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REVIEW ARTICLE

Seed priming: An overview of techniques, mechanisms, and applications

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Abstract

Seed priming is a pre-sowing seed treatment method that has gained significant attention in recent years due to its potential to improve seed germination and early seedling growth. This review article provides a comprehensive overview of seed priming techniques, their underlying mechanisms, and diverse applications in crop production during the recent years. The article introduces the concept of seed priming and its importance in optimizing seed performance, discussing various seed priming techniques including osmotic priming, hydro-priming, hormonal priming, and microbial priming. Each technique is described in detail, outlining the specific procedures and conditions involved, and their advantages and limitations are discussed. The underlying mechanisms of seed priming are explored, elucidating the biochemical, physiological, and molecular changes that occur during seed priming, and the interactions between priming substances and seeds. The article also provides an in-depth analysis of the applications of seed priming, discussing its positive effects on seed germination, seedling vigour, stress tolerance, and its potential for sustainable agriculture. This review article serves as a valuable resource for researchers, scientists and faculties working in the field of seed technological research and progressive farmers who can adopt this technology for enhancing crop yield. This article provides insights into the techniques, mechanisms, and applications of seed priming for optimizing seed performance and enhancing crop productivity in diverse agricultural systems.

Keywords

Seed; seed priming; seed quality; seedling vigour; seed germination

Introduction

Efficient crop production relies on successful plant stand establishment and high seedling vigour. These factors play a crucial role in determining uniform growth, maturity, and high productivity (1). However, adverse climate conditions and less vigorous seeds can lead to slow and non-uniform seed germination under field conditions. Seed priming is a physiological technique that involves the controlled hydration and dehydration of seeds to enhance pre-germinative metabolism for speedy germination (2). Primed seeds are known to emerge faster, grow more vigorously, and result in higher yields, which is especially important in unfavourable environmental conditions such as drought (3).

Seed priming is an essential tool for enhancing field emergence and crop stand establishment, which ultimately leads to higher productivity. Various physiological and non-physiological methodologies have been developed to enhance seed performance and withstand environmental stress (1). Seed invigoration through priming before sowing is critical for activating seed resources for efficient plant growth and high yield in combination with external ingredients. The main benefit of priming is the increase in the rate of germination at any temperature, and the uniform emergence of seedlings from primed seeds at a faster rate than non-primed seeds due to limited adverse environmental exposure. This is due to the shortening of the lag phase or metabolic phase of the germination process. Seed priming has been commercially used to eliminate or greatly reduce the effect of abiotic and biotic stresses, making it an effective approach for the successful production of field crops. Different seed priming techniques and their effects on crop plants are discussed in this study.

Objective of the review

The objective of this review is to examine recent advancements in seed priming technology for enhancing seed germination and seedling growth under abiotic stresses in agricultural crops.

Review methodology

A rigorous and comprehensive search for relevant literature on seed priming and its effects on different agricultural crops was conducted. Several research papers and review articles available on various databases, including ResearchGate, ScienceDirect, Google Scholar, and Academia, were analysed to compile this review.

Seed Priming

Seed priming is a technique that involves hydrating seeds to initiate metabolic processes prior to germination and then drying them back to their original moisture content to prevent actual emergence of the radicle. This method was proposed as a means of seed invigoration prior to sowing (4). The process involves immersing seeds in water or various solutions for a specified period under controlled conditions, followed by drying back to the original moisture content. Seed priming has been shown to stimulate various metabolic processes that improve germination and emergence of many seed species, especially those of vegetables, small seeded grasses, and ornamental species. This technique has been found to enhance the germination process and the rate of seedling emergence and production of vigorous seedlings even under unfavourable environmental conditions, such as drought, heat stress, salinity, nutrient stress, and several other environmental stresses resulting in better crop stand and higher crop yield (Fig. 1). Therefore, seed priming is a promising technique for dealing with unfavourable conditions in fragile lands.

Mechanism of Seed Priming

Seed germination is a complex process that involves several metabolic events leading to the activation of stored food reserves and emergence of radicles and plumules (5). Priming constitutes a pivotal seed pre-treatment method that effectively triggers the process of seed germination through a complex cascade of biochemical alterations within the seed. This intricate process encompasses the activation of enzymes, synthesis of growth-inducing substances, metabolic breakdown of germination-inhibiting compounds, and the repair of cellular impairments (6, 7).

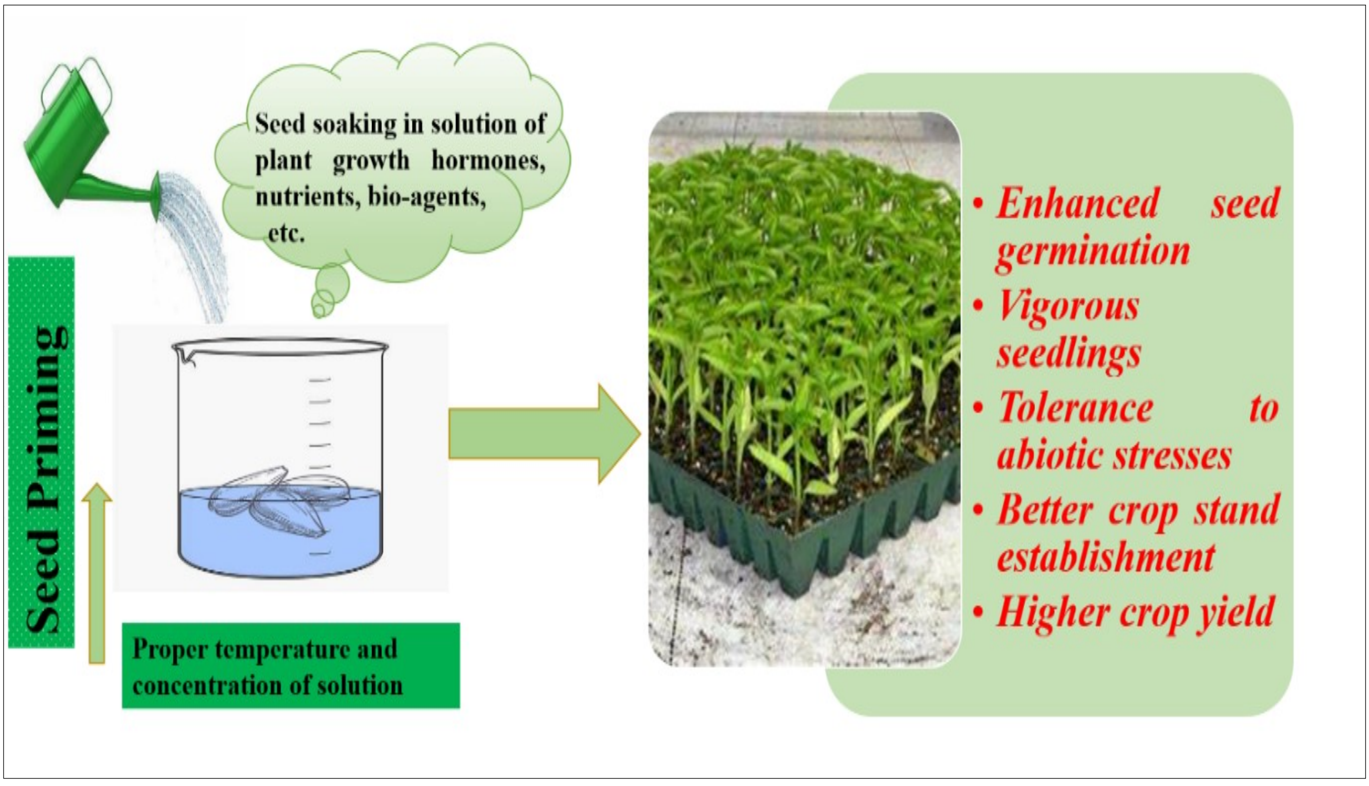

Fig. 1. Impact of seed priming on crop growth and yield.

The seed priming process involves three stages (Fig. 2) with the first phase being the imbibition phase, where the seed absorbs water rapidly due to its low water potential. Subsequent to the uptake of water, a sequence of cellular-level metabolic and reparative occurrences ensues in phase II, which is commonly referred to as the activation phase or lag phase. During this particular stage, there is an observable reduction in the level of moisture and a notable decrease in the synthesis of proteins. Furthermore, there is a concurrent development of fresh mitochondria, which are responsible for cellular respiration, activation of enzymes, and mending of DNA (8–10).

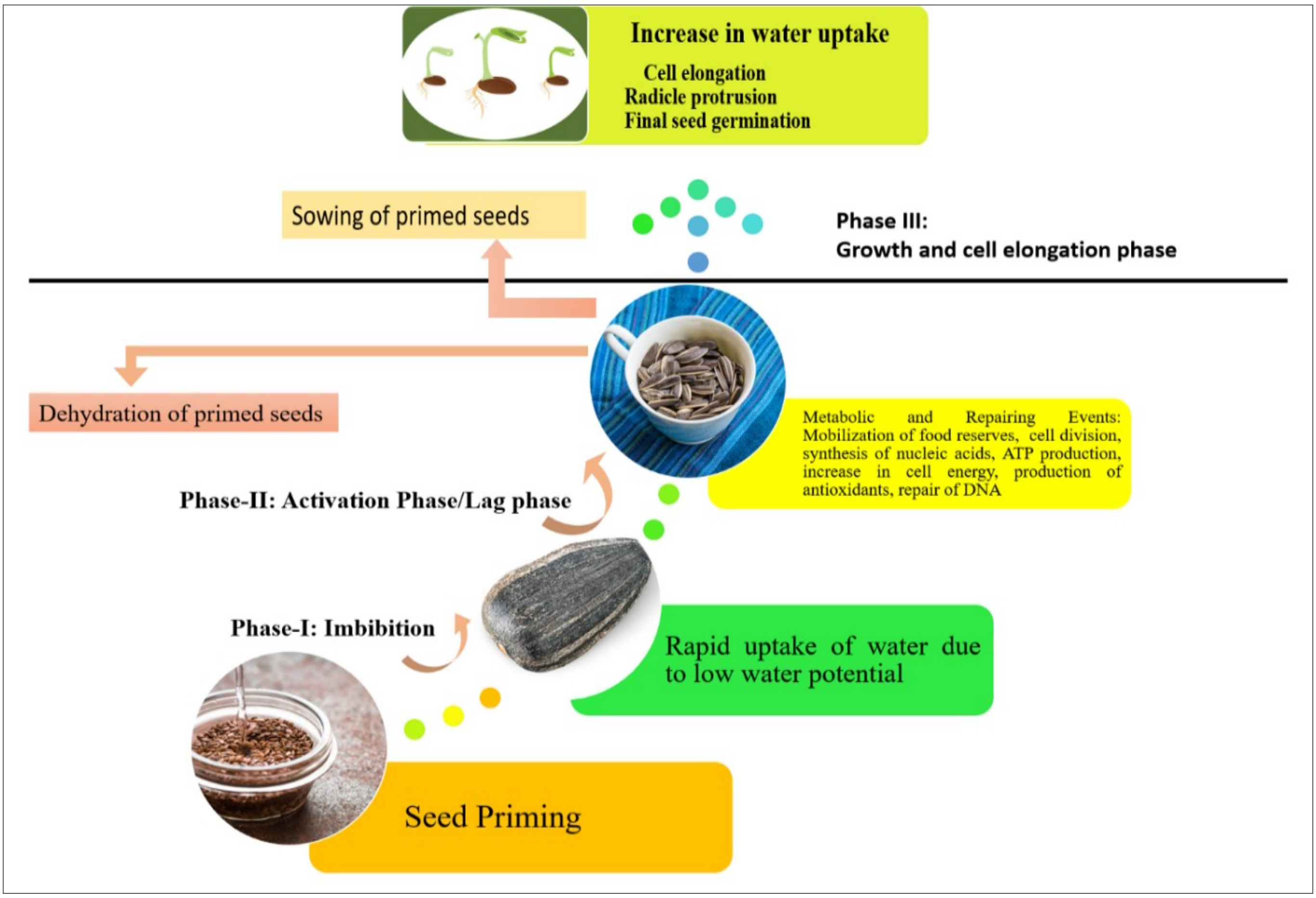

Fig. 2. Flow chart showing the mechanism of seed priming.

Throughout the activation phase, rehydration initiates a range of alterations in the seed's cellular composition, which encompasses cellular division, nucleic acid synthesis, protein synthesis, ATP production, heightened cellular energy, ATP/ADP ratio modulation to meet energy demands, essential lipid accumulation, antioxidant generation, and DNA repair mechanism activation. (9, 11, 12). The mending of DNA holds paramount significance in the restoration of cellular damage, as suboptimal repair processes may instigate oxidative damage, thereby inducing cell death in the course of germination. (12).

Research investigations have revealed that seed priming instigates the activation of proteins, carbohydrates, and enzymes that are intricately linked to lipid mobilization processes. One such enzyme is alpha-amylase, which catalyzes the hydrolysis of starch reserves into simpler sugar units, consequently increasing the overall concentration of soluble sugars (11, 13–15). Seed priming augments the process of protein synthesis through the elevation of ribosomal RNA synthesis and enhancement of ribosomal integrity. Additionally, seed priming prompts the production of antioxidant enzymes, such as superoxide dismutase, catalase, and peroxidase, which assists in maintaining a balance between the generation and breakdown of reactive oxygen species (ROS), including hydrogen peroxide, superoxide, and hydroxyl radicals, during stressful environmental conditions (16, 17).

In the course of stage III, there is a resurgence in water absorption by the seed, and the emergence of the radicle signifies the ingress of the germination process into the phase of cellular elongation and growth (10). Although the first and second phases occur during seed priming, the third phase does not occur (18). Seeds that undergo priming exhibit completion of both phase I and II of the germination process. Such primed seeds demonstrate an enhanced ability to swiftly finalize the imbibition process upon sowing, leading to a notable reduction in the temporal requirement for cellular metabolic and biochemical activities. Due to the activation of enzymes of nucleic acid, the quantity of DNA increases, leading to an increase in the amount of RNA and proteins (19).

Different Methods of Seed Priming

Different methods of seed priming include hydro-priming, which involves soaking seeds in water, osmo-priming using osmotic solutions, chemical priming with various compounds, bio-priming with beneficial microorganisms, solid matrix priming in controlled environments, and hardening priming with mild stressors (Fig. 3). These methods are chosen based on crop needs and environmental conditions, resulting in improved germination, seedling vigour, and overall crop yield in challenging growing situations.

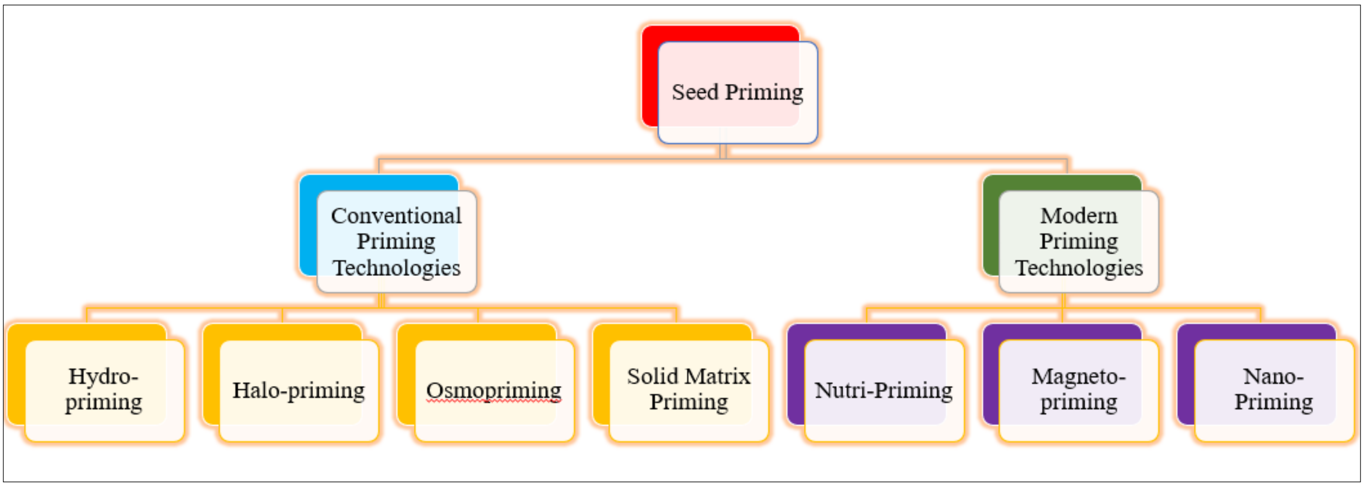

Fig. 3. Different types of seed priming technologies.

Conventional Techniques of Seed Priming

Hydro-Priming

Hydro-priming is an inexpensive, low-risk method in which seeds are soaked in distilled water at an appropriate temperature for a specific period of time and then dried again to approximate their original moisture content before sowing (20). This priming method is particularly useful in regions with unfavourable climatic conditions such as high temperatures and water stress, as it increases the efficiency of water uptake and seed hydration (21).

Hydro-priming has demonstrated a multitude of advantageous effects on crop production. Specifically, the submersion of paddy seeds in water for a duration of 24 hrs resulted in a complete germination rate of 100%, accompanied by the maximization of shoot fresh weight, root length, α-amylase activity, and total and reducing sugar content. These results are indicative of heightened physiological potential, manifested as improved germination and vigour (22, 23). Hydro-priming, a pre-sowing technique, has demonstrated a notable augmentation in both germination and seedling vigour in fine and coarse rice seeds. Furthermore, hydro-primed Malaysian Indica rice seeds exhibited superior germination percentage and germination index, along with a decreased mean germination time, compared to their non-primed counterparts when subjected to drought stress (23, 24). Furthermore, it has been ascertained that hydro-priming confers an augmented capacity to endure CO_2 stress and ameliorate oxidative damage in rice (25).

Maize is another crop that benefits from hydro-priming. The immersion of maize seeds in water for a duration of 18 hrs, succeeded by a subsequent period of surface drying lasting 2 hrs, has been shown to elicit a range of crucial physiological responses. These responses have been linked with the optimal emergence performance of the maize crop, including germination percentages of 85% and 95% at 30% and 60% moisture levels, respectively. Furthermore, hydro-priming has been associated with higher germination indices and mean germination times, indicating a marked improvement in overall seed viability and germination success (26). Optimal seed revitalization of maize inbred lines was observed subsequent to 36 hrs of hydro-priming, which resulted in a heightened germination rate, radical length, and vigour index (27). An alteration in the protein composition of the maize embryonic tissue accompanied by a hastened onset of germination in maize seeds was observed subsequent to a 12-hour hydro-priming treatment of said seeds (28). The application of hydro-priming has been demonstrated to enhance both the water usage efficiency and grain yield of maize under conditions of water stress (29).

Hydro-priming confers beneficial effects on the early emergence, total germination count, number of tillers, grain weight, as well as the biological and economic yield of late-sown wheat across varying moisture conditions (29). It leads to an elevation in the water utilization proficiency amid water-deprived circumstances which results in a higher and more uniform germination rate, consequently culminating in a noteworthy reduction in water consumption required for cultivating an equivalent quantity of wheat and reduces the cost of irrigation (30). Hydro-priming for a duration of 16 hrs culminated in the most optimal outcomes in terms of wheat germination, growth, yield parameters, and economic profitability (31). Furthermore, hydro-priming has been discovered to enhance the quality of mature wheat seeds, stimulate an increase in enzymatic activity, and ameliorate both germination and seedling traits (32).

Hydro-priming of barley seeds elevate the process of germination, augment the growth of seedlings, promote optimal stand establishment thereby culminating in a higher yield, and mitigate seed infection caused by the fungal pathogen *Fusarium culmorum* (33). It also exhibited significant enhancement in key morphological parameters of barley, including root length, root dry weight, plant height, and shoot dry weight per area (SPDA).

Halo-Priming

It denotes a pre-sowing seed priming methodology that entails immersing seeds in aqueous solutions of inorganic salts like KNO_3, $CaCl_2$ and $CaSO_4$ (34). This pre-treatment of seeds with inorganic substances has been found to enhance crop growth and enhance resistance to diverse abiotic stressors, ultimately leading to ameliorated germination, establishment, and yield of crops grown in saline soils (35).

Research has shown that priming wheat seeds with $CaSO_4$ (50mM) for 12 hrs at 25°C enhances germination percentage, root length, and seedlings' fresh and dry weight in both salinity stress and non-saline conditions compared to control. The seedlings also showed maximum potassium concentration, total sugars, and reducing sugars (36). Nutrient priming with zinc using 0.5M $ZnSO_4$ for 12 hrs under zinc-deficient soil conditions has been reported to increase the final yield by 27.1%, which is the highest improvement in comparison to other treatments (37). Additionally, application of a chitosan solution has been shown to stimulate resistance to various crop diseases and improve seed quality (38). Sorghum seeds treated with $CaCl_2$ or KNO_3 were found to enhance the activity of proteases and total amylase during germination under salinity stress (39).

For barley, nutrient priming with $ZnSO_4$ (10mM of Zn; KH_2PO_4; 50mM of P; 12 h) has been shown to enhance root growth and root biomass, uptake of P and Zn and water use efficiency in P and Zn- deficient soil and low water stress conditions (40). In pigeon pea, priming with $CaCl_2$ or KNO_3 was found to improve soluble sugars free amino acids and during germination under saline condition (41). Maize seed priming with NaCl has been shown to improve the growth of maize plants under both laboratory as well as field conditions (42).

Osmo-Priming

Priming with osmotic solutions is a seed invigoration technique of immersing seeds in the solution of osmolytes like PEG, glycerol, mannitol, or sorbitol for a specific duration and then air drying. This method restricts the entry of excess water into the seed during imbibition, reducing ROS accumulation and protecting the cells from oxidative injury. Seed invigoration through osmolyte priming results in higher and more uniform field emergence, greater vigour and better crop stand (43).

Numerous priming techniques have been studied for their effects on different crops. For example, osmo-priming with $CaCl_2$ was found to provide resistance against drought stress in wheat (44). Another study showed that PEG 6000ml or KH_2PO_4 osmo-priming increased germination percentage and seed vigour in wheat (45). Treatment with GA_3 and IAA improved onion seed attributes such as germination, seedling length, root length, and seedling dry weight (45) while treatment with GA_3 (1000ppm) resulted in the highest germination, seed yield, and weight of a thousand seeds (46). Osmo-priming with aerated $CaCl_2$ (1.5%, 12 hrs) was found to increase leaf area and tissue water content, enhance accumulation of osmolytes, reduce lipid peroxidation, activate transcription factors associated with antioxidant enzymes, and increase crop performance under drought stress in wheat (47). Chickpeas osmo-primed with $CaCl_2$ for 18 hrs showed positive effects, including increased specific leaf area, CO_2 net assimilation rate and relative water content, improved accumulation of leaf total soluble phenolics, free proline and ascorbic acid, increased activities of CAT, SOD, and APX, and enhanced chilling tolerance (17). Sesame seeds that were osmo-primed in 1% KNO_3 salt solution for 6 hrs showed greater seed germination and seedling height than those that were hydro-primed (48). Rape seedlings showed significantly increased seedling height, radicle length, leaf number, and dry weight under salinity conditions, although a specific priming technique was not reported (49).

Solid Matrix Priming

Solid matrix priming is a seed priming technique that involves mixing seeds with water and solid materials at specific proportions (50). Common solid carriers in this method include vermiculite, charcoal, clay, and sand. In solid matrix priming, the seeds are mixed with a medium that slowly wets them, making them ready for germination. Solid matrix priming has been found to be an effective method for improving seed vigour and germination in various crops. For instance, solid matrix priming of maize seeds using sand was shown to increase α-amylase activity, membrane system integrity, and speed ofemergence (51).

Studies have also demonstrated the effectiveness of solid matrix priming using other materials. For example, solid matrix priming has been found to enhance seed vigour and germination of soybean (52) and improve seed germination growth and emergence of onion seeds under sub-optimal and optimal conditions (53). These findings suggest that solid matrix priming is a promising technique for improving seed quality and promoting the growth and development of crops.

Hormonal Seed Priming

Hormonal seed priming is a technique that involves immersing seeds in a solution containing optimal concentrations of phytohormones, which enhances their metabolism (54). The process is known to improve germination, seedling growth, and yield by promoting nutrient uptake through increased physiological activities and root production (55, 56). This method is particularly useful in establishing crops under heat and drought stress conditions (57).

Studies have shown that hormonal seed priming induces various physiological processes such as growth, development, respiration, and transpiration in many crop species (58, 59). Phytohormones, including IAAs, cytokinins, gibberellic acid, ABA, salicylic acid, and ethylene, are commonly used in seed priming (54).

Bio-Priming

Several studies have shown the potential benefits of seed priming with different agents on crop growth and yield. Bio-priming with *Trichoderma harzianum* for 30 min significantly enhanced effective tillers by 59–153%, chlorophyll content by 174–189%, and root length by 27% in wheat when compared to control (60). Pearl millet treated with *Pseudomonas fluorescens* for 6 hrs at a concentration of 1 × 10^8 CFU mL^{-1} resulted in increased leaf surface area, Rhizobacteria-mediated induced systemic resistance, and reduced downy mildew severity caused by *Sclerospora graminicola* (61). In rice, *T. harzianum* priming for 24 hrs reduced the deteriorating effect of salinity and significantly increased proline, phenol content, and membrane stability compared to non-primed seeds. It also significantly enhanced the number of leaves, leaf area, and chlorophyll content (62). Bio-priming with *Bacillus amyloliquefaciens* and *Serratia marcescens* at a concentration of 1 × 10^7 CFU mL^{-1} significantly enhanced the activities of peroxidase (APX) and polyphenol oxidase (PPO) in rice seedlings, and reduced rice blast severity caused by *Magnaporthe oryzae* (63).

Azospirillum brasilense priming for 12 hrs resulted in significantly higher field emergence (96.3%), crop growth, performance, and yield in maize compared to control (64). Priming maize seeds with *T. lixii* for 24 hrs resulted in increasing the length of fresh and dry weight of root/shoot and a decrease in lipid peroxidation (65). The priming of maize with *Rhizophagus irregularis* and *P. fluorescens* resulted in shoot nutrient concentration increments for nitrogen, phosphorus, potassium, zinc, magnesium, and manganese (66).

Bio-priming of chickpea with *T. harzianum* for 12 hrs suppressed *Fusarium* wilt by 53.38–57.99% suppression and also increased the germination and plant growth parameters as compared with those of chemical fungicides and control (67). Priming of peas with *Trichoderma asperellum* for 24 hrs resulted in significant increases in shoot length, root length, number of leaves, shoot fresh weight, root fresh weight, shoot dry weight, and root dry weight by 35.29%, 96.49%, 28.13%, 36.10%, 146.26%, 30.17%, and 77.2%, respectively (68).

Bio-priming of rape seed with a hypovirulent *Sclerotinia sclerotiorum* strain DT-8 carrying a DNA virus SsHADV-1 for 18 hrs at 10 mL 5 g $seed^{-1}$ reduced stem rot severity caused by *S. sclerotiorum* and induced systemic resistance, influenced the composition and structure of the plant microbiome, and secreted oxalic acid (69).

Modern Technologies in Seed Priming

Nutri-Priming

Nutri-priming is a pre-sowing seed treatment technique that involves soaking seeds in a nutrient solution to improve their quality and enhance their nutrient content. Micronutrients play a crucial role in respiration and photosynthesis, which are essential for plant growth and development. Any disturbance in these processes can cause reduced growth and yield (70). To overcome this challenge, micronutrients can be directly applied to the seeds through nutri-priming.

Numerous studies have investigated the effects of nutri-priming on different crops, with promising results. For instance, paddy seeds soaked in solutions containing 0.001% and 0.1% boron showed improved stand establishment compared to non-treated seeds (71). Similarly, nutri-priming barley seeds with a zinc solution resulted in improved germination and seedling development, as well as increased mineral uptake, dry matter accumulation, and water use efficiency by 44% in drought-stressed plants (40).

Nutri-priming maize seeds with a 1% solution of $ZnSO_4$ for 16 hrs led to improved crop growth, higher grain yield, and increased grain zinc content (72). In another study, nutri-priming chickpea seeds with a 0.5 g/L solution of sodium molybdate resulted in an increase in yield by up to 27% (73). Additionally, a 0.05% solution of $ZnSO_4.7H_2O$ was found to increase seed yield by 19% and increase seed zinc content by 29% (74). Cobalt nitrate was used for nutri-priming pigeon pea and peanut seeds in a study that showed enhanced number of leaves, plant height, total yield and dry matter, nodule number, and leghaemoglobin content (75). The nutri-priming of mungbean seeds with sodium molybdate dehydrate at 0.02% and 0.04% for 5 hrs improved yield (76). These findings demonstrate the potential benefits of nutri-priming for crop production, highlighting the importance of nutrient uptake and the potential for enhancing crop yield and quality. The reviews suggest that nutri-priming can be an effective seed pre-treatment technique for enhancing seedling growth and improving crop yield, particularly under stress conditions. However, the optimal duration and concentration of nutrient solution may vary depending on the crop and growing conditions, and careful attention should be paid to avoid over-soaking and nutrient toxicity.

Nano-Priming

Seed nano-priming technology involves the use of nanomaterials to improve the quality and performance of seeds. Nano-priming involves treating seeds with a solution containing nanoparticles, which are typically between 1 and 100 nm in size. The nanoparticles are designed to interact with the seed surface, enhancing seed germination, growth, and productivity.

Nano-priming technology represents an innovative and cutting-edge approach that harnesses the potential of nanoparticles to augment the germination, seedling vigour, and growth of seeds. By utilizing nanoformulations as a media, nanoparticles like silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), and multi-walled carbon nanotubes (MWCNTs) are employed for seed priming (77). While the uptake of nanoparticles by the seed during nano-priming may be variable, it has been observed that a considerable amount of nanoparticles remain as a coating on the seed surface. This coating facilitates a myriad of benefits that augment seed performance, including the enhancement of α-amylase enzyme activity, an increase in soluble sugar content to promote seedling growth, and the stimulation of aquaporin genes in germinating seeds. Furthermore, nano-priming improves the seed's tolerance to stress by mitigating reactive oxygen species (ROS) production, creating nanopores for enhanced water uptake, activating the seed's antioxidant systems, generating hydroxyl radicals for cell wall loosening, and catalyzing the hydrolysis of starch (78). Ongoing research into the potential applications of nano-priming is promising and could have significant implications for the optimization of agricultural productivity.

The utilization of nanoparticles has emerged as a promising strategy to enhance crop growth and development. Among different nanoparticles, silver nanoparticles (AgNPs) applied at a concentration of 5ppm and 10ppm significantly improved the germination parameters and seedling vigour of paddy (78). Similarly, the application of zero valent iron (nZVI) nanoparticles at a concentration of 25 mg/L improved the germination and seedling growth of aromatic rice cultivar Gobindabhog (79). In addition, the application of chiston nanoparticles (20-170nm) at 0.5-20 mg/L improved plant morphology and biomass in paddy (80).

In wheat, silicon nanoparticles (90nm) applied at a concentration of 300-1200 mg/L improved the growth, yield, and chlorophyll contents while alleviating oxidative stress through increased activity of antioxidant enzymes (81). Moreover, seed treatment with metal nanoparticles, including Zn, Ag, Fe, Mn, and Cu, improved the tolerance against eyespot of wheat (82). Application of TiO_2, ZnO, and chitosan nanoparticles at a concentration of 50ppm enhanced the seed germination and seedling growth of wheat (83). Additionally, the application of Cu (15-30nm) and Fe (20-30nm) nanoparticles at 20-40 ppm increased the enzymatic, biochemical, and antioxidant activities, as well as the abiotic stress resistance in wheat (84).

In sorghum, the application of Fe nanoparticles (<50nm) at 10-500 mg/L significantly increased the seed and seedling vigour, biomass, and biochemical activity (85). Furthermore, seed coating with Fe NPs at a concentration of 25ppm improved the germination parameters such as germination percent, speed of germination, seedling growth, and vigour index of pigeon pea (86). In moong bean, seed priming with TiO_2 nanoparticles at a concentration of 0.02% improved seed germination and seedling growth (87).

In conclusion, nano-priming technology has emerged as a promising approach to enhance crop growth and development by improving germination, seedling vigour, and stress tolerance. However, further studies are needed to elucidate the underlying mechanisms and potential risks associated with the use of nanoparticles in agriculture.

Magneto-Priming

Magneto-priming, which involves exposing dry seeds to a magnetic field, has been shown to enhance crop germination, seedling vigour, yield, and stress tolerance (88, 89). This pre-sowing treatment can effectively mitigate the adverse effects of environmental stressors, such as drought, salinity, disease, and pests, during early crop growth and germination (89). In the course of magneto-priming, the seeds are subjected to a non-intrusive magnetic field stimulus for a predetermined timeframe, thereby instigating physiological alterations within the seed. The augmented properties of magnetically-primed seeds encompass elevated germination kinetics, augmented root and shoot development, amplified biomass yield, in addition to superior water absorption characteristics that expedite the hydration of enzymes, namely amylase, protease, and dehydrogenase. This leads to accelerated germination and heightened seedling robustness even under water deficit and salinity stress circumstances. The utilization of magneto-priming has been discovered to confer a statistically significant improvement in the overall germination and growth outcomes of maize, wheat, and chickpea seeds (89).

Various scientific investigations have examined the impact of the application of magnetic fields on the agricultural yield and productivity of crops. The application of a magnetic field with an intensity of 30 mT to wheat seeds results in the amplification of their antioxidative machinery in the context of flooding-induced stress, while showing no ameliorative effects on germination and seedling development (90). Chickpea seeds subjected to a magnetic field of 100 mT displayed augmented root volume and surface area, thereby affording the crop with an enhanced capacity to exploit elevated moisture levels during the active growth phase in conditions of moisture stress (91). The application of magnetic fields with strengths of 75, 150, and 300 mT elicited a significant improvement in the germination rate, seedling development, and overall chlorophyll content of lentil seeds (92).

The utilization of a magnetic field with an intensity of 5 mT in the treatment of *Vigna radiata* seeds resulted in a notable enhancement in both germination rates and α-amylase enzyme activity, indicating a potential influence on seed physiology that may be leveraged for agricultural applications (93). Sunflower seeds exposed to magnetic fields of 50 and 200 mT exhibited increased germination and seedling vigour, growth, and biomass production. Additionally, membrane integrity of the seed coat was improved, and the activity of enzymes such as alpha-amylase, dehydrogenase, and protease in germinating seeds was increased (94). In soybean, exposure to magnetic fields of 150 and 200 mT improved germination, seedling vigour, growth parameters, biomass accumulation, leaf area, photosynthetic efficiency, protein content of the leaf, and performance index of Photosystem II in leaves. This led to increased light harvesting efficiency of leaves and biomass accumulation (95, 96).

Pulsed magnetic fields (PMFs) have also been studied for their effects on crop performance. Exposure to PMFs with a frequency of 10 and 100 Hz and intensity of 1500 mT resulted in increased germination, fresh weight of shoots and roots, leaf area, plant height, total soluble sugar, total protein, and phenol content (97).

Overall, these studies suggest that exposure to magnetic fields, including PMFs, can have positive effects on crop performance in terms of germination, seedling growth, water use efficiency, and other growth parameters. However, the effects of magnetic fields on different crops may vary depending on the specific conditions of the experiment.

Conclusion

With increasing global warming, crop production in sustainable manner can be achieved through proper crop stand in the field. For this purpose, seed invigoration methods like different seed priming techniques which includes hydro-priming, halo-priming, osmo-priming, bio-priming, nutri-priming, nano-priming, magneto-priming etc., can play important role in modern agriculture. Seed priming is not only helpful in enhancing crop stands via better and uniform germination and seedling vigour but also shows better growth and development through improved metabolism which results in better yield under different stress conditions. Seed priming has emerged as a promising technology for mitigating stresses in crops to alleviate the undesirable effects of stress. Numerous experiments by researchers had revealed that enhanced germination and vigorous seedling growth in primed seeds occur due to mobilization of food reserves and gene activation responsible for synthesis enzymes. Priming of seed also repairs the damage that occurs in seed. There is need to standardize effective priming technique in different crops to overcome abiotic stress in sustainable manner. With the development of new and innovative seed priming methods, targeted seed priming, eco-friendly priming agents, and integration with precision agriculture, the potential benefits of this technology are expected to expand even further. As we continue to face the challenges of food security and environmental sustainability, seed priming can be a better solution.

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Authors contributions

MA devised the article, searched the literature, wrote the manuscript, and plotted figures. DP, AK and BA searched the literature and revised the work. A searched and supplemented the literature. FAK conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

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