Optimizing Seed Priming Protocols Using Surfactants for Improved Plant Establishment

Shachi Tiwari[1]* and Sangeeta Dayal[2]

[1]Ph. D. Scholar Department of Botany and [2]Head of Department of Botany and Biotechnology (Professor), Swami Vivekananda Subharti University Meerut (U.P.) 25000, India

Corresponding Author
Shachi Tiwari
Email: tiwarishachi1998@gmail.com

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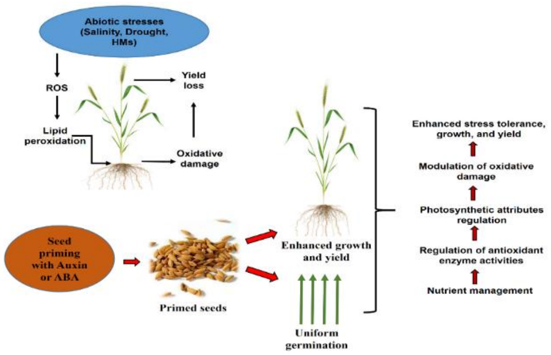
ABSTRACT

Seed priming is a pre-sowing technique that partially hydrates seeds to activate metabolic processes such as DNA repair, enzyme activity, and antioxidant buildup—leading to faster and more uniform germination after re-drying. While it improves seed performance and crop establishment, priming requires precise control over hydration and drying, posing challenges for small-scale farmers due to cost and complexity. In agriculture, seed priming is widely used to enhance germination, stress tolerance (drought, salinity, temperature extremes), disease resistance (via biopriming with beneficial microbes), and early crop establishment. It contributes to sustainable farming by reducing water, fertilizer, and pesticide use, ultimately increasing yields and supporting climate resilience and precision agriculture. A recent innovation in priming involves amphiphilic compounds like surfactants, which improve water uptake, break seed coat barriers, enhance nutrient delivery, and boost stress tolerance. These surfactants help in modifying seed-water interactions, enabling better germination, especially in hard-coated or dormant seeds. Looking forward, integrating seed priming with technologies like seed coating and genetic tools presents a promising approach for boosting productivity and ensuring food security. Continued research and optimization are crucial to fully exploit its benefits in sustainable and resilient agriculture.

INTRODUCTION

Seed priming is a pre-sowing treatment method applied to enhance the physiological and biochemical characteristics of seeds, thereby their germination and seedling establishment under various environmental conditions (Jatana *et al*., 2024). Seed priming is a process where seeds are soaked in water or certain solutions for a specified duration, enabling partial hydration of the seeds without causing germination. The application of indole-3-butyric acid encapsulated in SDS-AOT mixed micelles effectively promotes sorghum growth under stress conditions caused by organic salts (Tiwari *et al*., 2025). The treated seeds are then re-dried to their initial moisture content for storage or direct sowing. Plant hormones contribute significantly to the defense mechanisms that improve rice resilience against various abiotic stress conditions (Khan *et al*., 2023).



Types of Seed Priming

There are a number of types of seed priming, each of which is designed to address specific agricultural and environmental requirements:

1. **Hydropriming:** This is the most straightforward method, where seeds are soaked in water to trigger pre-germination metabolic processes. It is used extensively because it is cost-effective and easy to perform.

2. **Osmopriming:** In osmompriming, seeds are pre-treated by immersing them in solutions that include osmotically active ingredients like polyethylene glycol (PEG) or salts. It assists in regulating water absorption and imparting controlled hydration, which is helpful especially for plants under arid or saline conditions.

3. **Biopriming:** This consists of the application of beneficial microorganisms in seed treatment. Biopriming not only promotes germination but also gives seeds a protective layer of microbes, which can increase plant resistance against diseases and insects.

4. **Hormonal Priming:** Seeds are treated with growth regulators or plant hormones such as gibberellic acid, cytokinin, or ethylene, which can increase germination percentages and seedling strength.

5. **Nutripriming:** Seeds are primed using nutrient-rich solutions, giving them necessary macro- and micronutrients that support the initial growth phases.

Mechanism of Seed Priming

In priming, partial hydration stimulates the metabolism of the seed, causing repair of broken DNA, enzyme synthesis, and storage of necessary metabolites such as antioxidants. These activities condition the seed for quick germination when planted in the future. The re-drying process ensures that seeds may be stored without losing viability or gains made during priming.

Challenges and Limitations

As valuable as it is, seed priming has a few drawbacks. It needs a strict control over hydration levels, priming periods, and processes of re-drying to avoid seed damage or early germination. The technique can also bear extra costs related to materials like priming

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chemicals and equipment that may be insurmountable for small farmers.

Use of Seed Priming in Agriculture

Seed priming is a revolutionary agricultural method employed extensively to maximize crop yield and resistance under various environmental stresses. Through seed conditioning for maximum germination and establishment of seedlings, seed priming has established itself as an integral part of sustainable agriculture practices. Some major uses of seed priming in agriculture are presented below:

1. Enhancing Germination and Seedling Health

Seed priming increases seeds' physiological fitness, resulting in better germination rates and more rapid seedling emergence. It is especially essential in maintaining a uniform crop stand, which is crucial for mechanized agriculture and predictable crop performance. For instance, primed maize and wheat seeds exhibit accelerated and coordinated germination over the non-treated counterparts.

2. Increased Stress Tolerance

Primed seeds can resist biotic and abiotic stresses including:

- **Drought:** Seeds primed with hydropriming or osmopriming have improved water absorption efficiency, allowing seedlings to establish themselves in arid conditions.
- **Salinity:** Salt or osmotically active priming reduces the detrimental effects of salt soils by enhancing ion management and cellular metabolism in seeds.
- **Temperature Extremes:** Heat or cold stress will slow down germination; nevertheless, primed seeds are more resilient and capable of adapting to such conditions.

3. Inducing Disease Resistance

Biopriming that involves inoculating with useful microbes such as Trichoderma spp. or Pseudomonas spp. provides a microbial coat to seeds. This guards the seedlings against soil-dwelling pathogens, minimizing reliance on chemical fungicides and making it sustainable agriculture.

4. Promotion of Early Crop Establishment

Early crop establishment is important in crops grown in short-duration growing seasons or variable weather regimes. Primed seeds shorten the early growth stage, enabling farmers to achieve maximum yield potential within the given time frame. This is especially beneficial to crops such as rice and soybean.

5. Promotion of Sustainable Agriculture

Primed seeds save on water, fertilizers, and pesticides. Nutripriming, for example, provides seeds with basic nutrients during the priming treatment, reducing the demand for supplementary fertilization in initial growth stages. This makes for resource-saving agriculture and in tune with sustainable farming practices.

6. Increased Yield and Productivity

Priming seeds has been demonstrated to enhance total crop yields. The combination of enhanced germination, stress tolerance, and strong early growth means higher productivity in a range of crops, including cereals, legumes, and vegetables. For example, primed tomato and cucumber seeds result in healthier plants with increased fruit yields.

7. Managing Climate Challenges

With climate change threatening world agriculture ever more, seed priming provides an accessible solution to increasing crop resilience. By priming seeds to function more effectively in adverse weather, priming helps ensure food security in high-risk areas.

8. Precision Farming Applications

Seed priming is reinforcing precision farming methods, where maximized planting approaches are dependent on consistent and standardized seed performance. By providing every seed with the same ability to germinate and develop, priming enhances high-technology farming systems.

Impacts of Amphiphilic Compounds or Surfactants on Seed Priming

Amphiphilic compounds, such as surfactants, have been introduced as a novel method in seed priming for the improvement of seed performance. Amphiphilic compounds are characterized by both hydrophilic (water-attracting) and hydrophobic (water-repelling) traits, which allow them to modify water behavior, nutrient release, and biochemical reactions during seed priming. Nano-priming represents a cutting-edge seed priming approach, showing significant promise for promoting sustainability in agriculture through recent innovations and future potential (Nile *et al*., 2022). Double salt ionic liquids formulated from synthetic auxins offer superior physical properties and stronger biological activity for herbicidal use (Rzemieniecki *et al*., 2021). Their use has proven to have significant effects on seed germination, stress tolerance, and seedling establishment. The following discusses the impacts of these compounds on seed priming in greater detail.

1. Increased Water Uptake and Holding

Amphiphilic molecules enhance water handling during priming:

- Surfactants decrease the surface tension of water, enabling easier penetration of seed coats. This results in more even and controlled moisture absorption, essential to stimulate pre-germinative metabolic activities.
- Better hydration guarantees seeds take up the optimal water level without triggering early germination, a key requirement for successful priming.

2. Enhanced Germination Rates

Surfactants enable effective hydration and activation of germination-required enzymes:

- By improving water uptake and nutrient supply, such substances speed up the biochemical reactions required for seed germination.
- For seeds with impermeable or hard coats, like legumes or some cereals, surfactants assist in coating softening, allowing for faster germination.

3. Improved Nutrient Delivery

Amphiphilic substances enhance nutrient transport and solubility as well as other priming agents

- Surfactants transport hydrophobic nutrients and substances, making them more accessible to the seed.
- This primes seeds with an optimized level of nutrients, which gives them greater vigor and growth capabilities.

4. Breaking Hydrophobic Barriers

Surfactants in hydrophobic seeds break water resistance:

- Amphiphilic substances break down waxy barriers or hydrophobic barriers covering seed surfaces to facilitate effective exchange of water and oxygen.
- This is most useful for those species with barriers of dormancy, as they enable improved association with priming agents.

5. Stress Tolerance Enhancement

Surfactants can enhance the tolerance of seeds to abiotic stresses, i.e., salinity and drought:

- Through enhanced efficiency of water and nutrient uptake, surfactants prime seeds for extreme environmental conditions.

- Amphiphilic substances can further enable the delivery of stress-alleviating agents such as antioxidants or osmoprotectants during priming to improve the tolerance of the seed to unfavorable conditions.

Future Prospects

The combination of seed priming with other agro-technologies, like seed coating and genetic enhancement, promises to change crop production altogether. Further innovation and research will help farmers around the globe exploit the full value of this process. The seed priming is a very effective tool for contemporary agriculture. Its capacity to improve seed performance, encourage sustainability, and counteract environmental issues highlights its significance in attaining global food security.

In conclusion, amphiphilic compounds, such as surfactants, are a useful resource in contemporary seed priming techniques. Their capacity to enhance water dynamics, nutrient supply, and stress tolerance renders them a versatile tool for boosting seed germination and crop yield. Nevertheless, proper optimization of their use is necessary to optimize benefits while reducing possible disadvantages.

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