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Next-Generation Seed Priming: Nano-Bio stimulants for Rapid Germination under Climate Extremes

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One of the most delicate and important stages of the plant life cycle, seed germination is often interrupted by abiotic stressors that have increased in the Anthropocene. Under mild stress, traditional priming techniques have increased seed vigor; nevertheless, they are still inadequate when excessive drought, salt, heat, floods, and combination stressors are present. Engineered nanoparticles functionalized with bioactive substances, or nano-biostimulants, have become the next generation of seed priming instruments. Improved water absorption, nutrition delivery, ROS detoxification, osmotic adjustment, and the activation of stress-responsive gene networks are all made possible by their nanoscale characteristics. The physiological and molecular mechanisms of stress tolerance, the function of nano-biostimulants in quick germination, their integration with breeding and omics, and the prospects for climate-smart seed technologies are all summarized in this study. Critical attention is paid to biosafety, socioeconomic adoption, and policy aspects, with a focus on India and international settings..

Overview

Climate Extremes and the Anthropocene

Rising CO_2, unpredictable rainfall, frequent droughts, heat waves, and expanding salinity are all signs of the Anthropocene, which is characterized by human-driven environmental change. Globally, substantial production losses are caused by seed germination failures under such conditions (Rajjou et al., 2012; Zandalinas et al., 2021). Seasonal yield volatility in India is caused by delayed germination of pulses and grains under heat stress (ICAR, 2020).

Seed Germination Vulnerability

Hormonal signaling, reserve mobilization, and precisely calibrated imbibition are necessary for seed germination. By causing ROS buildup, osmotic imbalance, and decreased enzyme activity, stress interferes with this process (Bewley et al., 2013).

Traditional Priming: Achievements and Deficiencies

Under many or severe stressors, hydropriming, osmopriming, hormone priming, and biopriming all improve germination but provide varying outcomes (Paparella et al., 2015; Farooq et al., 2019).

Nano-Biostimulants' Ascent

Because of their large surface area, regulated release, and cellular penetration, nanomaterials including ZnO, SiO_2, TiO_2, carbon nanotubes, and chitosan nanoparticles increase the effectiveness of seed priming (Khot et al., 2012; Khodakovskaya et al., 2012).

Climate Extremes and Germination Challenges

Drought Stress: Drought stress reduces the amount of water available in the soil, which restricts the absorption of water by roots and lowers the turgor of leaves. This, in turn, slows the emergence and establishment of seedlings (Blum, 2011). Lack of water reduces the mobilization of seed stores, inhibits enzymatic activity necessary for germination, and impairs cell proliferation. In extreme situations, metabolic halt brought on by desiccation of seed tissues delays germination even further. Additionally, drought promotes the buildup of abscisic acid (ABA), which inhibits germination signals. Because of these physiological and biochemical limitations, seeds experiencing water deprivation exhibit uneven and sluggish emergence.

Heat Stress: Elevated temperatures cause lipid fluidity to increase, which compromises membrane integrity and allows vital solutes to seep out. Heat stress damages proteins, lipids, and nucleic acids by accelerating the production of reactive oxygen species (ROS). During germination, this kind of oxidative stress prevents the activation of seed enzymes. Heat-sensitive proteins, particularly those involved in respiration and reserve mobilization, are also denatured by prolonged exposure to heat. Heat shock proteins are used by plants as a defensive mechanism, but they are often inadequate to stop the quick cellular damage that occurs during seedling emergence.

Stress from Salinity: Osmotic imbalance and ion toxicity from excess Na^+ and Cl^+ are the two hazards that seeds face while under salinity stress (Munns & Tester, 2008). Imbibition, the first stage of germination, is suppressed by high osmotic potential, which decreases water intake. In the meanwhile, vital nutrients like calcium and potassium are displaced as sodium and chloride ions build up in tissues. Enzymatic activity, photosynthesis, and general seedling vigor are all hampered by this imbalance. Salinity is one of the most complicated abiotic factors affecting seedling development because ion buildup over time results in oxidative stress and damages cellular organelles.

Hypoxia and Flooding: The oxygen levels around the seed and root zone are reduced when flooding saturates the soil. Because aerobic respiration is hampered in such hypoxic environments, seeds must depend on less effective anaerobic routes to produce ATP. Cell division, elongation, and root penetration into the soil are all hampered by the lack of energy. Furthermore, harmful byproducts like lactic acid and ethanol build up and harm seed tissues. By increasing ethylene, hypoxia also throws off the hormonal balance and often prevents proper germination and seedling growth.

Stress from UV-B and Ozone: DNA is directly harmed by exposure to high UV-B radiation, which results in the creation of pyrimidine dimers and mutations in proliferating cells. Additionally, it damages photosystem II and chloroplast membranes, which lowers photosynthesis' effectiveness. On the other hand, ozone stress causes oxidative damage akin to that brought on by heat and dehydration by penetrating leaf tissues and producing ROS. When exposed to these stressors, seeds and seedlings often exhibit decreased chlorophyll content, slowed development, and poor germination. Plants become increasingly susceptible to additional abiotic stressors as a result of these stresses' gradual deterioration of the antioxidant system.

Increased CO_2: Increased CO_2 levels change how seeds respire and metabolize. In some species, more CO_2 might encourage seeds to accumulate more carbohydrates, which improves vigor and germination. The impact is not consistent, however; other research indicates that imbalances in the ratios of carbon to nitrogen cause germination to become unstable. Additionally, too much CO_2 alters the regulation of hormones, especially gibberellins and ABA, which control germination and dormancy. These changes have the potential to alter seedling development strategies over time, sometimes boosting quick early growth while lowering stress tolerance.

Physiological Pathways in Stress Tolerance

Changes in Photosynthetic Processes: Rubisco activity, which is necessary for CO_2 fixation during photosynthesis, is maintained with the use of nano-priming. It improves carbon absorption and reduces photorespiration losses by stabilizing chloroplast enzymes. Under adversity, this prolonged photosynthetic efficiency enables seedlings to establish more firmly.

Water Efficiency: By altering the expression of the aquaporin gene, nano-priming improves the hydraulic conductivity of roots. Even during drought, steady turgor maintenance is guaranteed by this enhanced water transfer. As a result, plants may produce more biomass with the same amount of water—or even less.

Osmotic Modification: Proline, glycine betaine, and soluble sugars are among the compatible solutes that are stimulated to accumulate by chitosan nanoparticles. These osmolytes protect harm from dehydration by balancing the water potential of cells. This adaptation gives seedlings a physiological defense against drought and salinity stressors.

Antioxidant Protection: By increasing the activities of SOD, CAT, and APX, ZnO and Si nanoparticles strengthen the network of antioxidant enzymes. By doing this, oxidative stress caused by excessive ROS produced during environmental extremes is decreased. Improved redox equilibrium maintains metabolic integrity and protects cellular membranes.

Hormonal Interaction: By fine-tuning ABA, GA, JA, and SA levels, nano-hormone priming controls stress reactions and dormancy release. Even under difficult circumstances, seeds may germinate thanks to this synchronized messaging. Such a hormonal combination simultaneously fortifies the defense and development pathways.

Subsequent Metabolites: According to Mahakhham et al. (2017), nano-priming enhances antioxidant and photoprotective chemicals by activating the biosynthesis of flavonoids and carotenoid molecules. These metabolites enhance nutritional quality in addition to providing UV and oxidative damage protection. Plants so benefit from both value addition and stress tolerance.

Next-Generation Breeding and Nano-Priming Integration

- **Selection Assisted by Markers (MAS):** More accurate breeding is made possible by the discovery of stress-responsive QTLs connected to seed germination. By focusing on candidate loci, MAS expedites the breeding cycle and guarantees that resilience characteristics are introduced into top cultivars more quickly.
- **Selection by Genomic (GS):** GS uses genome-wide markers to more accurately predict polygenic features like germination index. This increases the effectiveness of selection and enables breeders to assess huge populations without incurring expensive phenotyping.
- **Editing the CRISPR/Cas genome**: Seed stress tolerance is directly increased by using CRISPR/Cas to edit the genes for aquaporin, HSP, and LEA. With fewer yield trade-offs, these exact changes aid in the development of cultivars that can tolerate heat, salt, and drought.
- **Breeding by Epigenomics:** It is possible to inherit stress memory via DNA methylation and histone changes, which enhances germination under repeated stress. These epigenetic fingerprints are further amplified by nano-priming, which confers a long-term adaptive benefit.
- **A Look at Case Studies:** Successful breeding techniques are evident in the cases of the tomato under heat stress, the grape under drought, the banana under salinity, and the chrysanthemum under heat. These illustrations show how priming and molecular tools work together to enhance seed performance along crop-specific pathways.

Biotechnological and Omics Approaches

- **Transcriptomics:** Numerous stress-responsive transcription factors and signaling cascades are activated by nano-priming. By activating genes related to water balance, antioxidation, and growth control, this molecular reprogramming promotes early germination.

- **Proteomics:** Increased concentration of osmotic adjustment proteins and antioxidant enzymes is shown by proteomic profiling during nano-priming. By maintaining cellular structures and enhancing seedling survival under stress, these proteins serve as the first line of defense.
- **Metabolomics:** Proline, soluble sugars, and phenolic substances are highlighted by metabolomic investigations as trustworthy indicators of nano-primed seeds. Osmotic stability, ROS scavenging, and general metabolic preparedness for stress tolerance are all enhanced by their buildup.
- **Phenomics:** Automated seed imaging and growth analysis are two examples of high-throughput phenotyping tools that provide quick insights into the uniformity and vigor of seeds. These non-destructive methods aid in the more effective screening of nano-primed seeds across vast populations.
- **Systems Biology:** By using systems biology to integrate transcriptomic, proteomic, metabolomic, and phenomic data, comprehensive genotype–phenotype–environment models are produced. Predictive insights into how resilience pathways are shaped by nano-priming during climatic extremes are made possible by such models.

Physiology × Breeding Integration

- **Trait-based selection:** Antioxidant capacity, osmotic adjustment indices.
- **Rootstocks and grafting:** Enhancing seedling resilience in horticultural crops.
- **Controlled environment agriculture:** Hydroponics and vertical farming complement nano-priming.

Knowledge Gaps and Bottlenecks

- Limited understanding of multi-stress gene–trait interactions.
- Lack of standardized nano-priming protocols.
- Translation gap between lab trials and field validation.
- Biosafety, nanoparticle accumulation, and policy concerns.

Future Prospects

- **Climate-smart ideotypes:** Seeds primed for rapid, stress-resilient germination.
- **AI/ML tools:** Predictive modeling for nano-priming formulations.
- **Nano-encapsulation:** Controlled release of hormones and nutrients.
- **Wild relatives and landraces:** Genetic reservoirs for nano-priming synergy.
- **Policy support:** Standardization and farmer adoption strategies.

Conclusion

A revolutionary method for improving germination in the face of climatic extremes is next-generation seed priming using nano-biostimulants. Nano-priming guarantees quick and robust crop establishment by adjusting physiological pathways, triggering molecular defenses, and combining with superior breeding and omics. Adoption necessitates addressing regulatory frameworks, socioeconomic factors, and biosafety. Translating lab ideas into field-ready solutions for India and global agriculture requires interdisciplinary cooperation.

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