International Journal of Environmental & Agriculture Research (IJOEAR)
ISSN: [2454-1850]
[Vol-12, Issue-1, January- 2026]
Website: www.ijoear.com
Journal DOI: 10.25125/agriculture-journal

Seed Priming: Mechanisms, Methods, and Applications for Enhancing Crop Resilience in Fragile Ecosystems

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Received:- 25 January 2026/ Revised:- 04 February 2026/ Accepted:- 10 February 2026/ Published: 28-02-2026

Abstract— *Seed priming is a pre-sowing technique involving controlled hydration and dehydration to activate pre-germinative metabolism without radicle emergence. This review synthesizes the principles, methods, and multifaceted benefits of seed priming as a pivotal strategy for enhancing crop establishment and stress resilience. Priming improves germination uniformity, vigour, and yield across major cereals, pulses, and oilseeds by triggering complex physiological, biochemical, and molecular responses, including antioxidant system activation, DNA repair, and stress-responsive gene expression. Conventional methods such as hydropriming, osmo-priming, and biopriming, alongside advanced techniques like nano-priming and physical priming, are detailed. The paper highlights crop-specific applications, underscores the technology's role in mitigating abiotic stresses in fragile ecosystems, and discusses its limitations and future challenges. As a cost-effective and accessible intervention, seed priming is a vital tool for sustainable agricultural intensification and climate adaptation.*

Keywords— Seed priming, pre-germinative metabolism, abiotic stress, biopriming, nano-priming, crop resilience.

I. INTRODUCTION

Seeds are the cornerstone of agriculture, ensuring genetic continuity and food security. High-quality seeds are fundamental for uniform plant establishment and optimal productivity. Seed priming is a pre-sowing biotechnological practice that involves controlled hydration to initiate metabolic processes, followed by drying to prevent radicle protrusion. This technique, pioneered by Heydecker et al. (1973), enhances germination speed, uniformity, seedling vigour, and stress tolerance, leading to improved crop performance, especially under adverse conditions.

The global challenge of cultivating crops in fragile ecosystems—marked by drought, salinity, and extreme temperatures—necessitates resilient agricultural strategies. Seed priming offers a pragmatic, low-cost solution by inducing a "priming memory," enabling plants to mount faster and more robust cellular defences against subsequent stresses. This review comprehensively examines the benefits, underlying principles, physiological-biochemical-molecular mechanisms, diverse methods, and field applications of seed priming in major crops. It also critically addresses the limitations and future prospects of this technology for sustainable crop production.

II. THE PRINCIPLE AND PROCESS OF SEED PRIMING

Seed priming is defined as a controlled hydration process sufficient to activate pre-germinative metabolism but insufficient to allow radical protrusion (Heydecker et al., 1973; McDonald, 2000). The standard seed germination process consists of three phases: Phase I (rapid water imbibition), Phase II (activation of metabolic processes and repair), and Phase III (radicle emergence and growth). Priming meticulously regulates seeds within Phase II.

The procedure involves soaking seeds in a priming agent for a specific duration, followed by rinsing and drying back to the original moisture content (Fig. 1). This controlled cycle allows for the repair of cellular components (e.g., DNA, mitochondria), accumulation of germination-promoting metabolites, and induction of stress-responsive pathways, without the loss of desiccation tolerance characteristic of Phase III.

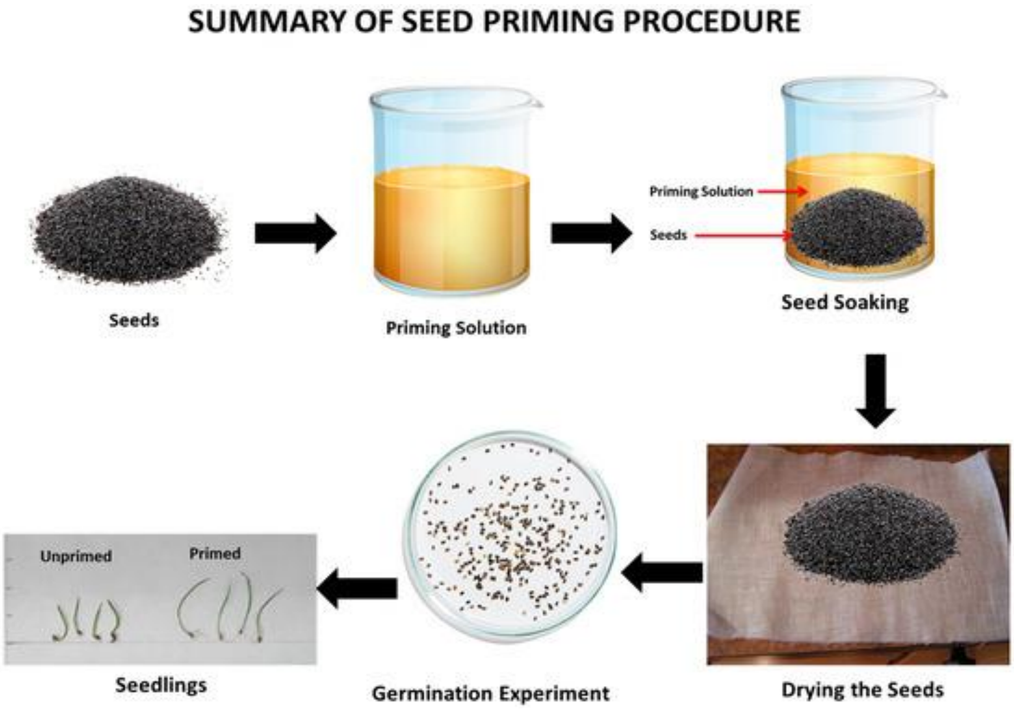

FIGURE 1: Schematic representation of the seed priming procedure.

III. BENEFITS OF SEED PRIMING:

The agronomic and physiological benefits of seed priming are extensive:

1. **Enhanced Germination & Establishment:** Promotes rapid, uniform germination and robust stand establishment, even under suboptimal conditions (Nakaune et al., 2012; Manikanta et al., 2020).

2. **Improved Stress Tolerance:** Induces cross-tolerance against abiotic (drought, salinity, temperature extremes) and biotic stresses by priming defence pathways (Basra et al., 2005; Miladinov et al., 2020).

3. **Increased Yield Potential:** Leads to better crop growth, early flowering, and higher yield by improving seedling vigour and resource use efficiency (Harris et al., 2007; Singh et al., 2015).

4. **Metabolic Activation:** Boosts the activity of key enzymes (α-amylase, antioxidant enzymes), hormonal balance (GA/ABA ratio), and reserve mobilization (Paparella et al., 2015).

5. **Socio-Economic Advantage:** A low-cost, eco-friendly technology accessible to smallholder farmers, reducing dependency on external inputs.

IV. PHYSIOLOGICAL, BIOCHEMICAL, AND MOLECULAR MECHANISMS:

Seed priming orchestrates a suite of interconnected mechanisms that prepare the seed for germination and stress resilience (Fig. 2, 3).

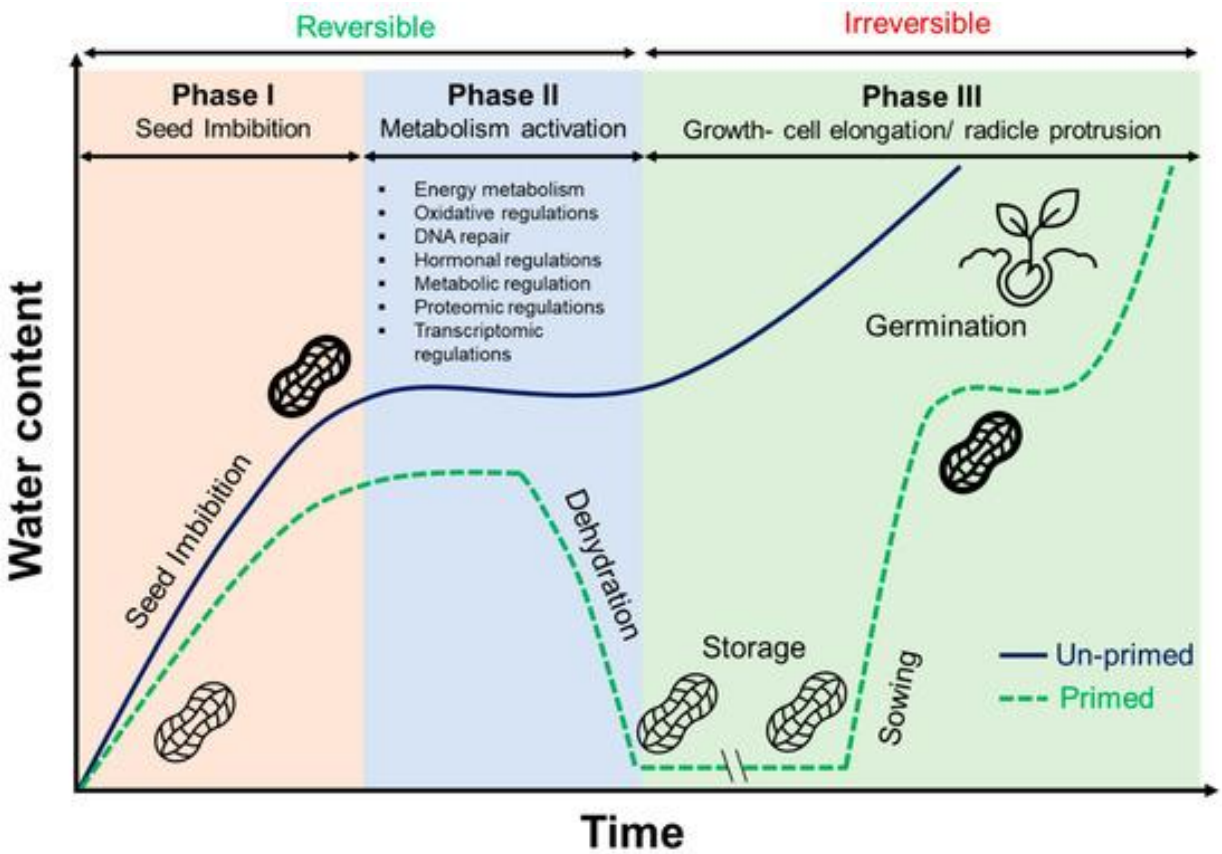

FIGURE 2: Hydration curves and germinating phases in unprimed vs. primed seeds.

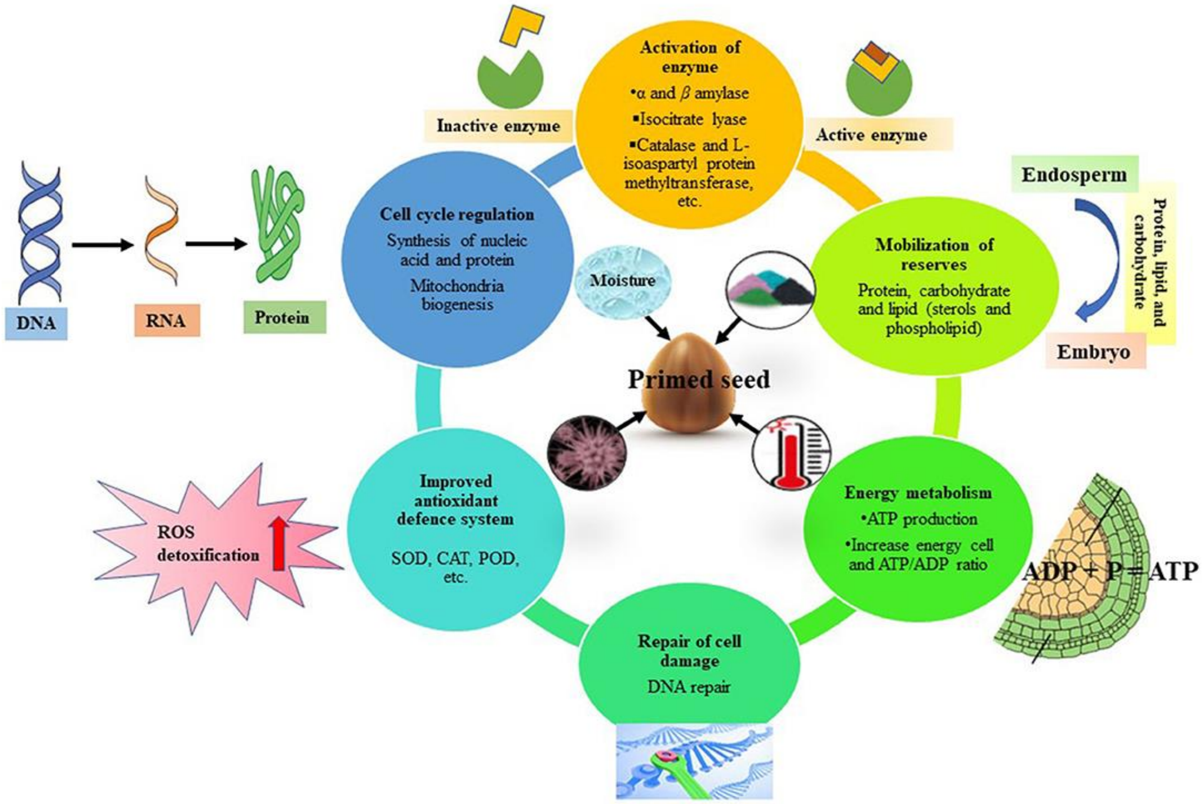

FIGURE 3: Summary of key biochemical and molecular changes induced by seed priming during Phase II.

4.1 Activation of Pre-germinative Metabolism and Repair:

During controlled imbibition, primed seeds undergo essential repair and preparatory events: mitochondrial repair and synthesis, DNA damage repair via Base Excision Repair (BER) and Nucleotide Excision Repair (NER) pathways, and *de novo* synthesis of proteins, nucleic acids, and ATP (Paparella et al., 2015; Wojtyla et al., 2016).

4.2 Antioxidant Defence and ROS Management:

Reactive Oxygen Species (ROS) are inevitable by-products of resumed metabolism. Priming upregulates both enzymatic (SOD, CAT, APX, POD) and non-enzymatic (glutathione, ascorbate) antioxidant systems, managing ROS levels as signalling molecules while preventing oxidative damage to lipids, proteins, and DNA (Bailly, 2004; Farooq et al., 2017).

4.3 Hormonal Regulation:

Priming modulates the critical balance between abscisic acid (ABA, a germination inhibitor) and gibberellins (GA, germination promoters). It often leads to a decline in ABA and a rise in GA, facilitating the transition from dormancy to germination (Kermode, 1990).

4.4 Expression of Stress-Responsive Proteins:

Priming induces the accumulation of protective proteins like Late Embryogenesis Abundant (LEA) proteins, dehydrins, and heat shock proteins (HSPs). It also upregulates aquaporins, enhancing water uptake efficiency during subsequent germination (Chen and Arora, 2013).

4.5 Cell Cycle Activation and Energy Metabolism:

Primed seeds show earlier activation of the cell cycle upon re-imbibition. Energy metabolism is optimized through increased α-amylase activity, breaking down starch into soluble sugars to fuel growth (Varier et al., 2010).

V. METHODS OF SEED PRIMING

Priming methods are categorized into conventional and advanced techniques.

5.1 Conventional Methods

- **Hydropriming:** Soaking seeds in water. Simple and low-cost but risks uncontrolled imbibition.
- **Osmo-priming:** Using osmotic solutions (e.g., PEG, mannitol, salts) to control water potential. Effective but can be expensive and reduce oxygen diffusion.
- **Halo-priming:** Use of inorganic salt solutions (KNO_3, $CaCl_2$).
- **Nutri-priming:** Soaking in solutions of macro/micronutrients (e.g., Zn, P).
- **Hormonal Priming:** Use of plant growth regulators (GA_3, SA, IAA).
- **Biopriming:** Integration of seed hydration with beneficial microorganisms (e.g., *Trichoderma*, *Pseudomonas*, *Rhizobium*). Enhances growth and suppresses diseases.
- **Solid Matrix Priming:** Hydration using a solid medium (vermiculite, peat) to control water uptake precisely.

5.2 Advanced Methods

- **Nano-priming:** Application of nanoparticles (ZnO, SiO_2, Fe_3O_4) for targeted nutrient delivery and enhanced stress response.
- **Physical Priming:** Use of physical agents like magnetic fields (magneto-priming), UV radiation, gamma irradiation, or cold plasma to stimulate metabolic activity.

VI. APPLICATIONS IN MAJOR FIELD CROPS: A SYNTHESIS

Seed priming has demonstrated significant positive effects across a wide range of field crops. The following table summarizes key findings from selected studies.

TABLE 1
SELECTED RESEARCH ON SEED PRIMING EFFECTS IN MAJOR FIELD CROPS

Crop	Priming Method	Key Observed Effects	Key References
Rice	Various	Improved germination, seedling growth, and stress tolerance; enhanced yield.	Adhikari and Sangita Bhujel Adhikari (2023); Basra et al. (2004, 2006); Farooq et al. (2007, 2010); Hussain et al. (2016); Tissarum et al. (2020); Gao et al. (2023)
Wheat	Various	Enhanced germination percentage, vigour, and heat stress tolerance; increased yield.	Ali et al. (2013); Ghasem et al. (2013); Balakhnina et al. (2015); Hussain et al. (2018); Bajwa et al. (2018); Al-Akhras M Ali et al. (2024)
Maize	Various	Better stand establishment, increased yield components under drought.	Akbari et al. (2007); Imran et al. (2013); Bakhtavar et al. (2015); Anjuman et al. (2015); Madhukeswar and Sajjan (2017); Kappor et al. (2023)
Sorghum	Various	Improved germination and early seedling growth under stress.	Kadiri et al. (1999); Iram et al. (2002); Amarnath et al. (2018); Chen et al. (2021); Koradhanyamah et al. (2024)
Mungbean	Various	Increased germination speed, seedling vigour, and stress tolerance.	Posmyk et al. (2007); Chauhan and Naiya et al. (2013); Reddy et al. (2013); Tiwari et al. (2016); Afrayeem et al. (2018); Vardhini and Singh (2021)
Blackgram	Various	Enhanced germination and seedling growth; improved stress tolerance.	Aryal et al. (2020); Ladumor and Singh (2022); Timisina et al. (2024); Jadhav et al. (2024); Midhul Rana and Satyanarayanan (2024); Krishnasamy et al. (2024)
Pigeonpea	Various	Improved germination and early seedling growth under water deficit.	Raj et al. (2008); Hareesh (2014); Tiwari et al. (2014, 2021); Kavitha and Srimathi (2022); Ashok et al. (2017); Raju and Rai et al. (2017)
Chickpea	Various	Enhanced chilling tolerance, antioxidant activity, and water relations.	Kumar et al. (2014); Laal et al. (2015); Vigneswara et al. (2017); Farooq et al. (2017); Kamithi et al. (2018)
Groundnut	Various	Improved pod yield, nutrient uptake, and drought resilience.	Sanojkumar et al. (2017); Sepeheri and Rouchi (2017); Pal et al. (2017); Hassan and Ismail (2018); Babu et al. (2018); Das and Mohanty (2018); Vardhini et al. (2021); Cagasan et al. (2022); Moharana et al. (2023); Hozyan et al. (2024); Hemalatha et al. (2024)
Sunflower	Various	Induced salt tolerance at germination and early seedling stage.	Bajebha et al. (2010); Aymen and Hannchi (2012); Shanthala and Siidiraju (2013); Sakpal and Ahmad (2023); Priya Reddy and Nanja Reddy (2024)
Soybean	Various	Increased nodulation, biomass, and yield under field conditions.	Saha et al. (1990); Bensen et al. (1990); Muhammad Arif et al. (2008); Bassi et al. (2011); Assefa et al. (2010, 2011); Golezani et al. (2011); Shine et al. (2011); Sadeghi et al. (2011); Bhowmick et al. (2013); Chavan et al. (2014); Radhakrishnan et al. (2013); Mangena (2020); Dugeswar et al. (2024); Alkamas et al. (2024)
Sesame	Various	Improved germination and seedling growth under stress.	Singh et al. (2002); Kand-Bo Shim et al. (2009); Shabbir et al. (2014); Singh et al. (2022); Askari et al. (2019); Ifran et al. (2024); Mori et al. (2024)

VII. LIMITATIONS AND CHALLENGES

Despite its promise, seed priming faces practical constraints:

1. **Species and Protocol Specificity:** Optimal priming parameters (agent, concentration, duration) vary greatly among crops and even cultivars, requiring extensive optimization.
2. **Reduced Storability:** Primed seeds often have shorter shelf-life due to increased metabolic activity, posing logistical challenges for seed companies and farmers.

3. **Scale-up and Cost:** Translating lab protocols to cost-effective, large-scale on-farm applications remains a hurdle, especially for methods involving expensive agents or equipment.
4. **Knowledge Gaps:** A deeper molecular understanding of "priming memory" and the long-term agronomic impacts under diverse, real-field multi-stress conditions is needed.

VIII. CONCLUSION AND FUTURE PERSPECTIVES

Seed priming is a scientifically robust and practically viable technology to enhance crop performance in fragile ecosystems. By activating a cascade of pre-adaptive mechanisms, it equips plants to withstand environmental stresses from the very start of their life cycle. Its simplicity and cost-effectiveness make it particularly suitable for resource-poor farming systems.

To fully realize its potential, future efforts should focus on:

- **Protocol Standardization:** Developing crop- and environment-specific priming protocols.
- **Molecular Breeding:** Identifying and integrating genetic markers associated with superior priming response into breeding programs.
- **Innovative Delivery Systems:** Exploring nano-formulations and seed coating technologies for easier application and extended efficacy.
- **Policy and Extension Support:** Strengthening extension services to bridge the gap between research and widespread farmer adoption.

Seed priming stands as a critical component of sustainable intensification strategies, offering a pathway to stabilize yields and enhance food security in the face of climate change.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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