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Review Article

Utilization and challenges of seed priming techniques in agricultural crops: Prospects for the future

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ABSTRACT

Seed priming is an effective pre-sowing technique that enhances seed germination, seedling vigor, and nutrient uptake, ultimately improving crop establishment and yield. While numerous studies have demonstrated the agronomic benefits of various seed priming methods, fewer have comprehensively addressed the associated challenges or explored future directions. This review highlights the multifaceted benefits of seed priming beyond crop performance enhancement, including its role in inducing biochemical, physiological, molecular, cellular, and subcellular changes that strengthen plant tolerance to biotic and abiotic stresses. Despite these advantages, significant knowledge gaps remain regarding the limitations of seed priming across different crop types and environmental conditions. The findings underscore the potential of seed priming as a sustainable tool for improving agricultural productivity and ensuring food security. The review advocates for future research into integrated priming strategies, such as combining multiple priming methods and calls for deeper investigation into the mechanisms governing interactions between priming duration, sowing time, seed quality, and crop response. These insights are vital for advancing the practical application of seed priming to address global food production challenges.

KEYWORDS: *Crop establishment, Food insecurity, Pre-sowing, Seed quality*

INTRODUCTION

Seed priming is a method that promotes germination and seed vigour by exposure to a predetermined condition of moisture and temperature (Ingale & Pathak, 2023). It is one of the pre-sowing management techniques for pulses to overcome drought, poor soil fertility, and stress. It also entails the partial germination of seeds by soaking them in water or nutrient solution for a specified period and then drying them before the radicle emerges. Priming stimulates many metabolic processes involved with the early phases of germination (Rehman *et al.*, 2015). It is a simple procedure that partially hydrates the seed in a controlled environment, followed by seed drying, so

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germination processes begin, without radicle emergence (Paparella *et al*., 2015). However, there is a paucity of information on optimal conditions, duration, stability, and quality of primed seeds during storage and before planting. The seed priming technique can be traced back to the ancient Greeks, Theophrastus (372-287 B.C.), who found that soaking cucumber seeds in water for a pre-sowing treatment could improve their germination (Evenari, 1984). Seed priming is a physiological technique involving seed hydration and drying to improve metabolic processes before germination, which has been used to commercially eliminate biotic and abiotic stress (Amir *et al*., 2024). It is a controlled hydration process that triggers metabolic processes during the early phases (I and II) of germination before radicle protrusion (Hussain *et al*., 2016).

The advantages of seed priming cannot be overemphasized as it is a low-cost, effective hydration technique to stimulate, synchronize, and increase emergence (Ghassemi-Golezani *et al*., 2012; Nawaz *et al*., 2017). Meanwhile, recent advancements in seed physiology and seed biochemistry, coupled with cutting-edge technology, have proved to be instrumental to seed quality improvement. For instance, Shabbir *et al*. (2014) showed that priming promotes germination by triggering various biochemical changes in the seed, which typically persist after desiccation and become available once the seeds absorb moisture after sowing. It also reduced the negative effects of lower temperature and non-optimal humidity conditions in the germination media on the germination rate. However, many factors, such as plant species, priming duration, temperature, priming media, and their concentration and storage conditions, have been found to affect the performance of seed priming. Moreover, despite the highlighted benefits, the primed seed's performance depends on factors such as the treatment technology, crop variety, crop imbibition behaviour, priming method, and imbibition time.

This review is conducted as a narrative review aimed at providing a comprehensive and integrative synthesis of current knowledge on seed priming techniques, their applications, limitations, and emerging trends. Given the broad scope and diversity of experimental approaches across different crop species and environments, a narrative approach was adopted to allow for flexible thematic exploration and conceptual integration. Relevant peer-reviewed journal articles, book chapters, and historical references were identified primarily through searches in Google Scholar, Web of Science, and Scopus using keywords such as "seed priming," "pre-sowing treatment," "hydropriming," "osmopriming," "biopriming," "nutri-priming," and "nanopriming." Inclusion focused on studies that discussed seed priming effects on germination, stress tolerance, nutrient uptake, and crop performance. Articles were excluded if they lacked experimental relevance or did not contribute meaningfully to the core themes of the review.

SEED PRIMING TECHNIQUES

Seed priming is a pre-sowing technique for improving seed germination and seedling vigour. There have been multiple ways of seed priming (Lechowska *et al*., 2019), each of which entails treating the seeds before germination to increase their performance under varied situations, like hydropriming, osmopriming, halopriming, hormonal priming, chemical priming, nutripriming, and biopriming. These are all kinds of seed priming that give substantial agricultural advantages.

Osmopriming

Soaking seeds in osmotic solutions is referred to as Osmo-priming. It is a strategy that limits seed hydration during the soaking period by using a low osmotic potential solution such as polyethylene glycol (PEG) to start the germination process while preventing radicle protrusion (Lei *et al*., 2021). According to Hrbáková *et al*. (2020), one of the primary benefits of osmopriming is its capacity to boost seed vigour and germination under adverse environmental conditions through the improvement in the kinetics of water intake (Jisha *et al*., 2013; Lechowska *et al*., 2019). This mechanism modifies the microstructural characteristics of the seed coat, causing microcracks to develop and changing the interior structure of the seed. Results from Lechowska *et al*. (2019) showed that osmopriming promotes cotyledon cell vacuolization, the accumulation of storage proteins, and alters aquaporin gene expression patterns. This aggregation is noted to enhance the overall performance of the seeds as it increases the expression of stress-related proteins and proteasome components, which improves the seeds' resistance to stress (Hrbáková *et al*., 2020). Farooq *et al*. (2019) proved that osmoprimed seeds boosted seedling dry weight, chlorophyll content, leaf calcium concentration, amylase activity, and total soluble sugars, which aided seedling development and biomass production. Although osmopriming with $CaCl_2$ increased resilience to drought stress in wheat (Hussain *et al*., 2018), it has been considered an alternative to osmopriming (Raj & Raj, 2019). It has slow imbibition when the seeds are incubated in a solid, insoluble matrix with a restricted amount of water (Raj &Raj 2019). Moreover, this approach is expensive due to the cost of osmotic agents coupled with technical issues with aeration. Therefore, more research efforts are needed on several alternatives to agents that can be cost-effective with advanced technical efficiencies.

Hydropriming

Hydropriming is a seed priming technique that involves submerging the seeds in water, which triggers the imbibition process and initiates germination. Hydropriming offers the advantage of the capacity to boost water absorption efficiency in seeds, particularly under harsh conditions such as high heat, salt, and water deficiency stress (Moreno *et al*., 2018; Adetunji *et al*., 2021). Moreover, it has been proven to promote water use efficiency (WUE) of wheat and activation of endospermhydrolyzing enzymes, which aids seed germination and seedling development (Bankole *et al*., 2019; Marthandan *et al*., 2020). In another report, Moreno *et al*. (2018) showed that hydropriming for certain plant species can activate separate specialized pathways in the soaking, drying, and final germination phases of primed seeds under salty circumstances. This priming method has increased resistance to CO_2 stress and oxidative damage in paddy rice and other crops like wheat, okra, parsley, onion, carrot, pepper, and cucumber (Nedunchezhiyan *et al*., 2020; Marthandan *et al*., 2020; Shokouhian and Omidi, 2021; Adetunji *et al*., 2021; Silva *et al*., 2022). According to Shokouhian and Omidi (2021), hydropriming has been shown to improve sugar beetroot seed salt tolerance by enhancing physiological properties and germination indices. It is crucial to note, however, that the length of hydropriming and the ambient conditions throughout the priming process might have a considerable impact on the results. For example, Adhikari *et al*. (2021) showed that 48 hours of hydro-primed seed was effective for increasing germination and seedling growth in bitter gourd, but further investigation is needed under large, open-field conditions with various varieties. Moreover, there are significant variations in the performance of hydro-primed seeds, as shown in Figure 1. This information suggests that the treatment impacts the redox environment, bringing the seed toward a genotype-specific set of pre-germinative metabolism compatible with improved germination performance. In another study, a long period of contact between water and seeds can be detrimental to germination (Silva *et al*., 2022). Therefore, maintaining optimal humidity and temperature is critical to avoiding uncontrolled water absorption and radicle protrusion (Adetunji *et al*., 2021).

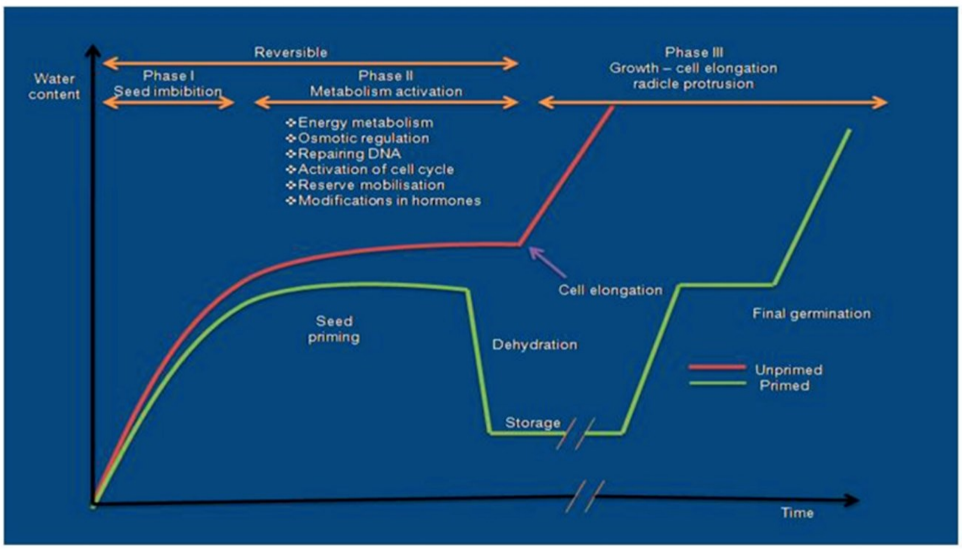

Figure 1. Seed imbibition curves and phases of seed germination in unprimed and primed seeds. (Marthandan *et al*., 2020).

Biopriming

Biopriming is a seed priming technique that includes inoculating seeds with helpful microorganisms such as bacteria or fungi to improve their performance in terms of seed viability, vigour, and resilience. This approach has been found to promote germination in the presence of several biotic and abiotic stressors (Rhaman *et al*., 2020). Besides, biopriming has been found to offer numerous benefits, including enhanced crop nutrient availability and utilization, decreased susceptibility to biotic and abiotic stressors (Sun *et al*., 2022; Nawaz *et al*., 2020), development of root and shoot growth (Chatterjee *et al*., 2018), and activation of systemic defenses against plant pathogens (Singh *et al*., 2020). Meanwhile, seed biopriming is favoured among other approaches because of its efficacy in seed surface bacterial inoculation (Roslan *et al*., 2020). Due to this, surface inoculation helps to improve the seedling emergence index and increase yield and yield characteristics, which is a promising strategy for preparing plants for stress tolerance before germination (Rhaman *et al*., 2020). For instance, seed bio-treatment, soil amendment, foliar spray, drip irrigation, and root dipping in bacterial suspensions are all ways for biopriming (Roslan *et al*., 2020). Furthermore, it has been shown to increase nitrogen absorption and plant early vegetative development (Forti *et al*., 2020). Beneficial microorganisms are essential for biopriming under screenhouses and field conditions. Several microorganisms used for biopriming have been reported. For instance, Saravanakumar and Samiyappan (2007) demonstrated that groundnut seeds treated with *Pseudomonas fluorescens* were less susceptible to salt stress, while Timmusk *et al*. (2014) found that biopriming with *Bacillus thuringiensis* enhanced the drought resistance of wheat seedlings. Trichoderma harzianum is another biopriming agent that induces plant growth by the creation of various phytohormones and activates plant supplements for better crop boosts (Swain *et al*., 2021). Therefore, more research efforts are needed on biopriming as an eco-friendly approach to enhance crop productivity through biological means, aligning with sustainable agricultural goals.

Solid matrix priming (SMP)

Solid matrix priming includes covering the seeds with clay or polymers to increase seed performance (Rhaman *et al*., 2020). SMP has been demonstrated to be efficient, relative to other priming approaches such as osmotic priming in some circumstances (Madsen *et al*., 2018). Moreover, the combined effect of solid matrix priming and biopriming has a significant synergistic effect on okra in the field, which is cost-effective (Hosamani *et al*., 2020). Solid matrix priming can boost metabolic processes before germination, resulting in quicker germination and higher crop production (Rhaman *et al*., 2020). SMP's usefulness as a priming strategy has been examined in a variety of crops, with encouraging results. Meanwhile, under normal and stress settings, this approach has been shown to improve seed germination and seedling development. In research on field crops, for example, six-hour solid matrix priming in 18% v/w sand was shown to be the most effective approach for most crops, indicating that SMP is an effective and possibly low-cost technology for enhancing germination (Nyoni *et al*., 2020). Another study on leek seeds discovered that solid matrix priming with O_2 resulted in higher germination rates and better seed quality than other treatments (Ozden *et al*., 2018).

SMP has been found to alleviate salt stress in plants and boost seed emergence and crop performance in okra, wheat, bitter gourd, and mung bean (Jafar *et al*., 2011; Paparella *et al*., 2015; Kanwar and Mehta, 2017; Sen and Mandal, 2018). Furthermore, it has been shown to have more pronounced benefits in lower-quality seed lots than in higher-quality seed (Ozden *et al*., 2018). However, the mechanism underlying the efficiency of solid matrix priming is unknown. Although it is thought to include regulated water intake by the seeds, it causes physiological and biochemical changes that improve germination and seedling vigour (Lutts *et al*., 2016). However, the hydrating substrate in SMP gradually moistens the seeds, mimicking the natural imbibition process that happens in the soil (Wu *et al*., 2017). This regulated water intake has been shown to result in quicker and more synchronized germination, as well as enhanced stress tolerance in early seedlings (Lutts *et al*., 2016). However, the solid also results in delayed protrusion of the radicle. Therefore, there is a need to standardize solid matrix priming, environmental temperature, and its duration for crops to allow the development of a simple priming protocol.

Hormonal priming

Hormonal priming is a seed priming technique that involves treating seeds with plant hormones like gibberellic acid or cytokinins to improve their performance (Rhaman *et al*., 2020). It is a priming technique that uses phytohormones to initiate seed metabolism. Relative to unprimed seeds, Ellouzi *et al*. (2024) showed that seed treatment with 100 mM of indole-3-acetic acid (IAA) significantly improved overall germination indices in both saline and non-saline conditions. However, more evaluations are needed to ascertain a good threshold of hormones needed across various crops for the enhancement of crop productivity. Under diverse settings, the hormonal priming approach has been demonstrated to promote seed germination uniformly and accelerate biochemical changes with seedling development (Rhaman *et al*., 2020). In another study, seed priming using cytokinins (plant growth substances) conferred salt stress resistance in wheat (Iqbal *et al*., 2006) and drought tolerance in soybean (Mangena, 2020). Moreover, the performance of primed seeds under drought conditions varies, as shown in Figure 2.

Many studies have confirmed the superiority of hormonally primed seeds over traditionally used untreated seeds on uniform germination, reduction in mean germination time, and broadening the tolerance range against environmental stresses (Srii et al., 2023). However, quite a few have considered many other types of hormones on crops of the same varieties and crops of the same species.

Nutri-priming

Nutri-priming is the process of priming seeds with a solution of mineral nutrients rather than soaking them in plain water, which combines the benefits of seed priming with increased nutrition delivery. Some mineral nutrients, such as potassium, zinc, and magnesium, are crucial for agricultural plant performance under environmental stress. The ultimate aims of nutri-priming are to increase seed quality, germination characteristics, and seedling establishment while providing more nutritional benefits (Farooq et al., 2012). K-priming was found to have a positive effect on cotton seedling development and nutritional status in salty circumstances (Shaheen et al., 2016). According to Houmani et al. (2024), the effect of Nutri-priming agents is phase-dependent (Figure 3). Depending on plant species, Nutri-priming has not only enhanced some micronutrients in cereals, but more research is needed on the choice of concentration of priming to avoid nutrient toxicity in the seeds. This is because some nutrients are required in smaller quantities

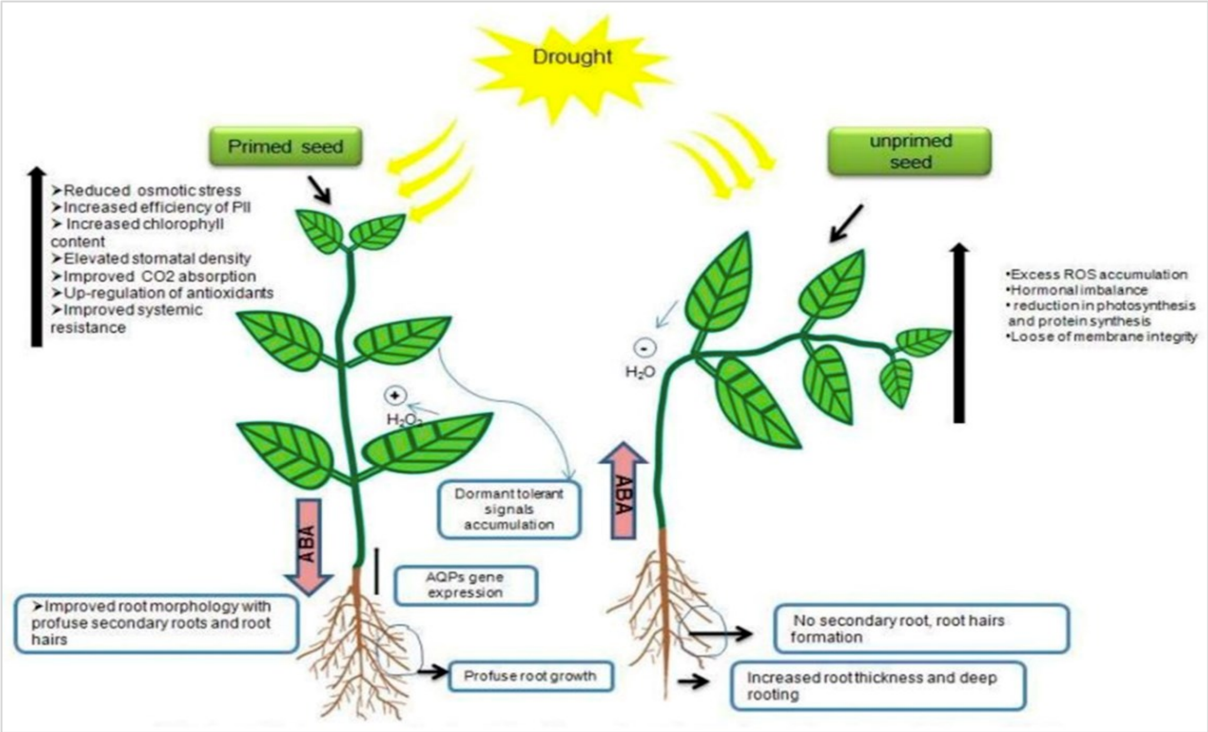

Figure 2. Performance of primed and unprimed seeds under drought conditions (Marthandan *et al*., 2020).

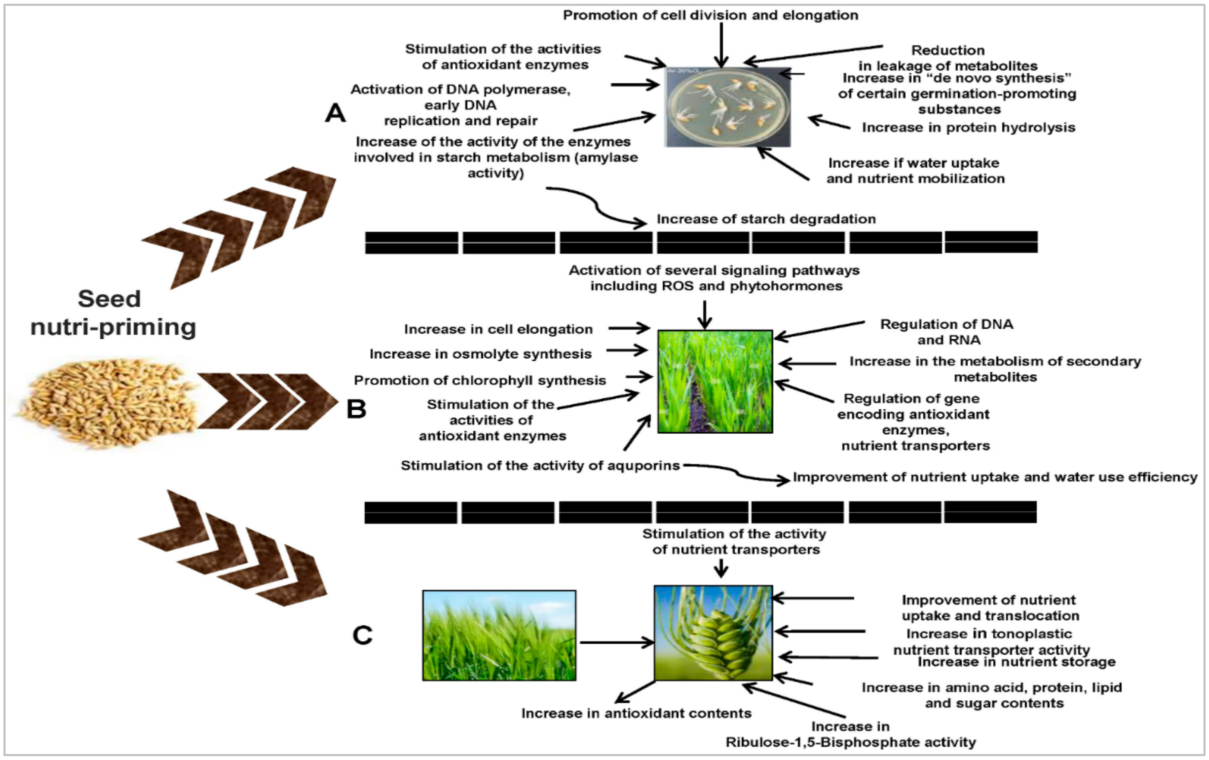

Figure 3. Mechanism of seed Nutri-priming at germination (A), vegetative (B), and reproductive stages (C).

Chemical Priming

Chemical priming is the process of priming a seed with multiple compounds that might improve seed performance under stress conditions. It aids plants in developing tolerance to abiotic stress by producing antioxidants and other protective substances such as salicylic acid, ascorbic acid, ethanol, selenium, $CuSO_4$, $ZnSO_4$, KH_2PO_4, choline, and chitosan, among others (Hemender *et al*., 2018). Moreover, chemical priming is a type of priming in which the seed is treated with either natural (organic acids, plant extracts, chitosan, polyamines, mannose, trehalose, etc.) or synthetic substances (sodium nitroprusside, sodium hypochlorite) (Jisha *et al*., 2013; Paparella *et al*., 2015; Lutts *et al*., 2016). Numerous studies show that chemical priming with various priming agents has a good influence in a variety of environmental settings (Khaliq *et al*., 2015). According to Fercha *et al*. (2014), priming with ascorbate mitigates the detrimental consequences of salt stress through changes in the number of proteins involved in metabolism, protein destination, and storage. However, the combination of natural and synthetic chemicals is also frequent in seed priming, which may be detrimental or enhance seed quality. For example, Bajwa *et al*. (2018) discovered that priming wheat seeds with sorghum extracts and benzyl aminopurine boosted crop performance under saline soil conditions. Whereas priming with potassium chloride, relative to potassium nitrate, had a stronger effect on seed viability, leading to reduced germination percentage by 12% and 9%, respectively, at the starting phases of germination (Miladinov *et al*., 2018). Therefore, more attention is needed on the types and concentration of chemical priming agents, as there is no universal applicability of primers, which either give a negative or positive response, depending on the genetic components of the seed.

Role of seed priming in enhancing nutrient uptake and utilization

The potential of seed priming to improve nutrient usage efficiency might be a response to the depletion of vital nutrient mineral stocks. This is because micro and macro nutrients are required in an adequate proportion. Under the current agricultural scenario, 50% of applied fertilizers are utilized by crops (Parihar *et al*., 2019), while the remainder is lost due to leaching, soil fixation, low mobility, and denitrification. Meanwhile, other factors that pose a threat to the environment and economy could be mitigated by seed priming to enhance nutrient uptake and minimize losses (Sarkar *et al*., 2021). When sprayed with 1/4th Nitrogen and an approved amount of potassium and phosphorus, biopriming wheat seed with *T. harzianum* enhanced nitrogen utilization efficiency agronomically by up to 3.36% (Meena *et al*., 2016). Under nutrient (P and Zn)-deficient and drought circumstances, nutrient priming of barley seed with P and Zn alone or in combination improved nutrient absorption and water usage efficiency (Ajouri *et al*., 2004). Priming mung bean seedlings with 0.01 and 0.02% P increased P absorption in a P-deficient tropical soil (Shah *et al*., 2012). Kumar *et al*. (2020) found that a consortium of *Burkholderia gladioli*, *Pseudomonas* sp., and *Bacillus subtilis* had the highest P-solubilizing activity and that applying this consortium through seed biopriming increased soil accessible P by 54%.

Seed priming enhances water usage efficiency and is hence appropriate for drought-prone locations. Seed priming is an age-old practice that is an effective method for plants in water-stress situations. Priming sesame seeds with various kinds of mycorrhizal fungi (*Funneliformis mosseae* and *Rhizoglomus intraradices*) improved water consumption efficiency by 6% to 10% during mild-to-severe drought circumstances (Askari *et al*., 2019). When treated under alternate wetting and drying circumstances, priming rice seeds with moringa leaf extract enhanced water production to the maximum level (relative to $CaCl_2$ and KCl) (Rehman *et al*., 2015). Osmopriming with various compounds (gibberellic acid and ammonium molybdate) increased water consumption efficiency in summer cowpea seeds grown in arid environments (Arun *et al*., 2017). Therefore, seed priming plays a significant role in nutrient uptake, utilization, and seed germination enhancement depending on the types of primers, species of the seeds, and the environmental conditions.

IMPORTANCE OF SEED PRIMING TO COMMERCIAL FARMING IN A CHANGING CLIMATE

Seed priming techniques offer numerous benefits for commercial agriculture, and their relevance is growing rapidly in the face of climate change. One of the primary advantages of seed priming is its ability to enhance germination rates compared to untreated seeds (Ahmed *et al.,* 2021). This is critically important for farmers, as it ensures higher crop establishment success and reduces the risk of stand failure-a risk that is expected to rise under increasingly erratic climate conditions. In addition to improved germination, seed priming enhances seedling vigour. Primed seeds demonstrate faster and stronger seedling growth, leading to quicker crop establishment and greater competitiveness with weeds (Ahmed *et al.,* 2021). For commercial farmers, this results in earlier planting opportunities, reduced time to harvest, and improved adaptability factors that are vital for maintaining profitability as growing seasons shift and weather patterns become less predictable.

Seed priming has also been shown to improve tolerance to abiotic stresses such as drought and salinity (Arun *et al.,* 2022). This is particularly significant in arid and semi-arid regions, where climate models project increasing water scarcity and soil salinization. Primed seeds exhibit superior performance under water-deficit conditions, improving crop resilience and yield stability. With climate change driving more frequent extreme weather events, including heatwaves, floods, and droughts; such stress tolerance is no longer an option but a necessary tool for climate-smart agriculture. Farmers traditionally compensate for low germination rates and poor seedling vigour by planting excessive seed quantities, by inserting four to five seeds per hole (Bankole *et al.,* 2020). However, this approach raises seed and input costs and can lead to uneven stands and wasted resources. Seed priming, when combined with high-quality seed selection, allows farmers to achieve optimal plant stand establishment using fewer seeds (Chatterjee *et al.,* 2018). Moreover, the improved vigour of primed seeds reduces the need for fertilizers and pesticides, particularly in conservation agriculture systems such as no-till farming (Tanwar *et al.,* 2023). These savings are increasingly valuable in the context of rising global input prices and the push toward more sustainable farming practices.

Beyond establishment, priming has been shown to increase yield potential (Kandhro *et al.,* 2021). Under good management, primed seeds can outperform non-primed seeds in both yield quantity and quality, providing farmers with higher marketable output and improved economic returns. This is especially relevant as climate-induced stresses threaten yield reliability and food security. Looking forward, the development of climate-specific seed priming protocols holds great promise. Traditional priming approaches are largely designed based on current environmental conditions, but the projected shifts in precipitation patterns, temperature extremes, and storm frequency call for more targeted solutions. Priming strategies that enhance drought tolerance and water-use efficiency will become increasingly valuable. Techniques such as osmopriming and hydropriming with controlled hydration levels can prepare seeds to withstand early-season dry spells or erratic rainfall distribution. Furthermore, priming can improve root system development, allowing crops to better exploit available soil moisture during prolonged dry periods.

Seed priming can also help mitigate the effects of rising temperature variability. Thermopriming, which exposes the seeds to sub-lethal heat during priming, has been shown to induce heat tolerance in several crop species. This pre-conditioning could help crops maintain productivity even under frequent heat waves or fluctuating day-night temperature cycles, both of which are projected to intensify under climate change. Priming may also enhance crop resilience to extreme weather events. For instance, priming can strengthen seedling cell membranes and antioxidant systems, improving tolerance to oxidative stress caused by flooding or sudden temperature drops. Developing such protocols will require a deeper understanding of stress physiology and molecular priming mechanisms.

Future research should prioritize the development of region- and climate-specific priming protocols that are tailored to projected future conditions rather than historical norms. This will involve integrating climate modeling with agronomic and seed physiology research. Additionally, participatory research with farmers in vulnerable regions will be crucial to ensuring that priming technologies are practical, scalable, and aligned with local needs.

EMERGING TRENDS IN SEED PRIMING RESEARCH AND TECHNOLOGY

Precision priming

Precision priming is a promising strategy in seed priming research and technology. It entails the use of nanomaterials such as silver nanoparticles (AgNPs), iron sulphide nanoparticles (FeS_2 NPs), and zero-valent iron nanoparticles (nZVI) to improve seed germination and early seedling growth (Nile *et al*., 2022). These nanomaterials have been shown to increase the activity of enzymes such as amylase and protease, resulting in better starch breakdown and nutrient availability for seedling growth (Nile *et al*., 2022). Furthermore, precise priming has been proven to reduce the deleterious impacts of abiotic stressors on seed germination and seedling development (Pawar and Laware 2018). Precise priming is especially beneficial for low-vigor seeds, minimizing seed loss during treatment and boosting overall seed quality and performance (Wzorek and Bose 2019).

Nanotechnology

Nanotechnology in seed priming is a new study and technological trend in seed priming. Seed nano-priming is the application of nanoparticles to seeds, which can have a variety of benefits for sustainable agriculture. Seed nano-priming has been proven in studies to boost plant growth and development, increase production, and improve food nutritional quality (Pereira *et al*., 2021; Salam *et al*., 2022). It can also boost crop tolerance to abiotic and biotic stress, lowering the demand for pesticides and fertilizers (Salam *et al*., 2022). The use of nanoparticles in seed priming is a low-cost method for improving seed germination and subsequent plant growth by activating plant physiological systems and offering resistance to a variety of stimuli (Pereira *et al*., 2021; Salam *et al*., 2022). Therefore, this nanotechnological method has the potential to increase agricultural output while also encouraging sustainable agriculture.

One area where nanotechnology has been applied in seed priming is in the management of phytopathogens, the controlled release of pesticides and fertilizers, and the enhancement of nutrient utilization in plants (Kim *et al*., 2017). Additionally, nanomaterials have been used to modulate the early growth of plants under stress conditions, such as cadmium stress, through seed priming (Karalija *et al*., 2022). In another study, nano-sensors have been developed to improve crop practices and food quality, leading to potentially better and healthier food products (Kim *et al*., 2017). This approach has shown positive effects on biochemical pathways, which can enhance the phytoextraction of cadmium from contaminated soils (Karalija *et al*., 2022).

Application of Plant Growth Regulators (PGRs)

Plant growth regulator (PGR) with seed priming is a well-established practice in seed priming research and technology. PGR seed priming is the process of treating seeds with growth regulators like gibberellic acid (GA_3) and Naphthalene acetic acid (NAA) to improve seed germination and seedling development. Soaking seeds in GA_3 and NAA has regularly been proven to promote seed germination and seedling growth in a variety of crops (Pangestuti *et al*., 2021). PGR priming has been shown to dramatically boost seedling germination, plant height, leaf number, leaf area, and vigour index (Pangestuti *et al*., 2021). PGR seed priming has also been found to increase the expression of aquaporin genes involved in water intake and accelerate starch breakdown, resulting in better seed germination (Nile *et al*., 2022).

Biostimulants and elicitors

Emerging advancements in seed priming research and technology include biostimulants and elicitors. Hydrogen peroxide (H_2O_2) and nitric oxide (NO) have been reported to have a role in fruit tree physiology, including fruit yield/size, tolerance to environmental challenges, and nutrient availability (Tanou *et al*., 2017). Furthermore, biostimulants applied to leaves may operate as whole-plant priming elicitors, potentially being detected systemically by roots (Tanou *et al*., 2017). Through seed priming, elicitors such as methyl jasmonate (MJ), salicylic acid (SA), and paclobutrazol (PB) have been demonstrated to increase drought tolerance in rice (Samota *et al*., 2017). Seed priming with these elicitors boosted total phenolic content, antioxidant activity, and the expression of drought-responsive genes in drought-stressed rice plants (Samota *et al*., 2017). Meanwhile, more emerging trends in research outcomes are now paying attention to seaweed as a biostimulant, and there is little or no research on its usage in seed priming in the literature.

Omics approaches

Omics techniques, which include genomics, transcriptomics, proteomics, and metabolomics are increasingly utilized in seed priming research and technology (Pagano *et al*., 2023). These methods offer deep insights into the molecular dynamics and regulatory networks activated during seed priming. For instance, transcriptomic analyses have revealed substantial changes in gene expression related to stress responses, hormone signaling, and metabolic pathways in primed seeds. Epigenetic modifications, such as DNA methylation and histone acetylation, have also been shown to contribute to priming-induced stress memory and enhanced tolerance (Pagano *et al*., 2023). Furthermore, proteomic studies indicate significant alterations in protein abundance and post-translational modifications that support improved germination and seedling vigor. The application of phytohormones in seed priming has been demonstrated to enhance germination rates and mitigate abiotic stress effects (Rhaman *et al*., 2020). Similarly, nanoparticle-based priming has been shown to enhance enzymatic activity and promote early radicle emergence (Nile *et al*., 2022). Moreover, multi-omics approaches have been employed to explore the influence of seed priming on immune-related processes, further broadening the scope of priming research (Chu *et al*., 2021).

However, despite mentioning biochemical and molecular modifications, many reviews—including this one—often lack detailed discussion of recent advances in understanding the specific molecular mechanisms underlying priming effects. A truly comprehensive synthesis should address gene expression dynamics, epigenetic reprogramming, and proteomic shifts that underpin the physiological improvements seen in primed seeds. Additionally, genetic variation within crop species significantly influences priming efficacy, yet this critical factor remains underexplored. Variability in genotype-dependent responses to priming highlights the need for integrating genomics and breeding strategies with priming technologies to optimize outcomes across diverse cultivars.

Micronutrient seed priming

Agronomic interventions such as nutrient seed priming (NSP) could significantly improve stand establishment in micronutrient-deficient soils. However, the effectiveness of the technique depends on the efficacy of the priming procedures (Nciizah *et al*., 2022). This suggests that with optimum micronutrient concentration levels and appropriate priming duration, NSP can improve germination, seedling growth, and crop yield (Nile *et al*., 2022; Kavitha & Srimathi, 2021). Through complex networks, Seed priming with micronutrients has been shown to improve seed germination, seedling vigour, and crop development (Kavitha & Srimathi, 2021). These smart priming technologies have the potential to address agricultural nutrient deficiencies and difficulties such as poor field emergence and the detrimental impacts of environmental pressures on seed vigour and crop output (Al-Baldawi and Hamza 2017; Shelar *et al*., 2021). However, precise priming procedures and strategies that are helpful to plants and the environment must be carefully selected, since certain nutrients might interact with each other, resulting in the priming methods being harmful

CHALLENGES AND LIMITATIONS ASSOCIATED WITH SEED PRIMING IMPLEMENTATION

Optimal priming conditions

The efficiency of seed priming can be affected by a variety of parameters, including the osmotic potential of the priming solution, the length of priming, the temperature, and the chemicals utilized (Raj & Raj, 2019). To get the intended results, treatments and circumstances must be carefully optimized. Solid matrix priming, for example, entails incubating seeds in a solid insoluble matrix with little water, and the time and kind of matrix utilized might influence the priming process (Raj & Raj, 2019). Furthermore, moisture conditions during seed emergence and subsequent development might alter priming effectiveness (Nakao *et al*., 2020).

Compatibility with seed coating

Seed priming using specific chemicals, such as benzyladenine and gibberellic acid, has been proven in studies to improve crop stand, yield, and seed quality (Kavitha & Srimathi 2021). The usage of seed coatings, on the other hand, may interfere with the absorption and efficiency of these priming compounds. Furthermore, iron-coated seeds have been shown to increase grain production while decreasing insect and disease incidence in wet direct-seeded rice (Kumar *et al*., 2022). The compatibility of seed priming procedures with iron coatings may be critical in this situation for attaining these effects. Seed priming is a method that connects seed germination and seedling establishment, both of which are essential stages for seedling survival in natural settings (Mondal & Bose 2022). Therefore, more research should be directed to the compatibility of priming agents and leguminous seeds that have difficulty germinating.

Environmental sensitivity

Environmental sensitivity poses a restriction on seed priming and its application. Hydropriming and natural priming can energize seedlings and increase germination speed and percentage (Becerra-Vázquez *et al*., 2020). However, environmental variables such as light, temperature, and water availability impact seed priming success (Raj & Raj, 2019). Environmental stressors such as salinity stress can have a deleterious impact on seed germination and seedling emergence (Aghbolaghi & Sedghi 2014; Costa *et al*., 2021). Seed priming has been demonstrated to reduce the impacts of environmental stressors and increase seed performance under salt-stress conditions (Costa *et al*., 2021). However, primed seeds' susceptibility to high relative humidity and temperature might result in lower viability and degradation during storage (Wang *et al*., 2018). To maintain the lifespan of primed seeds, careful storage conditions, such as vacuum or low relative humidity and temperature, are advised. Moreover, a detailed study of the interactions of the environmental stressors, priming agents, seeds of different classes or varieties, and their genetic component effect on seed and seedling establishment in a controlled environment and under field conditions is needed.

Scaling-up for Commercial Production

The necessity for large-scale infrastructure and resources to carry out the seed priming procedure is one of the issues that needs a detailed study in the literature. This includes seed treatment facilities such as hydro-priming or hydro-thermopriming, in which seeds are hydrated for a set amount of time using water treatment (Pereira *et al*., 2021). Large-scale implementation of these therapies necessitates substantial investment in equipment and infrastructure. Another issue is the requirement for standardized techniques and quality control measures to assure consistent and dependable seed priming results. Varying priming techniques can have varying impacts on seed germination and plant growth; hence, it is critical to develop standardized procedures to attain the desired results (Marthandan *et al*., 2020). To optimize the priming process for diverse crop species and climatic circumstances, substantial studies and testing are required. Furthermore, the availability and cost-effectiveness of priming agents may restrict the scalability of seed priming strategies. For commercial production, priming agents such as growth regulators, osmoprotectants, and plant mineral nutrients may need to be administered in considerable amounts, which can be expensive and uneconomical (Marthandan *et al*., 2020). The mechanisms by which an alternative means of using priming agents on a large scale for commercial purposes to enhance crop productivity with improved economic benefits should be well considered.

Interaction with soil conditions

The interaction of seed priming strategies with soil conditions might present problems and constraints. Seed priming treatments' efficiency may vary based on soil moisture content and other soil variables. Research on faba bean seeds, for example, discovered that hydro-priming increased germination characteristics such as germination speed and synchrony, as well as the seedling vigour index (Damalas *et al*., 2019). However, the same study found that hydro-priming did not affect seedling emergence in field experiments. Another research on rice seeds looked at the genetic variety of hydro priming efficacy under different soil moisture levels and discovered that seed priming effectiveness differed between genotypes (Nakao *et al*., 2020). A research effort that looks into the heterogeneity of the soil and soil types, crop types, moisture levels, and atmospheric/ climatic data as they influence seed priming and crop productivity is needed in the literature.

Crop-Specific Responses

Different crops have different seed coats and biochemical components with varied genetic quality, which shows the inherent capacity of the seed as a propagule. The differential impacts of seed priming strategies on various crops can be crop-specific responses. The seed priming efficiency in crops varies, depending on species, priming time, temperature, priming media, and storage conditions (Chatterjee *et al*., 2018). Osmopriming and halopriming, for example, have been shown to create stress tolerances in plants, such as drought resistance in wheat and osmotic stress tolerance in rice (Arun *et al*., 2022). There is, therefore, a need to understand the response of various crops to PGR as a priming agent, Nutri-priming, halo priming, Osmo priming, and their interactions

CONCLUSION AND RECOMMENDATIONS

This study showed that different priming methods may have varying effects on seed viability, vigour, and speed, showing a promising future for seed priming technology. It is recommended that future research should prioritize the exploration of hybrid priming strategies, which integrate multiple priming methods, to develop innovative approaches aimed at maximizing crop productivity. Further research is needed to optimize priming techniques for different field crops and to understand the mechanisms underlying seed priming and its timing under varied environmental conditions with sowing dates. In conclusion, seed priming technology is a valuable tool that offers numerous benefits, including improved germination, growth, and yield. Different priming methods can be employed depending on the crop and desired outcomes. The future of seed priming technology holds great potential for further advancements and applications in agriculture to ensure food security.

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Conceptualization, FNI Methodology, FNI & AR; and OOB: Validation, AR, FNI, SAO & OOB: Writing-Original draft preparation, FNI, and OOB: Writing- review and editing, FNI, OOB, AR, DE, DO: Visualization, FN1, OOB, EO-O and MO: Project administration, MOA, AN, & EO-O. All authors have read and agreed to the published version of the manuscript.

Ethical Statement

Not applicable

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