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NANO PRIMING SEEDS AND USE OF NANO TECHNOLOGY TO BOOST SEED RESILIENCE

Eva Rani Padhan, Soubhagya Behera and *Masoom Ankit Patel

Abstract: -

Abiotic stresses pose a substantial threat to agricultural productivity worldwide. This necessitates innovative approaches to enhance crop resilience under adverse conditions. Seed priming has emerged as a simple, eco-friendly, and effective technique to improve seed performance and seedling growth under stress. Recently, nanoparticle-based seed priming or 'nano-priming' has shown particular promise in augmenting abiotic stress tolerance in plants. In this review paper, we have explored the effects of nano-priming on seed germination and plant responses under various abiotic stress conditions. We have concluded that nano-priming is a very promising solution to improve plant growth and various processes including improved germination rates, enhanced seedling growth, and increased stress tolerance. Despite these positive outcomes, our understanding of the precise mechanisms underlying nano priming mediated mitigation of stresses remains limited, with specific gaps in knowledge concerning its efficacy under heat stress conditions. We emphasize the necessity of further research to elucidate the molecular and physiological mechanisms involved, investigate diverse nanoparticle types, and assess their long-term environmental implications.

Keywords: *Nano-priming, Seed priming, Nanotechnology in agriculture, Seed resilience, Nano-fertilizers, Seed germination enhancement, Seed vigour index, Stress tolerance, Abiotic stress etc.*

INTRODUCTION:

Agriculture is increasingly challenged by a wide range of abiotic stresses, including drought, salinity, extreme temperatures, and heavy metal toxicity. These stresses significantly impair plant growth, seed germination, and overall crop productivity,

Eva Rani Padhan, Soubhagya Behera and *Masoom Ankit Patel
Department of Seed Science and Technology, College of Agriculture,
OUAT, Bhubaneswar, Odisha, India- 751003

posing a serious threat to global food security. Therefore, there is an urgent need for sustainable, eco-friendly, and efficient strategies to enhance crop resilience against abiotic stresses.

Seed priming has emerged as a simple and cost-effective technique to improve germination performance and stress tolerance. Recent advancements in nanotechnology have introduced a novel approach known as nano priming, which involves treating seeds with nanoparticles at very low concentrations to enhance physiological and biochemical responses. Due to their ultra-small size and high surface area, nanoparticles can penetrate seed coats, modulate enzyme activities, stimulate antioxidant defence systems, and regulate stress-responsive genes. Nano priming has demonstrated promising results in improving germination rate, seedling growth, nutrient uptake efficiency, and tolerance to drought, salinity, heat, and heavy metal stress.

The integration of nanotechnology into seed science represents a transformative step toward developing climate-resilient crops. By improving seed resilience at the earliest developmental stage, nano priming offers a sustainable strategy to enhance crop establishment and productivity under challenging environmental conditions.

CONCEPT OF NANO PRIMING

Nano priming is an advanced seed enhancement technique that integrates principles of nanotechnology with conventional seed priming practices. It involves treating seeds before sowing with engineered nanoparticles, generally within the size range of 1–100 nm, either through soaking (nano-soaking), seed coating, or nano-encapsulation. At this nanoscale dimension, particles possess distinct physicochemical characteristics such as high surface area-to-volume ratio, increased surface reactivity, improved solubility, and enhanced mobility. These unique properties allow nanoparticles to interact more efficiently with seed tissues compared to bulk materials.

During nano priming, seeds are exposed to a carefully optimized concentration of nanoparticles for a specific duration, followed by drying back to their original moisture content. The nanoparticles can penetrate the seed coat through natural openings such as micropores and cracks formed during imbibition. Once inside, they influence various physiological, biochemical, and molecular processes that prepare the seed for improved performance under both normal and stress conditions.

Nanoparticles used in nano priming can function in multiple roles:

- **Nutrient carriers:** Nano-sized zinc, iron, or silica particles act as micronutrient sources, improving nutrient availability and uptake efficiency during early growth stages.

- **Growth stimulators:** Certain nanoparticles enhance enzyme activation, hormonal balance, and reserve mobilization, thereby accelerating germination and seedling vigour.
- **Antimicrobial agents:** Silver nanoparticles and chitosan nanoparticles exhibit strong antifungal and antibacterial properties, protecting seeds from seed-borne and soil-borne pathogens.
- **Stress modulators:** Nanoparticles stimulate antioxidant defence systems and regulate stress-responsive pathways, enhancing tolerance to drought, salinity, temperature extremes, and heavy metal toxicity.

MECHANISM OF ACTION OF NANO PRIMING

Nano priming enhances seed performance through interconnected physiological, biochemical, and molecular mechanisms initiated during imbibition. Because nanoparticles are extremely small and highly reactive, they penetrate seed coat micropores, modify permeability, and create microchannels that promote faster and more uniform water uptake. This improved hydration accelerates metabolic activation and ensures synchronized germination, particularly under suboptimal moisture conditions. Certain nanoparticles, such as carbon nanotubes and metal-based nanoparticles, also stimulate aquaporin (water channel protein) activity, further enhancing water movement into embryonic tissues. In addition, nano priming activates hydrolytic enzymes including α-amylase, protease, and lipase, which are responsible for mobilizing stored reserves like starch, proteins, and lipids. By acting as enzyme activators or cofactors, nanoparticles enhance enzymatic efficiency, leading to rapid conversion of reserves into soluble sugars, amino acids, and fatty acids that supply energy (ATP) and metabolic substrates for embryo growth. Consequently, nano primed seeds show faster radicle emergence, improved seed vigour, and stronger early seedling establishment.

Beyond metabolic activation, nano priming strengthens stress tolerance by enhancing antioxidant defence, osmotic regulation, gene expression, and nutrient utilization. Germination and environmental stresses generate reactive oxygen species (ROS), which at excessive levels cause oxidative damage; however, nano priming increases the activity of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase, thereby maintaining membrane stability and reducing lipid peroxidation. It also promotes the accumulation of osmolytes like proline, glycine betaine, and soluble sugars, which help maintain cellular hydration under drought or salinity stress, while regulating sodium and potassium ion balance to prevent toxicity. At the molecular level, nanoparticles function as signalling agents that modulate gene expression by upregulating stress-responsive genes, antioxidant-related genes, heat shock proteins, and ion transporter genes, effectively preconditioning seeds against future stress.

ROLE OF NANOTECHNOLOGY IN BOOSTING SEED RESILIENCE

Seed resilience refers to the capacity of seeds to germinate rapidly, establish healthy seedlings, and maintain growth under unfavourable environmental conditions. Since the germination and early seedling stages are highly sensitive to environmental stresses, strengthening seeds at this phase is crucial for ensuring stable crop production. Nanotechnology plays a significant role in enhancing seed resilience by modulating physiological, biochemical, and molecular processes that enable seeds to tolerate and adapt to stress conditions.

1. Drought Stress Tolerance

Drought stress limits water availability, disrupts cellular hydration, reduces enzyme activity, and ultimately suppresses germination and seedling establishment. Nanoparticles such as silicon (SiNPs) and zinc oxide (ZnO) help mitigate drought stress through several mechanisms.

They enhance root elongation and branching, allowing seedlings to explore deeper soil layers for moisture. Nanoparticles also stimulate the accumulation of osmolytes such as proline and soluble sugars, which maintain cell turgor and osmotic balance during water deficit conditions.

2. Salinity Stress Management

Salinity stress leads to osmotic imbalance and toxic accumulation of sodium ions (Na^+), which interfere with nutrient uptake and metabolic activities. Nano priming has been shown to regulate ion homeostasis by enhancing potassium (K^+) uptake while limiting excessive sodium accumulation.

Certain nanoparticles improve membrane stability and activate ion transporter proteins that maintain a favourable Na^+/K^+ ratio within cells. This ionic balance is critical for enzyme functioning and cellular metabolism. Additionally, Nano priming stimulates antioxidant defences and osmolyte production, reducing salt-induced oxidative damage and improving germination percentage under saline conditions.

3. Temperature Stress Resistance

Extreme temperatures, both high and low, disrupt membrane integrity, denature proteins, and impair metabolic functions during germination. Nanoparticles enhance temperature tolerance by stabilizing cellular structures and activating protective molecular mechanisms.

Under heat stress, nanoparticles promote the expression of heat shock proteins (HSPs), which protect cellular proteins from denaturation and maintain proper folding. They also enhance antioxidant systems to counteract heat-induced oxidative stress.

Under cold stress, nano priming improves membrane fluidity and reduces ice crystal formation within tissues. By maintaining cellular integrity and metabolic activity, nanoparticles enable seeds to germinate successfully under temperature fluctuations.

4. Disease Resistance

Seed-borne and soil-borne pathogens significantly reduce seed viability and seedling survival. Nanotechnology offers an effective strategy for enhancing seed protection against microbial infections. Silver nanoparticles (AgNPs) possess strong antimicrobial properties and can inhibit fungal and bacterial growth by disrupting microbial cell membranes and interfering with metabolic pathways. Chitosan nanoparticles not only exhibit antimicrobial effects but also act as elicitors, triggering plant defence responses such as the production of phytoalexins and pathogenesis-related proteins. By reducing pathogen load and stimulating innate defence mechanisms, Nano priming enhances seed health and early seedling establishment.

5. Improved Nutrient Use Efficiency

Efficient nutrient uptake during early growth stages is essential for strong seedling development. Nano-fertilizers and nutrient-based nanoparticles provide controlled and targeted nutrient delivery. Due to their small size and large reactive surface, nanoparticles increase nutrient solubility and absorption efficiency.

Unlike conventional fertilizers that may suffer from leaching, volatilization, or fixation in soil, nano-formulations allow slow and sustained nutrient release. This ensures optimal nutrient availability during germination and early growth while minimizing environmental losses. Improved nutrient use efficiency enhances chlorophyll synthesis, photosynthetic capacity, and overall plant vigour.

APPLICATIONS IN MAJOR CROPS

Nano priming has demonstrated significant positive effects across a wide range of agricultural and horticultural crops, improving seed performance, stress tolerance, and overall productivity. In cereal crops such as Wheat, Rice, and Maize, nano priming with zinc oxide, silicon, and iron nanoparticles has been shown to enhance germination percentage, accelerate seedling emergence, and improve root and shoot growth. These crops also exhibit increased chlorophyll content, improved antioxidant activity, and greater tolerance to drought, salinity, and heat stress when treated with appropriate nanoparticle formulations.

In pulse crops like Chickpea, nano priming has improved nodulation, nitrogen fixation efficiency, and early vigour, leading to better establishment under water-limited and saline conditions. Similarly, in vegetable crops such as Tomato, nanoparticle treatments have enhanced germination rate, seedling biomass, disease resistance, and fruit yield. Oilseed crops like Mustard have also shown improved stress resilience, increased photosynthetic efficiency, and enhanced yield components following nano priming treatments.

Conclusion

Nano priming represents a transformative advancement in seed technology. By utilizing nanoparticles to enhance germination, activate stress-responsive pathways, and improve nutrient efficiency, nanotechnology significantly boosts seed resilience. Although safety and environmental considerations must be addressed, nano priming has the potential to become a key strategy in sustainable agriculture.The future of nano priming and nanotechnology in seed science appears highly promising, particularly in the context of climate change and sustainable agriculture. Advancements in nano-engineering are expected to lead to the development of smart nanoparticles capable of targeted delivery and controlled release of nutrients, hormones, and protective compounds in response to specific environmental triggers. Biodegradable and bio-based nanoparticles are gaining attention as safer alternatives that minimize ecological risks while maintaining high efficiency. Integration of nano priming with molecular breeding, genomics, and precision agriculture tools may further enhance crop resilience by enabling customized seed treatments tailored to specific stress conditions and crop requirements.

REFERENCES

1. Abou-Zeid, M. A., El-Kholy, M. M., & El-Sayed, A. S. (2021). Seed nano-priming enhances stress tolerance and improves seedling growth under adverse environments. Journal of Plant Nutrition, 44(10): 1458–1474.
2. Gupta, D., Choudhary, S., Kumari, A., & Singh, A. (2022). Nano-priming with iron oxide nanoparticles improves salinity tolerance in tomato seedlings. Environmental Nanotechnology, Monitoring & Management, 17: 100720.

3. Iwai, H., Tanaka, Y., & Suzuki, K. (2022). Biopriming with beneficial microbes enhances
4. Manzoor, N., Shafeeq, M., & Hussain, R. (2021). Effect of chemical inputs and their role in stress management in field crops. Crop Protection Journal, 30: 220–235.
5. Praveen, N., Rai, V. K., & Mishra, S. (2023). Salinity and temperature stress effects on plant growth and yield: A global perspective. Plant Stress Physiology, 9: 45–65.
6. Rai, V. K., Tripathi, P., & Singh, A. (2020). Drought, heat and salinity stress: challenges and adaptive responses in crop plants. Plant Stress Biology, 2: 75–103.
7. Sardar, S., Ali, S., & Shahid, M. (2022). Enhancing seed vigor and stress tolerance through nanoparticles: Mechanisms and applications. Journal of Crop Improvement, 36(3): 333–355.
8. Yadav, S., Singh, A., & Sharma, R. (2020). Seed germination and early seedling growth under abiotic stresses: A review. Journal of Seed Science and Technology, 48: 1–15.