

Enhancing Seed Germination and Seedling Establishment through Priming Techniques

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Seed germination is the critical process by which a dormant seed resumes metabolic activity, absorbs water and develops into a seedling. The process begins with imbibition, during which the seed absorbs water, activating the embryo and leading to the emergence of the radicle and plumule. Successful germination requires adequate water, oxygen and optimal temperature. At this stage, the young plant begins to develop roots and shoots, enabling it to capture sunlight and initiate photosynthesis, marking the beginning of its life cycle.

To improve germination efficiency, enhance stress tolerance and ensure uniform seedling establishment, researchers and agronomists have developed seed priming techniques. Seed priming involves controlled hydration that triggers pre-germinative metabolic activities without allowing radicle protrusion. Primed seeds advance through three well-defined phases of germination:

- **Phase I:** Rapid water uptake via imbibition.
- **Phase II:** Controlled hydration promotes pre-germinative metabolic processes while preventing radicle emergence.
- **Phase III:** Germination and post-germination processes, culminating in seedling establishment.

Conventional Seed Priming Methods

Hydropriming involves soaking seeds in water, followed by drying them to their initial moisture content before sowing. This simple and eco-friendly approach improves germination rates, accelerates seedling growth and enhances seedling vigor. Hydropriming also revitalizes aged or low-vigor seeds, increasing grain yield per plant and per unit area. Priming reduces electrolyte leakage and promotes the repair of vital macromolecules, including DNA, RNA, proteins, enzymes and membranes. Consequently, hydroprimed seeds exhibit improved drought tolerance, faster germination, enhanced metabolic efficiency and better yield outcomes.

Osmopriming, or osmo-conditioning, uses osmotic solutions such as sugars or polyethylene glycol (PEG) to soak seeds before drying them. This method allows controlled water uptake, initiates pre-germinative metabolic activities and improves germination under both normal and stressful conditions, including salinity, drought, cold and waterlogging. Osmoprimed seeds show enhanced seedling vigor and crop performance, supported by biochemical

changes such as increased antioxidant activity, reduced endosperm constraint, stimulation of cell cycle processes and accelerated embryo growth. Enzymes like amylase, dehydrogenase, ATPase and endo- β -mannanase are activated, promoting early seedling development and robust crop establishment.

Biopriming combines seed priming with beneficial microorganisms such as *Trichoderma*, *Pseudomonas*, *Bacillus*, or *Azospirillum*. Seeds are soaked in microbial suspensions, dried and then planted. Biopriming facilitates early colonization of the seed surface and developing radicle by beneficial microbes while initiating metabolic processes. This enhances nutrient uptake, stimulates growth-promoting compounds and protects against seed- and soil-borne pathogens. Bioprimed seeds exhibit faster, more uniform germination, improved growth, higher yields and greater resistance to both biotic and abiotic stresses.

Hormonal priming involves treating seeds with dilute solutions of plant growth regulators to enhance germination, seedling establishment and stress resilience. This method improves physiological and biochemical activities during germination, increasing the accumulation of key osmolytes such as proline and glycine betaine, particularly under drought stress. Hormonal priming enhances seedling vigor, accelerates early growth and strengthens resistance to adverse conditions such as salinity, drought and extreme temperatures.

Halopriming is a pre-sowing treatment in which seeds are soaked in diluted solutions of inorganic salts (e.g., NaCl, KNO₃, CaCl₂, MgSO₄) and then dried back to their initial moisture content. This technique controls water uptake during imbibition and activates vital metabolic and enzymatic processes necessary for germination. Halopriming strengthens membrane stability, maintains ionic balance and improves nutrient availability, resulting in faster, more uniform germination and increased seedling vigor. It also promotes stress adaptation, making seedlings more resilient to drought, salinity and temperature extremes, while reducing oxidative damage through enhanced antioxidant defense mechanisms.

Nutrient seed priming involves soaking seeds in mineral-nutrient solutions followed by drying to original moisture levels. This approach enhances micronutrient availability, activates pre-germinative metabolic pathways and

improves germination, early seedling growth and stress tolerance. Optimized nutrient priming increases germination percentage, crop emergence, stand establishment, seedling growth, mineral uptake, dry matter accumulation, water use efficiency, leaf area and yield components. By stimulating metabolic processes, nutrient priming ensures the efficient use of stored sugars for protein synthesis and promotes steady plant growth.

Advanced Seed Priming Approaches

Nanoparticle-based priming is a modern technique that uses nanoparticles (NPs) to regulate morphological, physiological and biochemical traits. NP priming enhances germination, plant growth, yield and postharvest performance. Under both stress and non-stress conditions, NP-primed seeds demonstrate improved nutrient uptake, strengthened antioxidant defenses and reduced oxidative damage, resulting in more vigorous seedlings and higher crop productivity.

Ionizing physical agent priming employs radiation or other physical factors to stimulate seed germination and enhance seedling vigor. This approach can improve stress tolerance and crop yield while complementing conventional techniques. Ionizing agents exhibit a dose-dependent effect: high doses may reduce seed vigor due to stress, while low doses induce beneficial responses, a phenomenon termed hormesis.

Future Perspectives

The future of seed priming lies in integrating advanced technologies to improve crop resilience, productivity and sustainability. Nanotechnology, combined with precision priming techniques, offers potential for targeted delivery of nutrients and growth regulators,

enhancing germination under extreme environmental conditions. Molecular priming, using omics-based approaches, could allow the identification of key genes and metabolic pathways activated during pre-germination, enabling the design of crop-specific priming protocols. Integration with digital agriculture and seed coating technologies may facilitate large-scale application and real-time monitoring of seed performance. Moreover, combining priming with climate-resilient crop breeding can ensure that crops are better prepared to withstand salinity, drought and temperature extremes, addressing the challenges of global food security. Sustainable and eco-friendly priming solutions, such as microbial and nanoparticle-based techniques, are expected to play a crucial role in reducing reliance on chemical inputs while enhancing crop productivity.

Conclusion

Seed priming, encompassing both conventional and advanced methods, is a versatile and effective strategy for improving germination, seedling vigor and crop productivity. By activating pre-germinative metabolic processes, priming enhances stress tolerance, ensures uniform seedling emergence and promotes robust crop establishment. Techniques such as hydropriming, osmopriming, biopriming, hormonal priming, halopriming, nutrient priming, nanoparticle priming and ionizing agent priming provide sustainable and cost-effective tools for modern agriculture. With continued research and technological integration, seed priming is poised to play a pivotal role in enhancing global food security and ensuring resilient crop production in the face of climate change.
