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MINI REVIEW

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Seed priming techniques to enhance germination and crop yield

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ABSTRACT

Seed germination is an important phase in crop establishment that directly affects the growth of the plant and agricultural productivity. However, adverse environmental circumstances such as drought, salinity, and temperature extremes often restrict germination efficiency and uniformity. Seed priming has appeared as an effective pre-sowing approach to augment germination performance, seed vigour, and stress tolerance. This review offers a complete overview of various seed priming techniques, including hydropriming, osmopriming, halopriming, hormonal priming, biopriming, and nanopriming, highlighting their roles in improving seed physiological and biochemical processes. The original mechanisms of seed priming are discussed in terms of metabolic activation, enzyme induction, DNA repair, hormonal balance, and antioxidant defense systems. Recent developments in molecular biology and gene expression studies related to priming-induced stress tolerance are explored.

Despite its benefits, certain limits, including storage constraints and a lack of standardization, are also addressed. Finally, developing trends such as nanotechnology and microbial priming are highlighted as promising avenues for future research. The morphophysiological data was recorded on the height of the plant, number of tillers per plant, panicle height and panicle number, thousand -kernel weight, grain length and width, yield, and disease incidence.

KEY WORDS

Seed priming; Germination enhancement; Crop productivity; Abiotic stress tolerance; Hormonal regulation

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Introduction

Seed germination signifies a critical phase in the plant life cycle, determining the successful establishment of crops and ultimately influencing agricultural productivity. Uniform and fast germination is vital for attaining ideal plant density, effective resource utilization, and advanced yields. In many agroecosystems, seed germination and early seedling growth are adversely affected by unfavourable environmental conditions such as drought, salinity, temperature extremes, and soil degradation [1]. These stresses often result in late rise, low stand establishment, and reduced crop production.

In recent years, significant attention has been focussed toward developing sustainable and cost-effective strategies to improve seed performance under both optimal and stress conditions. Among these, seed priming has emerged as a promising pre-sowing technique that enhances germination efficiency and seedling vigour [2]. Seed priming involves controlled hydration of seeds to initiate pre-germinative metabolic activities without allowing radicle protrusion, followed by re-drying prior to sowing. This process enables seeds to complete the early phases of germination, resulting in faster and more synchronized germination upon planting.

Several seed priming techniques such as hydropriming, osmopriming, halopriming, hormonal priming, biopriming, and nanopriming, have been extensively studied across different crop species. These approaches have demonstrated particular improvements in germination rate, stress tolerance, and crop yield [3]. The beneficial effects of priming are attributed to enhanced enzymatic activity, improved membrane integrity, activation of antioxidant defense systems, and regulation of plant hormones.

Furthermore, progresses in molecular biology have given new perceptions into the mechanisms basic seed priming, including gene expression modulation and stress memory induction. Even with its advantages, storage stability, protocol standardization, and large-scale applications remain challenges [4].

This review focuses to give a broad overview of the techniques for the seed priming and their role in improving germination and crop yield, discusses about the involved physiological, biochemical, and molecular mechanisms, as well as current advances, limitations, and future perspectives for sustainable agricultural development [5].

Basic Concepts for Seed Germination

Seed germination is a complex physiological method that shows the transition of a seed from a quiescent state to an actively growing seedling. It contains a sequence of synchronized structural and metabolic alterations that eventually lead to the development of the radicle [6]. Generally, germination is categorized into three different stages: imbibition, lag phase, and radicle protrusion.

The first stage, imbibition, is measured by quick water uptake by the dry seed, leading to the rehydration of cellular components and swelling of seed tissues. This phase is mostly driven by physical forces and does not need metabolic energy. The second phase, known as the lag phase, includes initiation of metabolic processes, involving enzyme synthesis, DNA repair, protein synthesis, and mobilization of stored reserves such as starch, proteins, and lipids. During this stage, the seed makes for active growth but expresses negligible noticeable deviations [7]. Radicle protrusion is the final phase, marking the completion of germination and the start of seedling formation.

Several aspects impact seed germination, including intrinsic factors like seed viability, dormancy, and genetic makeup, as

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well as extrinsic factors such as temperature, moisture, oxygen availability, and light.

Effective germination is crucial for reaching uniform crop establishment and maximizing harvest capacity. However, under suboptimal situations, germination may be time consuming or repressed, leading to poor field performance [8]. Consequently, enhancing germination through innovative techniques such as seed priming has become a key focus in modern agricultural research.

Concept and Principles of Seed Priming

Seed priming is a pre-sowing treatment that involves exact hydration of seeds to start primary metabolic processes related to germination without permitting the emergence of the radicle. After priming, seeds are re-dried to their original moisture content, enabling them to be stored and handled like untreated seeds [9]. This technique allows seeds to avoid the early lag phase of germination, resulting in quicker and more uniform rise under field conditions.

The fundamental principle of seed priming lies in the regulation of water uptake. During priming, seeds absorb sufficient moisture to activate metabolic activities such as enzyme synthesis, nucleic acid repair, and reserve mobilization, but not enough to complete germination. This partial hydration ensures that the seeds remain physiologically active while maintaining structural integrity [10].

Primed seeds exhibit numerous advantages over non-primed seeds. These include improved germination rate, enhanced seedling vigor, better stress tolerance, and increased crop yield [11]. The useful properties of priming are mostly attributed to better membrane stability, accumulation of germination-related proteins, and activation of antioxidant defense systems that protect cells from oxidative damage [Table 1].

Seed priming also plays a vital role in mitigating the adverse effects of abiotic stresses such as drought and salinity. By preconditioning the seeds, priming enhances their capacity to cope with stress conditions during germination and early growth stages. Also, priming can lead to synchronized germination, which is mainly important for automated agriculture and uniform crop management [12].

Despite its efficacy, the success of seed priming depends on many factors, including priming duration, temperature, seed type, and the priming agent used. Therefore, optimization and standardization of priming protocols are essential for achieving consistent results across different crops and environments [13,14].

Table 1. Types of seed priming techniques and their characteristics.

Priming Technique	Agent Used	Mechanism	Key Benefits	Example Crops
Hydropriming	Water	Controlled hydration	Simple, cost-effective	Wheat, rice
Osmopriming	PEG, sugars	Osmotic regulation	Uniform germination	Maize, soybean
Halopriming	Salts (NaCl, KNO_3)	Ionic balance	Stress tolerance	Rice, barley
Hormonal priming	GA, ABA, auxins	Hormone regulation	Enhanced growth	Tomato, lettuce
Biopriming	Beneficial microbes	Microbial interaction	Disease resistance	Legumes
Nanopriming	Nanoparticles	Improved uptake efficiency	Stress resistance	Various crops
Solid matrix priming	Vermiculite, peat	Controlled hydration medium	Improved aeration	Vegetables

Types of Seed Priming Techniques

Seed priming encompasses a range of pre-sowing treatments that differ in methodology, priming agents, and physiological effects. These techniques are introduced to control seed hydration and trigger pre-germinative metabolism, thereby improving germination performance and crop establishment. The major seed priming methods are discussed below [15].

Hydropriming

Hydropriming is the cost-effective and simplest method, involving soaking seeds in water for an exact duration, followed by drying to their original moisture content. This method improves seed imbibition and initiates metabolic activities like enzyme activation and reserve mobilization. Hydropriming has been widely applied in crops like wheat, rice, and maize, where it mainly advances germination rate and uniformity. However, the lack of accurate control over water uptake may sometimes lead to over-imbibition and reduced seed viability.

Osmopriming

Osmopriming involves soaking seeds in osmotic solutions like polyethylene glycol (PEG), mannitol, or sorbitol, which regulate water uptake through osmotic potential. This measured hydration prevents radical protrusion while allowing metabolic activation. Osmoprimed seeds exhibit better germination under stress conditions. The technique also increases enzymatic activity and membrane integrity, making it appropriate for crops like soybean, maize, and sunflower [16].

Halopriming

Halopriming uses inorganic salt solutions such as sodium chloride (NaCl), potassium nitrate (KNO_3), or calcium chloride ($CaCl_2$) to prime seeds. The presence of ions helps in osmotic adjustment and improves ion homeostasis within the seed. Halopriming has been shown to enhance tolerance to salinity stress by regulating ion uptake and reducing toxic effects of sodium ions [17]. It is particularly effective in crops like rice, barley, and wheat grown in saline environments.

Hormonal priming

Hormonal priming involves the use of plant growth regulators such as gibberellic acid (GA_3), abscisic acid (ABA), auxins, and cytokinins. These hormones play a critical role in regulating germination and early seedling growth. For example, gibberellins promote enzyme synthesis and reserve mobilization, while ABA modulates stress responses [18]. Hormonal priming enhances germination speed, seedling vigor, and stress tolerance in crops such as tomato, lettuce, and pepper.

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Nutrient priming

Nutrient priming involves soaking seeds in solutions that have essential macro- and micronutrients like zinc, phosphorus, and iron. This method expands nutrient availability during primary growth stages, leading to improved seedling development and yield. Nutrient priming is mostly helpful in nutrient-deficient soils and has been effectively applied in cereals and legumes [19].

Biopriming

Biopriming integrates seed hydration with the inoculation of beneficial microorganisms such as bacteria and fungi. These microbes colonize the seed surface and enhance plant growth by producing growth-promoting substances, improving nutrient uptake, and providing protection against pathogens. Biopriming has gained significant attention due to its eco-friendly nature and role in sustainable agriculture. It is widely used in legumes, vegetables, and cereals.

Nanopriming

Nanopriming is an emerging technique that involves the use of nanoparticles to enhance seed performance. Nanoparticles improve water uptake, nutrient delivery, and stress tolerance by interacting with seed tissues at the molecular level. Studies have shown that nanopriming enhances antioxidant activity, enzyme function, and germination under stress conditions [20]. Despite its potential, concerns regarding toxicity and environmental impact need further investigation.

Solid matrix priming

Solid matrix priming involves mixing seeds with a solid carrier such as vermiculite, peat, or clay, along with a controlled amount of water. This method allows steady hydration and good aeration, reducing the risk of over-imbibition. It is mainly useful for small-seeded crops and horticultural species.

The selection of a priming technique depends on the crop type, environmental conditions, and expected outcomes. Combining different priming methods may further enhance their effectiveness and provide synergistic profits [21].

Physiological, Biochemical, and Molecular Mechanisms

The efficiency of seed priming is attributed to a series of complex physiological, biochemical, and molecular changes that happen during controlled hydration. These deviations prepare the seed for fast and efficient germination after sowing.

One of the primary effects of priming is the activation of metabolic processes. During priming, enzymes such as amylases, proteases, and lipases are synthesized and activated, leading to the breakdown of stored reserves into usable forms. This ensures a readily accessible energy source for the developing embryo.

Seed priming also helps DNA repair and protein synthesis. Due to aging and oxidative stress during seed storage, cellular components may undergo damage. Priming eases the repair of damaged DNA and membranes, thereby restoring cellular integrity. The synthesis of germination-related proteins augments seed viability and performance.

Hormonal regulation plays a vital role in priming-induced responses. Priming moderates the balance between growth-promoting hormones like gibberellins and inhibitory hormones like abscisic acid. This hormonal balance is important for initiating germination and refining stress tolerance [22].

Another key mechanism includes the parameter of reactive oxygen species (ROS). While excessive ROS can cause cellular damage, controlled levels act as signaling molecules that promote germination. Priming enhances the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which help in maintaining ROS balance and protect cells from oxidative stress.

At the molecular level, seed priming induces changes in gene expression associated with stress tolerance and germination. Stress-responsive genes, heat shock proteins, and transcription factors are upregulated, enabling seeds to better withstand adverse environmental conditions. Recent studies also suggest that priming may induce epigenetic modifications, leading to "stress memory" that enhances plant performance in subsequent growth stages [23].

These coordinated mechanisms collectively contribute to improved germination, enhanced seedling vigour, and better resilience to environmental stresses.

Role of Seed Priming in Stress Tolerance

Seed priming plays an important role in improving plant tolerance to various abiotic stresses, which are major limitations to agricultural productivity worldwide. By preconditioning seeds, priming enables plants to better cope with adverse environmental conditions during germination and early growth stages.

Drought stress

Drought is one of the most valuable factors limiting seed germination. Primed seeds exhibit enhanced water use competence and enhanced root development, enabling better water uptake under limited moisture conditions [24]. Osmopriming and hydropriming are specifically effective in improving drought tolerance.

Salinity stress

Salinity disturbs germination by producing an ionic imbalance and osmotic stress. Halopriming aids seeds in maintaining ion homeostasis by regulating sodium and potassium levels. Also, priming improves antioxidant activity, reducing oxidative damage triggered by salt stress [25].

Temperature stress

Extreme temperatures can inhibit enzymatic activity and disrupt cellular processes. Primed seeds show improved tolerance to both high and low temperatures due to enhanced membrane stability and enzyme function.

Heavy metal stress

Heavy metals such as cadmium and lead can negatively affect germination and plant growth. Priming techniques, especially biopriming and nanopriming, help reduce metal toxicity by enhancing detoxification mechanisms and antioxidant defense systems [26].

Overall, seed priming enhances stress tolerance by improving physiological resilience, activating defense pathways, and maintaining cellular homeostasis under adverse conditions.

Impact of Seed Priming on Crop Yield and Productivity

Seed priming has a substantial beneficial impact on crop yield and productivity by refining germination, seedling establishment, and plant growth. Uniform and rapid

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germination confirms optimal plant population, which is a key determinant of yield.

Primed seeds harvest vigorous seedlings with good root and shoot development, causing to improved nutrient and water uptake. This boosted early growth translates into healthier crop performance throughout the growing season. Studies have reported increased yield components such as number of tillers, grain weight, and biomass in primed crops [27].

In cereals such as rice and wheat, priming has been shown to improve grain yield under both normal and stress conditions. Similarly, in legumes and vegetables, priming enhances flowering, fruit set, and overall productivity. The benefits are particularly pronounced in stress-prone environments, where priming helps mitigate yield losses.

Furthermore, seed priming contributes to sustainable agriculture by reducing the need for external inputs such as fertilizers and irrigation. It is a low-cost and globally friendly technique that can be easily accepted by farmers.

However, the extent of yield improvement depends on factors such as crop species, priming method, and environmental conditions. Therefore, optimizing priming protocols is important for maximizing profits in diverse agricultural systems.

Applications of Seed Priming in Sustainable Agriculture

Seed priming is a tool promoting sustainable agriculture by enhancing crop performance while lessening external inputs. In the context of climate change and resource constraints, priming provides a practical and eco-friendly method to improve agricultural output.

Seed priming supports low-input farming systems by improving nutrient use competence and dropping dependence on chemical fertilizers. Nutrient-primed seeds can use obtainable soil nutrients more efficiently, leading to improved growth and yield with reduced fertilizer application. Likewise, biopriming with helpful microorganisms offers soil health and plant protection, minimizing the requirement for chemical pesticides.

In rainfed and marginal agricultural systems, where water availability is less, priming plays a crucial role in improving water use efficiency and crop establishment. This makes it mainly valuable for smallholder farmers in developing regions [28].

Seed priming can be integrated with modern agricultural practices, including precision farming and conservation agriculture, to enhance resource use and enhance production. Its simplicity, cost-effectiveness, and adaptability make it a feasible approach for achieving sustainable strengthening of agriculture.

Recent Advances and Emerging Trends

Seed priming holds significant potential for addressing the challenges of global food security and sustainable agriculture. Future research should focus on developing standardized and crop-specific priming protocols to ensure consistent and reliable outcomes across diverse agro-climatic conditions.

Advancements in molecular biology and biotechnology can further clarify the mechanisms underlying priming-induced stress tolerance, enabling the growth of improved crop varieties with enhanced receptiveness to priming. The incorporation of nanotechnology and microbial approaches offers promising opportunities, but their environmental safety and long-term effects must be carefully evaluated.

There is also a need to advance the storage consistency of primed seeds, which remains a major limitation for commercial application. Innovations in seed coating and packaging technologies may help extend shelf life and maintain seed quality [29].

The use of AI and precision agriculture tools can ease the large-scale acceptance of seed priming by adjusting treatment conditions and improving decision-making. Cooperative efforts among researchers, policymakers, and farmers will be vital to translate laboratory findings into field-level applications.

Conclusion

Seed priming has developed as an actual and sustainable strategy for enhancing seed germination, seedling establishment, and crop productivity.

In addition to improving germination and early growth, seed priming contributes to increased crop yield and resource use efficiency, making it a valuable tool for sustainable farming systems. However, challenges such as reduced storage life, lack of standardization, and scalability issues need to be addressed to fully realize its potential.

Recent advances in nanotechnology, microbial applications, and data-driven optimization have opened new avenues for enhancing the effectiveness of seed priming. With continued research and technological innovation, seed priming is poised to play a crucial role in meeting the growing demand for food while ensuring environmental sustainability.

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