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Nano-priming as an Innovative Seed Technology for Mitigating Abiotic Stresses in Agriculture

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Abiotic stresses such as salinity, drought, and heavy metal toxicity pose significant challenges to seed germination, seedling establishment, and overall crop productivity. Seed nano-priming has emerged as a promising strategy to enhance plant resilience under these adverse conditions. This technique involves the treatment of seeds with nanoparticles (NPs), which interact with seed tissues to trigger physiological, biochemical, and molecular responses that improve stress tolerance. Nano-priming enhances water uptake, activates antioxidant defense systems, regulates osmolyte accumulation, modulates phytohormonal balance, and improves nutrient uptake and use efficiency. Various nanoparticles, including ZnO, TiO_2, CeO_2, SiO_2, carbon-based nanomaterials, chitosan, and iron-based magnetic nanoparticles, have demonstrated significant improvements in germination, seedling vigor, photosynthetic efficiency, redox homeostasis, and overall plant growth under stress. Despite its potential, the large-scale adoption of seed nano-priming requires careful optimization of nanoparticle type, concentration, exposure conditions, and consideration of environmental and biosafety impacts. Overall, seed nano-priming represents a cost-effective, eco-friendly, and scalable approach to enhance crop performance, offering a viable tool for sustainable agriculture and food security in stress-prone environments.

Keywords: Seed nano-priming; Abiotic stress; Nanoparticles; Germination; Antioxidant defense; Sustainable agriculture

Introduction

Abiotic stress factors adversely affect plant growth, development, and seed productivity by inducing a wide range of biochemical, physiological, and molecular alterations (Hussain *et al*., 2018). To counteract these challenges, seed priming has emerged as an effective strategy that enables plants to initiate faster and more robust defense responses when exposed to stress conditions (Filippou *et al*., 2013) . Priming triggers a series of metabolic adjustments in seeds and seedlings that enhance their capacity to tolerate diverse abiotic stresses. As a result, plants previously exposed to priming stimuli often exhibit improved growth performance and enhanced stress resilience during subsequent stress events (Kandhol *et al*., 2022). Priming can be induced by various agents, including pathogens, pests, beneficial microorganisms, natural and synthetic compounds, nanomaterials, as well as mild exposure to abiotic stress factors.

In recent years, the application of nanotechnology in agriculture has expanded significantly, with nanoparticles (NPs) being explored for use as nanopesticides, nanofertilizers, and nanosensors to improve agricultural sustainability. Owing to their unique physicochemical properties, nanoparticles can enhance plant growth, development, and tolerance to adverse environmental conditions. Their use as seed-priming agents has gained increasing attention due to their ability to improve seed germination, seedling vigor, crop yield, and nutritional quality. The ultra-small size, large surface area, and controlled release behavior of nanoparticles facilitate efficient nutrient uptake and utilization by plants (Rawat *et al*., 2018). Moreover, nanoparticle-based priming modulates plant metabolism, physiological processes, enzyme activities, and phytohormonal interactions, thereby strengthening plant stress responses. This article highlights the potential of seed nanopriming as an innovative approach for mitigating abiotic stresses in agricultural systems.

Mechanisms of Nano-priming in Mitigating Abiotic Stresses

Nano-priming mitigates abiotic stresses by triggering a cascade of physiological, biochemical, and molecular responses during early seed germination and seedling establishment. Due to their ultra-small size and high reactivity, nanoparticles interact efficiently with seed tissues, enabling plants to better withstand adverse environmental conditions such as drought, salinity, temperature extremes, and nutrient deficiency.

1. Enhanced Water Uptake and Uniform Germination

Nano-priming improves seed hydration by modifying seed coat permeability and facilitating rapid and uniform imbibition. Nanoparticles create nano-scale pores or alter membrane fluidity, allowing efficient water entry into the embryonic tissues. This results in faster germination, improved emergence, and synchronized seedling growth, which are crucial for crop establishment under stress-prone environments.

2. Activation of Antioxidant Defense Systems

Abiotic stresses induce excessive generation of reactive oxygen species (ROS), leading to oxidative damage of lipids, proteins, and nucleic acids. Nano-priming enhances the activity of enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), as well as non-enzymatic antioxidants. This strengthened antioxidant machinery helps maintain cellular redox homeostasis and protects seedlings from stress-induced oxidative injury.

3. Regulation of Osmolyte Accumulation

Nano-primed seeds exhibit increased accumulation of osmoprotectants such as proline, soluble sugars, and glycine betaine. These compounds help maintain cellular turgor, stabilize proteins and membranes, and protect metabolic processes under drought and salinity stress. Enhanced osmotic adjustment enables plants to sustain growth even under limited water availability.

4. Modulation of Phytohormonal Balance

Nano-priming influences the biosynthesis and signaling of plant hormones involved in stress adaptation. It promotes favorable levels of growth-promoting hormones such as gibberellic acid (GA) and auxins while regulating stress-related hormones like abscisic acid (ABA). This hormonal modulation ensures better germination, root development, and adaptive responses to abiotic stresses.

5. Improved Nutrient Uptake and Use Efficiency

Nanoparticles, particularly micronutrient-based NPs (e.g., ZnO, Fe_2O_3, SiO_2), enhance nutrient availability and mobility within plant tissues. Nano-priming ensures efficient nutrient uptake at early growth stages, reduces nutrient fixation in soil, and improves enzymatic activities associated with metabolism and photosynthesis. This is especially beneficial under nutrient-deficient or degraded soil conditions.

Seed nanopriming in abiotic stress mitigation

Environmental pollution and climate change expose seeds to abiotic stresses that negatively affect germination and early growth (Shelar *et al*., 2021). Stress perception occurs at multiple cellular compartments, including the plasma membrane, chloroplasts, mitochondria, and peroxisomes, leading to changes in gene expression and protein modifications involved in stress responses.

Under normal conditions, seed hydration activates the gibberellic acid (GA) pathway, promoting endosperm degradation and sugar release for germination. However, stress conditions impair water uptake, activate abscisic acid (ABA) signaling, increase reactive oxygen species (ROS) production, and delay germination (Khan *et al*., 2022). Seed nanopriming mitigates these effects by enhancing antioxidant enzyme activities, such as superoxide dismutase and catalase, thereby reducing ROS accumulation and protecting seed cells under stress.

Seed nanopriming under salt stress

Salinity is a major abiotic stress that limits seed germination and crop productivity by inducing osmotic and oxidative stress. Seed nanopriming has been shown to enhance salt tolerance by improving germination, nutrient balance, and antioxidant defense. Mn nanoparticle priming increased root growth and improved macro- and micronutrient redistribution in *Capsicum annuum* under saline conditions (Ye *et al*., 2020). Similarly, TiO_2 nanoparticles enhanced germination, seedling vigor, biomass, relative water content, and antioxidant activity in maize and *Paeonia suffruticosa* under salt stress.

Cerium oxide nanoparticle priming in rapeseed improved germination, water uptake, antioxidant enzyme activities, soluble sugar content, and Na^+/K^+ balance while reducing ROS accumulation. Other nanoparticles, including iron nanochelates in lentil, chitosan nanoparticles in milk thistle, and water-derived nanoparticles in cucumber, also alleviated salt stress by enhancing physiological and biochemical responses. ZnO nanopriming increased photosynthetic pigments, antioxidant enzymes, and reduced lipid peroxidation in lupine and wheat, thereby improving salt tolerance. Water-soluble carbon nanoparticles further enhanced germination and chlorophyll content in lettuce under saline conditions.

Seed nanopriming under drought stress

Drought stress restricts plant growth and reduces crop yield. Seed nanopriming enhances drought tolerance by improving germination, root–shoot growth, membrane stability, photosynthetic pigments, antioxidant activity, and reducing ROS accumulation. Multi-walled carbon nanotubes increased germination and seedling growth in *Alnus subcordata* under dry conditions, while chitosan nanoparticles improved membrane integrity and growth in *Catharanthus roseus* (Ali *et al*., 2021). Cu nanoparticles enhanced relative water content, chlorophyll, carotenoids, and anthocyanins in maize under drought stress (Van Nguyen *et al*., 2022). Silicon nanoparticles increased flavonoid content and antioxidant activity in marigold (Rahimi *et al*., 2020). Iron-based magnetic nanoparticles and nanozymes (Fe_3O_4, γ-Fe_2O_3) further alleviated drought stress by reducing H_2O_2 and lipid peroxidation and enhancing growth, as reported in rapeseed(Palmqvist *et al*., 2017).

Seed nanopriming under heavy metal stress

Heavy metal toxicity severely impairs plant growth. Nanoparticle priming mitigates metal stress by reducing metal toxicity, enhancing antioxidant enzymes, decreasing ROS and lipid peroxidation, and improving germination and biomass. Green-synthesized sulfur nanoparticles alleviated Mn stress in sunflower by activating antioxidant defenses. Zinc nanoparticles improved enzymatic activity and seedling growth in rice under Cd stress, while TiO_2 nanoparticles enhanced germination and water retention in wheat. ZnO nanopriming reduced ROS and MDA levels and improved growth and photosynthesis in maize under cobalt stress (Salam *et al*., 2022). Overall, nanoparticle priming modulates physiological and biochemical responses to alleviate heavy metal stress.

Conclusion

Seed nano-priming has emerged as a promising and innovative seed enhancement technology for improving crop resilience under diverse abiotic stress conditions. As highlighted in this review, abiotic stresses such as salinity, drought, and heavy metal toxicity severely impair seed germination, seedling establishment, and overall plant productivity. Nano-priming effectively mitigates these constraints by activating early physiological, biochemical, and molecular responses that strengthen plant defense mechanisms from the initial stages of growth. The beneficial effects of nano-priming are primarily attributed to improved water uptake, enhanced antioxidant defense systems, regulation of osmolyte accumulation, modulation of phytohormonal balance, and improved nutrient uptake and utilization efficiency. Nanoparticles such as ZnO, TiO_2, CeO_2, SiO_2, carbon-based nanomaterials, chitosan, and iron-based magnetic nanoparticles have demonstrated consistent improvements in germination performance, photosynthetic efficiency, redox homeostasis, and stress tolerance across a wide range of crop species. By reducing reactive oxygen species accumulation and stabilizing cellular structures, nano-priming enables plants to better withstand adverse environmental conditions.

Despite its significant potential, the large-scale application of seed nano-priming in agriculture requires careful consideration of nanoparticle type, concentration, exposure duration, and crop specificity. Further research is needed to elucidate long-term environmental impacts, nanoparticle fate in soil–plant systems, and biosafety concerns associated with their use. Integrating nano-priming with sustainable agricultural practices and regulatory frameworks will be essential to ensure its safe and effective adoption. Overall, seed nano-priming represents a cost-effective, eco-friendly, and scalable strategy to enhance crop performance under abiotic stress conditions. Continued interdisciplinary research and field-level validation will be crucial for translating this emerging technology into practical solutions that contribute to sustainable agriculture and global food security.

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