Agri Articles

(e-Magazine for Agricultural Articles)

Volume: 06, Issue: 01 (JAN-FEB, 2026)

Available online at http://www.agriarticles.com

Mechanism of Seed Priming in Enhancing Physiological and Molecular Activities of Seed

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Seed priming is a cost-effective, eco-friendly pre-sowing technique that enhances crop productivity and resilience by synchronizing germination and bolstering plant defences. This review examines the triphasic mechanism of priming i.e. imbibition, lag, and drying/memory phases which facilitates DNA repair, membrane stabilization, and metabolic reprogramming. Various methods, including hydropriming, osmopriming, halopriming, and nanopriming, are analysed for their ability to optimize hormonal balances, boost antioxidant enzyme activity (SOD, CAT, APX), and upregulate stress-responsive genes. The impacts on crop stand include improved water relations, enhanced nutrient use efficiency, and faster seedling establishment. Furthermore, priming provides a dual defence strategy: accumulating osmolytes for abiotic stress tolerance and inducing systemic resistance against biotic pathogens and pests.

Keywords: Seed Priming, Germination, Seed Vigour, DNA Repair, Imbibition phase, Lag Pase, Memory phase, Water Uptake, Hormonal Regulation, ROS, Antioxidants

Introduction

Achieving rapid and uniform crop establishment is a fundamental challenge for global food security under the pressures of climate change and population growth. Seed priming (including hydropriming, osmopriming, halopriming and osmopriming, matrix priming, hormonal and nutripriming) which is a low-cost, low-risk approach used worldwide to improve seed performance (Patel *et al.*, 2025). Seed priming has emerged as a vital physiological strategy to bridge the gap between seed dormancy and vigorous growth. This technique involves controlled hydration to a point where pre-germinative metabolic activities are activated such as DNA restoration, mitochondrial reactivation, and reserve mobilization without allowing the radicle to emerge.

By returning the seed to its original moisture content through a "memory" phase, the seed remains in a state of heightened readiness. This process not only ensures synchronized emergence across diverse field conditions but also "immunizes" the plant's internal systems. By pre-activating antioxidant pathways and hormonal signalling, priming prepares the plant to withstand a spectrum of environmental (abiotic) and biological (biotic) threats, making it an essential tool for sustainable precision agriculture.

History of Seed Priming

The evolution of seed physiology transitioned from ancient empirical wisdom to sophisticated molecular science. Focusing on seed physiology, the Greek Theophrastus (c. 372–287 BC) proposed that the germination process may be momentarily halted. According to the Roman scientist Gaius Plinius Secundus, Roman farmers pre-hydrated their legume seeds before spreading them in order to speed up and synchronize germination. (Koushali *et al.*, 2024).

This understanding was refined during the 17th and 18th centuries by scientists like John Evelyn and Jan Ingenhousz, who identified temperature and light as key triggers for seedling development. By the 19th century, Julius Sachs documented the morphological changes and chemical roles of amino acids, setting the stage for the 1920s discovery of plant hormones and their essential functions in cell division and reserve mobilization.

The late 20th century saw the formalization of the "Priming Revolution," introducing systematic methods like hydropriming and osmopriming that became commercial staples for precision agriculture in the 1980s and 90s. From the 2000s to the present, the field has entered the Molecular and Nano Era, where research now focuses on cellular repair mechanisms, such as DNA restoration and epigenetic memory, alongside cutting-edge techniques like nanopriming and biopriming. This historical progression has transformed seed priming into a cornerstone of sustainable agriculture, providing a robust defence against modern climate-induced stresses.

Seed Priming and Its Types

Seed priming is a hydration treatment that allows controlled imbibition and initiation of metabolic activities, but prevents radicle emergence, followed by re-drying to the original moisture content (ISTA,2003). This ensures that primed seeds remain physiologically “ready to germinate” but can still be stored, transported, and handled like untreated seeds. Priming enhances germination rate, seedling uniformity, vigour, and tolerance to environmental stresses such as salinity, drought, and temperature extremes.

Table(1): Types of priming, its method and key applications

Method	Mechanism	Key Applications
Hydropriming	Soaking in water to trigger DNA repair and enzyme activation.	Cereals and pulses in arid regions; simple and low-cost.
Osmopriming	Uses osmotic agents (PEG, mannitol) for gradual water uptake.	Small-seeded vegetables (tomato, carrot); improves uniformity.
Solid Matrix Priming (SMP)	Seeds mixed with moist solid carriers (vermiculite, clay) to mimic soil moisture.	Large-seeded crops and sensitive vegetables; prevents imbibitional injury.
Halopriming	Uses salt solutions (KNO_3, NaCl) for ionic balance.	Salt-tolerant crops (rice, barley); enhances nutrient signalling.
Hormonal Priming	Uses PGRs (GA_3, Salicylic acid) to break dormancy.	Overcoming thermodormancy; inducing drought resistance.
Nutripriming	Enriches seeds with micronutrients (Zn, Mo, Fe).	Boosting root growth; Mo-priming improves N-fixation in legumes.
Biopriming	Inoculates seeds with beneficial microbes (*Trichoderma*, PGPR).	Pathogen suppression and induced systemic resistance.
Nanopriming	Uses nanoparticles (ZnO, SiO_2) to speed water uptake.	High-tech enhancement of seedling vigour and stress tolerance.

Mechanism of Seed Priming

The imbibition phase is the initial stage of priming, triggered by rapid water uptake due to the seed's low water potential. This hydration serves as a "cellular reset," restoring membrane integrity and reactivating vital organelles like mitochondria to resume ATP production. During this phase, critical DNA and protein repair mechanisms are launched, alongside the activation of hydrolytic enzymes such α-amylase and lipases to mobilize stored nutrients. Additionally, a transient accumulation of reactive oxygen species (ROS) acts as a molecular signal, triggering the plant's antioxidant defences and preparing the metabolic foundation for successful seedling development.

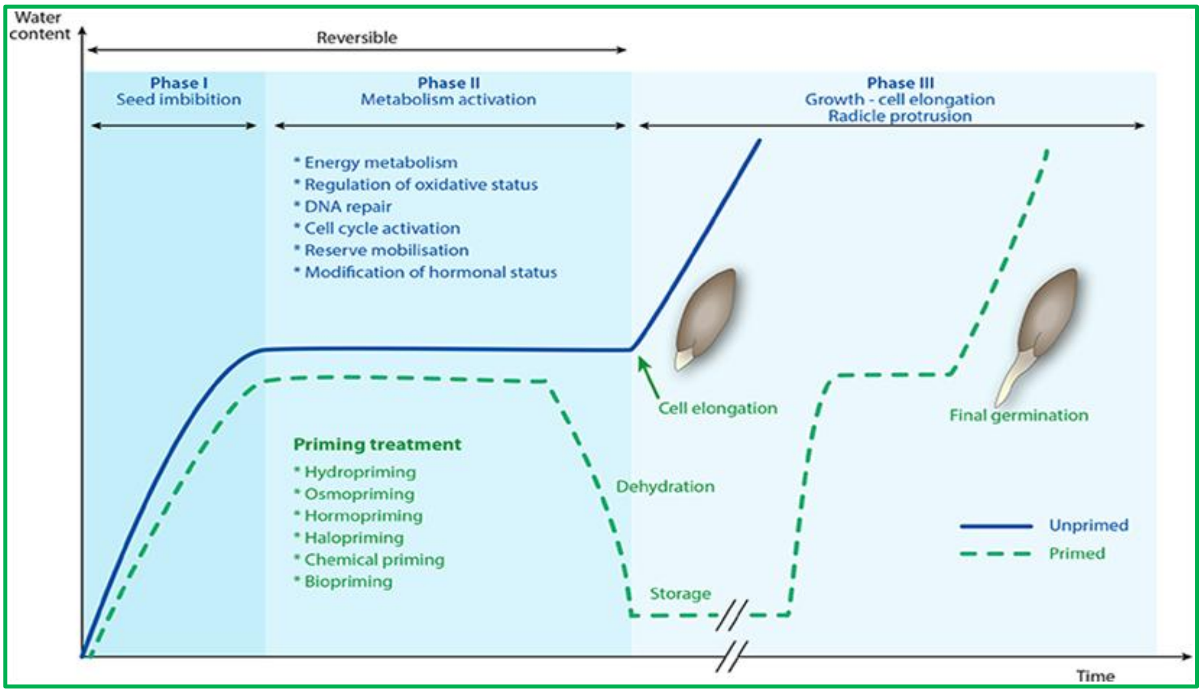

Fig: Seed Priming: Molecular and Physiological Mechanisms Underlying Biotic and Abiotic Stress Tolerance (Bhupinder Singh Jatana *et al.*)

The lag phase is a period of intense metabolic reprogramming despite a plateau in water uptake and the absence of visible radicle protrusion. During this phase, the seed converts stored carbohydrates, lipids, and proteins into soluble sugars and amino acids to fuel future growth. Key protective mechanisms are activated, including antioxidant enzymes (SOD, CAT, POD) to detoxify ROS and stress-stabilizing proteins (dehydrins and LEA proteins) to protect cellular integrity. Simultaneously, hormonal shifts occur as growth-promoting gibberellins (GA) increase and dormancy-inducing abscisic acid (ABA) declines. These changes, coupled with the upregulation of aquaporins and cell-wall-loosening enzymes, prepare the seed for rapid emergence upon re-sowing.

Priming reactivates metabolic pathways that remain quiescent in dry seeds, including DNA repair, RNA synthesis, and initiation of protein synthesis. Activation of repair mechanisms (particularly DNA repair and protein turnover) preserves genome and biomolecular integrity, reducing the incidence of abnormal seedlings after sowing (Hernández *et al.*, 2024). The drying and memory phase completes the priming process by returning seeds to their original moisture content, effectively halting germination while "locking in" physiological progress. During this stage, seeds develop a priming memory through the accumulation of osmoprotectants like proline and trehalose, which stabilize cellular structures. This phase also involves epigenetic modifications and the continued activation of antioxidant systems, ensuring the genome is pre-programmed for rapid defence. By preserving this state of metabolic readiness, the seed is poised to resume germination immediately upon re-sowing, resulting in faster, synchronized, and more resilient seedling emergence.

Physiological and Molecular Effects of Seed Priming

Improved Water Uptake

Seed priming enhances germination through both mechanical and physiological modifications. Primed seeds exhibit faster imbibition compared to unprimed seeds due to changes in seed coat structure, such as tears and depressions that facilitate water entry. X-ray analyses revealed tissue detachment and void formation, which improve water flow and tissue hydration. At the molecular level, priming alters aquaporin gene expression, enabling faster water transport. In chickpea, osmo-priming improved relative water content, water potential, and osmotic potential, indicating enhanced plant water relations.

DNA Repair

During seed maturation and storage, DNA is often damaged by oxidative stress, threatening seed viability. Priming stimulates DNA repair pathways such as Base Excision Repair (BER) and Nucleotide Excision Repair (NER) before DNA replication begins. Genes encoding DNA repair enzymes, including topoisomerases and tyrosyl-DNA phosphodiesterases, are upregulated during imbibition in primed seeds. These mechanisms restore genomic integrity, enabling proper cell cycle progression and improved seed vigour.

Energy and Carbohydrate Metabolism

Priming accelerates the mobilization of stored reserves. Enhanced amylase activity promotes starch breakdown into soluble sugars, ensuring a steady energy supply during early seedling growth. In chickpea, osmo-priming maintained higher sugar contents and enzyme activity under chilling stress, highlighting its role in stress tolerance.

Seed Vigour and Plant Growth

Priming improves all three phases of water uptake, especially Phase II, where metabolic activation occurs. Treated seeds show improved germination percentage, uniformity, and seedling growth. Reproductive parameters such as pod and seed number, as well as grain yield, also improve. Zinc and gibberellic acid priming further enhance early establishment and vigour.

ROS Regulation and Antioxidant Defence

Reactive oxygen species (ROS) play dual roles in germination: signalling and oxidative stress. Priming balances ROS production by enhancing antioxidant defence systems. Activities of catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase (APX) increase in primed seedlings, protecting against oxidative damage and enhancing seed longevity.

Membrane Integrity

Primed seeds maintain better membrane stability by reducing lipid peroxidation and electrolyte leakage. This reorganization of phospholipids ensures proper membrane functioning during imbibition and reduces seed deterioration.

Cell Cycle and Protein Metabolism

Priming synchronizes the cell cycle at the G2 phase, ensuring uniform progression upon rehydration. Proteins related to metabolism, stress tolerance, and cytoskeleton organization (e.g., tubulins, catalase isoforms, and heat shock proteins) accumulate during priming, facilitating radicle protrusion and early growth.

Hormonal Regulation

Priming influences hormonal balance, particularly by enhancing gibberellic acid (GA) synthesis and reducing abscisic acid (ABA) levels. GA promotes endosperm weakening and radicle emergence, while priming enhances ethylene and auxin biosynthesis, further supporting germination.

Other Molecular and Physiological Responses

Primed seeds display improved aquaporin expression for water transport, accumulation of dehydrins under stress, enhanced chlorophyll content and photosynthetic efficiency, and upregulation of genes linked to DNA repair and antioxidant defence. Collectively, these changes strengthen stress tolerance, uniform germination, and seedling establishment.

Conclusion

Seed priming represents a sophisticated intersection of plant physiology and agricultural technology. By strategically managing the seed's metabolic "restart," growers can produce robust, uniform crop stands naturally equipped to handle external stressors. From the biochemical stabilization of membranes during drought to the induction of systemic resistance against pests, priming maximizes the genetic potential of the seed. The integration of advanced methods, such as nanopriming and biopriming, offers a path toward reducing reliance on synthetic fertilizers and pesticides. As agricultural systems move toward sustainable intensification, seed priming stands as a cornerstone technology for safeguarding yields, shortening crop cycles, and ensuring resilience in an increasingly unpredictable global climate.

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