Seed Priming: Small Step, Strong Start–A Smart Solution for Climate-Resilient Farming

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ABSTRACT

Seed priming is a climate-smart and eco-friendly seed enhancement technology to improve germination, seedling vigor and stress tolerance. Primed seeds undergo quicker establishment and improved performance under drought, salinity and temperature stress as they activate early metabolic and enzymatic processes prior to germination. Seed priming has been shown by studies to improve germination, stabilize yield and enhance plant resilience via physiological and molecular mechanisms. Seed priming is emerging as a promising strategy for sustainable and climate-resilient agriculture due to its low cost, scalability and effectiveness.

INTRODUCTION

Agriculture supports over 60% of India's population but is increasingly threatened by erratic rainfall, soil degradation, and climate extremes. Although the Green Revolution improved productivity through high-yielding varieties and intensive inputs, the sustainability of these systems is now challenged, especially under drought, salinity, and nutrient-deficient conditions intensified by climate change. Globally, about 33% of arable land is degraded, and agriculture contributes nearly one-fourth of greenhouse gas emissions. In this context, improving resource-use efficiency at the seed

level is crucial. Seed priming offers a climate-smart, farmer-friendly solution by physiologically pre-conditioning seeds for rapid germination, uniform emergence, and better stress tolerance under adverse field conditions.

Fragile ecosystems: Farming on the edge

Many agricultural regions of the world are subject to serious biotic and abiotic stresses, including drylands, mountains, wetlands, and coastal areas. Such stresses include salinity, erosion, nutrient depletion, and climate extremes. Such conditions are detrimental for the establishment of seedlings and the growth of crops, particularly in sensitive ecosystems across India. Seed priming is an efficient strategy for climate adaptation, as it promotes fast and uniform germination, stronger root development and better crop establishment under stressful environments.

Seed priming: concept and mechanism

Seed priming is a pre-sowing seed enhancement method that boosts germination, seedling vigor, and stress tolerance through physiological, biochemical and molecular conditioning (Farooq *et al*., 2019; Jatana *et al*., 2024). Various methods include hydropriming, osmopriming, halopriming, biopriming, hormonal priming, and nano-priming, activate metabolic processes such as enzyme activity, antioxidant accumulation, DNA repair, and hormonal balance without triggering visible germination. Primed seeds show faster and uniform germination, improved membrane stability, enhanced tolerance to drought, salinity and temperature stress by activation of stress-responsive genes and stress memory mechanisms (Hussain *et al*., 2016; Basit *et al*., 2021). Therefore, seed priming has become an integrated climate smart approach to improve crop establishment in difficult agro-ecosystems. Examples of seed priming for seed enhancement are given in Table 2.

Table 1. Types of seed priming and field relevance

Type	Priming Agent	Major Benefit	References
Hydropriming	Water	Improves germination	Adhikari *et al*. (2021); Christos *et al*. (2019)
Osmopriming	PEG, Mannitol	Enhances drought tolerance	Debta *et al*. (2023); Farooq *et al*. (2019)
Halopriming	NaCl, KNO_3, $CaCl_2$	Improves salt tolerance	Lutts *et al*. (2016); Gul *et al*. (2022)
Biopriming	PGPR, *Trichoderma*, *Azospirillum*	Enhances vigor and disease resistance	Rodríguez *et al*. (2015); Rani *et al*. (2024)
Hormonal priming	GA_3, SA, JA	Regulates growth and stress response	Gul *et al*. (2022); Lutts *et al*. (2016)
Nano-priming	ZnO, Si, Fe nanoparticles	Enhances vigor and stress memory	Nile *et al*. (2022); Rani *et al*. (2024)

Table 2. Examples of seed priming for better germination, growth, stress tolerance and future innovations

Crop Group	Priming Method	Major Benefit	References
Mungbean, Sunflower, Faba Bean, Cotton	Hydropriming	Improved germination and vigor	Farooq *et al*. (2019); Paparella *et al*. (2015)
Tomato, Brinjal	Hormonal/Halo priming	Enhanced disease resistance	Singh *et al*. (2020); Mahesh *et al*. (2017)
Rice	Chemical priming / Biopriming	Improved stress tolerance	Basit *et al*. (2021); Hussain *et al*. (2016)
Wheat, Chickpea	Osmo-/ Chemical priming	Better crop performance under stress	Jatana *et al*. (2020); Farooq *et al*. (2019)
Barley, Pea, Maize, Soybean	Nutrient/ Biopriming/ Osmopriming	Enhanced emergence and vigor	Batool *et al*. (2022); Paparella *et al*. (2015)
Pearl Millet, Rapeseed	Biopriming	Reduced disease severity	Anup *et al*. (2015); Abuamsha *et al*. (2011)
Tobacco	Chemical priming	Improved chilling tolerance	Hussain *et al*. (2016); Farooq *et al*. (2019)

Physiologically, primed seeds complete Phase I (imbibition) and Phase II (metabolic activation) of germination but arrest prior to Phase III (radicle protrusion). "Half-germination" has many advantages:

- Activates enzymes such as α-amylase and dehydrogenase for faster germination.
- Enhances nutrient mobilization from endosperm to embryo.
- Strengthens antioxidant defense through increased SOD, CAT, and POD activity.
- Improves membrane stability and reduces solute leakage.
- Regulates hormones by lowering ABA and increasing GA levels.
- Induces "stress memory," improving tolerance to future stresses.

Such biochemical and physiological responses allow primed seeds to germinate more rapidly, uniformly and vigorously than unprimed seeds, even under sub-optimal conditions.

Global adoption and research progress

Seed priming is widely recognized as a climate-smart technology. In India, ICAR institutes and State Agricultural Universities have reported 10–25% yield improvement under stress conditions, including late-sown wheat. China has commercialized hydro- and nano-priming in rice and maize, while Bangladesh and Nepal use priming effectively in rainfed rice–wheat systems. FAO- and CIMMYT-supported projects in Africa have enhanced crop establishment and drought tolerance in maize and sorghum. Global organizations such as IRRI, CIMMYT, and OneCGIAR, along with companies like Bayer, Corteva, and Rallis India, are advancing large-scale seed priming technologies.

Benefits to Farmers and Environment

- Promotes rapid, uniform germination with vigorous root and seedling growth.
- Enhances tolerance to drought, salinity, and temperature stress.
- Improves resource-use efficiency, weed competitiveness, and reduces agrochemical use.
- Increases early yield potential while remaining cost-effective and environmentally safe.

These benefits translate into higher productivity and lower risk for smallholders, making seed priming one of the easiest climate-adaptation practices.

Seed Priming and climate resilience

Abiotic stresses cause 20–40 percent of global yield losses in major crops (IPCC, 2023). Seed priming overcomes such losses by strengthening the plants' innate mechanisms of defense and repair. Primed seeds show better osmotic regulation, less ion toxicity and improved ROS scavenging under stress (Basit *et al*., 2021). Recent molecular studies show that priming causes epigenetic modifications and activation of stress-responsive genes (e.g., DREB, WRKY, HSP) with a long-lasting "stress-memory" effect (Jatana *et al*., 2024). These seeds will react more quickly to any subsequent shock in the form of drought, salinity or temperature. The technique is easily integrated into existing farmer practices and uses minimal external inputs. This is in line with the FAO's Climate-Smart Agriculture and UN Sustainable Development Goals 2 (Zero Hunger) and 13 (Climate Action).

Innovations and Opportunities in the Future

- Nano-, bio-, and molecular priming improve seed vigor, stress resilience, and disease resistance.

- Polymer coatings and AI-based monitoring enhance seed storage, sowing, and quality control.
- Public–private partnerships can scale seed priming into a mainstream climate-smart technology.

CONCLUSION

Seed priming is a simple, low-cost and climate-smart technology that enhances germination, seedling vigour and stress tolerance. Its potential for sustainable and resilient agriculture is further enhanced by developments in nano- and bio-priming. Its scalability and environmental safety make it a promising approach for enhancing food and livelihood security under changing climate conditions.

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