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Optimizing Cereal Crop Performance with Nutrient Priming

Vincy Alex [a++], Jacob D. [b#*], Shalini Pillai P. [a†], Sheeja K Raj [c#], Joby Bastian [d‡] and Navya M.V. [a^]

[a] *Department of Agronomy, College of Agriculture, Vellayani, Thiruvananthapuram 695 522, India.*
[b] *On Farm Research Centre, Onattukara Regional Agricultural Research Station, Kayamkulam 690 502, India.*
[c] *Department of Organic Agriculture, College of Agriculture, Vellayani, Thiruvananthapuram 695 522, India.*
[d] *Farm Power Machinery, Rice Research Station, Moncompu 688 503, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The fundamental building blocks for the success of stand establishment for any crop plant are better germination and robust seedlings. Pre-treatment of the seeds is one of the best methods that may possibly improve germination and maintain the uniformity and stability of the seedlings. Primed seeds usually exhibit synchronized and early germination and sometimes greater total germination

[++] *PG scholar;*
[#] *Assistant Professor (Agronomy) and Head;*
[†] *Professor and Head;*
[‡] *Professor;*
[^] *PhD Scholar;*
**Corresponding author: E-mail: jacob.d@kau.in;*

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percentage over a range of environmental conditions. This enhancement has been linked to osmotic correction, metabolic repair during imbibition, and the accumulation of chemicals that promote germination. Nutri-priming is a good alternative to meet plant nutritional requirements. Seed priming with macro or micronutrient (nutripriming) application has been recently done on various agronomic crops including rice, maize and wheat; lead to better germination and establishment. It aims to combine the positive effects of hydro priming with the nutritional aspect of fertilizers. Crop seeds can be primed with either micro or macronutrients, which improves the nutrient content and increases the germination, sprouting, and water uptake efficiency. Primed seeds performed better under diverse environments especially under sub optimal conditions at sowing and resulted in higher yield compared to unprimed seeds. Priming requires specific temperature and time, if it is not followed then the seed can be deteriorated due to embryo protrusion. Due to readily available food during germination, primed seed are better able to complete the process of germination in a short time and cope with environmental stresses including low temperatures. In fact, it may be regarded as a useful method for enhancing crop establishment in regions with unfavourable agro-climatic conditions (rainfed, dry farming, and dry land farming) with increased yield, tolerance to stressful situations, resistance to diseases, crop competitiveness against weeds, and water use efficiency.

Keywords: Nutripriming; germination; seedling vigour; higher yield; environmental stress.

1. INTRODUCTION

In addition to being necessary for our dietary requirements, cereal grains are also used in industrial processing and as animal feed. All members of the grass family (Poaceae), the cereal species of agricultural importance are rice, wheat, maize, rye, barley and oats. The fundamental building blocks for successful stand establishment of any crop plant are better germination and robust seedlings. Pre-treating seeds is one of the most efficient techniques for improving the process of germination and ensuring uniform stability in seedlings [1]. Seed priming is a pre-sowing technique which involves partially hydrating seeds to start germination-related metabolic processes before the radicle actually emerges [2]. Seeds that primed frequently showed earlier and more coordinated germination, as well as a higher percentage of germination overall environmental circumstances [3,4,5]. This enhancement has been linked to osmotic adjustment., metabolic restoration that occurs after imbibition and the accumulation of substances that promote germination. These effects are connected to the swift reinitiation of RNA and protein synthesis, the production of germination-promoting substances, early DNA replication, increased ATP availability, and cellular structure restoration, osmotic adjustment, and occasionally, enhanced activity of defence enzymes and antioxidants [6].

The osmotic potential of the medium gets lowered by the addition of salts to the priming solution, thereby regulating the rate of hydration of seed [7]. The improved performance associated with priming is linked to the repair and increased protein production, membrane repair, synthesis of nucleic acids and enhanced antioxidant systems [8,9,10]. Nutripriming seeks to merge the benefits of hydropriming (which involves hydration of seed without osmotic agents) with the nutritional advantages of fertilizers. Nutri-priming is an effective method for addressing plant nutritional needs [11]. It holds significant potential for improving seed germination and establishment of crop in conditions of limited soil moisture [12]. When seeds are primed with micronutrients, they can quickly absorb water, resume metabolism, and initiate germination. This leads to better stand establishment, increased resistance to pests and drought, and ultimately higher yields [13]. Recently, Nutri-priming, or seed priming with macro or micronutrient treatments, were used recently on a number of agronomic crops, such as rice, maize, wheat [14,15,16] and lead to better germination and establishment.

2. CURRENT STATE OF SEED PRIMING

Seed priming is an effective technique for boosting productivity of crop. Farmers in Botswana, Malawi, Zimbabwe, India, Nepal, and Pakistan commonly use hydropriming as a seed priming method. The Centre for Arid Zone Studies (CAZS) has set "safe limits" for priming of upland rice, maize and wheat in on farm, specifying the maximum duration seeds can be soaked.

Nowadays, seed priming appears to be a good and extensively used technology. Farmers and researchers are increasingly using seed priming techniques across various crops, including cereals, legumes, and vegetables. In thirty on-farm studies, it resulted in an average yield increase of 50 per cent. Specifically, on-farm seed priming boosted maize yields by approximately 22 per cent in Zimbabwe and India, wheat yields by about 37 per cent in India and Pakistan, and upland rice yields by around 70 per cent in West Africa [17]. Ongoing research studies focuses on optimizing priming techniques, understanding the physiological mechanisms involved, and evaluating the long-term benefits on growth, yield and stress resilience. Seed priming helped to enhance productivity while using fewer resources, making it suitable sustainable agriculture.

3. SEED PRIMING PROCESS

The development of a number of priming techniques, such as biopriming, or treating seed with microorganisms (Pseudomonas, Trichoderma, Azospirillum, Rhizobium), hydropriming, halopriming, osmo-priming, matrix priming, osmohardening, hormone or growth regulator priming, on-farm priming and micronutrient seed priming (Nutripriming) has led to an improvement in seed quality. Seed priming involves partially hydrating seeds to initiate metabolic activity in a controlled way, preparing them to start essential pre-germination processes.

During seed priming, several key adjustments take place, including growth of the embryo, modifications to the tissues surrounding the embryo in the endosperm, breaking dormancy, and improvement of pre-germination metabolism. As a result of these processes, primed seeds exhibit higher germination rates, earlier and more uniform germination, faster emergence, improved growth characteristics and improved crop establishment [18].

4. IMPACT OF SEED PRIMING ON GERMINATION PROCESS

Rapid and synchronized crop emergence, along with quick root development, is crucial for successful crop establishment. Seed germination generally involves three distinct phases such as Imbibition phase, the activation phase, and the germination phase, during which the root and hypocotyl emerge from the seed. Both Phase I and III involve an increased water content and hydration occurs stable in phase II. Germination remains reversible until the end of phase II, allowing seeds to be dried and stored while still remaining viable. They can reinitiate germination under favourable conditions. Priming treatments are applied during this reversible stage of germination. These treatments were different according to the osmotic potential of priming solution, length of priming process, the temperature in which the priming process occurs, and the chemicals utilized.

5. FACTORS AFFECTING PRIMING

Temperature, aeration, light, length and seed quality are the main variables that influence seed priming [19].

Aeration: It affects the seed viability and respiration, that helps in timely germination and ensures a safer seed habitat. Aeration has different effects depending on the species.

Light: The impact of light on seed priming varies significantly between species. The quality of light influenced the action of seed priming.

Time: The length of the priming process depends on the temperature and osmotic potential of the solution at which priming occurs.

Temperature: Radicle emergence during priming may be restricted if the soaking is maintained below the ideal temperature.

6. METHODS OF SEED PRIMING

6.1 Conventional Methods of Seed Priming

Hydro-priming: Hydro-priming is a cost-effective method in which seeds were soaked in water for a particular time period then dried to a specific moisture content prior to sowing [20,21]. This method is better in adverse environmental circumstances, like intense heat and drought stress, because it improves seed hydration and water uptake efficiency [22].

Osmo-priming: Osmo-priming is a seed treatment technique that is most effective at higher water potentials (−0.3 to −1.5 MPa) and with shorter priming durations of 12 hours to 2 days [23,24,25,26]. When using more negative water potentials and/or extending priming times, oxidative processes can occur, leading to the accumulation of substances that are harmful to germination [27]. Most frequently used as a solute for osmo-priming is high-molecular-weight polyethylene glycol (PEG). It induces high osmotic pressure and thereby modifies the availability of water in the germination medium [28]. However, high concentrations of PEG lead to increased viscosity, which limits oxygen transfer and necessitates effective aeration during the priming process.

Halo priming: Halo-priming induces a physiological response in seeds that enhances their stress memory, enabling plants to react swiftly and effectively to upcoming abiotic stresses [29]. Plant stress memory is preserved through seed halo-priming and exposure to osmotic stress [30,31]. As a result, mild pretreatment stress can enhance tolerance to subsequent stresses [31]. Thus, seed halo-priming is highly effective in boosting plant tolerance to unfavourable environmental conditions and improving grain yield [32,33,34,35,36].

Solid matrix priming: This process involves mixing moistened seeds with an organic carrier and adjusting the moisture content of the mixture to just below the level needed for seed sprouting. Solid matrix priming can further improve the effectiveness of antagonists in treated seeds, as they proliferate on the seed surface during the priming process, thereby increasing the number of propagules [37].

Bio-priming: Bio-priming is another method of seed priming where seeds soaked in a solution containing bio-control agents, such as bacteria. This treatment activates specific signalling pathways during early stages of crop development, leading to quicker plant defence responses. Compared to chemical treatments, bio-priming offers several benefits, including being more cost-effective, time-efficient, environmentally friendly, and enhancing desirable traits in the treated seeds.

Nutripriming: Nutrient priming is the process of saturating seedlings with a particular amount of nutrients for a set of time prior to planting [38]. Seeds can be primed with micro or macronutrients, which improves the nutritional content, increases the germination, sprouting, and water absorption efficiency.

Priming with plant growth regulators: The addition of plant growth regulators (PGRs) to seedlings mitigates the detrimental effects of various kinds of environmental conditions [29].

Priming with plant extract: Steroids, alkaloids, terpenoids, flavonoids, saponins, phenolic compounds, and flavonoids are examples of allelochemicals that can either impede or promote plant growth. Saponins can enhance nutrient absorption due to their high solubility in water. Satish et al. [39] showed that alkaloids, phenolic compounds and saponins found in the leaves of most of the plants contribute antioxidant activities and offer protection against pathogens. Srimathi et al. [40] found that seeds that primed with 10% prosopis leaf extract and then 10% moringa leaf extract exhibited improved seed quality characteristics, including vigour index I and II, dry matter production, seedling length, and germination percentage and speed and in the field evaluation, increased seed yields and yield related parameters such as cob length and girth, total number of seeds cob^{-1}, 100 grain weight, grain yield per ha, and harvest index, were seen in the seeds primed with 10% prosopis leaf extract and 10% moringa leaf extract.

6.2 Advance Method of Seed Priming

Seed priming with nano particles: Nanotechnology, which uses particles with a size of less than 100 nm, offers a potential future in altering agriculture and food production [41].

Seed priming through physical agents: Some physical agents employed for seed priming include the UV radiation, X-rays, gamma radiation, magnetic field and microwaves [42]. It was discovered that priming with a magnetic field increased seedling biomass, seedling vigour, germination rate and resistance to different environmental conditions.

7. MERITS OF SEED PRIMING

Priming the seed enhances establishment of seedlings and helps in uniform germination, leading to more efficient harvesting and potentially higher crop yields [19]. It enhances a number of parameters related to seed performance, including seedling vigour, mean germination time, germination index and speed of germination. Compared to unprimed seeds, primed seeds typically yield more because they function better in a number of situations, especially when the environmental conditions are not ideal, such as excessive moisture and severe temperatures. Caseiro et al. [43] said that increased adaptation to adverse conditions of environment helps to overcome the dormancy.

8. DEMERITS OF SEED PRIMING

- Priming requires precise temperature and timing; failing to adhere to these conditions can lead to embryo protrusion and seed deterioration.
- Osmotic seed treatment can be costly.
- Continuous aeration of seeds in the solution is necessary; otherwise, seeds may suffer from the adverse effects of insufficient oxygen.
- As the treatment is done over a long period, it is important to take proper precautions to prevent microbial contamination.

9. EFFECT ON NUTRIENT USE EFFICIENCY

Priming can improve the efficiency of nutrient utilization by inducing the overexpression of genes that code for certain transporters. Singh et al. [44] described that by increasing nitrate reductase enzyme activity, this helps plants for better absorption of nitrogen. Phosphorus priming in cereals led to a reduction in infestation by *Striga hermonthica* (parasitic weed) [45]. Phosphorus uptake can be enhanced through nutripriming with phosphorus in rice [46]. Ahmed et al. [47] discovered that priming seeds with silicon (Si) had increased the Si content in plants, thereby enhancing their resistance to abiotic and biotic stresses. According to Harris et al. [15] investigation into the effects of nutripriming with zinc (Zn) on maize yield attributes showed that total biomass, yield of (grain, cob and straw), shelling percentage, and thousand grain weight were all comparable to seed priming with 1 per cent Zn, and applying 2.75 kg Zn per hectare to the soil.

10. NUTRIENT PRIMING

Nutrient priming refers to the process of saturating seeds with a particular nutrients levels for a predetermined amount of time prior to planting [38]. It seeks to integrate the benefits of hydropriming with the nutritional advantages of fertilizers. Crop seeds primed with macro or micronutrients, increasing the nutrient content and increasing the efficiency of germination, sprouting, and uptake of water. Seed priming with micronutrient is a widely recognized technique for enhancing osmosis for water management in seeds during germination process [48].

Similarly, the most successful method is macronutrient seed priming [49]. For instance soaking the crop seeds in potassium can increase the plant's ability to withstand various environmental stress conditions. In case micronutrient seed priming, priming wheat with Zn solutions can increase grain yield [50]. Similar to this, Harris et al. [51] said that Zn priming can help plants overcome Zn deficit in moderately deficient soils like alkaline soil. According to Shivay et al. [38] it enhances crop growth productivity and nutrient uptake.

11. EFFECT OF NUTRIPRIMING ON CROP PRODUCTION

The method of controlling a seed moisture content to promote the metabolic processes necessary for germination while inhibiting radicle emergence is known as seed priming. Radicle emergence needs high water content in seed. After sowing, seeds typically spend a considerable amount of time for absorbing water from the soil. Research has shown that primed seeds emerge more quickly, grow more vigorously, flower earlier, mature sooner, and produce higher yields. According to Farooq et al. [52] and Rehman et al. [53] seed priming is a straightforward and cost-effective technique that involves soaking the seeds in a solution that containing various salts, nutrients, or other osmotic agents for a specific period, followed by drying before sowing process.

11.1 Influence of Nutripriming on Growth and Yield

Nutripriming seeds boosts germination uniformity rate and speed even under suboptimal field conditions, thereby promoting the development of a consistent and healthy crop stand. Farooq et al. [52] found that the readily available nutrients during germination enable primed seeds to complete the germination process more quickly and effectively manage adverse environmental conditions, including low temperatures [54,18]. Seed priming with nutrients also substantially increase the number of total and fertile tillers.

Rice: An experiment was conducted by Ancy et al. [55] run to determine how nutripriming affected the tray nursery method for rice. The seeds cultivated in seedling trays filled with a growth medium undergone the following nutripriming treatments composed of 60% rice husk charcoal, 20% coir pith compost and 20% soil: 0.01% borax, 0.05% $ZnSO_4$, 0.1% urea, combinations of urea along with borax and $ZnSO_4$, 1% PGPR mix I and 1% Pseudomonas fluorescens. Among these, the combined application of urea, zinc, and borax proved to be the most effective for optimizing seedling and mat growth parameters.

Therefore, it was determined that nutripriming with 0.1% Urea + 0.05% $ZnSO_4$ + 0.01% Borax was a better.

A field trial attempted by Farooq et al. [18] to improve seedling yield of nursery rice (*Oryza sativa* L.) by applying seed treatment and to find the effect of seed treatment on yield after planting. The priming agents used during the study are pre-germination, hydrogen priming for 48 hours, vitamin priming with 10 ppm ascorbic acid for 48 hours, osmo hardening with $CaCl_2$ and KCl (ψs-1.25 MPa) for 24 hours, and seed hardening for 24 hours. The germination rate, spread, root and shoot length, fresh and dry weight of the seedlings nitrogen content of the seedlings, number of secondary roots, activity of α-amylase and total sugars were all improved by all priming techniques. The best results were obtained by osmocuring by $CaCl_2$, which was followed by hardening and osmo hardening with KCl. This method demonstrated superior germination rate, seedling vigournes and starch metabolism.

However, untreated rice also showed improved starch metabolism during osmosis with KCl. Higher concentrations of calcium (Ca) and potassium (K) were noted in seeds osmohardened with $CaCl_2$ and KCl. The highest yields of straw and grains, together with the best yield index, were obtained through osmohardening with fine rice ($CaCl_2$) and coarse rice (KCl). Higher nitrogen concentration in seedlings and decreasing sugars were associated with more secondary roots and increased α-amylase activity, respectively.

Boron (B) is one of the most important micronutrients that rice needs especially during reproduction. Farooq et al. [7] looked into the possibility of boron nutrients to enhance rice germination and early plant growth in a laboratory study. Super Basmati, a fine-grained fragrant rice variety, was prepared with aerated boron (B) solutions at 0.5%, 0.1%, 0.01% and 0.001% (w/v) concentrations where untreated dry seeds serving as the control. In terms of germination time, germination percentage, germination rate, germination energy and mean germination time, seed priming in 0.1% and 0.001% B solutions increased germination by up to 50%. Higher concentrations had minimal or no adverse effects on the rice seeds.

In cases treated with diluted B solution i.e. 0.001%, plumule length, radicle length and secondary roots were better than other treatments, because inhibition of these traits was observed with B treatments except the control. Priming seeds in a highly concentrated boron (B) solution, specifically 0.5%, entirely inhibited both germination and growth.

The investigation was conducted by Afreen et al. [56] for both the nursery and the transplanted field in the paddy *var.* Shabhagi Dhan to examine how iron and zinc micronutrient treatments to paddy seed affect development and productivity. A single seed lot was treated with four different concentrations of $ZnSO_4$ and $FeSO_4$ solutions (0.25%, 0.5%, 1.0%, and 2.0%) at room temperature for 24 hours. In the nursery, $ZnSO_4$ at 1.0% produced the tallest seedlings, $FeSO_4$ at 2.0% resulted in the highest seedling biomass, $FeSO_4$ at 0.5% achieved the highest zinc concentration, and $ZnSO_4$ at 0.5% yielded the highest iron concentration.

In a transplanted field trial, treating seeds with $FeSO_4$ (0.5%) significantly increased the number of tillers per square metre and panicles per square meter compared to both the control and hydropriming. $ZnSO_4$ (1.0%) treatment resulted in higher iron and zinc content in the plants compared to the control and hydropriming. Meanwhile, $FeSO_4$ (2.0%) treatment led to notable improvements in the height of plant, number of productive tillers per hill, panicle length, seed yield per hill, and harvest index per hill.

By using several priming procedures, including on-farm priming, hydropriming, hardening, and osmohardening using $CaCl_2$ and KCl, research was carried out by Rehman et al. [52] to examine the on-farm evaluation of direct seeded rice. The control group used untreated seeds. Osmohardening with $CaCl_2$, followed by KCl, led to increased plant height, more tillers, higher straw and kernel production, an improved harvest index, and a stronger crop stand. This was demonstrated by reduced time to emergence, higher emergence index and final emergence, enhanced crop growth rate, and improved plant height.

Wheat: Iqbal et al. [16] aimed to maximize the benefits of seed priming treatments with B in order to improve wheat germination and early seedling growth and development. Mairaj (2008) and Faisalabad (2008) wheat cultivar seeds were soaked in aerated B solution at different concentrations (0.001, 0.01 & 0.1% w/v) for a duration of 12 hours. Regarding controls, there were dry seeds that were not treated and seeds that were hydroprimed for 12 hours. Wheat seedlings primed in 0.01% and 0.001% boron (B) solutions showed a reduction in both 50% GT and MGT, although ultimate germination rates remained unaffected. Seed priming with 0.001% boron (B) also enhanced shoot and root length, along with increasing seedling dry weight. For more uniform plant stands and earlier seedling growth, priming wheat seeds with 0.001% B is recommended.

Poor crop stand and production are caused by zinc (Zn) deficiency, a significant micronutrient disease in wheat. Rehman et al. [57] conducted two experiments, one in sand-filled pots and the other in Petri plates, to examine the effect of different Zn seed priming treatments on growth of seedlings and stand development of two bread wheat cultivars. $ZnCl_2$ and $ZnSO_4$solutions in concentrations of 1.0, 0.5, 0.1, 0.05 and 0.01 M were utilized for priming seeds for a duration of 12 hours. Hydropriming (HP) and dry seeds were utilized as controls. In the Petri plate experiment, hydropriming improved seed performance, but priming with Zn improved seedling size, final germination, and rate of germination (reduced mean germination time) even more. The most significant improvements were observed with priming using 0.1 M $ZnCl_2$ and 0.5 M $ZnSO_4$. These treatments are more effective than others in the experiment conducted with sand-filled pots, enhancing crop establishment and seedling development in both cultivars. However, enhancing the concentration of Zn solutions beyond 0.5 M $ZnSO_4$ and 0.1 M $ZnCl_2$ proved detrimental. Therefore, a 0.5 M $ZnSO_4$ solution is recommended for priming wheat seeds to boost early seedling development and stand establishment.

A study was done by Choudhary et al. [58] to see how two varieties of wheat, HUW-234 (V1) and BHU-3. (V2), responded to various priming treatments in both laboratory and field conditions. Seeds of wheat varieties were primed with water (hydro), $ZnSO_4$, Mg $(NO_3)_2$ and a mixture of the two salts. The effects of treatment passed on to the germination and vegetative phases of growth, as was observed. The effectiveness of non-primed control seeds served as the baseline for all comparisons. Maximum germination percentage was noted with Mg $(NO_3)_2$, while maximum root and shoot lengths, dry and fresh weights for both varieties were recorded in combination of two salts.

Primed sets were consistently found to be superior than non-primed controls, despite the fact that vigour index I and II indicated varietal differences. Studying the performance of plant height, fresh and dry weights, leaf number and area, of all leaves, and stem under the use of both salts namely, $ZnSO_4$ and Mg $(NO_3)_2$ showed the greatest performance.

The conclusion is that priming seeds with $ZnSO_4$and Mg $(NO_3)_2$ increased growth characteristics in the field and functioned synergistically at the varietal level.

Reis et al. [59] examined the effects of priming seeds with various doses (1 mg L^{-1} to 8 mg L^{-1}) of Zn and Fe on bread wheat variety "Jordo" germination, mitosis, and yield as compared to control. Overall, the findings indicate that micronutrient levels exceeding 4 mg L^{-1} have a detrimental effect on germination. More specifically, concentrations of Fe and Zn above 2 mg L^{-1} cause a considerable an increase in the proportion of abnormal cells and decrease in the mitotic index. It has been demonstrated that treatments containing 8 mg L^{-1} of Zn and 8 mg L^{-1} of Fe had a detrimental effect on grain yield, mitosis, and germination. On the other hand, seed priming containing 2 mg L^{-1} Zn and 2 mg L^{-1} Fe results in a high germination rate (80%) and a normal cell division rate (90%).

An experiment conducted by Sarlach et al. [60] had eight treatments which includes: (T_1) control, (T_2) hydro priming, (T_3)10 g/ml cobalt chloride priming, (T_4)15 g/ml cobalt chloride priming, (T_5) 1.0% potassium nitrate priming, (T_6), 2.0% potassium nitrate priming, (T_7) 0.5% calcium chloride priming, and (T_8) calcium chloride 1.0% priming. Results showed that after 24 hours of priming, the treatments T_4 (15 g/ml $CoCl_2$ priming) and T_6 (2. 0% KNO_3) were equal in terms of seedling length, seedling vigour index, and seedling fresh weight. Mean days to germination (MDG) were likewise shorter in all treatment groups compared to controls. In the field trial, seed priming for 12 hours with 15 g/ml $CoCl_2$ and 2.0% KNO_3 significantly increased grain production compared to control. With 15 g/ml $CoCl_2$ and 2.0% KNO_3, grain production increased by 19.98% and 18.3% after just 12 hours of seed priming. Water priming (T_2) and $CaCl_2$ 0.5% priming (T_7) for 24 hours, resulted in a grain yield that was lower than the control. It is possible to draw the conclusion from this study that 12 hours of seed priming is helpful to improve uniform seedling emergence and to increase wheat grain production.

Maize: The purpose of this study by Canak et al. [61] was to compare the effects of different seed priming techniques on the germination characteristics of maize at varied temperatures. Seeds were primed in water (hydropriming) and (0.1% and 0.5 %) of KNO_3 by soaking at 25^{o}C for 17h. At 25°C, 15°–25°C, and 15°C, germination parameters were examined. Some aspects of seed germination at low and mixed temperatures responded favourably to seed priming. The most beneficial treatment was 0.5% KNO_3 treatment. During the low and mixed-temperature treatments, Time to 50% germination and Mean Germination Time (MGT) were decreased. According to the study, seed priming with KNO_3 can be utilized to improve seedling establishment in maize under low temperature settings.

In order to find out the impact of priming methods on the features of viability of locally grown maize seeds preserved for five years, an experiment was carried out by Hussein et al. [62] used seeds that were stored until 2014 after being directly harvested from the farms of the Babil governorate during the 2009–2010 growing season. Various priming media, such as 2% and 4% KH_2PO_4, 0.5% and 1.5% $ZnSO_4$, hydropriming, and untreated seeds as the control, were applied to the seeds for six hours at 25°C. The results of the seed germination percentage, germination speed, length of shoot, length of root, seedling length, seedling vigour index (SVI), and seedling fresh and dry weights showed that the seeds primed with 2% KH_2PO_4 and 0.5% $ZnSO_4$ had the greatest values when compared to the control.

The effects of zinc (Zn) combined with boron (B), manganese (Mn) and phosphate (P) during seed priming were studied by Muhammad et al. [63]. The amount of primed nutrients in seeds was dramatically boosted by nutritional seed priming. The treatments included unprimed seeds, hydro primed seeds, and seeds primed with various solutions: 4 mM Zn + 2.5 mM Mn (from $ZnSO_4 \cdot H_2O$ and $MnSO_4$), 5 mM boron (from H_3BO_3), and 0.2 M phosphorus (from K_2HPO_4). Compared to the control, maize plants primed with Zn + Mn showed over 50 to 100% increases in growth, respectively, in a nutritional solution (NS) lacking Zn and Mn. The primed nutrients effectively reached the developing shoots and maintained Zn and Mn supply for three weeks. In soil culture, while phosphorus (P) and zinc (Zn) deficiencies impacted plant growth, priming with P and Zn + Mn provided some benefit. The extremely calcareous soil in particular had a deleterious impact on the transfer of Zn in seed stores to the shoot tissue. The field experiment showed the potential for the benefits of nutritional seed priming, as Zn + Mn seed priming boosted grain production by 15%.

Barley: The investigation conducted by Abdulrahmani et al. [64] sought to determine how barley seedling vigor was affected by hydropriming, osmo priming (using 2.5 mM $CaCl_2$, 5 mM $CaCl_2$,10% PEG and 20% PEG,), and nutritional priming (using KH_2PO_4 solutions containing 10 mM P, 50 mM P, and 100 mM P and $ZnSO_4$ solutions with 10 mM Zn, 50 mM Zn, and 100 mM Zn). The germination rate, electrical conductivity (EC) of seed leachates, percentage of viable seeds, seedling dry weight and root and shoot dry weight, were significantly impacted by seed priming, according to an analysis of variance performed on laboratory data. Among the different priming methods, nutrient priming in phosphorus (P) solutions proved to be the most effective. By 25 and 12.5%, respectively, above unprimed seeds, this priming medium increased root and shoot dry weight. The seeds were treated with the most effective methods in the lab, including hydropriming, 10% PEG, 5 mM $CaCl_2$, 10 mM Zn, 50 mM P, 100 mM P, 10 mM Zn + 50 mM P, and 10 mM Zn + 100 mM P solutions, before being sown outside. The mean seedling emergence percentage in the field were significantly affected by priming treatments ($p \leq 0.05$). The greatest seedling emergence % and rate were attained using priming of 10 mM Zn + 100 mM P and 100 mM P. Therefore, these methods could be utilized to enhance the establishment of seedlings of barley in the field.

Another study was conducted by Ghassemi-golezani et al. [65] to assess how seed priming influenced yield, grain enrichment, and nutrient absorption in barley under dryland conditions. Barley seeds were divided into nine samples. Eight of these samples were primed with different treatments: water (hydro-priming), 5 mM $CaCl_2$, 10 mM Zn, 50 mM P, 100 mM P, 10 mM Zn + 50 mM P, and 10 mM Zn + 100 mM P and 10%

PEG solutions, and dried back to their original moisture content. One sub-sample was maintained as the control (unprimed). Treatments with priming significantly seedling establishment, increased seedling emergence, grain production, survival in winter, green ground cover and rainfall productivity index. The best priming strategies helped barley grains become 45, 21, 40, 36, and 32% more enriched in P, Zn, Fe, Mn, and Cu, respectively. The advantages of seed priming for barley grain yield and nutrient enrichment were helped to quicker seedling emergence and establishment, enhanced survival under winter, a greater ground cover, and more effective use of soil moisture, light and nutrients by the crops grown from the primed seeds.

11.2 Influence of Nutripriming on Growth and Yield under Stress Condition

Kshik. et al. [66] looked at the possibility for rice to develop salt tolerance through seed priming. Aerated solutions of PEG 2%, KNO_3 2%, $CaCl_2$ 2%, ascorbic acid 100 ppm, and control (distilled water) were each used to prime two batches of rice seeds with high and low vigour of the cultivar Sakha 106 variety for 24 hours. Two trials were carried out in a lab and in pots. The primed seeds were sown in 0 ppm, 3000 ppm, 4500 ppm, 6000 ppm, and 7500 ppm of NaCl. The experiments revealed that priming with 2% KNO_3 was the most effective at enhancing salt tolerance, followed by controls, 2% $CaCl_2$, 100 ppm ascorbic acid, and 2% PEG. This improvement was attributed to better seed germination, increased seedling vigour index, faster germination speed, higher germination rate, and improved seedling emergence.

Higher germination rates (80%) were seen with recently harvested seed. Because, KNO_3 maintained seedling vigour and seed viability better than other treatments and it is advised that it should be used for priming seed of rice below 3000 ppm. Reduced germination parameters can be seen as a result of salinity levels rising to 7500 ppm. The results were found that under salinity stress, all seed quality traits increased when KNO_3 or $CaCl_2$ were treated at a rate of 2%. The findings signify that priming agents and high vigour play a role in controlling salinity affects in pre-treated seed, and how these agents may be used as potential growth regulators to enhance the growth of common seedlings under salinity stress.

The purpose of the study conducted by Mirza et al. [67] was to ascertain how seed priming affected the germination of two different wheat varieties in conditions of high salinity, high temperature, and drought. He employed halo priming (5mM NaCl, 10mM NaCl), Osmopriming (5mM KNO_3, 10mM KNO_3), and hydro priming (distilled water). Here hydro priming increased the maximum germination index to 70 and 65 percent under heat stress and drought, respectively. While 5 mM KNO_3 priming increased the germination index to 75 percent under salinity stress. Under salt stress, 5mM KNO_3 priming produced the greatest seedling vigour index, with an increase of 86 percent. In heat and drought stressed seeds, hydro primed seeds demonstrated the largest percentage increases in germination stress tolerance index, at 50 and 45 percent. Under salt stress, 5mM KNO_3 primed seedlings had a 51 percent higher germination tolerance index. It has been demonstrated that seed priming is a very beneficial method for boosting resistance to abiotic stress.

Nciizah et al. [68] conducted laboratory and glass house research to determine the effects of Nutrient seed priming (NSP) content of Zn, B, and Mo and during priming on maize germination and early emergence of seedling and growth in micronutrient deficient soils. The laboratory experiment utilized five concentrations (0.01%, 0.05%, 0.1%, 0.5%, and 0% as the control) and with three priming durations of 24 hours, 12 hours, and 8 hours, while the experiment in glasshouse excluded the 0.5% concentration and the 8-hour duration. The duration of seed priming, its concentration levels, and their combinations had significant impacts ($P < 0.05$) on germination percentage (GP), germination rate (GR), coefficient of velocity of germination (CVG), days to germination (DG) and mean germination time (MGT). Longer durations of priming at lower micronutrient concentrations enhanced these characteristics.

Similar to this, within glasshouse circumstances, NSP was at lowest dosage but for the longest period caused seedling emergence to occur up to 50 percent earlier than the control. When compared to the control, priming with 0.01 percent B decreased the time it took for seedlings to emerge by 94 percent, increased fresh and dry weight of seedling. Moreover, the increased fresh and dry seedling weight, along with greater shoot and root mass compared to the control, may be attributed to earlier seedling emergence. The study suggests that optimal levels of micronutrient concentrations and suitable priming durations can enhance germination and seedling growth, ultimately leading to improved yield parameters.

Youseff et al. [69] studied the effects of priming seeds with several agents ($CaCl_2$, KCl, and KNO_3) on germination and the growth of seedlings in the barley species of *Hordeum maritimum* and *Hordeum vulgare (L.Manel)*, which were exposed to three different salt concentrations of 0, 100, and 200 mM NaCl. The findings showed that salinity stress considerably decreased the average daily germination rate, ultimate germination rate, seedling length, and dry weight in unprimed conditions. Different priming strategies increased seedling growth rate and markedly improved critical nutrient concentrations and germination parameters. Seed priming helps to reduce sodium ion accumulation and alleviate oxidative stress in seeds caused by salt exposure.

12. CONCLUSION

Nutrient-primed seeds serve as a conduit for delivering specific amounts of fertilizer, which supports improved seedling growth. Nutri-priming boosts the nutrient content within seeds, reduces the average time required for germination, and enhances both the percentage and rate of germination. Additionally, it mitigates the negative effects of sodium chloride-induced stress by increasing antioxidant enzyme activity. This method is especially beneficial for enhancing crop establishment in challenging agroclimatic conditions such as rainfed, dry farming and dryland farming. It also contributes to increased yield, better stress tolerance, disease resistance, weed competitiveness, and water use efficiency.

Nutripriming has gained recognition as a promising strategy for enhancing crop performance due to its precise application of small amounts of nutrients and efficient absorption. However, a significant drawback of this approach is that the best treatment varies depending on the priming and drying concentrations and times. The best method for each case must thus be determined after several attempts. However, seed priming with micronutrients is a safe, environmentally beneficial, economically viable, and long-term solution for farmers and the environment. Therefore, it can be concluded that one useful strategy for advancing sustainable agriculture is seed priming.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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