and effectiveness. Foliar-applied nano-fertilizers provide rapid absorption by plants, supplying essential vitamins and elements not present in soil, and have been shown to enhance plant uptake of nitrogen, phosphorus, and potassium, with mesoporous silica nanoparticles reducing nutrient volatilization and environmental impact. Foliar nanoparticles also address nutrient deficiencies quickly and can biofortify crops with essential nutrients, with studies showing that zinc oxide nanoparticles promote zinc augmentation in plants and fullerene nanoparticles improve drought response by enhancing water storage and alleviating oxidative stress [46].

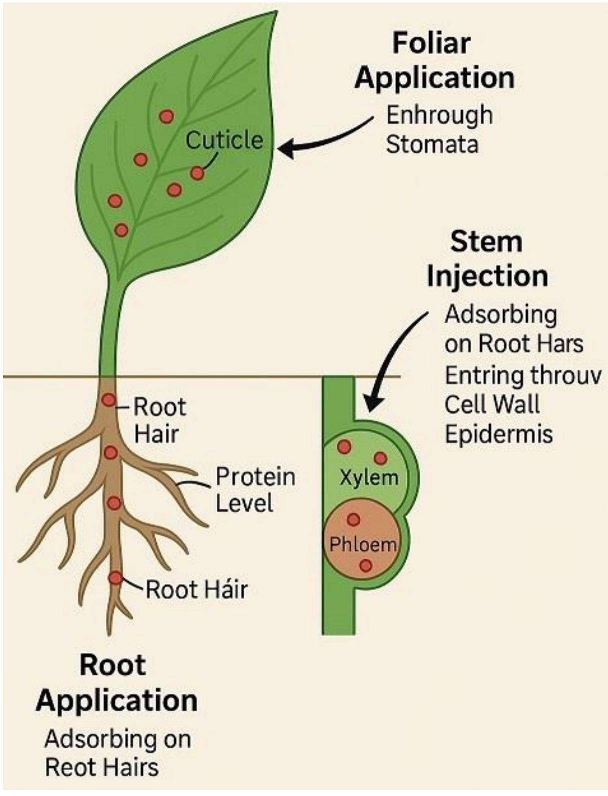

Figure 1. Various entry pathways of nanoparticles in plants.

Silver nanoparticles exhibit antibacterial activity, are used in fungicides, and biologically synthesized silver nanoparticles show high antimicrobial activity, with bimetallic nanoparticles such as copper and zinc serving as both insecticides and antibacterial agents. The absorption of foliar nanofertilizers depends on the residence time of nanoparticles on the leaf, their penetration through the epidermis, and their availability to the plant, and is influenced by plant species, environmental conditions, and nanoparticles' properties [47]. Dicotyledons tend to accumulate more nanoparticles than monocotyledons, and plants with large leaf surface areas or certain physical features can accumulate more atmospheric nanoparticles. Nanoparticle penetration through stomata is a primary absorption pathway, and younger leaves have a higher nutrient absorption capacity due to thinner wax layers. Atmospheric nanoparticles can settle on leaves, with fine particles penetrating through leaf trichomes, and smaller particles are more efficiently transported through the plant [48,49]. Endocytosis facilitates nanoparticles' entry into plant cells, and their surface modifications affect their absorption and internal transport. Nanoparticles initially interact with plants via root application, adhering to the root surface primarily via adsorption, influenced by negative charges on substances such as mucus or organic acids secreted by root hairs. This process targets the root surface for the accumulation and uptake of positively charged nanoparticles. The growth of lateral roots provides new adsorption sites, facilitating the interaction of nanoparticles and entry into the plant. Nanoparticles encounter the root tip's less-developed epidermis and penetrate through semi-permeable walls with small pores, acting as a selective barrier against larger nanoparticles [50]. Stem injection, also known as stem feeding, uses the plant's vascular system to efficiently deliver nanoparticles, providing direct access to the plant's vascular network. This method overcomes external barriers such as cuticles, ensuring immediate nanoparticle availability, minimizing losses, and improving distribution efficiency [51]. External barriers typically limit nanoparticle uptake in plants; however, stem injection circumvents these barriers, enabling higher nanoparticle concentrations to be delivered to intended targets within the plant. Nanoparticles, once inside, rapidly move to various tissues via the xylem and phloem, ensuring uniform distribution. An application of stem injection is in disease control, such as using copper nanoparticles to manage citrus canker in citrus trees, effectively addressing plant health.

3.2. Root application.

Once inside, nanoparticles navigate through the plant via pathways such as ion channels, endocytosis, and interactions with cell membrane proteins, as well as through physical damage. Endocytosis enables size-independent nanoparticle uptake, as demonstrated by the uptake of carbon nanoparticles in wheat [52]. Additionally, nanoparticles can bind to transport proteins on the root's external epidermis, providing another absorption route. Particle size significantly affects root absorption; smaller nanoparticles are more efficient. Cerium oxide nanoparticles show effective root uptake in plants like broad bean and Lemna minor or duckweed [53]. However, nanoparticles larger than 140 nm face absorption challenges; exceptions include silicon-based nanoparticles and natural polymer-derived nanoparticles, which can be absorbed despite being larger than 100 nm. The root cell wall's negative charge significantly influences interactions with nanoparticles of various charges, thereby affecting uptake efficiency [54]. Although uncharged and negatively charged nanoparticles can be absorbed, positively charged nanoparticles may remain on the root surface without penetrating deeper.

3.3. Comparison of foliar vs. root application.

Foliar application provides rapid nutrient delivery and precise dosing, reducing nutrient losses and environmental contamination [8]. However, it requires formulation stability against environmental factors (e.g., sunlight and rain) and may face limitations related to leaf surface characteristics and nanoparticle penetration barriers [45]. Root application enables sustained nutrient release and interaction with the rhizosphere but is subject to greater variability due to soil complexity, potential nanoparticle immobilization, and slower uptake rates.

3.4. Nanoparticle degradation and environmental fate.

Nanoparticles applied to plants can undergo degradation through physical, chemical, and biological pathways. Photodegradation by sunlight, oxidation-reduction reactions, and microbial degradation in soil influence nanoparticle stability and transformation [15]. These processes affect the bioavailability, persistence, and potential toxicity of nanoparticles in agricultural environments. Understanding degradation pathways is crucial for designing nanoformulations that are both effective and environmentally safe, thereby preventing nanoparticles from accumulating to harmful levels or causing unintended ecological impacts [13].

4. Stress Reduction

4.1. Environmental stresses.

Abiotic or environmental stresses, like water shortage, salt stress, and high or low temperatures, disrupt growth and productivity by triggering complex physiological and molecular responses. Central to these responses is the accumulation of stress hormones, such as abscisic acid, which plays a critical role in regulating plant adaptations to adverse conditions (Figure 2). Silver nanoparticles have been shown to enhance abscisic acid synthesis during drought, improving water retention and promoting drought tolerance by optimizing water use efficiency [55]. Nanoparticles also mitigate oxidative stress by boosting the activity of antioxidant enzymes, which neutralize reactive oxygen species and prevent cellular damage. For example, titanium dioxide nanoparticles in salt stress significantly enhance antioxidant enzyme activity, thereby improving stress resilience [56]. Furthermore, nanoparticles stimulate the production of osmolytes, such as proline, which help maintain cellular water balance and protect plant structures under stress. Silicon nanoparticles in heat-stressed wheat have been observed to increase proline levels, fostering improved growth and tolerance to high temperatures. In addition to these physiological effects, nanoparticles interact with specific biochemical pathways to counteract stress. Selenium nanoparticles, for instance, enhance the Halliwell–Asada pathway in mustard plants exposed to heavy metals, thereby decreasing reactive oxygen species levels by promoting the detoxification of heavy metals via enzyme activity [57]. Similarly, silicon dioxide nanoparticles enhance salt tolerance by modulating the salt-overly sensitive pathway, stabilizing ion balance through increased expression of the SOS1 gene in salt-stressed plants [58]. Nanoparticles also regulate cellular signaling networks, such as the mitogen-activated protein kinase pathway, which coordinates stress-responsive gene transcription. Gold nanoparticles have been shown to activate signaling pathways involving serine–threonine kinases in Arabidopsis, thereby enhancing resistance to oxidative stress [59]. In wheat, tricalcium phosphate nanoparticles improve drought tolerance by modulating calcium signaling, a crucial pathway that activates stress-responsive genes [60]. Meanwhile, zinc oxide nanoparticles fine-tune reactive oxygen species levels in salt-stressed plants, ensuring that stress signals are efficiently managed [61]. Copper oxide nanoparticles in wheat exposed to high temperatures enhance heat shock protein production by activating heat shock factor signaling, thereby safeguarding cells from thermal damage [62].

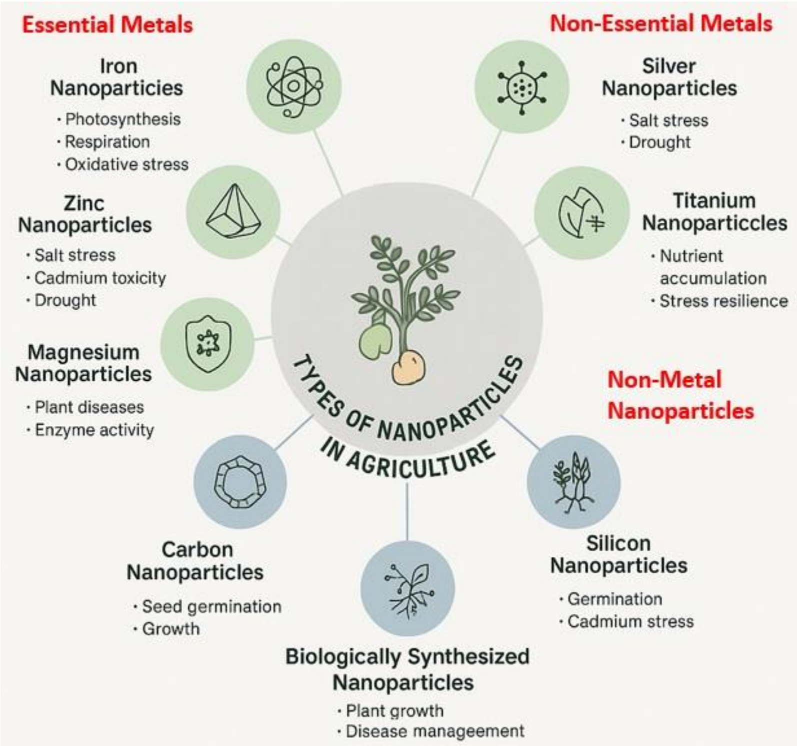

Figure 2. Various nanoparticles are used in stressed conditions.

4.2. Biotic stresses.

Biotic stresses, including attacks from pathogens, pests, and weeds, activate a plant's induced immunity systems through pattern recognition receptors that identify pathogen-related structures. Silver nanoparticles have demonstrated the ability to enhance this immune response, enabling plants to mount stronger defenses against invading pathogens. Zinc oxide nanoparticles, for example, trigger systemic resistance against tobacco mosaic virus by promoting the production of defense-related and biochemical molecules [63]. Similarly, copper oxide nanoparticles strengthen plant defenses by inducing systemic resistance, making plants more resilient to fungal pathogens [64]. Nanoparticles can also modulate plant hormone signaling pathways to enhance biotic stress tolerance. Zinc oxide nanoparticles stimulate salicylic acid production, a key hormone for defending against biotrophic pathogens, while titanium dioxide nanoparticles enhance jasmonic acid pathways, which are essential for resisting necrotrophic pathogens and pests [65]. Silver nanoparticles further enhance plant immunity by modulating ethylene signaling and improving resistance to fungal pathogens. Beyond hormonal pathways, nanoparticles exhibit direct antimicrobial properties. Silver nanoparticles have highly negative effects on most bacteria and fungi, including Alternaria alternata and Botrytis cinerea, as well as bacterial pathogens such as *Erwinia* species and *Fusarium graminearum* [66]. They also provide broad-spectrum protection against foodborne and agricultural pathogens. Other nanomaterials, such as chitosan nanoparticles and gold nanoparticles, offer additional antifungal and antibacterial capabilities. Chitosan nanoparticles, for instance, have been shown to combat pathogens like Macrophomina phaseolina and Alternaria alternata [67], while gold nanoparticles exhibit strong antibacterial activity against *Escherichia coli* [68]. Copper nanoparticles and silver-chitosan composites also display significant antimicrobial effects, particularly against *Pseudomonas syringae* [69]. Additionally, magnesium oxide and silicon dioxide nanoparticles demonstrate versatile antimicrobial action, effectively addressing bacterial and fungal threats to crops [70]. Nanotechnology offers a transformative procedure for managing biotic stresses in agriculture. By integrating nanoparticles' unique properties into plant protection strategies, researchers are developing innovative, targeted, and environmentally sustainable solutions. These advances have the potential not only to enhance crop productivity but also to reduce the environmental footprint of agricultural practices, paving the way for a more resilient food production system.

4.3. Cohesion and cross-comparison of nanoparticle-mediated stress reduction.

While abiotic stresses differ in origin and physiological impact, they often trigger overlapping molecular and cellular defense mechanisms within plants (Figure 3). Nanoparticles uniquely address both abiotic and biotic stresses by modulating shared pathways, enhancing plant resilience in a multifaceted manner. Oxidative stress is a common consequence of both environmental and pathogen-induced challenges, while nanoparticles such as titanium dioxide, zinc oxide, and selenium enhance antioxidant enzyme activity, which neutralizes reactive oxygen species generated under drought, salinity, or pathogen attack [59]. This cross-protective antioxidant boost reduces cellular damage and preserves physiological functions across stress types. Similarly, nanoparticles influence key stress signaling pathways, including abscisic acid, salicylic acid, jasmonic acid, and ethylene signaling, which coordinate adaptive responses to both abiotic and biotic factors. Zinc oxide nanoparticles stimulate salicylic acid pathways that confer resistance to pathogens, while also supporting drought tolerance through improved water-use efficiency [19, 52].

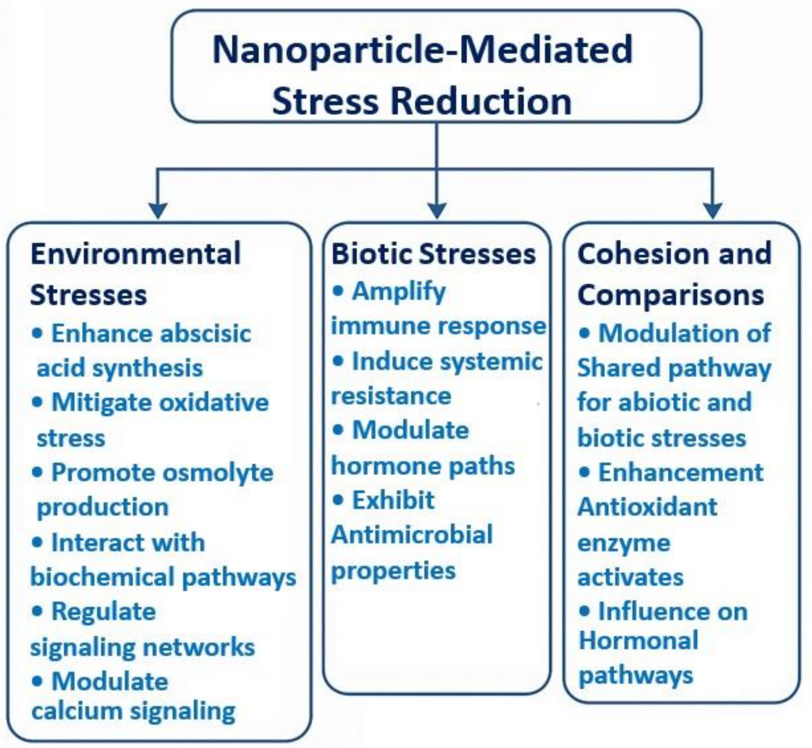

Figure 3. Diagram of the roles of nanoparticles in stressed conditions.

Titanium dioxide nanoparticles enhance jasmonic acid signaling pathways, which are critical for defense against insect pests and necrotrophic pathogens, and also play roles in abiotic stress mitigation [31, 56]. Moreover, nanoparticle-mediated regulation of ion homeostasis, osmolyte accumulation (e.g., proline), and heat shock proteins contributes broadly to cellular protection and stress adaptation [56]. Such mechanisms are pivotal in maintaining cell turgor and protein stability under both high salinity and pathogen-induced oxidative stress. The dual antimicrobial properties of nanoparticles, including silver and copper variants, complement their physiological effects by directly inhibiting pathogen growth, thus combining biochemical resilience with targeted biocontrol [22, 25]. This integrative approach contrasts with conventional agrochemicals, which typically target abiotic or biotic stresses in isolation. The multifunctionality of nanoparticles enables a holistic approach to stress management in plants, simultaneously enhancing tolerance to diverse environmental conditions and strengthening innate immunity. This cross-compatibility supports the development of integrated crop protection strategies, reducing the need for multiple chemical inputs and advancing sustainable agriculture.

5. Abiotic Physiologic Reactions

The application of nanoparticles induces substantial physiological, biochemical, and molecular responses in plants, significantly enhancing their tolerance to abiotic stresses. For instance, iron (II) oxide nanoparticles effectively mitigate the toxic effects of heavy metals like cadmium and lead by boosting plant biomass, chlorophyll content, and antioxidant enzyme activity [71]. Similarly, silicon nanoparticles alleviate arsenic stress in maize by preserving chlorophyll, carotenoid, and protein levels while improving photosystem II efficiency [72]. These nanoparticles also reduce the accumulation of toxic ions from heavy metals such as cadmium and lead in wheat, rice, and pea plants, underscoring their role in detoxification and stress mitigation. In the context of drought, silicon and chitosan nanoparticles have been shown to enhance relative water content, photosynthetic efficiency, and antioxidant activity, thereby improving yield and biomass [73]. These nanoparticles also mitigate oxidative stress and improve water use efficiency. Under salinity stress, silicon nanoparticles enhance germination, photo assimilation, and antioxidative mechanisms in *Ocimum basilicum* [74]. Similarly, iron (II) oxide nanoparticles promote the growth of Dracocephalum moldavica, increase chlorophyll content, and enhance antioxidant enzyme activities, while reducing salt ion accumulation [75]. Additional research highlights silicon nanoparticles improving seed germination and growth in lentils under salinity [76]. Multi-walled carbon nanotubes can enhance salinity tolerance in some important crops by lowering reactive oxygen species production and optimizing the sodium-to-potassium cation ratio [77]. Silicon dioxide nanoparticles improve nutrient absorption and photosynthetic performance under combined water and salt stress in cucumber plants. Analcite nanoparticles and zinc oxide nanoparticles facilitate seed germination and promote growth rate in conditions of extreme heat and dryness in arid environments [78]. Copper and zinc nanoparticles can increase antioxidant activity and moisture retention in cucumber seedlings, thereby preserving photosynthetic pigments under drought stress [79]. In maize seedlings, silicon dioxide nanoparticles increase shoot length and relative water content while minimizing superoxide production and membrane damage [80]. Titanium dioxide nanoparticles counteract drought-induced yield losses, whereas copper nanoparticles improve leaf water content, biomass, and pigment concentration in food crops under drought stress [81].

Silicon dioxide nanoparticles display varying effects depending on the species and conditions; for example, they reduce photosynthesis and stomatal conductance in hawthorn under drought, yet silicon nanoparticles successfully mitigate drought stress. Foliar application of silicon nanoparticles has been shown to enhance antioxidant activity and essential oil production in summer savory (Satureja hortensis) under moderate drought conditions [82]. Similarly, foliar application of silicon and titanium dioxide nanoparticles helps mitigate the harmful effects of water shortage on rapeseed [83]. Soil applications of silicon nanoparticles increase moisture retention in some crops, while silicon and selenium nanoparticles improve growth, root ion selectivity, and overall yield performances in saline environments [84]. Nanoparticles are also effective in tackling combined stresses. Nanoparticles represent a promising and multifaceted approach to enhancing plant resilience to environmental stresses. By modulating physiological, biochemical, and molecular reactions, nanoparticles not only improve stress tolerance but also contribute to achieving sustainable farming operations that overcome the challenges of environmental stress.

6. Nanoparticle Roles in Climate Change

Nanotechnology plays a transformative role in addressing the impacts of climate change on plants by offering multifaceted solutions spanning biological, physical, chemical, and bioengineering domains. From cellular processes to whole-plant systems, nanotechnology supports enhanced plant metabolism and resilience, while its broader applications in renewable energy and precision agriculture contribute to climate mitigation and environmental conservation [51]. Nanotechnology aligns directly with climate change by reducing greenhouse gas emissions through innovative molecular mechanisms. One notable advancement is the development of nano-enhanced plants, which are genetically modified and treated with nanoparticles to improve photosynthetic efficiency. These plants absorb more carbon dioxide from the atmosphere, significantly enhancing carbon sequestration, so nanomaterials also act as soil amendments, reducing nitrous oxide emissions, a potent greenhouse gas [9]. By improving soil structure and nutrient availability, nanomaterials reduce reliance on synthetic fertilizers, a primary source of nitrous oxide emissions. Furthermore, nano-infused hydrogels enhance soil water retention and stabilize water availability, reducing crop vulnerability to drought.

Nanotechnology revolutionizes agricultural practices through precision interventions. For instance, nano-formulated pesticides and fertilizers are designed to address specific plant needs with minimal waste, ensuring efficient resource utilization. Silica nanoparticles deliver water and nutrients directly to plant roots, improving drought resistance while reducing unnecessary water consumption [85]. Additionally, nano-sensors based on carbon enable online management of soil water content and nutrient supply, enabling precise irrigation and fertilization. This targeted approach minimizes water and chemical usage, supports ecosystem health, and increases agricultural sustainability and efficiency. Nanotechnology enhances plant resilience to climate change by improving their resistance to abiotic and biotic stresses. Nanoparticles used for nutrient delivery help revitalize degraded soils, enhance plant growth, and boost productivity. For example, silica nanoparticles improve water uptake, while carbon-based nanomaterials alleviate oxidative stress in plants under adverse conditions such as salinity or drought [42]. Nano-based solutions also reduce the environmental impact of agriculture by promoting eco-friendly pest and disease management. Nano-pesticides and bio-nanocomposites offer precise control over pests and pathogens, reducing chemical runoff and soil contamination. Nanotechnology's contributions extend beyond individual plants to broader climate mitigation efforts. By reducing resource wastage, minimizing emissions, and enhancing carbon capture, it supports sustainable agricultural systems. However, fully leveraging nanotechnology's potential requires further research, sustainable application practices, and international collaboration to address environmental, health, and regulatory challenges. Nanotechnology offers critical tools to combat climate change and improve agricultural sustainability. Its ability to increase energy efficiency, enhance plant resilience, and support precision agriculture makes it indispensable in the fight against climate impacts. Continued innovation and cooperation will ensure that nanotechnology serves as a cornerstone for building a more sustainable future.

6. Other Roles of Nanoparticles

Nanoparticles can regulate plant signaling pathways to enhance resistance to various environmental stresses like heavy metals, water stress, salt stress, and heat. Their mechanism of action involves modulating gene expression associated with antioxidant defense systems and stress response pathways. This regulation leads to increased plant resilience under stress conditions. Nanoparticles affect gene expression in pathways related to antioxidant defense and stress responses. For example, zinc oxide nanoparticles can alter cytosine methylation patterns, impacting gene expression related to stress tolerance, whereas this modification helps plants, such as tomatoes, reduce the genotoxic effects of salinity stress and improve [86]. Zinc oxide nanoparticles increase antioxidant gene expression, showing how nanoparticles can modulate genetic mechanisms in plants for stress adaptation. The effects of nanoparticles on plants are not always straightforward; for instance, when plants are exposed to zinc nanoparticles under salinity stress, gene expression shows variability, so this demonstrates the nuanced regulatory impact nanoparticles can have on plant genetics [87]. Silicon nanoparticles in rice suppress genes involved in cadmium uptake, highlighting their potential to mitigate heavy metal stress [71]. Nanoparticles also influence key signaling pathways, such as the mitogen-activated protein kinase cascade, which regulates stress-responsive genes. This cascade involves components such as mitogen-activated protein kinase-2, which play a critical role in modulating phytohormone signaling and antioxidant defenses.

Nanoparticles enhance phytoremediation, a process where plants absorb and detoxify pollutants from the environment. They do this by increasing the uptake, translocation, and sequestration of pollutants, as well as improving plant-cell membrane permeability to facilitate efficient internalization. Nanoparticles, such as metal and metal oxide particles, help degrade organically based pollutants and enhance the uptake of heavy metals, thereby reducing their bioavailability and toxicity. Carbon-based nanoparticles, such as carbon nanotubes, aid in the degradation and translocation of pollutants, thereby enhancing plant enzymatic detoxification [88]. Iron-based nanoparticles also enhance the solubilization and uptake of heavy metals, aiding soil remediation. Some plants, such as red clover, cucumber, and ryegrass, can take up nanoparticles, including titanium dioxide, silver sulfide, and zinc oxide, making them effective for water phytoremediation [51]. This highlights their potential for mitigating nanoparticle pollution in aquatic ecosystems. Zero-valent iron nanoparticles help chelate metallic particles in soils, enabling plants to absorb and remediate metals such as arsenic, lead, and mercury. This process enhances plant growth and germination, facilitating cleaner soils. Nanoparticles are also used to enhance plant immunity against biotic stress factors, such as pathogens and pests, by modulating natural defense responses. They enable targeted delivery of agrochemicals, genes, or RNA molecules to improve immune responses in crops. Silver, copper, and zinc oxide nano-sized particles can be effective components in protecting plants against pathogens. For example, copper nanoparticles protect grapes from downy mildew, while silver nanoparticles boost tomato resistance to Ralstonia solanacearum, a bacterial pathogen [89]. Nanoparticles can initiate plant defense mechanisms, such as fortifying cell walls and inducing proteins related to disease resistance, thereby enhancing systemic acquired resistance. This prepares plants to fight off future threats. Nanoparticles, such as gold nanoparticles, can deliver RNA molecules into pathogens or pests, silencing genes crucial to their survival or infectivity. This approach targets pests such as Brassica cinerea in a highly specific and sustainable manner, reducing reliance on chemical pesticides. In summary, nanoparticles have an important role in inducing plant stress tolerance, improving phytoremediation, and boosting plant immunity, offering potential for sustainable agricultural practices and environmental cleanup.

8. Environment-Friendly Farming

Nanoparticles are transforming the delivery of nutrients, agrochemicals, and other compounds to plants, enabling more efficient, environmentally friendly farming practices. These innovative fertilizers use nanoparticles to deliver nutrients like nitrogen in a controlled manner, reducing nutrient loss and improving yield performance. Nano-hydroxyapatite serves as a slow-release phosphorus fertilizer, enhancing phosphorus availability to plants and minimizing waste [90]. Similarly, nano-encapsulation of urea improves nitrogen use efficiency, reducing fertilizer application frequency and its environmental impact. Urea-hydroxyapatite nanohybrids extend nitrogen release, supporting plant growth while enhancing nitrogen use efficiency. Nanoparticles also serve as smart delivery systems that can precisely target agrochemicals, reducing off-target effects and environmental harm. Mesoporous silica nanoparticles have been used for the controlled release of plant growth regulators, such as auxins and gibberellins [91]. These nanoparticles release compounds in response to pH changes, enabling targeted delivery. Similarly, nano-capsules loaded with herbicides selectively target weed species, minimizing harm to non-target plants. Chitosan nanoparticles can carry essential oils for controlled release, improving biopesticide activity. Nanoparticles offer novel ways to protect plants from pathogens and pests, improving agricultural sustainability. Silver nanoparticles are widely used for their antimicrobial activity, targeting plant pathogens such as bacteria, fungi, and viruses. They disrupt microbial cell walls and membranes, leading to pathogen cell death. Silver nanoparticles have been proven effective against various plant diseases. Nanoparticles are also used to enhance the delivery of biopesticides, targeting pests with increased precision while minimizing side effects on beneficial organisms. For example, chitosan nanoparticles loaded with essential oils have shown effectiveness against insect pests, such as the diamondback moth [92]. This technology improves the efficacy of biopesticides, reduces required dosages, and minimizes environmental risks. Nanoparticles are increasingly used to improve soil quality, enhancing its structure, fertility, and microbial activity. Nanoparticles can enhance soil water retention, aeration, and nutrient availability. For example, silicon nanoparticles help soil retain water, which is particularly beneficial in drought conditions [73]. Biochar nanoparticles can improve soil fertility by retaining nutrients and reducing nutrient leaching, thereby ensuring sustainable nutrient cycling. Certain nanoparticles, such as iron (II) oxide, can help remediate polluted soils by immobilizing contaminants, thereby reducing their bioavailability. Additionally, zinc oxide nanoparticles can promote beneficial microbial activity, improving soil health. Some nanoparticles foster a healthier soil ecosystem by boosting the activity of beneficial microbes, supporting soil fertility and plant growth. Nanotechnology is not only revolutionizing agriculture but also improving energy efficiency across sectors such as biofuel production and the automotive industry. Nanotechnology is helping to create lighter, more fuel-efficient vehicles, reducing environmental impacts such as greenhouse gas emissions. Nanomaterials used in automotive manufacturing can reduce vehicle weight while maintaining strength and safety, thereby lowering fuel consumption and emissions. Nanotechnology also has an important role in improving the efficiency of biofuel production. By manipulating the nanoscale structures of plant cell walls, such as nanofibrils, the breakdown of cellulose into sugars becomes more efficient [93]. This enhancement is achieved through nano-catalysis, which optimizes the conversion of cellulose into biofuels. Additionally, engineered nanoscale enzymes, such as glycol hydrolases and lignin-degrading enzymes, are being used to improve the conversion of cellulose into sugars, enhancing biofuel production. Nanoparticles have a profound impact on creating more sustainable and efficient agricultural practices. They improve nutrient delivery, enhance pesticide efficacy, improve soil health, and contribute to energy efficiency in agriculture and beyond. These advances pave the way for more eco-friendly and resource-efficient farming systems.

9. Conclusions and Future Insight

The application of nanotechnology in agriculture holds substantial promise for enhancing plant resilience to both biotic and abiotic stresses. Nanoparticles have shown the ability to modulate physiological and biochemical responses, regulate key signaling pathways, and influence gene expression, thereby improving plant defense mechanisms and contributing to increased crop productivity and sustainability. Innovations such as slow-release nanofertilizers and smart delivery systems represent important steps toward more efficient, environmentally conscious agricultural practices [94]. These technologies help optimize nutrient uptake, reduce input waste, and support resource conservation. However, translating these theoretical advantages into practical field applications presents several important challenges. Key areas needing further attention include the fabrication, characterization, and standardization of nanoparticles to ensure consistent performance and safety across diverse agricultural contexts. Moreover, the long-term environmental fate and potential nanotoxicity of these materials remain insufficiently understood. Research into their biodegradability, accumulation in soil and water systems, and interactions with non-target organisms is crucial to preventing unintended ecological consequences. In addition, extensive field validation is necessary to adapt nanoparticle applications for specific crops, environments, and stress conditions. Understanding their impacts on biodiversity, soil health, and ecosystem services will guide responsible use. Bridging existing regulatory gaps will also be essential for safe deployment and public acceptance of nano-enabled agricultural technologies. To drive widespread adoption of nanotechnology-based solutions, it is essential to engage with farmers and educate them on the potential benefits of nano-encapsulated fertilizers and other nanoparticle applications. By raising awareness, farmers can make informed decisions about integrating these technologies into their practices. Achieving large-scale adoption of nanotechnology in agriculture will require collaboration between scientists, extension workers, and government agencies. Reliable government support and well-designed policies will be necessary to promote research, funding, and the dissemination of knowledge about the science behind nanoparticle applications in agriculture. To fully realize these benefits, future research and development should also explore several key aspects. A deeper understanding of nanotoxicity and the environmental fate of nanoparticles will be essential to ensure safe and responsible use. Additionally, the field validation of laboratory findings, along with the development of appropriate regulatory frameworks, will support broader implementation. As agriculture becomes increasingly data-driven, the integration of nanotechnology with precision agriculture platforms, such as smart delivery systems and nano-enabled sensors, can further enhance input efficiency and crop monitoring. In summary, while nanotechnology offers innovative solutions to address the issues generated by climate alteration and other agricultural pressures, the road to practical, widespread implementation remains long. Continued research and collaboration will be crucial in making nanotechnology a cornerstone of sustainable agriculture, leading to a more resilient and efficient food production.

Author Contributions

Conceptualization, N.S. and M.J.; software, N.S.; validation, M.J.; resources, N.S.; writing—original draft preparation, N.S.; writing—review and editing, N.S. and M.J.; visualization, N.S.; supervision, N.S.; project administration, M.J. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Cui, H.; Ke, S.; Lu, X. An empirical study on the impact of green transition of farmland use on agricultural economic growth: A case of Hubei Province of China. *Habitat Int.* **2024**, *148*, 103090, https://doi.org/10.1016/j.habitatint.2024.103090.
2. Junaid, M.D.; Gokce, A.F. GLOBAL AGRICULTURAL LOSSES AND THEIR CAUSES. *Bull. Biol. All. Sci. Res.* **2024**, *9*, 66, https://doi.org/10.54112/bbasr.v2024i1.66.
3. Sustek-Sánchez, F.; Rognli, O.A.; Rostoks, N.; Sõmera, M.; Jaškūnė, K.; Kovi, M.R.; Statkevičiūtė, G.; Sarmiento, C. Improving abiotic stress tolerance of forage grasses – prospects of using genome editing. *Front. Plant Sci.* **2023**, *14*, 1127532, https://doi.org/10.3389/fpls.2023.1127532.

4. Sumel, A.; Amisha, R.; Sabahat, J.; Lavanya, L.; Shilpa Amit, G.; Sneha, D.; Shubneesh, K. Artificial Intelligence Integration with Nanotechnology: A New Frontier for Sustainable and Precision Agriculture. *Curr. Nanosci.* **2025**, *21*, 242-273, https://doi.org/10.2174/0115734137275111231206072049.
5. Kumar, A.; Singh, G.A.; Gourkhede, P.H.; Goutam, P.K.; Laxman, T.; Pandey, S.K.; Singh, P. Revolutionizing Agriculture: A Comprehensive Review of Nanotechnology Applications. *Int. J. Environ. Clim.* **2023**, *13*, 3586-3603, https://doi.org/10.9734/ijecc/2023/v13i113534.
6. Mondejar, M.E.; Avtar, R.; Diaz, H.L.B.; Dubey, R.K.; Esteban, J.; Gómez-Morales, A.; Hallam, B.; Mbungu, N.T.; Okolo, C.C.; Prasad, K.A.; She, Q.; Garcia-Segura, S. Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet. *Sci. Total Environ.* **2021**, *794*, 148539, https://doi.org/10.1016/j.scitotenv.2021.148539.
7. Ikumapayi, O.M.; Laseinde, O.T. Nanomanufacturing in the 21st Century: A Review of Advancements, Applications and Future Prospects. *J. Eur. Syst. Autom.* **2024**, *57*, 1235-1248, https://doi.org/10.18280/jesa.570430.
8. Sabaghnia, N.; Javanmard, A.; Janmohammadi, M.; Nouraein, M. The Influence of nano-TiO_2 and Nano-Silica Particles Effects on Yield and Morphological Traits of Sunflower. *Helia* **2018**, *41*, 213-225, https://doi.org/10.1515/helia-2018-0010.
9. Munir, A.; Salah, M.A.; Ali, M.; Ali, B.; Saleem, M.H.; Samarasinghe, K.G.B.A.; De Silva, S.I.S.; Ercisli, S.; Iqbal, N.; Anas, M. Advancing Agriculture: Harnessing Smart Nanoparticles for Precision Fertilization. *BioNanoScience* **2024**, *14*, 3846-3863, https://doi.org/10.1007/s12668-024-01597-5.
10. Yadav, A.; Yadav, K.; Ahmad, R.; Abd-Elsalam, K.A. Emerging Frontiers in Nanotechnology for Precision Agriculture: Advancements, Hurdles and Prospects. *Agrochemicals* **2023**, *2*, 220-256, https://doi.org/10.3390/agrochemicals2020016.
11. Wahab, A.; Muhammad, M.; Ullah, S.; Abdi, G.; Shah, G.M.; Zaman, W.; Ayaz, A. Agriculture and environmental management through nanotechnology: Eco-friendly nanomaterial synthesis for soil-plant systems, food safety, and sustainability. *Sci. Total Environ.* **2024**, *926*, 171862, https://doi.org/10.1016/j.scitotenv.2024.171862.
12. Dhiman, S.; Yadav, A.; Debnath, N.; Das, S. Application of Core/Shell Nanoparticles in Smart Farming: A Paradigm Shift for Making the Agriculture Sector More Sustainable. *J. Agric. Food Chem.* **2021**, *69*, 3267-3283, https://doi.org/10.1021/acs.jafc.0c05403.
13. Yousefzadeh, S.; Sabaghnia, N. Nano-iron fertilizer effects on some plant traits of dragonhead (*Dracocephalum moldavica* L.) under different sowing densities. *Acta Agric. Slov.* **2016**, *107*, 429-437.
14. Bidabadi, S.S.; Sabbatini, P.; VanderWeide, J. Iron oxide (Fe_2O_3) nanoparticles alleviate PEG-simulated drought stress in grape (*Vitis vinifera* L.) plants by regulating leaf antioxidants. *Sci. Hortic.* **2023**, *312*, 111847, https://doi.org/10.1016/j.scienta.2023.111847.
15. Sabaghnia, N.; Yousefzadeh, S.; Janmohammadi, M. Treatment by Trait Biplot Analysis of Organic Manure and Nano-Fertilizers on Sunflower Production. *Helia* **2018**, *41*, 241-251, https://doi.org/10.1515/helia-2017-0017.
16. Hassan, U.U.; Khan, M.; Younas, Z.; Raja, N.I.; Mashwani, Z.U.R.; Sohail. Effect of phytogenic iron nanoparticles on the bio-fortification of wheat varieties. *Green Process. Synth.* **2023**, *12*, 20238002, https://doi.org/10.1515/gps-2023-8002.
17. Umair Hassan, M.; Huang, G.; Haider, F.U.; Khan, T.A.; Noor, M.A.; Luo, F.; Zhou, Q.; Yang, B.; Ul Haq, M.I.; Iqbal, M.M. Application of Zinc Oxide Nanoparticles to Mitigate Cadmium Toxicity: Mechanisms and Future Prospects. *Plants* **2024**, *13*, 1706, https://doi.org/10.3390/plants13121706.
18. Singh, A.; Sengar, R.S.; Rajput, V.D.; Minkina, T.; Singh, R.K. Zinc Oxide Nanoparticles Improve Salt Tolerance in Rice Seedlings by Improving Physiological and Biochemical Indices. *Agriculture* **2022**, *12*, 1014, https://doi.org/10.3390/agriculture12071014.
19. Sánchez-Palacios, J.T.; Henry, D.; Penrose, B.; Bell, R. Formulation of zinc foliar sprays for wheat grain biofortification: a review of current applications and future perspectives. *Front. Plant Sci.* **2023**, *14*, 1247600, https://doi.org/10.3389/fpls.2023.1247600.
20. Gatou, M.-A.; Skylla, E.; Dourou, P.; Pippa, N.; Gazouli, M.; Lagopati, N.; Pavlatou, E.A. Magnesium Oxide (MgO) Nanoparticles: Synthetic Strategies and Biomedical Applications. *Crystals* **2024**, *14*, 215, https://doi.org/10.3390/cryst14030215.
21. Ahmed, N.; Zhang, B.; Bozdar, B.; Chachar, S.; Rai, M.; Li, J.; Li, Y.; Hayat, F.; Chachar, Z.; Tu, P. The power of magnesium: unlocking the potential for increased yield, quality, and stress tolerance of horticultural crops. *Front. Plant Sci.* **2023**, *14*, 1285512, https://doi.org/10.3389/fpls.2023.1285512.

22. Su, C.; Chen, A.; Liang, W.; Xie, W.; Xu, X.; Zhan, X.; Zhang, W.; Peng, C. Copper-based nanomaterials: Opportunities for sustainable agriculture. *Sci. Total Environ.* **2024**, *926*, 171948, https://doi.org/10.1016/j.scitotenv.2024.171948.
23. Feigl, G. The impact of copper oxide nanoparticles on plant growth: a comprehensive review. *J. Plant Interact.* **2023**, *18*, 2243098, https://doi.org/10.1080/17429145.2023.2243098.
24. F Fortis-Hernández, M.; González-Rodríguez, T.; Espinosa-Palomeque, B.; Preciado-Rangel, P.; Gallegos-Robles, M.A.; Rueda-Puente, E.O. Foliar biofortification with copper nanoparticles and its effect on phytochemical quality and enzymatic activity in lettuce. *Hortic. Bras.* **2024**, *42*, e2617, https://doi.org/10.1590/s0102-0536-2024-e2617.
25. Alabdallah, M.N.; Hasan, M.M.; Salih, M.A.; Roushdy, S.S.; Al-Shammari, S.A.; Alsanie, I.S.; El-Zaidy, M. Silver nanoparticles improve growth and protect against oxidative damage in eggplant seedlings under drought stress. *Plant, Soil Environ.* **2021**, *67*, 617-624, https://doi.org/10.17221/323/2021-PSE.
26. Khan, I.; Awan, S.A.; Raza, M.A.; Rizwan, M.; Tariq, R.; Ali, S.; Huang, L. Silver nanoparticles improved the plant growth and reduced the sodium and chlorine accumulation in pearl millet: a life cycle study. *Environ. Sci. Pollut. Res.* **2021**, *28*, 13712-13724, https://doi.org/10.1007/s11356-020-11612-3.
27. Soliman, S.; Wang, Y.; Samaan, M.S.F. Titanium dioxide nanoparticles alleviate phosphorus deficiency stress in apple plants. *Sci. Rep.* **2025**, *15*, 24443, https://doi.org/10.1038/s41598-025-07987-3.
28. Javan, M.; Selahvarzi, Y.; Sayyad-Amin, P.; Rastegar, S. Potential application of TiO_2 nanoparticles to improve the nutritional quality of strawberry cv. Camarosa under drought stress. *Sci. Hortic.* **2024**, *330*, 113055, https://doi.org/10.1016/j.scienta.2024.113055.
29. Kolenčík, M.; Ernst, D.; Urík, M.; Ďurišová, Ľ.; Bujdoš, M.; Šebesta, M.; Dobročka, E.; Kšiňan, S.; Illa, R.; Qian, Y.; Feng, H.; Černý, I.; Holišová, V.; Kratošová, G. Foliar Application of Low Concentrations of Titanium Dioxide and Zinc Oxide Nanoparticles to the Common Sunflower under Field Conditions. *Nanomaterials* **2020**, *10*, 1619, https://doi.org/10.3390/nano10081619.
30. Tighe-Neira, R.; Reyes-Díaz, M.; Nunes-Nesi, A.; Recio, G.; Carmona, E.; Corgne, A.; Inostroza-Blancheteau, C. Titanium dioxide nanoparticles provoke transient increase in photosynthetic performance and differential response in antioxidant system in *Raphanus sativus* L. *Sci. Hortic*. **2020,** 269, 109418. https://doi.org/10.1016/j.scienta.2020.109418.
31. Alharby, H.F.; Rizwan, M.; Iftikhar, A.; Hussaini, K.M.; Zia ur Rehman, M.; Bamagoos, A.A.; Alharbi, B.M.; Asrar, M.; Yasmeen, T.; Ali, S. Effect of gibberellic acid and titanium dioxide nanoparticles on growth, antioxidant defense system and mineral nutrient uptake in wheat. *Ecotoxicol. Environ. Saf.* **2021**, *221*, 112436, https://doi.org/10.1016/j.ecoenv.2021.112436.
32. Wani, A.K.; Khan, Z.; Sena, S.; Akhtar, N.; Alreshdi, M.A.; Yadav, K.K.; Alkahtani, A.M.; Wani, A.W.; Rahayu, F.; Tafakresnanto, C.; Latifah, E.; Hariyono, B.; Arifin, Z.; Eltayeb, L.B. Carbon nanotubes in plant dynamics: Unravelling multifaceted roles and phytotoxic implications. *Plant Physiol. Biochem.* **2024**, *210*, 108628, https://doi.org/10.1016/j.plaphy.2024.108628.
33. Fonseca, J.D.d.S.; Wojciechowska, E.; Kulesza, J.; Barros, B.S. Carbon Nanomaterials in Seed Priming: Current Possibilities. *ACS Omega* **2024**, *9*, 44891-44906, https://doi.org/10.1021/acsomega.4c07230.
34. González-García, Y.; Cadenas-Pliego, G.; Alpuche-Solís, Á.G.; Cabrera, R.I.; Juárez-Maldonado, A. Effect of carbon-based nanomaterials on *Fusarium* wilt in tomato. *Sci Hortic.* **2022**, *291*, 110586, https://doi.org/10.1016/j.scienta.2021.110586.
35. Alsamadany, H.; Alharby, H.F.; Ahmad, Z.; Al-Zahrani, H.S.; Alzahrani, Y.M.; Almaghamsi, A. Improving Alkaline Stress Tolerance in Maize through Seed Priming with Silicon Nanoparticles: A Comprehensive Investigation of Growth, Photosynthetic Pigments, Antioxidants, and Ion Balance. *Silicon* **2024**, *16*, 2233-2244, https://doi.org/10.1007/s12633-023-02833-5.
36. He, S.; Lian, X.; Zhang, B.; Liu, X.; Yu, J.; Gao, Y.; Zhang, Q.; Sun, H. Nano silicon dioxide reduces cadmium uptake, regulates nutritional homeostasis and antioxidative enzyme system in barley seedlings (Hordeum vulgare L.) under cadmium stress. *Environ. Sci. Pollut. Res.* **2023**, *30*, 67552-67564, https://doi.org/10.1007/s11356-023-27130-x.
37. Huang, Q.; Ayyaz, A.; Farooq, M.A.; Zhang, K.; Chen, W.; Hannan, F.; Sun, Y.; Shahzad, K.; Ali, B.; Zhou, W. Silicon dioxide nanoparticles enhance plant growth, photosynthetic performance, and antioxidants defence machinery through suppressing chromium uptake in *Brassica napus* L. *Environ. Pollut.* **2024**, *342*, 123013, https://doi.org/10.1016/j.envpol.2023.123013.

38. Aqeel, U.; Parwez, R.; Aftab, T.; Khan, M.M.A.; Naeem, M. Silicon dioxide nanoparticles suppress copper toxicity in *Mentha arvensis* L. by adjusting ROS homeostasis and antioxidant defense system and improving essential oil production. *Environ. Res.* **2023**, *236*, 116851, https://doi.org/10.1016/j.envres.2023.116851.
39. Faisal, M.; Faizan, M.; Soysal, S.; Alatar, A.A. Synergistic application of melatonin and silicon oxide nanoparticles modulates reactive oxygen species generation and the antioxidant defense system: a strategy for cadmium tolerance in rice *Front. Plant Sci*. **2024**, *15*, 1484600, https://doi.org/10.3389/fpls.2024.1484600.
40. Ullah, H.; Khan, I.; Mustafa, G.; Shehzad, J.; Hasan, M.; Saeed, U.; Chaudhari, S.K. Molecular Characterization and Mitigative Role of Silicon Dioxide Nanoparticles in *Ocimum Basilicum* Under Lead (Pb) Stress. *Silicon* **2023**, *15*, 2551-2565, https://doi.org/10.1007/s12633-022-02178-5.
41. Xu, L.; Zhu, Z.; Sun, D.-W. Bioinspired Nanomodification Strategies: Moving from Chemical-Based Agrosystems to Sustainable Agriculture. *ACS Nano* **2021**, *15*, 12655-12686, https://doi.org/10.1021/acsnano.1c03948.
42. Thabet, S.G.; Alqudah, A.M. Unraveling the role of nanoparticles in improving plant resilience under environmental stress condition. *Plant Soil* **2024**, *503*, 313-330, https://doi.org/10.1007/s11104-024-06581-2.
43. Ikram, M.; Javed, B.; Hassan, S.W.U.; Satti, S.H.; Sarwer, A.; Raja, N.I.; Mashwani, Z.-u.-R. Therapeutic Potential of Biogenic Titanium Dioxide Nanoparticles: A Review on Mechanistic Approaches. *Nanomedicine* **2021**, *16*, 1429-1446, https://doi.org/10.2217/nnm-2021-0020.
44. Shoukat, A.; Pitann, B.; Zafar, M.M.; Farooq, M.A.; Haroon, M.; Nawaz, A.; Wahab, S.W.; Saqib, Z.A. Nanotechnology for climate change mitigation: Enhancing plant resilience under stress environments. *J. Plant Nutr. Soil Sci.* **2024**, *187*, 604-620, https://doi.org/10.1002/jpln.202300295.
45. Sabaghnia, N.; Janmohammadi, M. Influence of some nano-fertilizers on chickpeas under three irrigation strategies. *Plant Nano Biol.* **2023**, *4*, 100037, https://doi.org/10.1016/j.plana.2023.100037.
46. Chandrashekar, H.K.; Singh, G.; Kaniyassery, A.; Thorat, S.A.; Nayak, R.; Murali, T.S.; Muthusamy, A. Nanoparticle-mediated amelioration of drought stress in plants: a systematic review. *3 Biotech* **2023**, *13*, 336, https://doi.org/10.1007/s13205-023-03751-4.
47. Dhaliwal, S.S.; Sharma, V.; Shukla, A.K.; Verma, V.; Kaur, M.; Shivay, Y.S.; Nisar, S.; Gaber, A.; Brestic, M.; Barek, V.; Skalicky, M.; Ondrisik, P.; Hossain, A. Biofortification—A Frontier Novel Approach to Enrich Micronutrients in Field Crops to Encounter the Nutritional Security. *Molecules* **2022**, *27*, 1340, https://doi.org/10.3390/molecules27041340.
48. Avellan, A.; Yun, J.; Morais, B.P.; Clement, E.T.; Rodrigues, S.M.; Lowry, G.V. Critical Review: Role of Inorganic Nanoparticle Properties on Their Foliar Uptake and in Planta Translocation. *Environ. Sci. Technol.* **2021**, *55*, 13417-13431, https://doi.org/10.1021/acs.est.1c00178.
49. Sabaghnia, N.; Janmohammadi, M. *Carthamus tinctorius* L. response to nano-silicon foliar treatment under organic and inorganic fertilizer application. *Acta Agric. Slov.* **2024**, *120*, 1-9, https://doi.org/10.14720/aas.2024.120.4.18624.
50. Wang, X.; Xie, H.; Wang, P.; Yin, H. Nanoparticles in plants: uptake, transport and physiological activity in leaf and root. *Materials,* **2023,** *16(8)*, 3097. https://doi.org/10.3390/ma16083097.
51. Joshi, S.; Allabun, S.; Ojo, S.; Alqahtani, M.S.; Shukla, P.K.; Abbas, M.; Wechtaisong, C.; Almohiy, H.M. Enhanced Drug Delivery System Using Mesenchymal Stem Cells and Membrane-Coated Nanoparticles. *Molecules* **2023**, *28*, 2130, https://doi.org/10.3390/molecules28052130.
52. Zhu, J.; Wang, J.; Zhan, X.; Li, A.; White, J.C.; Gardea-Torresdey, J.L.; Xing, B. Role of Charge and Size in the Translocation and Distribution of Zinc Oxide Particles in Wheat Cells. *ACS Sustainable Chem. Eng.* **2021**, *9*, 11556-11564, https://doi.org/10.1021/acssuschemeng.1c04080.
53. Liu, Y.; Zhao, X.; Ma, Y.; Dai, W.; Song, Z.; Wang, Y.; Shen, J.; He, X.; Yang, F.; Zhang, Z. Interaction of Cerium Oxide Nanoparticles and Ionic Cerium with Duckweed (*Lemna minor* L.): Uptake, Distribution, and Phytotoxicity. *Nanomaterials* **2023**, *13*, 2523, https://doi.org/10.3390/nano13182523.
54. Sabaghnia, N.; Janmohammadi, M.; Yousefzadeh, S. Graphical biplot assessment of pre-sowing procedures on the seeds of Dracocephalum moldavica L. employing diverse nanoparticles. *Biologija* **2024**, *70*, 1–9, https://doi.org/10.6001/biologija.2024.70.1.1.
55. Sarwar, M.; Saleem, M.F.; Ullah, N.; Khan, M.J.; Maqsood, H.; Ahmad, H.; Tanveer, A.; Shahid, M. Silver nanoparticles protect tillering in drought-stressed wheat by improving leaf water relations and physiological functioning. *Funct. Plant Biol.* **2023**, *50*, 901-914, https://doi.org/10.1071/FP23036.

56. Khalid, M.F.; Jawaid, M.Z.; Nawaz, M.; Shakoor, R.A.; Ahmed, T. Employing Titanium Dioxide Nanoparticles as Biostimulant against Salinity: Improving Antioxidative Defense and Reactive Oxygen Species Balancing in Eggplant Seedlings. *Antioxidants* **2024**, *13*, 1209, https://doi.org/10.3390/antiox13101209.
57. Li, L.; Wang, S.; Wu, S.; Rao, S.; Li, L.; Cheng, S.; Cheng, H. Morphological and Physiological Indicators and Transcriptome Analyses Reveal the Mechanism of Selenium Multilevel Mitigation of Cadmium Damage in *Brassica juncea*. *Plants* **2023**, *12*, 1583, https://doi.org/10.3390/plants12081583.
58. Soni, S.; Jha, A.B.; Dubey, R.S.; Sharma, P. Nanowonders in agriculture: Unveiling the potential of nanoparticles to boost crop resilience to salinity stress. *Sci. Total Environ.* **2024**, *925*, 171433, https://doi.org/10.1016/j.scitotenv.2024.171433.
59. Tang, Y.; He, R.; Zhao, J.; Nie, G.; Xu, L.; Xing, B. Oxidative stress-induced toxicity of CuO nanoparticles and related toxicogenomic responses in Arabidopsis thaliana. *Environ. Pollut.* **2016**, *212*, 605-614, https://doi.org/10.1016/j.envpol.2016.03.019.
60. Aljeddani, G.S.; Hamouda, R.A.; Abdelsattar, A.M.; Heikal, Y.M. Stress-Responsive Gene Expression, Metabolic, Physiological, and Agronomic Responses by Consortium Nano-Silica with Trichoderma against Drought Stress in Bread Wheat. *Int. J. Mol. Sci.* **2024**, *25*, 10954, https://doi.org/10.3390/ijms252010954.
61. Zulfiqar, F.; Ashraf, M. Nanoparticles potentially mediate salt stress tolerance in plants. *Plant Physiol. Biochem*. **2021**, *160*, 257-268, https://doi.org/10.1016/j.plaphy.2021.01.028.
62. Abasi, F.; Raja, N.I.; Mashwani, Z.-u.-R.; Ehsan, M.; Ali, H.; Shahbaz, M. Heat and Wheat: Adaptation strategies with respect to heat shock proteins and antioxidant potential; an era of climate change. *Int. J. Biol. Macromol.* **2024**, *256*, 128379, https://doi.org/10.1016/j.ijbiomac.2023.128379.
63. Eid, N.A.; Ibrahim, A.M.H.; Elsharawy, A.A.; Salem, K.F.M. Nanofertilizers for Plant Viral Disease Management. In Nanofertilizers for Sustainable Agriculture: Assessing Impacts on Health, Environment, and Economy, Kumar, P., Dubey, R.C., Eds.; Springer Nature Switzerland: Cham, **2025**; pp. 149-187, https://doi.org/10.1007/978-3-031-78649-5_7.
64. Chen, J.-n.; Wu, L.-t.; Song, K.; Zhu, Y.-s.; Ding, W. Nonphytotoxic copper oxide nanoparticles are powerful “nanoweapons” that trigger resistance in tobacco against the soil-borne fungal pathogen *Phytophthora nicotianae*. *J. Integr. Agric.* **2022**, *21*, 3245-3262, https://doi.org/10.1016/j.jia.2022.08.086.
65. Joshi, H. Exploring the efficacy of green nanoparticles in enhancing plant defense: a mechanistic investigation into immune response activation. *J. Nanopart. Res.* **2025,** 27(2), 29. https://doi.org/10.1007/s11051-025-06226-0.
66. Abbas, A.; Naz, S.S.; Syed, S.A. Antimicrobial activity of silver nanoparticles (AgNPs) against *Erwinia carotovora* subsp. *atroseptica* & *Alternaria alternata*. *Pak. J. Agric. Sci.* **2019,** 56(1), 113-117. https://doi.org/10.21162/PAKJAS/19.3886.
67. Iqbal, N.; Shoaib, A.; Fatima, Q.; Farah, M.A.; Raja, V. Synthesis and antifungal efficacy of chitosan nanoparticles against notorious mycotoxigenic phytopathogens. *Plant Stress* **2024**, *14*, 100614, https://doi.org/10.1016/j.stress.2024.100614.
68. Sathiyaraj, S.; Suriyakala, G.; Dhanesh Gandhi, A.; Babujanarthanam, R.; Almaary, K.S.; Chen, T.-W.; Kaviyarasu, K. Biosynthesis, characterization, and antibacterial activity of gold nanoparticles. *J. Infect. Public Health* **2021**, *14*, 1842-1847, https://doi.org/10.1016/j.jiph.2021.10.007.
69. Shahryari, F.; Rabiei, Z.; Sadighian, S. Antibacterial activity of synthesized silver nanoparticles by sumac aqueous extract and silver-chitosan nanocomposite against *Pseudomonas syringae* pv. *syringae*. *J. Plant Pathol.* **2020**, *102*, 469-475, https://doi.org/10.1007/s42161-019-00478-1.
70. Salas-Leiva, J.S.; Luna-Velasco, A.; Salas-Leiva, D.E. Use of magnesium nanomaterials in plants and crop pathogens. *J. Nanoparticle Res.* **2021**, *23*, 267, https://doi.org/10.1007/s11051-021-05337-8.
71. Ghouri, F.; Sarwar, S.; Sun, L.; Riaz, M.; Haider, F.U.; Ashraf, H.; Lai, M.; Imran, M.; Liu, J.; Ali, S.; Liu, X.; Shahid, M.Q. Silicon and iron nanoparticles protect rice against lead (Pb) stress by improving oxidative tolerance and minimizing Pb uptake. *Sci. Rep.* **2024**, *14*, 5986, https://doi.org/10.1038/s41598-024-55810-2.
72. David, O.A.; Labulo, A.H.; Hassan, I.; Olawuni, I.; Oseghale, C.O.; Terna, A.D.; Ajayi, O.O.; Ayegbusi, S.A.; Owolabi, M.O. Complexation and immobilization of arsenic in maize using green synthesized silicon nanoparticles (SiNPs). *Sci. Rep.* **2024**, *14*, 6176, https://doi.org/10.1038/s41598-024-56924-3.
73. Shinde, N.A.; Kawar, P.G.; Dalvi, S.G. Chitosan-based nanoconjugates: A promising solution for enhancing crops drought-stress resilience and sustainable yield in the face of climate change. *Plant Nano Biol.* **2024**, *7*, 100059, https://doi.org/10.1016/j.plana.2024.100059.

74. Farouk, S.; Elhindi, K.M.; Alotaibi, M.A. Silicon supplementation mitigates salinity stress on *Ocimum basilicum* L. via improving water balance, ion homeostasis, and antioxidant defense system. *Ecotoxicol. Environ. Saf.* **2020**, *206*, 111396, https://doi.org/10.1016/j.ecoenv.2020.111396.
75. Moradbeygi, H.; Jamei, R.; Heidari, R.; Darvishzadeh, R. Investigating the enzymatic and non-enzymatic antioxidant defense by applying iron oxide nanoparticles in *Dracocephalum moldavica* L. plant under salinity stress. *Sci Hortic.* **2020**, *272*, 109537, https://doi.org/10.1016/j.scienta.2020.109537.
76. Janmohammadi, M.; Sabaghnia, N.; Ahadnezhad, A. Impact of silicon dioxide nanoparticles on seedling early growth of lentil (*Lens culinaris* Medik.) genotypes with various origins. *Agric. Forest.* **2015**, *61*, 19-33, https://doi.org/10.17707/AgricultForest.61.3.02.
77. Zhao, G.; Zhao, Y.; Lou, W.; Su, J.; Wei, S.; Yang, X.; ... Shen, W. Nitrate reductase-dependent nitric oxide is crucial for multi-walled carbon nanotube-induced plant tolerance against salinity. *Nanoscale*, **2019,** *11(21),* 10511-10523. https://doi.org/10.1039/C8NR10514F.
78. El-Saadony, M.T.; Saad, A.M.; Soliman, S.M.; Salem, H.M.; Desoky, E.-S.M.; Babalghith, A.O.; El-Tahan, A.M.; Ibrahim, O.M.; Ebrahim, A.A.M.; Abd El-Mageed, T.A.; Elrys, A.S.; Elbadawi, A.A.; El-Tarabily, K.A.; AbuQamar, S.F. Role of Nanoparticles in Enhancing Crop Tolerance to Abiotic Stress: A Comprehensive Review. *Front. Plant Sci.* **2022**, *13*, 946717, https://doi.org/10.3389/fpls.2022.946717.
79. Ghani, M.I.; Saleem, S.; Rather, S.A.; Rehmani, M.S.; Alamri, S.; Rajput, V.D.; Kalaji, H.M.; Saleem, N.; Sial, T.A.; Liu, M. Foliar application of zinc oxide nanoparticles: An effective strategy to mitigate drought stress in cucumber seedling by modulating antioxidant defense system and osmolytes accumulation. *Chemosphere* **2022**, *289*, 133202, https://doi.org/10.1016/j.chemosphere.2021.133202.
80. Sharf-Eldin, A.A.; Alwutayd, K.M.; El-Yazied, A.A.; El-Beltagi, H.S.; Alharbi, B.M.; Eisa, M.A.M.; Alqurashi, M.; Sharaf, M.; Al-Harbi, N.A.; Al-Qahtani, S.M.; Ibrahim, M.F.M. Response of Maize Seedlings to Silicon Dioxide Nanoparticles (SiO_2NPs) under Drought Stress. *Plants* **2023**, *12*, 2592, https://doi.org/10.3390/plants12142592.
81. Wahab, A.; Batool, F.; Muhammad, M.; Zaman, W.; Mikhlef, R.M.; Naeem, M. Current Knowledge, Research Progress, and Future Prospects of Phyto-Synthesized Nanoparticles Interactions with Food Crops under Induced Drought Stress. *Sustainability* **2023**, *15*, 14792, https://doi.org/10.3390/su152014792.
82. Farajzadeh Memari-Tabrizi, E.; Yousefpour-Dokhanieh, A.; Babashpour-Asl, M. Foliar-applied silicon nanoparticles mitigate cadmium stress through physio-chemical changes to improve growth, antioxidant capacity, and essential oil profile of summer savory (*Satureja hortensis* L.). *Plant Physiol. Biochem.* **2021**, *165*, 71-79, https://doi.org/10.1016/j.plaphy.2021.04.040.
83. Spalevic, V.; Dudic, B.; ErciŞLi, S.; Janmohammadi, M.; Sabaghnia, N. Foliar spray of Si and Ti nanoparticles affected enzymatic antioxidants in rapeseed (Brassica napus L.). *Not. Bot. Horti Agrobot. Cluj-Na.* **2022**, *50*, 12859, https://doi.org/10.15835/nbha50412859.
84. Kale, S.S.; Chauhan, R.; Nigam, B.; Gosavi, S.; Chaudhary, I.J. Effectiveness of nanoparticles in improving soil fertility and eco-friendly crop resistance: A comprehensive review. *Biocatal. Agric. Biotechnol.* **2024**, *56*, 103066, https://doi.org/10.1016/j.bcab.2024.103066.
85. Mohamadzadeh, M.; Janmohammadi, M.; Abbasi, A.; Sabaghnia, N.; Ion, V. Physiochemical response of Cicer arietinum to zinc-containing mesoporous silica nanoparticles under water stress. *BioTechnologia* **2023**, *104*, 263-273, https://doi.org/10.5114/bta.2023.130729.
86. Singh, A.; Rajput, V.D.; Lalotra, S.; Agrawal, S.; Ghazaryan, K.; Singh, J.; Minkina, T.; Rajput, P.; Mandzhieva, S.; Alexiou, A. Zinc oxide nanoparticles influence on plant tolerance to salinity stress: insights into physiological, biochemical, and molecular responses. *Environ. Geochem. Health* **2024**, *46*, 148, https://doi.org/10.1007/s10653-024-01921-8.
87. Ahmed, M.; Tóth, Z.; Decsi, K. The Impact of Salinity on Crop Yields and the Confrontational Behavior of Transcriptional Regulators, Nanoparticles, and Antioxidant Defensive Mechanisms under Stressful Conditions: A Review. *Int. J. Mol. Sci.* **2024**, *25*, 2654, https://doi.org/10.3390/ijms25052654.
88. Cao, X.; Chen, Q.; Xu, L.; Zhao, R.; Li, T.; Ci, L. The intrinsic and extrinsic mechanisms regulated by functional carbon nanodots for the phytoremediation of multi-metal pollution in soils. *J. Hazard. Mater.* **2024**, *462*, 132646, https://doi.org/10.1016/j.jhazmat.2023.132646.
89. L. dos Santos, O.A.; dos Santos, M.S.; Antunes Filho, S.; Backx, B.P. Nanotechnology for the control of plant pathogens and pests. *Plant Nano Biol.* **2024**, *8*, 100080, https://doi.org/10.1016/j.plana.2024.100080.
90. Arora, V.; Khosla, B. Synthesis of phosphorus nano-fertilisers their strategic applications and effect on plant growth. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 6161-6180, https://doi.org/10.1007/s13762-024-06110-9.

91. Igiebor, F.A.; Ohanmu, E.O.; Omoregie, G.O.; Jennifer, O.O.; Musa, S.I.; Ejale, D.; Okojie, N.; Afe, R.; Ivbobie, S.; Ikhajiagbe, B. Nanobioherbicides and Plant Growth Hormone Synthesis and Stress-Mediated Hormones. In Handbook of Agricultural Biotechnology; Adetunji, C.O., Oloke, J.K., Eds.; Scrivener Publishing LLC: **2024**; pp. 125-149, https://doi.org/10.1002/9781394234769.ch20.
92. Mohan, K.; Kandasamy, S.; Rajarajeswaran, J.; Sundaram, T.; Bjeljac, M.; Surendran, R.P.; Ganesan, A.R. Chitosan-based insecticide formulations for insect pest control management: A review of current trends and challenges. *Int. J. Biol. Macromol.* **2024**, *280*, 135937, https://doi.org/10.1016/j.ijbiomac.2024.135937.
93. Cosgrove, D.J. Structure and growth of plant cell walls. *Nat. Rev. Mol. Cell Biol.* **2024**, *25*, 340-358, https://doi.org/10.1038/s41580-023-00691-y.
94. Sabaghnia, N.; Janmohammadi, M. Evaluation of nitrogen fertilizer and nano silicon spray on seed yield performance and components of sunflower. *Ratar. Povrt.* **2024,** *61(3)*, 74-84. https://doi.org/10.5937/ratpov61-48514.

Publisher’s Note & Disclaimer