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Seed Priming to Enhance Plant Stand under Stressed Environment: A Review

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ABSTARCT: Seed germination is the very first stage of a plant's life. For a successful crop yield, good germination is essential which is the most vulnerable stage to any unfavourable environmental condition. Crop plants are subjected to a variety of stresses throughout their life cycle because of increasing stress frequency in view of global climate change. Seed germination, being the very first stage, defines the plant growth and development in a particular environment. Thus, any approach that aids the crop in successful plant establishment is worth putting to use in unfavourable field conditions. Seed priming is a low-cost approach that promotes homogeneous seed germination and early seedling growth in a variety of conditions. The most basic form of seed priming is hydropriming which includes soaking seeds in water for a specific period of time. The use of salt, plant growth regulators, mineral nutrients, biological agents, and other chemicals as the priming agents have been developed over time for increased seed/seedling performance. Hence, this review has been compiled for effect of different seed priming techniques on germination characteristics as well as overall crop performance under both stressed and non-stressed conditions.

Keywords: Abiotic stress, Germination, Hydropriming, Osmopriming, Plant stand, Seedling growth

Crop cultivation in the current changing climatic environment is becoming difficult for sustainable crop yields. Plants are subjected to a variety of stresses, and the effects of these stresses begin to manifest themselves as soon as the seeds are sown in the field. A plant's life cycle begins with the germination of a seed, which is the very first step. A successful crop production depends on the germination and establishment of a good plant stand. If seeds do not germinate properly, the plant population in the field will be diminished, resulting in a reduction in yield and an economic loss. When seedlings emerge quickly and uniformly, they develop a deep root system before the upper soil layers dry up, harden or reach above-optimal temperatures [1].

A potential yield loss has been documented as a result of the highly variable environment during seed germination. Germination can be slowed or prevented, resulting in a decrease in cropping density [2,3]. Crops mature unevenly as a result of this delayed germination, which increases the crop's susceptibility to temperature stress as the growth season progresses [4-6]. Seeds lose their ability to absorb moisture during germination if the soil substrates contain excessive salt [7].

The current intensive agricultural pattern has resulted in an imbalanced ecology, which gives rise to problems such as abiotic stresses. Temperature extremes, floods, droughts, salinity, acidity, mineral toxicity, and nutrient deficiencies have emerged as major challenges for agricultural sustainability. Less known stresses include poor edaphic conditions, high radiation, compaction, contamination, rapid dehydration during seed germination, and so on. The combined effect of stresses would be more harmful than individual stress. Furthermore, previous efforts to improve agricultural productivity in order to meet food demand were accompanied by land degradation and the impact of episodic climate variability, all of which have increased the components, frequency, and magnitude of abiotic stresses.

Worldwide, these stresses cause average yield reductions of up to 50 percent in major crops [8], with high temperature (20%), low temperature (7%), drought (9%), and other forms of stress being the most common (4%). In reality, only 9 percent of the world's land is suitable for crop production, while the remaining 91 percent is under stress. Global warming has increased the frequency and duration of droughts virtually affecting every agricultural region [9-11]. Soil salinization, threatening approximately 20 percent of arable farmland [12] is rapidly increasing at a rate of 1-3% every year and is expected to affect 50 percent of arable cropland by 2050 [12,13].

In such scenario, there is a need to utilize feasible and economic methods for seed germination under unfavourable climatic conditions of drought or salinity to have better plant stand and finally crop yield. With a better understanding of the germination process, seed-based methods that are applicable at the field level are being developed. These are referred to as "seed enhancement techniques." The most common method is known as "seed priming" [14,15]. Seed priming entails an initial exposure to an evoking factor that increases the plant's tolerance to stress in its forthcoming life cycle [16,17].

Seed priming

Malnassy [18] coined the term "seed priming," which refers to a practice that promotes rapid and uniform seedling emergence, which is beneficial for crop establishment in the field. It is a procedure that involves controlled hydration of the seed in a specialized environment, followed by dehydration of the seed, so that germination processes begin but the radicle does not emerge [19]. Seed priming boosts defense mechanisms to withstand environmental stresses during germination [20,21]. The proposed priming mechanisms include epigenetic changes and the aggregation of both transcription factors and signalling proteins in an active state. When exposed to stress, these mechanisms harmonize, resulting in the development of a high-efficiency defense mechanism [17,22]. These treatments result in faster and more uniform germination and seedling emergence [23-29], as well as improved crop establishment under stress [14, 30-35].

Seed priming is a value-added technique that is usually performed on a seed lot of marginal quality and is beneficial for quick germination and uniform emergence [36]. It has been shown to improve germination and seedling establishment in a wide range of field and horticultural crops [37,38]. The advantages of priming seeds include faster and more synchronized germination, increased nutrient uptake, ease of phytochrome-induced photo and thermo-dormancy, a wider temperature range for germination, more efficient water use, and uniform crop maturation [39]. The literal meaning of 'Priming' is the trigger that causes stress tolerance through moderate to intermittent stress.

Seed priming increases seed vigour, which is a complex agronomic trait influenced by various genetic and environmental factors [40,41]. Seed priming can be of several types based on the priming material, including hydro-priming (continuous or successive addition of a specific amount of water to the seeds), osmo-conditioning or osmo-priming (exposing seeds to relatively low external water potential), and halopriming (pre-sowing soaking of seeds in salt solution), Hormonal priming (soaking seeds in solutions containing a limited amount of growth regulators or hormones rather than just water), nutripriming (soaking seeds in solutions containing plant growth inhibiting nutrients rather than just water), bio-priming (coating of seeds with biocontrol agents) and solid matrix priming (the process of combining seeds with a solid or semisolid material and a measured amount of water) [42].

The physiological basis of seed priming

Priming is a water-based technique that allows controlled seed hydration to trigger "pre-germinative metabolism," but does not allow the seed to progress to full germination. Despite the fact that seed priming has long piqued people's interest, the physiological basis of this fascinating technique is still poorly understood. However, a better understanding of pre-germinative metabolism during priming treatment and subsequent germination will aid in the more efficient use of this simple and inexpensive but unique technique. When a dry seed is immersed in water, it goes through three distinct stages before germinating [43]. Phase I is imbibition, which occurs when there is a rapid initial water uptake due to the seed's lower water potential than outside. Initially, there is water movement in apoplastic spaces, proteins are synthesized from existing mRNAs, and DNA and mitochondria are repaired during this phase. In phase II, metabolic activities and repairing processes are activated, as well as protein synthesis via translation of newly formed mRNAs and new mitochondria synthesis, whereas phase III is associated with regaining rapid water uptake capacity and the initiation of growing processes associated with cell elongation, which leads to radicle protrusion. Priming allows the seed to hydrate up to a threshold seed moisture content during phase I and before the end of phase II, when germination is still reversible and just short of radicle protrusion [44]. Priming, in essence, stimulates 'pre-germinative metabolism,' which involves a wide range of physiological functions. This initiates DNA repair pathways and ROS scavenging schemes (for seed repair response) while also preserving genome integrity [15]. Improved seed germination status after priming contributes to increased seed germination under stressful conditions [36]. Furthermore, it promotes the start of significant germination-related activities such as increased energy metabolism, early reserve mobilization, embryo expansion, and endosperm weakening [45].

Biochemical basis of seed priming

As the hydration process advances during the seed priming, the biochemistry of a seed gets altered as well. The first significant change related with priming is the activation of enzyme activities that are critical for germination. Several enzymes, important in pre-germinative metabolism and others which are related with ROS scavenging, are active in the primed seed, indicating the phase I of germination. As a result of priming, the content of non-enzymatic antioxidants such as polyphenols, carotenoids, glutathione, and others also get increased. In general, after priming, biochemical indications of stress tolerance mechanism, germination commencement, and food reserve mobilization are increased, as demonstrated in nearly most of the seed priming studies [49, 51].

Hydropriming is most fundamental among seed priming techniques

The most basic seed priming method, hydropriming, is actually the soaking of seeds in pure water and then re-drying to the initial moisture state prior to sowing. Because no additional chemical agents are required, this method is both cost effective and environmental friendly. The main limitation of hydropriming is unchecked water uptake by seeds due to free water accessibility. The only check factor for rate of seed water uptake is the tissue affinity of the seed to water [36]. Furthermore, this method may cause non-uniform seed hydration, resulting in unsynchronized metabolic activation in seeds and non-homogeneous emergence [46]. Given the limitations mentioned above, it is critical to define the specifics of this technique, such as treatment duration, temperature, and water volume, to ensure desired seed hydration prior to radical protrusion. Despite the limitations mentioned above, hydropriming has been shown to improve seed germination and seedling growth in a range of 10-40% in a variety of crops including chickpea, maize [47], wheat [48], Indian mustard [49], sunflower [50], rice [51], mung bean [52], and durum wheat [53] under both stressed and non-stressed conditions.

Drum priming is a commercial form of hydropriming that was first patented in the early 1990s [54,55]. Seeds are gently rotated in a drum, and water is gradually added in vapour form as a source of hydration. Drum priming could be an alternative to conventional hydropriming because the imbibition is controlled here. A specially designed apparatus allows for the precise regulation of time and water during the hydration process, resulting in an appropriate and uniform moisture level of the seeds [56]. Drum priming with 24-epibrassinolide improves bell pepper germination time and seedling growth while also increasing superoxide dismutase (SOD), catalase (CAT), and peroxidase (POX) activities [57]. Another type of hydropriming is “on-farm priming,” which consists of seed soaking in water, surface drying, and subsequent sowing. The duration of treatment must not exceed the “safe limit” (maximum time of priming without risk of seed or seedling damage by premature germination) [58]. This method has a positive impact on crop emergence and yield [59].

On-farm priming is particularly beneficial for resource-constrained farmers in marginal tropical environments [60]. The effect of hydration conditions on rice seed quality was studied, and it was observed that emergence time decreased while shoot elongation rate increased [61]. Hydropriming and halopriming in wheat improved germination characteristics [62], while, in sunflower, it reduced the time taken to 50 percent emergence and mean emergence time (MGT), resulting in more final emergence, energy of emergence, more plant population, achene yield and yield contributing factors, and achene proteins [63]. Similarly, hydropriming wheat and barley seeds for 5.5-6.5 hours improved germination, seedling growth, resistance to *Fusarium*, radical, coleoptiles, and side roots emergence speed, and fresh weight of seedlings [64]. An optimization study of the duration and temperature of seed priming in wheat seed revealed that 12 hours of priming time and 20°C temperature are optimal in terms of germination percent, speed of germination, and vigour index [65].

Similarly, a study was carried out to determine the best conditions for hydropriming lucerne seeds which showed that the total water weight required to prime lucerne seeds was 80-120 percent of the seed’s original weight, and best results were obtained with water priming at 5°C for 3-5 days with 90-100 percent water to seed weight [66].

Furthermore, standardization of the duration and volume of water used for hydropriming in cowpea revealed that 2 hours of soaking with double volume followed by equal volume resulted in maximum germination, seed vigour, field emergence index, and minimum electrical conductivity. More than 2 hours of priming resulted in a decrease in germination and vigour of cowpea seeds [67]. The effects of hydropriming durations on seedling vigour and field establishment of maize revealed that the best improvement in vigour and field emergence was obtained after 18 hours of hydropriming [68]. The optimization of hydropriming techniques for rice seed was also attempted, and the greatest vigour enhancement was observed in seeds hydroprimed for 48 hours followed by 36 hours [69]. A study on barley seed revealed that safe limit of hydropriming depends upon respiratory activities in the seed. It was observed that a surge in respiration coincides with the starts of each distinct phase of germination and one can optimize the soaking duration using seed respiration or CO_2 exchange rate [70].

Osmopriming

Osmopriming, also known as osmoconditioning, is the process of soaking seeds in solutions with low water potential [41]. The degree and rate of imbibition are limited in osmopriming by exposing seeds to low external water potential. Osmopriming is similar to long-term seed imbibition, which stimulates metabolic activity even before germination. Osmopriming preserves the integrity of the plasma membrane and results in a higher germination percentage than hydropriming. This effect is attributed to osmopriming's prolonged precise seed hydration [71]. Researchers use a variety of chemicals to create solutions with low water potential. In this context, PEG (polyethylene glycol) is the most commonly used chemical compound because it is nontoxic and has a large molecular size that reduces the water potential of the solution without affecting the seeds during soaking [72]. *Trifolium alexandrinum* seed osmopriming with PEG increased seedling growth and germination percentage [73]. Similarly, osmopriming with an adequate concentration of PEG improved seedling growth and germination in rice when compared to hydropriming [74]. PEG osmopriming was also found efficient in stored seeds as well. Under storage conditions, sunflower seeds treated with PEG exhibited significantly higher germination, germination speed, root and shoot length, seedling dry weight, seedling vigour index, and lower electrical conductivity [75].

Other chemicals used to create low water potential solutions include $MgSO_4$, KH_2PO_4, K_3PO_4, KCl, KNO_3, mannitol, NaCl, $CaCl_2$, and others [41]. The osmopriming technique is more difficult to implement financially, technically, and methodologically than hydropriming [76]. Plants grown from osmoprimed NaCl seeds have greater osmotic adjustment ability due to higher endogenous Na^+ and Cl contents in roots and higher levels of organic acids and sugar in their leaves than plants grown from non-primed seeds [77]. In canola and chickpea, seed osmopriming with NaCl increased seedling emergence, seed germination, and plant growth [78,79]. In *Zea mays*, NaCl seed priming also stimulated the antioxidant system and reduced lipid peroxidation. NaCl priming dramatically increased corn plant growth, shoots' and roots' fresh and dry weights and decreased salt stress's negative effect on seedling growth [80]. Similarly, salt priming improved wheat salinity tolerance by increasing metabolite reserves, seedling vigour, and K^+ and $Ca2^+$ contents while decreasing Na^+ contents [81]. Seed osmopriming with a lower NaCl dose alleviated the inhibitory effects of salinity on mung bean plants by increasing osmolytes accumulation, chlorophyll contents, antioxidant defence system, and osmotic adjustment [82].

Osmopriming using copper sulphate and zinc sulphate increased field emergence of maize by 43% and 29%, respectively, however sodium sulphate seed priming did not significantly boost emergence [83]. Similarly, priming wheat with $CaSO_4$ accelerated germination under saline circumstances. $CaSO_4$ treatment resulted in the greatest seedling vigour, followed by $CaCl_2$. Na^+ and K^+ concentrations in seedlings also altered dramatically following priming. However, the concentration of Na^+ was highest in seedlings raised from NaCl-primed seeds, whereas the concentration of K^+ was highest in seedlings raised from $CaSO_4$-primed seeds. $CaCl_2$ treatment resulted in the highest total and reducing sugars, followed by $CaSO_4$ therapy. In conclusion, several salts used to prime wheat seeds increased salt stress tolerance; nevertheless, $CaSO_4$ and $CaCl_2$ were shown to be the most efficient agents [84].

Osmopriming with mannitol reduced the inhibitory effects of salinity and drought on chickpea plant growth. Plants grown from seeds soaked in different concentrations of mannitol (2 and 4%) had higher biomass and shoot and root length under saline conditions than plants grown from unprimed seeds [85]. Similarly, mannitol osmopriming increased seedling growth and germination in salinity-stressed alfalfa. Plants from mannitol-primed seeds had higher antioxidant enzyme activities (SOD, POD, and CAT) and less electrolyte leakage and malondialdehyde (MDA) content, and alfalfa plants were protected from salinity stress damage [86].

A variety of other chemicals are also used for osmopriming. Priming rice seeds with $CaCl_2$, KCl, and ascorbate, for example, increased germination percentage and seedling growth. Additionally, plants emerged from primed seeds had significant changes in calcium and nitrogen homeostasis of seedlings, associated with increased -amylase activity and lower levels of reducing sugars [41].

Priming with hormones

Plant hormones and other plant growth regulators can improve plant growth under stressful conditions when used as a seed pre-sowing treatment [41]. ABA (abscisic acid) is a plant hormone that mediates plant responses to a variety of abiotic stresses such as osmotic, low-temperature, and drought stress [87]. Aside from its role in upregulating the expression of stress-related genes, exogenous ABA application improves plant salinity tolerance. Some ABA-induced genes encode different signal transduction pathways, such as transcription factors, protein kinases/phosphatases, and putative receptors, which could improve plant salinity tolerance [88]. Mustard plants derived from ABA-primed seeds germinated at a higher rate than non-primed seeds [49]. Under low-temperature, drought, or salt stress, ABA-primed canola seeds outperformed non-primed seeds in terms of germination percentage [89].

There are several reports in the literature that show seed soaking in GA_3 (gibberellic acid) improves germination [41,90]. GA_3 improved Ca and K levels in cotton and faba beans when used as a pre-sowing seed treatment [91]. Auxin seed priming increased hypocotyl dry weight, hypocotyl length, and seedling fresh and dry weight in wheat [92]. Priming with GA_3 and ethrel improved seed quality and increased seedling length, dry weight, germination speed, and mean germination time in french bean. Additionally, increased enzyme activity was also observed [93]. In another study, seed priming with ABA and GA increased antioxidant enzyme activity in plants grown from unprimed seeds under drought conditions [94]. Hormonal priming induces cell division in the root's apical meristem and also increases tissue cytokinin and IAA levels, resulting in increased plant growth [95].

Chemical priming

The use of different chemicals for seed priming has also shown prominent effects on seed performance and early seedling growth. For example, the effects of cycocel (CCC) seed priming on crop seed germination, early growth, and vegetative growth was studied in six crops, including wheat, barley, maize, sunflower, safflower, and rapeseed under controlled conditions. Priming with the optimal CCC concentration significantly alleviated the negative effects of stress on these crops. In wheat, maize, and rapeseed, the beneficial effect of CCC priming was observed only at moderate osmotic levels, whereas in barley and safflower, the priming effect was observed at all osmotic levels. Sunflower, on the other hand, did not respond to CCC priming treatments, which could be attributed to its thick achene covering. CCC priming was found to be successful at diverting a significant proportion of assimilates to the root, as evidenced by an increase in the root to shoot dry weight ratio following CCC treatment under all osmotic stress conditions [96]. Cotton seed priming with H_2O_2 at an 80 mM (0.272 %) concentration was found to be efficient under moisture stress conditions. Increased germination and seedling growth, as well as reduced electrical conductivity values in seed leachates from H_2O_2 treated seeds, indicated that treated seeds had increased membrane stability. Simultaneously, a rise in the activity of anti-oxidants such as peroxidase and catalase, as well as malate dehydrogenase, was detected, corroborating H_2O_2's beneficial impact [97]. In paddy, pretreatment with ascorbic acid and salicylic acid at concentrations of 200 and 50 ppm, respectively, resulted in an increase in germination under heat stress conditions due to their antioxidant ability [98]. Ascorbic acid priming gave better results in wheat over other priming agents such as GA_3, kinetin and salicylic acid [99]. Seed priming with ascorbic acid enhances durum wheat's salt tolerance. A study was conducted on proteome analysis comparing unprimed and ascorbate-primed wheat seed during germination in saline and non-saline settings. Pretreatment with ascorbate avoids and reverses the effects of salt on the majority of the proteins studied and alters the abundance of 35 additional proteins, majorly involved in metabolism, protein destination, and storage categories [100].

Nutrient priming

Seed priming with nutrients is an innovative practice that has a positive impact on nutrient supply [101]. Seeds are soaked in nutrient-depleted solutions, while seeds are also soaked in water for comparison [102]. Reports in literature show that plants with a higher nutrient supply are able to withstand abiotic stress and establish better under varying field conditions [103]. Macronutrients like nitrogen, phosphorus and potassium as well as micronutrients like zinc, iron, chlorine etc. play important role for survival of plants under different environmental stresses. Seed soaking in Zn^{2+} improved yield in wheat and chickpea in this context [104]. In a variety of crops, seed priming using KNO_3 was found to be quite efficient. In maize, KNO_3 priming included substantially more proline in comparison to water and urea priming. Priming maize seeds with potassium nitrate and urea results in increased germination percentage, germination rate, and seedling length, antioxidant defence enzyme activity and increases the seed's tolerance to abiotic stimuli such as salt and drought [105, 106]. Similarly, seed priming with potassium nitrate influenced germination percentage and emergence in two salinity-stressed soybean cultivars (Gorgan-3 and Sahar). Under salinity stress, seed priming with KNO_3 increased emergence, germination percentage, plumule and radical length, plant dry weight, leaf area, plant height, and seedling dry weight compared to plants raised from unprimed seeds [107]. However, in wheat, priming with $Mg(NO_3)_2$ outperformed KNO_3 for some parameters. The $Mg(NO_3)_2$ toughened set outperformed the KNO_3 treated set in terms of harvest index, grain yield, biological yield, and test weight. However, both the nitrate treatments increased chlorophyll, nitrogen, protein, and proline contents, as well as NR and SOD activities as compared to control [108].

Bio-priming

Callan et al. [109] coined the term biopriming when they coated sweet corn seeds with bacteria and immersed them in warm water for imbibition of up to 35–40% water. Biopriming, also known as biological seed priming, involves the use of biological material for seed priming [110]. It has been explained as the application of bacteria or fungus to the seeds during the hydration process, as is done in other seed priming techniques [111]. Aqueous extracts of plants have also been used along with other biological materials for seed priming [112,113]. Different researchers have defined and explained this technique differently [31,46], but it simply involves the application of beneficial microbes to seed in conjunction with seed hydration [114,115] unlike biohardening [116].

Biopriming improves seed viability, germination, plant vigour, growth, and yield in tomato and pearlmillet [117, 118]. Biopriming, like other seed priming treatments, aids in the start of physiological processes prior to sowing and the multiplication of 'Plant Growth Promoters' in the area surrounding the seed [119]. The use of *Pseudomonas aureofaciens* via a drum priming system improved tomato stand establishment [56]. The use of *Trichoderma* has grown in importance in plant stress tolerance, particularly under biotic stress, but its use in plant growth promotion has also been documented. *Trichoderma*, when applied to pea seeds as a biopriming agent, significantly improved plant growth parameters, proving biopriming to be an effective method [120]. Among other *Trichoderma* biopriming applications, it increased wheat growth, nitrogen uptake and recovery, agronomic and physiological use efficiency, and performed well even at 75% of the recommended fertilizer dose [121]. Similarly, in an experiment with six crops, brinjal, chilli, guar, okra, ridge gourd, and tomato, it was discovered that seed germination was dependent on a specific dose of *Trichoderma* spores, which enhanced plant growth and induced systemic resistance-related enzyme activity [115]. Aside from that, the authors observed increased germination, vegetative and reproductive growth, and response of snapdragon to biopriming with *Trichoderma* and *Bacillus subtilis* [122]. In another experiment, *Trichoderma* and *Pseudomonas* were applied through biopriming for varying durations, and *Pseudomonas* improved seedling growth and vigour more than *Trichoderma*, but both performed significantly better when compared to non-primed seeds [123]. The use of *Trichoderma* in seed biopriming increased enzyme activity by causing the release of specific metabolites in the maize plant [124]. Priming with two 'Plant Growth Promoters' strains improved barley growth and yield at different fertilizer levels [125]. Plant growth and productivity have been linked to PGP activities when the PGPR and PGPF are applied through priming, and the mechanisms of growth promotion by beneficial bacteria and fungi have been extensively reviewed [126]. Major beneficial effects linked with biopriming are nitrogen fixation; increased solubility and availability of phosphorus, potassium, and iron; production of hormones, vitamins, enzymes, and organic acids from bacteria and other microorganisms; facilitation of nutrient uptake through hyphal networks; and release of several metabolites from fungi which results in faster seed emergence and more vigorous initial growth.

Factors influencing priming outcomes

What should be the seed soaking time?

During the priming process, one question that is certain to arise is: “How long should we immerse the seed in water/any other solution in order to achieve the optimum outcomes from seed priming?” Each combination of conditions under which the priming process is carried out yields a distinct result. A variety of factors influence the duration of the procedure, including plant species, genotypes, temperature or microclimate around the procedure’s setup, among others. Because of this, standardizing the soaking time in different crops/seeds is critical in order to achieve the best results from primed seeds. The practical utility of soaking duration is heavily depending upon on-field conditions such as the season of sowing, the availability of appropriate equipment, the quality of the water, and the availability of time etc.

Temperature of the soaking

The temperature of the seed priming environment can have an impact on the rate of hydration and imbibition. The temperature should be within an acceptable range (suitable for the crop/ species); otherwise, it can have a negative impact on the priming process. Under the same set of seed priming conditions, a higher temperature can accelerate the quick absorption of water, whereas a lower than optimal temperature can result in insufficient hydration. Furthermore, priming at a high temperature increases the likelihood of fungal infection as well as seed injury as a result of excessive moisture.

Volume of water

Additionally, the weight of the seeds in relation to the volume of water used for soaking is a significant component that influences the hydration and respiratory status of the seeds. If the seeds are completely submerged in water, anaerobic conditions will prevail, however if the seeds are partially submerged in water, aerobic conditions would prevail. In general, the amount of water should be sufficient to fully immerse all of the seeds and ensure that no seed remains dry during the priming process. It is possible to standardize the ideal priming conditions for a certain crop/genotype/seed by making adjustments to the water volume, container, and physical alignment (single layer or multilayer) of seeds in the priming set up.

Rate of hydration

The rate at which seeds are hydrated has a significant impact on the outcome of seed priming. Simpler priming methods, such as those in which the seed comes into direct contact with water, are easy to perform over more complex approaches, such as those in which water absorption is controlled. On the other hand, the results of controlled hydration procedures are found to be more prominent. However, when seeds remain in direct contact with the solution, the chances of uncontrolled hydration are more. Therefore, it is suggested to control the hydration rate by modifying different conditions i.e. soaking duration, temperature of priming, volume of solution, shape of container etc.

Quality of water

Another component affecting the priming process is the water’s quality. If the water is of poor quality, the beneficial effects of seed priming in terms of germination percentage may not be up to the mark or sometimes shows even negative effects. For instance, the presence of salts or any other hazardous component in the water used for priming can have a deleterious effect on the seed. However, use of salts in halo or osmopriming produces beneficial effects but the concentration of salts in these methods is very less i.e. usually in ppm. In practice, farmers often use water from their irrigation supply, and sometimes the quality of groundwater might alter the priming dynamics. Canal water, on the other hand, is normally of good quality and should be used whenever possible. Generally, water whose electrical conductivity is less than 2 dSm^{-1} and free from any hazardous element can be considered good for priming. Therefore, farmers should keep this element in mind when practicing seed priming at the farm level. Additionally, researchers should investigate and standardize the probable impacts of priming with various water sources.

The role of seed priming in reducing the effects of abiotic stress in crop plants

Abiotic stresses are the prime threats to plant growth and their productivity especially under the changing environmental conditions. Proper germination, seedling establishment in field and early growth are very crucial for a successful crop. Seed priming can induce beneficial changes in the seed germination pattern under varying field environments and help the crop to establish more easily. The role of seed priming for imparting tolerance in various crops against abiotic stresses has been studied extensively by many researchers. In maize, germination percentage, germination index as well as chlorophyll and carotenoid content decreased under salt stress. These effects were alleviated by seed priming which chloride salts (NaCl, $CaCl_2.2H_2O$) induced metabolic changes that helped in better acclamation of maize plants under salinity stress [127]. Salt tolerance is induced in rice cultivars by seed priming with $CaCl_2$ and KCl, as evidenced by increased germination efficiency, seedling growth, and dry weight in saline medium [128]. Similarly, H_2O_2-treated seed improved salt tolerance in wheat cultivars [129]. Under common salt and PEG stress, mustard seed primed with water, $CaCl_2$, and abscisic acid exhibited higher germination, and crop raised from primed seed has a high dry weight and chlorophyll content [49]. Under salinity and water deficit stress, hydropriming and KNO_3 treatment significantly improved germination and seedling growth in sunflower [50]. Halopriming reduces salt stress in mungbean by increasing antioxidant enzyme synthesis, H_2O_2 production, and proline accumulation [82]. Under saline-sodic conditions, water-soaked seeds yielded more grain and straw than non-primed seeds in barley [130]. Priming seeds in distilled water, $CaCl_2$, KCl, and NaCl for 12 hours was found to be effective in mitigating the negative effects of salt stress in wheat in terms of shoot fresh and dry weights, as well as grain yield [131]. Seed priming treatments with 0.5 percent KH_2PO_4 and water had a significant effect on germination and seedling characteristics of hexaploid triticale under different osmotic potentials of NaCl and PEG solutions. Under high stress conditions, KH_2PO_4 priming improved germination percentage and seedling growth, whereas hydropriming was found to be very effective under low stress conditions [132]. The effect of pre-sowing chilling and hydropriming of seeds on the performance of two wheat varieties was investigated [133], and it was discovered that chilling was far more effective than hydropriming and control under salt stress in increasing germination rate and subsequent growth. Similarly, the potential of various seed priming agents was tested in wheat varieties (SARC-1 and MH-97) under saline conditions. Seed priming treatments significantly improved stand establishment, with osmopriming (with $CaCl_2$) coming out on top. Similarly, in both varieties tested, plants raised from osmoprimed (with $CaCl_2$) seeds followed by ascorbate priming had the most fertile tillers, grains per spike, 1000-grain weight, grain yield, and harvest index. Priming treatments improved the leaf K+ contents while decreasing the Na+ concentration, with osmopriming being the most effective. Similarly, osmoprimed (with $CaCl_2$) seeds with ascorbate priming had the highest total phenolic content, total soluble proteins (TSP), -amylase, and protease activities [134]. The effect of salicylic acid seed priming on *Vicia faba* under different levels of salt stress revealed that 0.25 mM SA concentration improves germination percentage and speed [135]. Salicylic acid (SA) and thiourea (TU) seed priming and foliar application in two crops (pearlmillet and wheat) improved physiological traits, biochemical traits, and ultimately grain production. SA and TU both increased plant height and grain yield, although increase with SA application was higher than TU. The average yield improvement with the application of SA and TU was 14.42 and 12.98 percent in pearl millet, whereas, it was 12.90 and 17.36 percent in wheat, respectively [136]. All the above mentioned studies established the role of pre-sowing seed priming treatments in abiotic stress tolerance. It is evident from this analysis that seed priming with water or any other chemical agent, salt, growth regulator or biological agent can induce the early and uniform emergence under hostile environments. However, there is a need to standardize the nature of priming agents and their concentrations for extracting the best possible results of seed priming treatments.

Conclusion

Seed priming techniques have the potential to enhance the seed performance in a practical sense. Evidence suggests that seed priming prior to sowing aids in uniform and vigorous seedling establishment. Furthermore, under stressed environment, these techniques result in better plant stand and also impart tolerance.

Future prospects

The methods of seed priming should be standardized with respect to soaking time and temperature, water quality and volume, and dimensions of priming container etc as per crop/ variety. Furthermore, the comparative efficacy of various treatments must be evaluated with respect to physiological, biochemical and molecular aspects. Moreover, the benefit: cost analysis is necessary in every case. So, the evaluated technique would be practically applicable on farmers' field.

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