

Nano-Seed Priming under Heavy Metal and Abiotic Stress: A Critical Assessment of Efficacy, Toxicity Thresholds, and Application Safety

Alaa Abdulghani Hussein 

Department of Center of Desert Studies, University of Anbar, Iraq

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*Corresponding Author: Alaa Abdulghani Hussein | Email Address: alaa.a.hussain@uoanbar.edu.iq

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Abstract

Recently, it has been considered a prospective approach for seed germination and early seedling establishment under heavy metal and abiotic stress conditions. Though the number of studies examining nanoparticle-assisted priming is increasing rapidly, most of the existing reviews describe this approach broadly, with insufficient attention being paid to dose-dependence, toxicity thresholds, and material-specific safety at the seed stage. Four types of nanoparticles: metallic nanoparticles, metal oxide nanoparticles, silicon nanoparticles, carbonaceous nanoparticles, and biopolymer nanoparticles have been investigated for seed priming under the conditions of heavy metal and abiotic stress, which will be critically reviewed here, drawing on recent literature. The current evidence provides a strong dependence on NP type, concentration, and plant genotype, which shows that nano-seed priming can improve water uptake, activate antioxidant defense systems, and increase stress tolerance. Of the various materials compared, silicon-based nanoparticles almost always strike a more favorable compromise between effectiveness and low risk of phytotoxicity, while a number of metal and metal-oxide nanoparticles show limited safety windows where modest changes in concentration may change plant responses from stimulation to toxicity. This review highlights the necessity of distinct, material-specific toxicity thresholds and standardized protocols to guide application by combining comparative performance with safety. Conclusion: Overall, the review offers decision-making guidelines on choosing the nanoparticles that are safe and effective for seed priming and emphasizes a precision-based application as a prerequisite for reproducible agricultural benefits and environmental sustainability.

Keywords: Nano-seed priming; Heavy metal stress; Abiotic stress tolerance; Antioxidant defense system; Seed germination physiology; Nanoparticle toxicity thresholds; Plant growth regulation.

Introduction

Abiotic stresses such as drought, salinity, extreme temperatures, and heavy metal pollution are among the most serious factors limiting global crop production and threatening food security [1], [2], [3]. Although biotic stresses also contribute to yield losses, a large proportion of plant damage is indirectly linked to abiotic stress conditions that weaken plant defense systems and increase susceptibility to pathogens [4], [5]. Heavy metal contamination, largely driven by industrial and anthropogenic activities, causes significant economic losses worldwide and poses long-term risks to agricultural sustainability [6], [7]. These challenges call for further development of climate-smart and sustainable agricultural practices to improve cropping system resilience as well as increase productivity stability across variable climatic conditions [8], [9].

Thus, nanotechnology to be more specific nano-enabled seed priming (NESP) has emerged as a promising pre-sowing approach for enhancing germination and early stage seedling adaptability to stress (individually or in combination) [1], [10], [11]. The application of nanoparticles offers a small size and high surface area that enable these materials to penetrate and interact efficiently with seed tissues, thereby affecting early physiological processes [12]. PreNanoparticle-based seed priming has previously been reported to increase water uptake, induce antioxidant defense systems, activate starch-degrading enzymes, and stimulate metabolic activation during germination, improving seedling quality during abiotic stress conditions [1], [13]. These effects may also extend into a cushion of immediate nutrient supply, which helps support initial development within a harsh environment.

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Nano-priming effects on plants, however, depend strictly on the type, concentration, size, surface charge, and solubility of nanoparticles, controlling their penetration through the seed coat and their localization in seed tissues [14], [15]. There is increasing literature reporting beneficial effects of nano-priming; however, a few major knowledge gaps remain. Lack of standardized dosage ranges among different types of nanoparticles, and cellular and molecular interactions of nanoparticles with plant tissue are not well-understood, especially after their release in soil environments [16], [17]. Moreover, nanoparticles may pose environmental risks, including the fact that nanoparticles can lead to environmental hazards such as mean residence times in soils, bioaccumulation along the food chain, and disruption of microbial communities [1], [18], [19]. Nanoparticles can also cause oxidative stress, genotoxic effects, inhibition of enzymes, and inhibition of photosynthetic processes at high doses, making it important to define safe dose limits [1], [20]. In other words, information regarding the transport pathways and environmental fate of nanoparticles, as well as their interactions with soil microorganisms, needs to be understood before their use in agriculture is recommended at large scale [1], [16]. Addressing these issues will allow nano-enabled seed priming to be developed as a precision-based and environmentally responsible tool for improving crop establishment and stress tolerance under heavy metal and abiotic stress conditions [1].

Types of Nanoparticles Used in Seed Priming and Their Effects under Stress

Different types of nanoparticles have been tested for seed priming to improve germination and early seedling growth under heavy metal and abiotic stress. Although many studies report positive effects, the results are not always the same because plant responses depend on nanoparticle type, dose, and plant species [1], [21]:

1. Iron-Based Nanoparticles

Iron-based nanoparticles are widely used in seed priming because iron plays a key role in plant metabolism [1]. At low to moderate concentrations, these nanoparticles improve photosynthesis, increase the activity of antioxidant enzymes, and reduce oxidative damage caused by stress. As a result, seedlings generally show better tolerance to drought, salinity, and heavy metal stress. In contrast, when iron nanoparticles are applied at higher concentrations, they may disrupt the internal redox balance of plant cells, leading to reduced growth. Therefore, the positive effects of iron nanoparticles in seed priming depend strongly on using appropriate concentrations (Figure 1) [6], [22], [23].

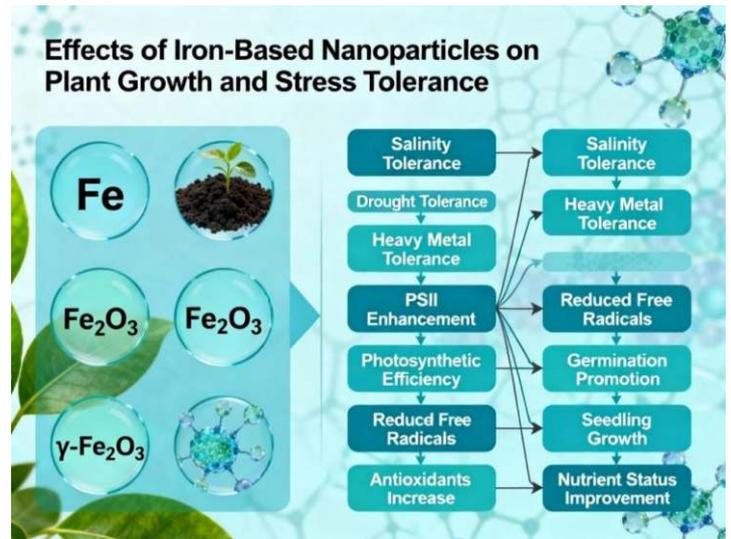


Figure 1. Germination and Plant Stress Responses Modulated by Fe-Based Nanoparticles

2. Zinc Oxide Nanoparticles

Zinc oxide nanoparticles (ZnO NPs) are commonly used because they can both reduce stress effects and supply plants with an important micronutrient. When applied at low concentrations, ZnO nanoparticles enhance antioxidant defenses, support osmotic balance (Figure 2), and improve the movement of nutrients within seedlings. These effects help promote seed germination and early growth under salinity and drought stress conditions [15], [21], [22], [24]. However, ZnO nanoparticles also have a very narrow therapeutic index between the dosage which is beneficial and toxic [25]. High sulfate levels often cause oxidative stress, damage to the membrane, and the blocking of germination [26]. This clear dose-dependent response makes ZnO NPs efficient but also dangerous, especially in the absence of standardized priming protocols [25].



Figure 2. ZnO Nanoparticles: Seed Germination and Plant Stress Response Effects

3. Titanium Dioxide Nanoparticles

Titanium dioxide nanoparticles (TiO₂ NPs) are well known for their photocatalytic properties. When used at appropriate levels, they can improve photosynthetic efficiency and enhance energy use during the early stages of plant development (Figure 3). Research has shown that TiO₂ NPs can enhance seed germination by enhancing uptake of water and promoting the metabolism of carbohydrates [27], [28], [29]. However, at improper concentrations, TiO₂ nanoparticles are also capable of causing adverse effects, such as genetic instability and metabolic disorder [30], [31]. As a result, their application in seed priming also demands strict regulation of dosage and exposure time to prevent undesirable physiological responses [26], [28].

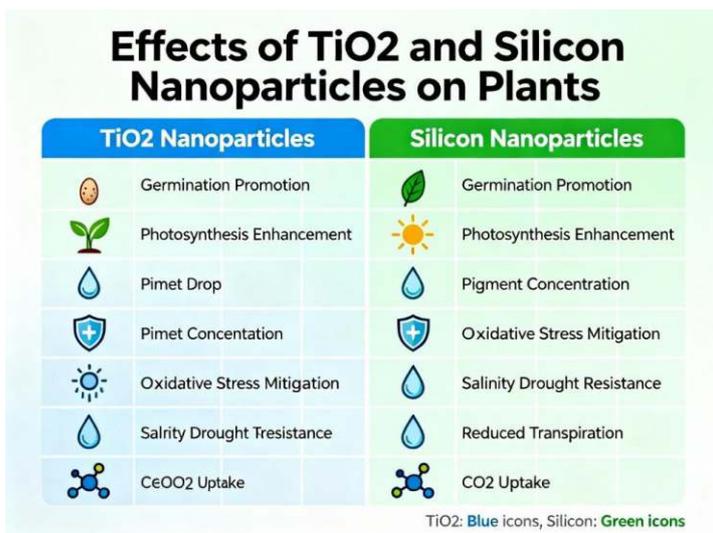


Figure 3. Seed Germination and Growth Responses to TiO₂ and Silicon Nanoparticles

4. Silicon-Based Nanoparticles

Silicon-The reliability in seed priming under heavy metal and abiotic stress is highest with silicon (SiO₂ NPs, silicon nanocarriers) based nanoparticles (Figure 4). Such nanoparticles improve seed hydration, increase the integrity of the cell wall, and induce antioxidant defence system [1], [32], [33]. Notably, silicon nanoparticles have been constantly found to lower the absorption as well as usage of hazardous heavy metals like cadmium and lead [34], [35].



Figure 4. Impact of SiO₂ Nanoparticles on Germination, Seedling Development, and Heavy Metal Stress Mitigation

5. Carbon-Based Nanoparticles

Carbon-based nanomaterials such as carbon nanotubes and carbon nanodots affected seed germination primarily by increasing water absorption and oxygen permeability through seed coats (Figure 1). Which can enhance germination rate and early seedling growth of seedlings under stress conditions. On the other hand, these carbon nanomaterials also provoke concerns about their toxicity, persistence, and long-term environmental fate [36], [37]. Excessive levels or unsuitable particle size may result in cytotoxicity and reduce root growth [38]. Thus, their application in seed priming is still encouraging but should be judiciously assessed [13].

Table 1. Carbon-Based Nanoparticles (Carbon Nanotubes and Carbon Nanomaterials)

Parameter	Effect of Carbon NPs	Proposed mechanism
Germination %	↑↑	Enhanced membrane permeability
Root length	↑↑	Improved water/nutrient uptake
Water uptake	↑↑	Nano-channels formation
O ₂ diffusion	↑	Membrane modification
Carbohydrate breakdown	↓	Slowed enzymatic activity
Toxicity threshold	High dose (>X mg/L)	ROS generation, membrane disruption

6. Biopolymer Nanoparticles (Chitosan)

These include MWCNTs and carbon particles (Figure 5). It has been reported that they can inhibit carbohydrate decomposition reactions, improve oxygen diffusion through membranes, and improve plants' water uptake [39], [40]. While they have been shown to significantly increase germination percentages and promote the growth of plants even at high concentrations, excessive amounts can be harmful at an early developmental stage of plants [41], [42].

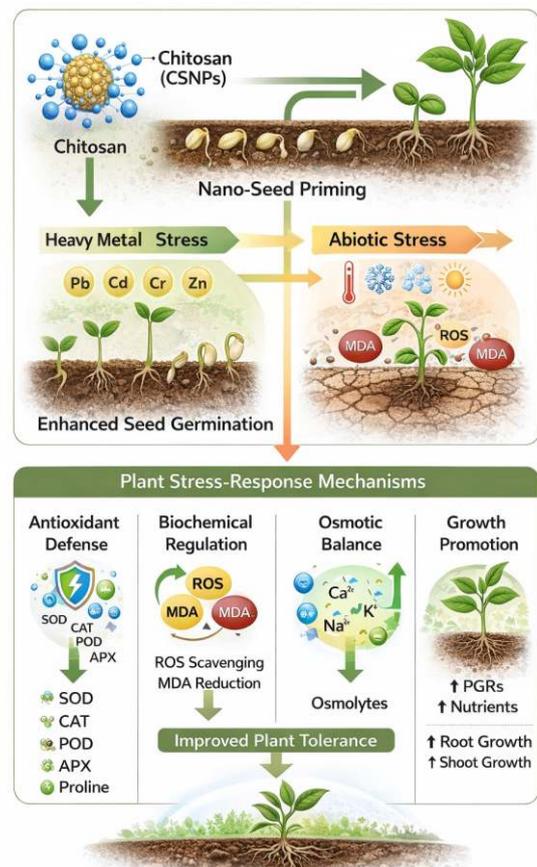


Figure 5. Impact of Chitosan Nanoparticles on Seed Germination and Plant Stress-Response Mechanisms

Mechanisms Comparative Efficacy and Toxicity Assessment of Nanoparticles

Though numerous types of nanoparticles are able to enhance seed germination and seedling development under stress, the defensible utility of such results will ultimately rest on the effectiveness-phytotoxicity balance [15]. Nanoparticle classes clearly differ with regard to safety margins and uniformity of beneficial effects, as evidenced by a comparative analysis of published studies. Among the different types of nanoparticles, silicon-based nanoparticles present the best ratio of effectiveness (Table 2): safety, regularly enhancing germination, stress tolerance, and the accumulation of heavy metals across several crop species [22], [43], [44]. Iron nanoparticles also appear as promising, but necessitate a tighter control of the dose to prevent a redox imbalance. In contrast, zinc oxide, silver, and titanium dioxide nanoparticles are believed to have lower safety windows with only small changes in concentration inducing a shift in plant response toward stimulation or toxicity

[22], [30], [45], [46]. While carbon-based nanomaterials may provide rapid physiological benefits within the timeframe of germination, their potential for persistence in the environment and long-term ecological impact is far from resolved. In fact, biopolymer nanoparticles, especially chitosan, are a middle ground because they are biodegradable and can induce stress in plants. But have the proper dosage if they just work. In contrast, this comparison emphasizes that nano-seed priming should not be regarded as a homogeneous technology since the performances are dependent on the kind of nanoparticle used and/or application conditions [47], [48], [49]. Consequently, nanoparticle choice and anticipated agronomic setting should both be material-specific performance and toxicity-inspired thresholds and limitations [13], [38]. These examples of a comparative framework enable the engineering of seed priming methods to maximize benefits to a target species while minimizing undesirable environmental and physiological side effects [13], [15], [50].

Table 2. Comparative efficacy and toxicity profile of nanoparticle classes used in seed priming

Nanoparticle Type	Main Beneficial Effects	Safety Margin	Potential Risks	Overall Assessment
Silicon-based NPs (SiO ₂)	Improve germination, enhance stress tolerance, reduce heavy metal uptake	Wide	Low toxicity at optimized doses	Best balance of efficacy and safety
Iron-based NPs (Fe, Fe ₂ O ₃)	Enhance photosynthesis, activate antioxidant enzymes, improve vigor	Moderate	Redox imbalance at high doses	Promising, but dose-sensitive
Zinc Oxide NPs (ZnO)	Improve antioxidant defense and nutrient translocation	Narrow	Oxidative stress and growth inhibition	Effective but high risk if misapplied
Titanium Dioxide NPs (TiO ₂)	Enhance energy use and early growth	Narrow	Genetic and metabolic disturbances	Requires strict dose control
Silver NPs (Ag)	Stimulate germination at low doses	Very narrow	Phytotoxicity and genotoxicity	High risk, limited practical use
Carbon-based NPs (CNTs, C-dots)	Improve water uptake and oxygen diffusion	Variable	Environmental persistence, root damage	Short-term benefits, long-term risk unclear
Biopolymer NPs (Chitosan)	Enhance antioxidant activity, stress tolerance	Moderate	Growth inhibition at high doses	Eco-friendly but dose-dependent

Table 3. Summary of Nanoparticle Types and Their Primary Effects on Seed Germination

Nanoparticle Type	Positive Effects	Potential Risks	Key Notes
Fe/Fe ₂ O ₃ NPs	Enhance PSII, increase antioxidant activity, improve vigor	High doses may alter redox balance	Strong metabolic support under stress
ZnO NPs	Improve osmotic balance, activate antioxidant enzymes	Toxic at high concentrations	Effective micronutrient + stress mitigator
TiO ₂ NPs	Stimulate photosynthesis, enhance starch breakdown	Genetic instability at high doses	Strong photocatalytic activity
SiO ₂ NPs	Reduce Cd/Pb uptake, strengthen cell walls	Minimal toxicity when optimized	Best for heavy metal tolerance
CNTs (Carbon Nanotubes)	Improve oxygen diffusion and water uptake	Toxic if diameter/concentration too high	Supports faster germination
Chitosan NPs	Boost antioxidant system, improve nutrient uptake	Overuse may inhibit germination	Biodegradable and eco-friendly

Methodology (Simplified and Review-Appropriate) A General Approach

This review is an outcome of the scrutinized investigation of all available studies on the application of nanoparticles as a seed priming material under the impact of heavy metal and abiotic stress [51], [52]. Available studies were compared based on nanoparticle type, dosage, and seed treatment approach. We restricted analyses to studies that measured physiological responses to stress-wave responses and that reported changes in uptake. [1], [32], [38] (Table 3).

Entry of Nanoparticles into Seeds and Their Interaction with Plant Cells

The success of nano-enabled seed priming as a paradigm goes beyond growth stimulation, but also entails the capability of nanoparticles to cross the outer seed layers, move inside the seeds, and interact with plant tissues. Studies show that nanoparticles are able to pass through natural micropores in the seed coat or enter cells via active transport mechanisms, thereby reaching the embryo. After being taken into the seed, nanoparticles could then affect the development of the

embryo or the subsequent growth of the seedling [1], [51].

Once in plant cells, nanoparticles can interfere with essential metabolic processes through the following means:

- Controlling levels of reactive oxygen species (ROS) with regulatory potential [1].
- Activating or inhibiting specific enzymes [1].
- Improving germination and growth-related pathways [1].
- Modifying hormone-related stress response pathways [1].

The size, chemical composition, and surface characteristics of nanoparticles, and the duration of their retention on the seed surface, govern the transport of nanoparticles inside the seed and thus their behavior during seed priming. There have been some advances in this area, but the mechanisms underlying seed priming with nanoparticles remain elusive. This will provide a better insight into these processes that'll help in the development of effective and safe priming strategies [13].

Characterization of Nanoparticles

A fundamental step in knowing how nanoparticles behave in the short and long run during seed priming and planting is the characterization of these nanoparticles due to their physicochemical properties. Other extensively studied features are particle size and shape, zeta potential, solubility, ion release rate, and crystal structure [53]. A range of approaches is implemented to examine these characteristics, including Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM) [54], [55]. Fitted with Energy-Dispersive X-ray Spectroscopy (SEM-EDS) and spectroscopic techniques. Additionally, the elemental composition of a plant can be measured using methods such as X-ray Fluorescence (XRF), which can also track the movement of nanoparticles through various plant tissues.

Meaningful Knowledge: The Aim to Bridge Between Nanoparticle Properties and Biological Effects. These Tools Establish Links Between NP Properties and Effects [17].

Physiological and Biochemical Indicators Used in Reviewed Studies

In the reviewed studies, different physiological and biochemical indicators were employed to assess the impacts of nano-seed priming [38], [56]. Physiological parameters consisted of germination percent, root and shoot length, seedling dry weight, seedling vigour index, photosynthetic efficiency, and stomatal behavior [57], [58]. Biochemical responses were primarily determined as the activity of antioxidant enzymes (catalase, peroxidase, and superoxide dismutase), and malondialdehyde (MDA) levels as an indicator of oxidation damage [59], [60]. Glucosemia resistance, in addition to changes in absolute sugar and protein content, changes in the expression of genes associated with stress responses were also reported in many studies [61].

Role of Carbon-Based Nanomaterials

Carbon-based nanomaterials, especially carbon nanotubes, have gained the attention of researchers, and their impact on seed physiology is very prominent; numerous studies have been reported on the topic [37], [62]. As mentioned [8], these materials have reported to decrease hydrogen peroxide accumulation, serve as membrane protectant and promote water uptake during germination. Thus, it was reported that carbon nanomaterials could cause root injury by damaging root cell membranes at very high concentrations under extreme conditions [1], [63]. In summary, the application of carbon-based nanomaterials has great potential for enhancing early growth stress tolerance, while the negative effects of the application should be avoided by careful dose control [37], [64].

Molecular and Hormonal Regulation

Several studies have shown that seed priming with nanoparticles can influence molecular and hormonal pathways involved in germination and early seedling growth [21], [52] [1]. These effects include activation of genes related to nutrient uptake, stimulation of antioxidant defense systems, and regulation of key plant hormones such as gibberellins and abscisic acid [1], [65]. When nanoparticles are able to pass through the seed coat and reach the embryo, they often accelerate the shift from dormancy to active growth. This process is commonly associated with improved photosynthetic performance and increased biomass production under stress conditions [1], [51].

Methodological Summary

These methodologies indicate that nano-seed priming generally improved germination, early growth, enzymatic activity, and stress tolerance [1], [13]. Nevertheless, such effects are highly particle-type-, particle concentration- and surface property-dependent [66]. To make sure that the outcomes are reproducible and environmentally safe, experimental design and detailed nanoparticle characterization are required [67]. More importantly, long-term studies are necessary to clarify the environmental destinies of the nanoparticles and to utilize them sustainably in agriculture [68], [69].

Synthesis of Evidence

Our review of the findings of all the studies in this domain shows that nano-seed priming can have a positive effect on the seed germination and early seedling growth under heavy metal and abiotic stress, but this response is not uniform for all the conditions tested. This strategy relies on the nature of the nanoparticle, the applied dose, and the type of plants [21], [52], [70]. This shows that nano-seed priming is not anyone's magic bullet, as its effects only occur within a defined degree of existence [38]. One of the most clear patterns seen across many studies is a dose-response. At lower concentrations, nanoparticles frequently increase physiological and biochemical factors (e.g., antioxidant activity, water uptake,

and stress signalling) during the germination stage and increase seedling vigor. On the other hand, at high concentrations, they often induce adverse effects, such as oxidative stress, membrane damage, and inhibited growth [71], [72], [73]. While this pattern receives widespread reportage, there is scant delineation of a safe dose threshold in most studies, which renders them less than practically useful [74]. Nanoparticle types also differ from each other. Silicon-based and biopolymer nanoparticles usually have a more stable and safer response, whereas the safety range for metal and metal-oxide nanoparticles is narrow, so that a minor dose adjustment can turn the plant response from beneficial to detrimental [17], [72], [75]. While carbon-based nanomaterials can promote early physiological reactions, we still do not know if they persist in plants or ecosystems. Another important limitation of authors in the available literature is the lack of standardization for the various existing definitions [17], [32], [76]. Comparison of results among different studies is not feasible due to differences in nanoparticle preparation and characterization techniques, as well as in seed treatment methods and parameters measured [1], [62]. Moreover, many findings have been based on short-range laboratory experiments and may not reflect field conditions or longer-term environmental interactions. In conclusion, our evidence suggests that nano-seed priming is a precise technique rather than a general agronomic practice [38], [77]. Before large-scale employment is recommended that the safe dose ranges must be defined, and greatly standardized experimental protocols applied, as well as the plant response and environmental impacts must be better understood. [1], [17], [38].

Conclusion

In spite of this, nano-enabled seed priming to ameliorate seed germination and early seedling establishment of heavy metal as well as other abiotic stress-affected seeds holds great promise, but is still subject to major challenges because of their highly context-dependent beneficiary exposure systems [38], [51], [78]. The current review synthesis revealed that the positive effects of nano-priming are primarily under the control of three main factors: nanoparticle type, dose, and plant genotype [52], [78]. Among all the materials characterized, silicon-based NPs have reliably provided the most reliable balance between relieving and inducing stress by enhancing antioxidant defenses and suppressing metal translocation [22], [44]. For comparison notes, nanostructures based on metals and metal oxides, such as ZnO, Ag, and TiO₂, have a narrow therapeutic index: low concentration gradients can shift the biological response from stimulation to toxicity [20], [22] [22]. Conclusions: Nano-seed priming is not a magic bullet, agronomically based solution, but a precision-based solution. This requires conducting the relevant due diligence on dosage refinement, the application of standardized characterization protocols, and long-term environmental risk assessment prior to widespread agronomic release [1], [79].

References

1. A. Shelar et al., "Nanoprimers in sustainable seed treatment: Molecular insights into abiotic stress tolerance mechanisms for enhancing germination and improved crop productivity," *The Science of The Total Environment*, vol. 951. Elsevier BV, p. 175118, Aug. 02, 2024. doi: 10.1016/j.scitotenv.2024.175118.
2. R. K. Yadav et al., "Genome Editing and Improvement of Abiotic Stress Tolerance in Crop Plants," *Life*, vol. 13, no. 7. Multidisciplinary Digital Publishing Institute, p. 1456, Jun. 27, 2023. doi: 10.3390/life13071456.
3. H. Zhang, Z. Lang, J. Zhu, and P. Wang, "Tackling abiotic stress in plants: recent insights and trends," *Stress Biology*, vol. 5, no. 1, Jan. 2025, doi: 10.1007/s44154-025-00216-x.
4. *Advances in Plant Defense Mechanisms*. IntechOpen, 2022. doi: 10.5772/intechopen.98128.
5. S. Kumar, "Abiotic Stresses and Their Effects on Plant Growth, Yield and Nutritional Quality of Agricultural Produce," *International journal of food science and agriculture*, vol. 4, no. 4, p. 367, Oct. 2020, doi: 10.26855/ijfsa.2020.12.002.
6. R. Azam, K. Malik, T. Sultana, F. Arooj, and A. Kazmi, "Plant-mediated bioinspired iron nanoparticles as an alternative to enhance crop resistance against biotic and abiotic stress; a review," *Physiological and Molecular Plant Pathology*, vol. 136. Elsevier BV, p. 102586, Jan. 21, 2025. doi: 10.1016/j.pmpp.2025.102586.
7. I. Morkunas, A. Woźniak, V. Chung, R. Rucińska-Sobkowiak, and P. Jeandet, "The Role of Heavy Metals in Plant Response to Biotic Stress," *Molecules*, vol. 23, no. 9. Multidisciplinary Digital Publishing Institute, p. 2320, Sep. 11, 2018. doi: 10.3390/molecules23092320.
8. C. Agho et al., "Integrative approaches to enhance reproductive resilience of crops for climateproof agriculture," *Plant Stress*, vol. 15, p. 100704, Dec. 2024, doi: 10.1016/j.stress.2024.100704.
9. D. Thingujam et al., "Climate-Resilient Crops: Integrating AI, Multi-Omics, and Advanced Phenotyping to Address Global Agricultural and Societal Challenges," Jun. 2025, doi: 10.20944/preprints202506.2364.v1.
10. O. Al-Dossary, L. M. Alnaddaf, and J. M. Al-Khayri, "Crop management to enhance plant resilience to abiotic stress using nanotechnology: towards more efficient and sustainable agriculture," *Frontiers in Plant Science*, vol. 16, Oct. 2025, doi: 10.3389/fpls.2025.1626624.
11. S. Rawat, "Nanopriming Technology for Sustainable Agriculture," in *Advances in environmental engineering and green technologies book series*, IGI Global, 2023, p. 21. doi: 10.4018/978-1-6684-7232-3.ch002.
12. N. Kandhol et al., "Nano-priming: Impression on the beginner of plant life," *Plant Stress*, vol. 5, p. 100091, Apr. 2022, doi: 10.1016/j.stress.2022.100091.
13. M. S. Rhaman et al., "Seed Priming with Nanoparticles: An Emerging Technique for Improving Plant Growth, Development, and Abiotic Stress Tolerance," *Journal of soil science and plant nutrition*, vol. 22, no. 4, p. 4047, Sep. 2022, doi: 10.1007/s42729-022-01007-3.
14. D. Mittal, G. Kaur, P. Singh, K. Yadav, and S. A. Ali, "Nanoparticle-Based Sustainable Agriculture and Food Science: Recent Advances and Future Outlook," *Frontiers in Nanotechnology*, vol. 2, Dec. 2020, doi: 10.3389/fnano.2020.579954.

15. A. Singh, R. S. Sengar, R. Sharma, P. Rajput, and A. K. Singh, "Nano-Priming Technology for Sustainable Agriculture," *Biogeosystem Technique*, vol. 8, no. 2, Dec. 2021, doi: 10.13187/bgt.2021.2.79.
16. X. Wang, H. Xie, P. Wang, and H. Yin, "Nanoparticles in Plants: Uptake, Transport and Physiological Activity in Leaf and Root," *Materials*, vol. 16, no. 8. Multidisciplinary Digital Publishing Institute, p. 3097, Apr. 14, 2023. doi: 10.3390/ma16083097.
17. T. Akhter, R. A. Rather, S. Bashir, R. John, and R. John, "Nanoparticles in plant systems: Omicsbased perspectives on stress adaptation and toxicological implications," *Plant Nano Biology*, vol. 13, p. 100181, Aug. 2025, doi: 10.1016/j.plana.2025.100181.
18. G. R. Guru, P. W. Ramteke, C. Veres, and C. Vágvölgyi, "Potential impacts of nanoparticles integration on micropropagation efficiency: current achievements and prospects," *Frontiers in Plant Science*, vol. 16, Oct. 2025, doi: 10.3389/fpls.2025.1629548.
19. M. Bakshi and A. Kumar, "Copper-based nanoparticles in the soil-plant environment: Assessing their applications, interactions, fate and toxicity," *Chemosphere*, vol. 281. Elsevier BV, p. 130940, May 20, 2021. doi: 10.1016/j.chemosphere.2021.130940.
20. V. D. Rajput et al., "Nano-enabled solutions for sustainable agriculture by managing abiotic stress: Critical evaluation on unraveling the pros and cons with ecological impacts," *Plant Stress*, vol. 18, p. 101060, Sep. 2025, doi: 10.1016/j.stress.2025.101060.
21. A. R. Khan et al., "Nanoparticles and their crosstalk with stress mitigators: A novel approach towards abiotic stress tolerance in agricultural systems," *The Crop Journal*, vol. 12, no. 5, p. 1280, Oct. 2024, doi: 10.1016/j.cj.2024.09.010.
22. B. Sen, D. Roy, M. Narayan, and H. Sarma, "Nanoparticle-driven stress alleviation: exploring the roles of metal and metal oxide nanoparticles in plant abiotic stress management," *Discover Plants*, vol. 2, no. 1, Mar. 2025, doi: 10.1007/s44372-025-00153-z.
23. A. Bhatia, A. Khatri, M. Yadav, A. Kumari, S. Mona, and R. Bhatia, "Potential of iron oxide nanoparticles in enhancing growth and development of plants: A review," *Physiological and Molecular Plant Pathology*, vol. 139. Elsevier BV, p. 102746, May 19, 2025. doi: 10.1016/j.pmpp.2025.102746.
24. D. Li et al., "THE ROLE OF NANO-PARTICLES IN PLANT TOLERANCE AGAINST DROUGHT STRESS: REVIEW AND FUTURE PERSPECTIVE," *Applied Ecology and Environmental Research*, vol. 23, no. 4, p. 6329, Jan. 2025, doi: 10.15666/aeer/2304_63296358.
25. D. Donia and M. Carbone, "Seed Priming with Zinc Oxide Nanoparticles to Enhance Crop Tolerance to Environmental Stresses," *International Journal of Molecular Sciences*, vol. 24, no. 24, p. 17612, Dec. 2023, doi: 10.3390/ijms242417612.
26. A. Ghorbani et al., "Nano-enabled agrochemicals: mitigating heavy metal toxicity and enhancing crop adaptability for sustainable crop production," *Journal of Nanobiotechnology*, vol. 22, no. 1, Mar. 05, 2024. doi: 10.1186/s12951-024-02371-1.
27. A. Nongbet et al., "Nanofertilizers: A Smart and Sustainable Attribute to Modern Agriculture," *Plants*, 2022. doi: 10.3390/plants11192587.
28. S. H. Nile et al., "Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives," *Journal of Nanobiotechnology*, 2022. doi: 10.1186/s12951-022-01423-8.
29. C. Li et al., "Exposure to low levels of photocatalytic TiO₂ nanoparticles enhances seed germination and seedling growth of amaranth and cruciferous vegetables," *Scientific Reports*, vol. 12, no. 1, p. 18228, Oct. 2022, doi: 10.1038/s41598-022-23179-9.
30. M. Rehman et al., "Titanium dioxide nanoparticles TiO₂ NPs in crop stress management: Mechanisms, applications, and abiotic stress mitigation," *Plant Nano Biology*, vol. 14, p. 100207, Oct. 2025, doi: 10.1016/j.plana.2025.100207.
31. A. Ali, S. S. Hashmi, J. M. Palma, and F. J. Corpas, "Influence of metallic, metallic oxide, and organic nanoparticles on plant physiology," *Chemosphere*, vol. 290. Elsevier BV, p. 133329, Dec. 16, 2021. doi: 10.1016/j.chemosphere.2021.133329.
32. N. Yadav, S. Bora, B. Devi, C. Upadhyay, and P. Singh, "Nanoparticle-mediated defense priming: A review of strategies for enhancing plant resilience against biotic and abiotic stresses," *Plant Physiology and Biochemistry*, vol. 213. Elsevier BV, p. 108796, Jun. 10, 2024. doi: 10.1016/j.plaphy.2024.108796.
33. M. T. El-Saadony et al., "Role of Nanoparticles in Enhancing Crop Tolerance to Abiotic Stress: A Comprehensive Review," *Frontiers in Plant Science*, vol. 13. Frontiers Media, Nov. 02, 2022. doi: 10.3389/fpls.2022.946717.
34. L. Koleva et al., "Iron Oxide and Silicon Nanoparticles Modulate Mineral Nutrient Homeostasis and Metabolism in Cadmium-Stressed *Phaseolus vulgaris*," *Frontiers in Plant Science*, vol. 13, p. 806781, Mar. 2022, doi: 10.3389/fpls.2022.806781.
35. G. Yan et al., "Silicon nanoparticles in sustainable agriculture: synthesis, absorption, and plant stress alleviation," *Frontiers in Plant Science*, vol. 15, Mar. 2024, doi: 10.3389/fpls.2024.1393458.
36. S. Krumova et al., "Seed Priming with Single-Walled Carbon Nanotubes Grafted with Pluronic P85 Preserves the Functional and Structural Characteristics of Pea Plants," *Nanomaterials*, vol. 13, no. 8, p. 1332, Apr. 2023, doi: 10.3390/nano13081332.
37. O. Zaytseva and G. Neumann, "Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications," *Chemical and Biological Technologies in Agriculture*, vol. 3, no. 1, May 2016, doi: 10.1186/s40538-016-0070-8.
38. F. Çig et al., "Nano-Priming as Seed Priming Technology for Sustainable Agriculture," *Nanotechnology for Agriculture: A Potential Tool for Abiotic Stress Tolerance*, 2025, doi: 10.1201/9781003622321-2/NANO-PRIMING-SEED-PRIMING-TECHNOLOGYSUSTAINABLE-AGRICULTURE-FATIH-.
39. M. F. Khalid et al., "Nanoparticles: The Plant Saviour under Abiotic Stresses," *Nanomaterials*, vol. 12, no. 21. Multidisciplinary Digital Publishing Institute, p. 3915, Nov. 06, 2022. doi: 10.3390/nano12213915.

40. H. K. Chandrashekar et al., "Nanoparticle-mediated amelioration of drought stress in plants: a systematic review," *3 Biotech*, vol. 13, no. 10. Springer Science+Business Media, p. 336, Sep. 08, 2023. doi: 10.1007/s13205-023-03751-4.
41. L. Chu, M. Bagavathiannan, H. Wang, S. M. Sharpe, W. Meng, and J. Yu, "Osmopriming with Polyethylene Glycol (PEG) for Abiotic Stress Tolerance in Germinating Crop Seeds: A Review," *Agronomy*, vol. 11, no. 11. Multidisciplinary Digital Publishing Institute, p. 2194, Oct. 30, 2021. doi: 10.3390/agronomy11112194.
42. J. A. Hernández, P. Díaz-Vivanco, J. R. Acosta-Motos, and G. Barba-Espín, "Potassium Nitrate Treatment Is Associated with Modulation of Seed Water Uptake, Antioxidative Metabolism and Phytohormone Levels of Pea Seedlings," *Seeds*, vol. 1, no. 1, p. 5, Dec. 2021, doi: 10.3390/seeds1010002.
43. Y. Cao et al., "Engineered nanomaterials reduce metal(loid) accumulation and enhance staple food production for sustainable agriculture," *Nature Food*, vol. 5, no. 11, p. 951, Oct. 2024, doi: 10.1038/s43016-024-01063-1.
44. K. K. Verma et al., "Nanosilicon: An approach for abiotic stress mitigation and sustainable agriculture," *Frontiers in Plant Science*, vol. 13. Frontiers Media, p. 1025974, Dec. 20, 2022. doi: 10.3389/fpls.2022.1025974.
45. M. Kang, Y. Liu, Y. Weng, H. Wang, and X. Bai, "A critical review on the toxicity regulation and ecological risks of zinc oxide nanoparticles to plants," *Environmental Science Nano*, vol. 11, no. 1. Royal Society of Chemistry, p. 14, Nov. 07, 2023. doi: 10.1039/d3en00630a.
46. Z. Hossain, G. Mustafa, and S. Komatsu, "Plant Responses to Nanoparticle Stress," *International Journal of Molecular Sciences*, vol. 16, no. 11. Multidisciplinary Digital Publishing Institute, p. 26644, Nov. 06, 2015. doi: 10.3390/ijms161125980.
47. A. Hidangmayum and P. Dwivedi, "Chitosan Based Nanoformulation for Sustainable Agriculture with Special Reference to Abiotic Stress: A Review," *Journal of Polymers and the Environment*, vol. 30, no. 4. Springer Science+Business Media, p. 1264, Sep. 29, 2021. doi:10.1007/s10924-021-02296-y.
48. K. Divya and M. S. Jisha, "Chitosan nanoparticles preparation and applications," *Environmental Chemistry Letters*, vol. 16, no. 1, p. 101, Oct. 2017, doi: 10.1007/s10311-0170670-y.
49. S. K. Sen and D. Das, "A sustainable approach in agricultural chemistry towards alleviation of plant stress through chitosan and nano-chitosan priming," *Discover Chemistry*, vol. 1, no. 1, Nov. 2024, doi: 10.1007/s44371-024-00046-2.
50. P. Dudi, L. Verma, A. Pathak, S. Haq, and S. Kachhwaha, "Enhancing agronomic traits of finger millet (*Eleusine coracana* (L.) Gaertn) through seed nano-priming using silicon dioxide nanoparticles (SiO₂NPs)," *Journal of Stored Products Research*, vol. 112, p. 102654, Apr. 2025, doi: 10.1016/j.jspr.2025.102654.
51. M. Faizan et al., "Nano-priming: Improving plant nutrition to support the establishment of sustainable agriculture under heavy metal stress," *Plant Nano Biology*, 2024, doi: 10.1016/j.PLANA.2024.100096.
52. J. H. J. Lee and D. M. Kasote, "Nano-Priming for Inducing Salinity Tolerance, Disease Resistance, Yield Attributes, and Alleviating Heavy Metal Toxicity in Plants," *Plants*, vol. 13, no. 3, p. 446, Feb. 2024, doi: 10.3390/plants13030446.
53. M. M. Modena, B. Rühle, T. P. Burg, and S. Wuttke, "Nanoparticle Characterization: What to Measure?," *Advanced Materials*, vol. 31, no. 32, May 30, 2019, doi: 10.1002/adma.201901556.
54. A. Marwal, "The dual role of nanoparticles: Technological enablers and incipient environmental pollutants," *Next research*, vol. 3, p. 101121, Nov. 2025, doi: 10.1016/j.nexres.2025.101121.
55. C. J. Chirayil, J. Abraham, R. K. Mishra, S. C. George, and S. Thomas, "Instrumental Techniques for the Characterization of Nanoparticles," in *Elsevier eBooks*, Elsevier BV, 2017, p. 1, doi: 10.1016/b978-0-323-46139-9.00001-3.
56. A. Hameed et al., "Priming with chitosan-based nanocomposite modulates biochemical attributes and reduces cadmium toxicity in wheat (*Triticum aestivum* L.) seedlings," *Kuwait Journal of Science*, vol. 53, no. 1, p. 100484, Aug. 2025, doi: 10.1016/j.kjs.2025.100484.
57. T. Guha, G. Gopal, H. Das, A. Mukherjee, and R. Kundu, "Nanopriming with zero-valent iron synthesized using pomegranate peel waste: A 'green' approach for yield enhancement in *Oryza sativa* L. cv. Gonindobhog," *Plant Physiology and Biochemistry*, vol. 163, p. 261, Apr. 2021, doi: 10.1016/j.plaphy.2021.04.006.
58. K. A. Bora et al., "Recent progress in bio-mediated synthesis and applications of engineered nanomaterials for sustainable agriculture," *Frontiers in Plant Science*, vol. 13, Oct. 03, 2022, doi: 10.3389/fpls.2022.999505.
59. T. Tounekti, M. Mahdhi, Z. I. A. Al-Faifi, and H. Khemira, "Priming improves germination and seed reserve utilization, growth, antioxidant responses and membrane stability at early seedling stage of Saudi sorghum varieties under drought stress," *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, vol. 48, no. 2, p. 938, Jun. 2020, doi: 10.15835/nbha48211841.
60. S. M. Kumar et al., "Nanopriming with zinc oxide nanoparticle boosts seed vigour, photosynthesis, osmolytes accumulation and antioxidant activity in tomato," *Scientific Reports*, vol. 15, no. 1, p. 37375, Oct. 2025, doi: 10.1038/s41598-025-09269-4.
61. H. AbdElgawad, G. Zinta, G. T. S. Beemster, I. A. Janssens, and H. Asard, "Future Climate CO₂ Levels Mitigate Stress Impact on Plants: Increased Defense or Decreased Challenge?," *Frontiers in Plant Science*, vol. 7, May 02, 2016, doi: 10.3389/fpls.2016.00556.
62. A. Shelar et al., "Recent Advances in Nano-Enabled Seed Treatment Strategies for Sustainable Agriculture: Challenges, Risk Assessment, and Future Perspectives," *Nano-Micro Letters*, vol. 15, no. 1, Feb. 16, 2023, doi: 10.1007/s40820-023-01025-5.
63. A. Sharma et al., "Phytomelatonin: Molecular messenger for stress perception and response in plants," *Environmental and Experimental Botany*, vol. 201, p. 104980, Jul. 2022, doi: 10.1016/j.envexpbot.2022.104980.

64. S. K. Verma, A. K. Das, S. Gantait, V. Kumar, and E. Gürel, "Applications of carbon nanomaterials in the plant system: A perspective view on the pros and cons," *The Science of The Total Environment*, vol. 667, p. 485, Feb. 27, 2019, doi: 10.1016/j.scitotenv.2019.02.409.
65. F. Khalid et al., "Nanoparticle-Mediated Phytohormone Interplay: Advancing Plant Resilience to Abiotic Stresses," *Deleted Journal*, vol. 77, no. 2, Mar. 2025, doi: 10.1007/s10343-02501121-z.
66. M. Mouradi, M. Farissi, A. Khadraji, A. Bouizgaren, A. Qaddoury, and C. Ghoulam, "Seed Priming and Nano Priming Techniques as Tools to Alleviate Osmotic Stress in Legumes," 2023, p. 143, doi: 10.1007/978-3-031-24279-3_7.
67. X. Zhou et al., "Nanoparticles: a promising tool against environmental stress in plants," *Frontiers in Plant Science*, vol. 15, Jan. 27, 2025, doi: 10.3389/fpls.2024.1509047.
68. S. A. Atanda, R. O. Shaibu, and F. O. Agunbiade, "Nanoparticles in agriculture: balancing food security and environmental sustainability," *Discover Agriculture*, vol. 3, no. 1, Feb. 2025, doi: 10.1007/s44279-025-00159-x.
69. S. G. Thabet and A. M. Alqudah, "Unraveling the role of nanoparticles in improving plant resilience under environmental stress condition," *Plant and Soil*, vol. 503, p. 313, Mar. 2024, doi: 10.1007/s11104-024-06581-2.
70. M. F. Maqsood et al., "Biogenic nanoparticles application in agriculture for ROS mitigation and abiotic stress tolerance: A review," *Plant Stress*, vol. 10, p. 100281, Nov. 01, 2023, doi: 10.1016/j.stress.2023.100281.
71. M. Hassanisaadi, M. Barani, A. Rahdar, M. Heidary, A. Thysiadou, and G. Z. Kyzas, "Role of agrochemical-based nanomaterials in plants: biotic and abiotic stress with germination improvement of seeds," *Plant Growth Regulation*, vol. 97, no. 2, p. 375, Jan. 2022, doi: 10.1007/s10725-021-00782-w.
72. M. Gao, J. Chang, Z. Wang, H. Zhang, and T. Wang, "Advances in transport and toxicity of nanoparticles in plants," *Journal of Nanobiotechnology*, vol. 21, no. 1, Mar. 02, 2023, doi: 10.1186/s12951-023-01830-5.
73. H. Liu, J. Yang, Y. Jiang, R. Sun, P. Zhou, and J. Li, "Behavior of Microplastics and Nanoplastics in Farmland Soil Environment and Mechanisms of Interaction with Plants," *Polish Journal of Environmental Studies*, vol. 33, no. 3, p. 2499, Feb. 2024, doi: 10.15244/pjoes/175021.
74. R. Tighe-Neira, J. González-Villagra, A. Nunes-Nesi, and C. Inostroza-Blancheteau, "Impact of nanoparticles and their ionic counterparts derived from heavy metals on the physiology of food crops," *Plant Physiology and Biochemistry*, vol. 172, p. 14, Jan. 04, 2022, doi: 10.1016/j.plaphy.2021.12.036.
75. B. Ruttkay-Nedecký, O. Kryštofová, L. Nejdil, and V. Adam, "Nanoparticles based on essential metals and their phytotoxicity," *Journal of Nanobiotechnology*, vol. 15, no. 1, Apr. 26, 2017, doi: 10.1186/s12951-017-0268-3.
76. C. Liné, C. Larue, and E. Flahaut, "Carbon nanotubes: Impacts and behaviour in the terrestrial ecosystem - A review," *Carbon*, vol. 123, p. 767, Jul. 31, 2017, doi: 10.1016/j.carbon.2017.07.089.
77. A. do E. S. Pereira, H. C. Oliveira, L. F. Fraceto, and C. Santaella, "Nanotechnology Potential in Seed Priming for Sustainable Agriculture," *Nanomaterials*, vol. 11, no. 2, p. 267, Jan. 20, 2021, doi: 10.3390/nano11020267.
78. A. Salam et al., "Nano-Priming against Abiotic Stress: A Way Forward towards Sustainable Agriculture," *Sustainability*, vol. 14, no. 22, p. 14880, Nov. 2022, doi: 10.3390/su142214880.
79. M. S. Hanif, M. Tayyab, E. H. Baillo, M. Islam, W. Islam, and X. Li, "Plant microbiome technology for sustainable agriculture," *Frontiers in Microbiology*, vol. 15, p. 1500260, Nov. 2024, doi: 10.3389/fmicb.2024.1500260.