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Enhancing Agricultural Resilience Through Seed Priming: A Review

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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

Seed priming is an innovative pre-sowing technique that enhances germination, seedling emergence, and crop resilience, offering significant potential for addressing modern agricultural challenges. This review examines various seed priming methods, including hydropriming, osmotic

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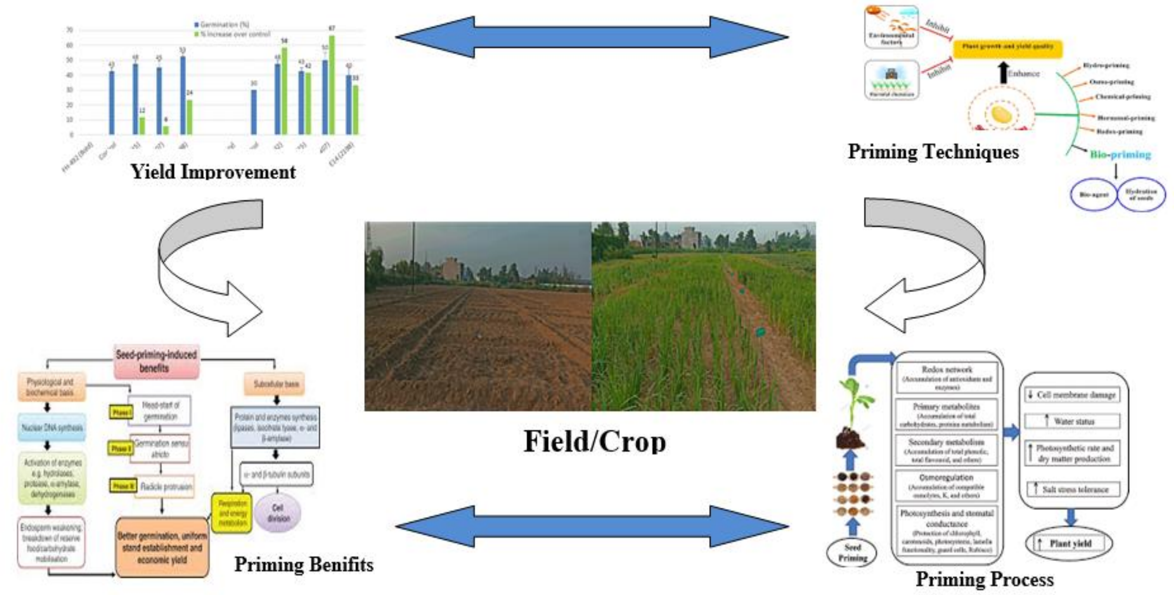
priming, halo-priming, and nanopriming, and their application across diverse crops. These techniques enable seeds to withstand abiotic stresses such as drought, salinity, and heat, which are increasingly critical due to climate change and resource limitations. Research highlights the effectiveness of hydropriming in wheat, where soaking seeds in water enhances germination rates and uniformity, particularly under saline conditions. Similarly, halopriming with potassium nitrate (KNO_3) or sodium chloride (NaCl) solutions improves salt stress resilience in tomato plants, increasing root length and seedling vigor. These findings illustrate the ability of seed priming to support crop establishment in challenging environments, including arid and semi-arid regions. Seed priming also offers broader agricultural and environmental benefits. Techniques like on-farm priming are cost-effective, eco-friendly, and accessible to farmers with limited resources, making advanced practices more widely adoptable. By reducing reliance on chemical inputs and enhancing resistance to soil-borne diseases, seed priming promotes sustainable farming practices. Moreover, advanced methods such as nanopriming provide precise delivery of nutrients and growth agents, opening avenues for more efficient agriculture. Future research should focus on optimizing priming protocols for specific crops and environments, assessing long-term impacts on yield, soil health, and crop quality, and developing solutions tailored to climate extremes and marginal lands. Additionally, exploring biopriming with beneficial microorganisms could further enhance plant health and resilience. Seed priming is a transformative agricultural tool with the potential to boost productivity, mitigate the impacts of climate change, and ensure food security. Expanding its adoption through strategic research, supportive policies, and farmer education will be critical to maximizing its global impact.

GRAPHICAL ABSTRACT



Keywords: Seed priming; priming techniques; benefits; cereals; vegetable; fruit crops.

1. INTRODUCTION

Cereals are annual grasses with long, slender stalks that are grown all over the world for their edible grain (Sarwar, 2013). Around 50% of all calories are provided by cereals, which are grown on 700 million hectares of land (Dunwell, 2014). Around 95% of the overall dietary demand is met by the main grains (Asgari et al., 2017; Zargar et al., 2017). As they are essential to human nourishment, vegetable and fruit plants are also in high demand everywhere. Global warming, heat stress, drought, salinity, and other abiotic stresses have also increased along with rising population, which has increased the demand for food and commodities (Maiti and Satya, 2014). As a result, the productivity of these crops is now in jeopardy. By 2050, there will be an additional 10 million people on the planet. We only have a little amount of agricultural area, and the field crops' ability to reproduce is all we have to guarantee food security (Sher et al., 2019). Yet, the globe is working to increase the grain production per unit of land as a result of the worsening effects of climate change (Singer et al., 2019). For a decent crop, quick seed germination and seedling development are necessary. Scientists and farmers agree that maintaining dependable and high-quality food supply is a significant challenge (Chivasa et al., 1998; Murunguet al., 2004).

Seed preparation is a direct and convenient method to compare seed germination, promote germination and seed production, among other methods“(K.Ghassemi-Golezaniet al., 2012)”. Farmers have been removing biotic and abiotic stressors for a very long time thanks to a promising seed priming technology that provided ground-breaking media that supports close monitoring“ (Sivasubramaniam et al., 2011)”. In many field crops, including cereals, seed priming offers the significant benefit of promoting resilience to conditions like drought stress, heat stress, salt, etc. The outcomes of research on seed priming have clearly demonstrated the significance of priming for improved crop strand and emergence“ (Nawaz et al., 2013)”. There are several techniques for rejuvenating seeds and removing environmental stress, such as hydro priming, which hydrates seeds beforehand and triggers early germination activities“ (Lutts et al., 2016)”. Many field crops, including cereals, have benefited from priming treatments like hydro priming, which are efficient in increasing seed vigour“(Tian et al., 2014; Prasad et al.,2012; Bakht et al., 2011)”. The effective establishment of the seedling is a result of quick and uniform root development“(Lutts et al., 2016)”.

1.1 Seed Priming

Before planting, a process called seed preparation requires adequate moistening of the seed to allow for metabolic processes prior to germination once radicle protection is established-(Nascimento et al., 2004; Rehman et al., 2011), Seed priming is a preparatory method applied before sowing, where seeds are partially hydrated under controlled conditions to begin the germination process without permitting full radicle emergence. This procedure typically involves immersing the seeds in water or a priming solution for a defined period, followed by drying them to their original moisture content (Giri et al., 2024). Priming is a process that exposes seeds to different organic or inorganic substances and temperature (Kamithi et al., 2016). To prevent radicle germination before planting, the seeds should be soaked in different solutions for a while under controlled conditions and then dried to normal moisture levels. In addition to preventing the negative consequences of seed spoilage (Ghassemi-Golezaniet al., 2012), this supports many metabolic processes and thus Improves the germination and emergence of different seed types, especially seed plants, small-seeded grass seeds and ornamental plants. species-(Tavili et al., 2011). Seed preparation is considered simple, effective, inexpensive and risk-free. Seed treatment is beneficial because it has many advantages such as uniformity and quick and rapid emergence (Musa et al., 1999)-planting crops, using water efficiently, improving deep roots, allowing germination in the latent period, promoting seed maturation and earlier, flowering by increasing metabolic activity and initiating reproductive development (Singh et al., 2015), Improving plant competition and abiotic stress tolerance (Elouaeret al., 2013, Aghbolaghi&Seaghi 2014)-together with the protection of problematic soil-borne diseases (*Fusarium* spp., *Sclerotiniasclerotiorum*, *R. solani*, etc.).

2. PRIMING TECHNIQUES

Many priming strategies are currently being investigated to improve seed quality. Hydraulic priming, halo-priming, osmotic priming, matrix priming, osmotic hardening, on-farm priming, hormone or growth promoter priming, micronutrient seed priming (Nutripriming), and biological priming (or treating seeds with microorganisms such as *Pseudomonas aureofaciens*, *Trichoderma* (NPs) are examples of this process. Every crop needs a distinct, optimal priming procedure. The factors that go into optimisation for each cultivar are standardised by trial and error. These parameters include the time needed for treatment, the priming or coating material, the vigour of the seeds, and the storage conditions (temperature, moisture, oxygen demand, etc.) (Selvarani et al., 2011).

1. Hydro-priming

Soak the seeds in hot or cold water for a while (7-14 hours) and then cure the seeds under water before spreading them into the field or other growing areas. As a result, the seeds are able to absorb moisture and gradually weaken their coating, allowing the plant to germinate quickly and easily. Although germination has started, no rootlets have formed. Cover the seeds with the primer solution and allow to dry. As a result, the number of intermediate metabolites (intermediate metabolites) involved in seed germination and the number of enzymes involved in the production of germination energy causes the seeds to constantly absorb more moisture than the oxygen in the air. Seeds should be weighed twice, banded and stored in jars at room temperature (25+2°C), depending on the application. To measure water absorption, the seeds are weighed after processing and removal of excess or excess water. The formula is as follows:

$$\text{Water imbibitions\%} = \frac{Weight of seed priming - Weight of seed before priming}{Weight of seed before priming} X\ 100$$

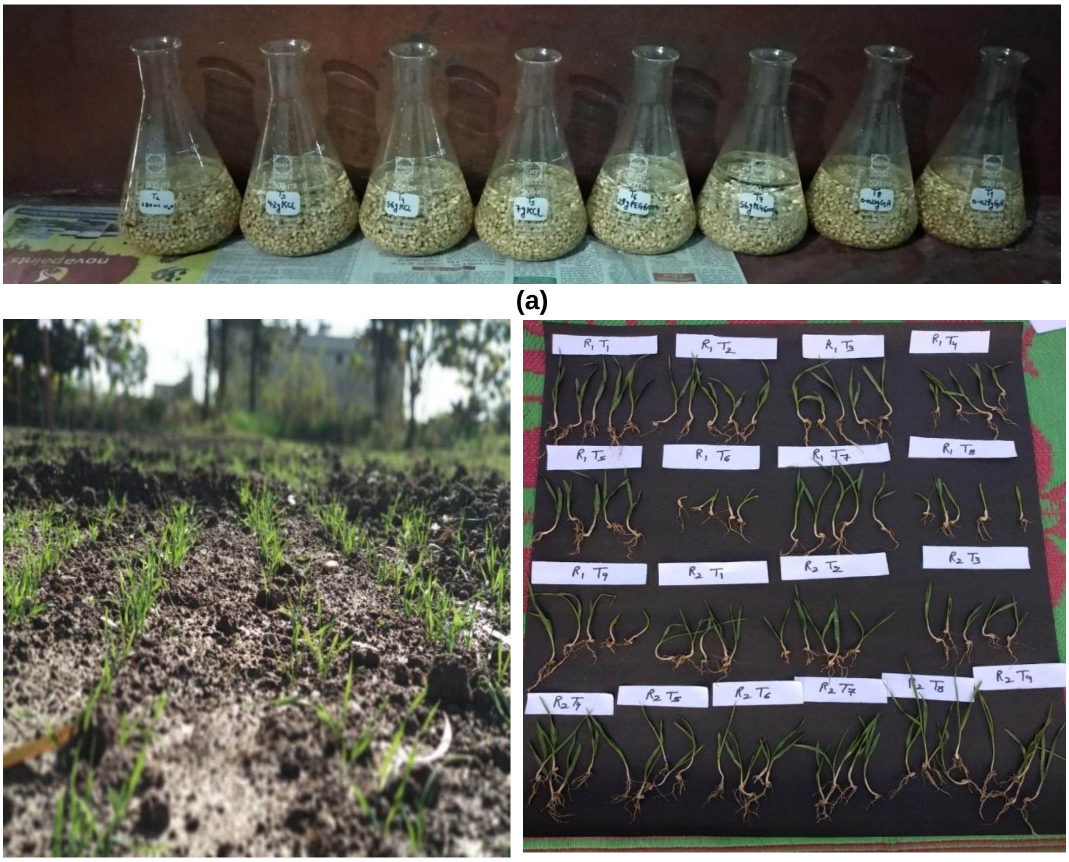
Before spreading the wet seeds on the main field that has already been prepared, the seeds will be dried for roughly 45 hours in the bottom of the hut. In each treatment area, seeds are planted at the chosen crop's prescribed dates. Based on daily observations of static seeds, the following formula is used to determine the germination rate:

$$\text{Germination\%} = \frac{Number of germinated seeds}{Number of total seed} X\ 100$$

One of the most effective, inexpensive, accessible, and ecologically friendly techniques for slowing down and promoting seed germination is hydro-priming. increases the uniformity and rate of germination. Additionally, it makes garden plant storage better. Shortly after germination, it begins to grow quickly. enhances the emergence of seedlings and the germination process ina salty and saline environment (Srivastava et al., 2022).

2. On farm priming

On-farm priming of seeds meanssoaking the seeds in water for about 12 hours (Rehmanet al., 2011), 17 hours in semi-arid tropics, 8 hours in semi-arid regions or overnight in dry ground (Musa et al., 1999), and sow the seeds next day.



(a) (b) (c)

Fig. 1. (a) The soaking of wheat seeds in different priming solutions, (b) The emergence of seedlings of wheat up to first 20 days of sowing and (c) The seedlings at 20 DAS (Kumar et al., 2023)

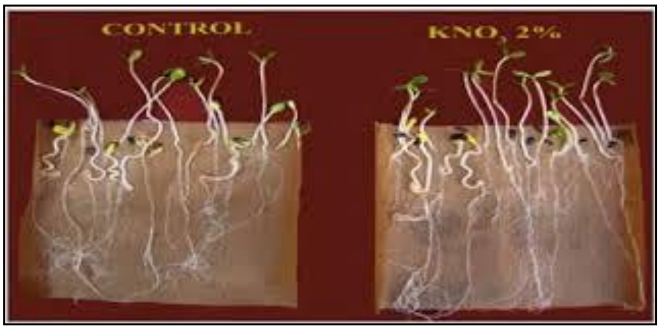


Fig. 2. Effect of seed priming in germination and seedling vigour of sunflower hybrid (Manonmani et al., 2014)

3. Halo priming

It occurs by soaking seeds in inorganic saltsolutions such as sodium chloride (NaCl), potassium nitrate (KNO_3), calcium chloride ($CaCl_2$), and calcium sulfate ($CaSO_4$). Use different types of salt to flavor the seeds. The use of germinations stimulating solutions promotes the emergence of seeds and seedlings even in adverse environmental conditions. A tolerable NaCl solution is used to treat the seeds. The results of extensive study on halopriming regeneration include notable enhancements in seed germination, seedling emergence, and establishment, as well as the elimination of agricultural yields in salty soils as reprisal for halo-priming. When preparing seeds, sodium chloride (NaCl) and potassium chloride (KCl) were particularly effective in removing the negative effects of salt. (Srivastava et al., 2022)

4. Osmotic priming

Osmotic priming, also known as osmotic-priming or osmotic-conditioning, involves immersing seeds in an osmotic solution rather than pure water in shallow water. Due to the low water content of the osmotic solution, water gradually enters the seeds, increasing water absorption and promoting seed growth while preventing the production of free radicals. Inorganic salts such as sodium chloride (NaCl), potassium chloride (KCl), potassium nitrate (KNO_3), tripotassium phosphate (K_3PO_4), potassium dihydrogen phosphate (KH_2PO_4), and calcium chloride ($CaCl_2$). Due to its unique properties, PEG is the most commonly used drug for osmotic priming. The size of the PEG molecule limits its ability to enter the seed, reducing the direction of damage to the seed and limiting the ability of the seed to penetrate. PEG has other disadvantagessuch as high viscosity which reduces the rate at which oxygen can diffuse into the solution. Therefore, mechanical aeration is often used during PEG installation (Srivastava et al., 2022).

5. Hormonal priming

Hormonal seed priming is a method of boosting plant growth and development by dispersing hormone-laced seeds ahead of time. Seeds take in plant growth inhibitors when hormones are being made, which eventually has a direct impact on seed metabolism. Gibberellic acid, auxin, gibberellin, kinetin, ethylene, polyamines, salicylic acid, and gibberellin are among the most often utilised priming agents. Because inorganic salts improve germination and the bounds of pure seed development, more seeds emerge and germinate. Garden and vegetable crops benefit from KNO_3 since it boosts production and fruit size as well as crop quality. Soybean germination and emergence are enhanced by gibberellic acid seed preparation. Cytokinins are primarily responsible for removing certain seeds from dormancy and are also employed as priming agents. (Srivastava et al., 2022).

6. Solid Matrix priming

Unlike osmotic priming, solid matrix priming (SMP), also known as matrix-conditioning, employs seeds to inhibit water absorption. By managing the water content of the seeds, Solid Matrix Priming (SMP) enhances the biological control of *Trichoderma*. This enables the seed area to be well colonised before the seeds are sown with the appropriate pH and matrix material. In order to make the mixture's water content slightly lower than what is necessary for seed germination, informed seed is mixed with an organic carrier in this technique. After being manufactured in a solid matrix, the seeds are mixed and placed in a solid water carrier for a period of time. After being taken out of the matrix solution, the seeds are carefully cleaned and dried once more. Strongmedia imitates the soil's natural absorption mechanism by allowing seedlings to absorb water more slowly. “(Srivastava et al., 2022)”.

Fig. 3. Caraway seedlings (25 days old) (A) from non-primed seeds and (B) from primed seeds with 5% PEG for 24 h. (Mirmazloumet al., 2020)

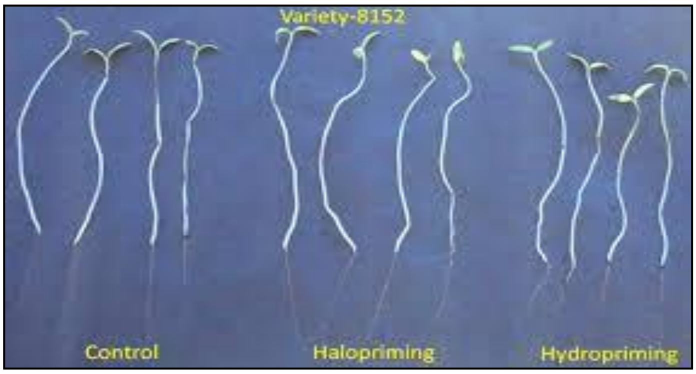


Fig. 4. Tomato variety-8152 showing increased root length in halopriming compared to control and hydropriming (Maiti et al., 2013)

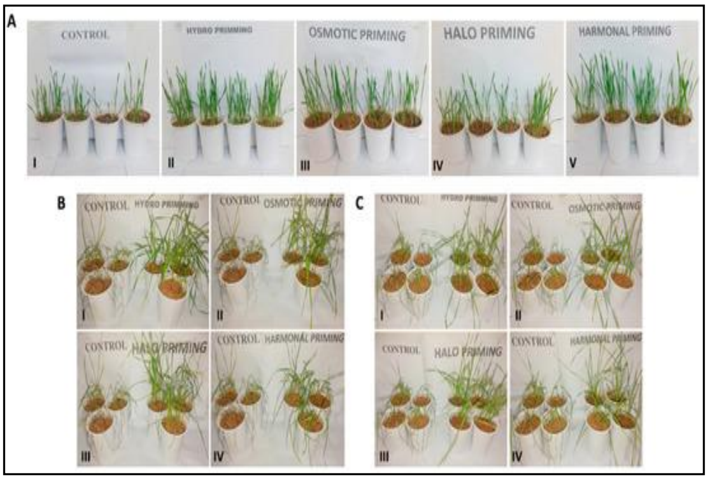


Fig. 5. Effect of different priming methods on the growth of wheat plants (Gul et al., 2022)

Table 1. Response to various seed priming strategies in various crops

S No.	Crop	Priming Technique	Results	Reference
1.	Wheat	Hormonal-priming	Reduces germination time and boosts fresh and dry weight	Afzal et al., 2006
		Hydro-priming	Increases germination rate, fasters growth and higher grain yield	Rajpar et al., 2006
		Seed priming	Enhances germination, crop-stand establishment, tillering, grain and straw yields, and the harvest index.	Farooq et al., 2008
		Osmo-priming (PEG)	Improves the seedling stand establishment parameters	Salehzade et al., 2009
		Hormonal-priming	Increases emergence count	Sharma et al., 2010
		KH_2PO_4 and KCl	Enhances germination, emergence, growth and grain yield	Yari et al., 2010
		Hydro-priming	Improves germination indices, seedling growth and crop establishment	Meena et al., 2013
		Halo-priming	Increases speed of emergence, seedling length, dry weight	Kumar et al., 2023
2.	Maize	Potassium Nitrate	Increases germination rate, yield, harvest index and tassel weight.	Vazirimehr et al., 2014
		Hydro- priming	Recorded highest grain yield, produces more panicles and 1000 grain weight	Mahajan et al., 2011
		Nutrient seed priming	Enhances seedling growth and nutritional content in maize seeds	Imran et al., 2013
		1 % $ZnSO_4$	Increases not only plant growth but also ultimate grain production and seed Zn content in plants cultivated in soil with low Zn availability.	Harris et al., 2007
		Chitosan	Improves germination and seedling development when exposed to low temperatures.	Guan et al., 2009
3.	Rice	Hydro-priming	Produces more panicles per meter square, filled grain per panicle, 1000 grain weight and spikelet sterility.	Mahajan et al., 2011
		Nitrate salts ($Mg(NO_3)_2$ and KNO_3)	Increases plant height, leaf area, and number of leaves, as well as yield-related features.	Srivastava and Bose, 2012
		Ascorbic acid @ 200 ppm andSalicyclic acid @ 50 ppm	Because of its antioxidant capability, it improves rice germination under heat stress conditions.	Kata et al., 2014
4.	Sorghum	Halo-priming	Accelerates emergence, increases plant height	Shehzad et al., 2012
		Osmo-priming/ PEG	Helpful in mitigating the unfavourable impact of low water potential on seed germination in inadequate temperature circumstances.	Patane et al., 2009
5.	Millets	Halo-priming	Improves millet germination components under salinity stress circumstances	Aghbolaghi and Sedhgi,2013
6.	Chickpea	2% SSP	Records higher seed yield and significantly higher N uptake	Patter et al., 2014
		Water	Influences plant height and nodule dry weight	Gupta and Singh, 2012
7.	Cowpea	Osmo-priming/ KNO_3	Increases seed germination, plant height, and dry matter buildup.	Singh et al., 2014a

S No.	Crop	Priming Technique	Results	Reference
8.	Soybean	Primed seeds	Good establishment, earlier flowering, higher yield	Harris et al., 2007
		KNO_3	Enhances pods per plant, seeds per plant and seed yield per plant	Golezaniet al., 2011
		$CaCl_2.\ 2H_2O$	Improves plant height, number of branches, number of pods per plant, number of seeds per pod, seed yield	Chavan et al., 2014
		Seed priming for 0-14 hrs.	Increases speed of germination	Assefa and Hunje et al., 2011
		Hormonal-priming/ GA_3@ 50 ppm	Enhances emergence, germination and speed of germination	Bassi et al., 2011
9.	French bean	Hormonal-priming/ GA_3	Improves seed quality, as evidenced by increased seedling length, dry weight, seedling vigour index, germination speed, and mean germination time.	Sarika et al., 2013
		Hydro-priming	Improve plant performance	Ghassemi-Golezaniet al., 2010
10.	Okra	Solid matrix-priming/ Calcium aluminium silicate	Increases seed germination, seedling vigour, mean germination time and marketable fruit yield	Sharma et al., 2013
		Hydro priming	Greatest mean stem length and diameter.	Sharma et al.,2014
11.	Tomato	KNO_3	Increases the NR activity, germination time, germination rate	Lara, 2014
		Hydro priming	Uniform seedling growth	Maiti, et al., 2009
		Hormonal-priming	Increased germination by 30.56%.	Soubhagyabehera, 2016
12.	Spinach	$SSP+Na_2CO_3$	Improves emergence, germination percentage, plant height, leaf area, leaf yield, and seed weight by 100 percent.	Alam et al., 2013
		Halo priming with $ZnSO_4.7H_2O$	Improved resistance to biotic and abiotic stimuli, as well as early seedling development.	Chen, et al., 2011
13.	Brinjal	Osmo-priming	Increase the amount of leaves, plant height, fruit yield, fruit length, and blooming days by 50%.	Satishkumar, et al., 2005
14.	Cucumber	Hydro priming (CaCl2)	Physiological changes include total seedling weight, dry weight, and seedling vigour index. Total soluble sugars and proteins, dehydrogenase activity, amylase activity isoenzyme, protein profile are all biochemical markers.	Pandey, et al., 2017
15.	Pumpkin	Hydro-priming	Enhance metabolic activities as well as biochemical parameters.	Pritima, et al., 2017
16.	Fennel	0.25 and 0.5 Mm of Salicylic acid	Improves germination, germination rate, seed stamina index, hypocotyl length, radical length, seedling fresh and dry weight.	Farahbakhsh, 2012

S No.	Crop	Priming Technique	Results	Reference
17.	Fenugreek	4 g/l NaCl	Fenugreek seeds had significant effects on total germination %, mean germination time, germination index, and coefficient of velocity.	Soughir et al., 2012
18.	Canola	NaCl	Increases total emergence and dry weight	Farhoudi and Sharifzadeh, 2006
19.	Safflower	NaCl	Total germination %, mean germination time, germination index, and coefficient of velocity of safflower seeds were all significantly affected.	Aymen and Hannachi, 2012
		5g/L NaCl and Kcl	Increases germination by 8.66% and 5.06%, respectively	Elouaer and Hannachi, 2012
20.	Wolf apple	Hydro-priming	Enhances seed germination and seedling growth	Anese et al., 2011
21.	Cumin	Osmo-priming	Enhances quick and uniform emergence and contributes to high vigour and higher yields.	Nematollahi et al., 2009
		Seed priming	Improves germination characteristics	Rahimi 2013
22.	Linola	Osmo-priming	Reduces emergence time while increasing seedling fresh and dry weights.	Rehman et al., 2014
23.	Sunflower	NaCl, KNO_3	Increases germination percentage and seedlings growth	Bajehbaj 2010
24.	Marigold	GA_3, NaCl	Higher germination rate, seedling establishment, plumule length	Sedghi et al., 2010

7. Nutri priming

Nutripriming involves soaking seeds in nutrient solutions prior to improve seed quality by increasing nutritional content. Micronutrients are necessary for plant growth because they enable photosynthesis and respiration, two vital plant functions that when impaired can diminish grain production and overall growth (Farooqet al., 2012). Micronutrients can be applied in three different methods to address this issue: directly to seeds, as a soil amendment, or as a plant or leaf spray.

8. Bio-priming

Biopriming is a seed treatment that combines seed hydration (as part of the immune system) with injection into the seed (as part of seed control). Generally speaking, biopriming entails injecting microorganisms into seedlings. Bioagents with seed hydration results in seed biopriming.(Srivastava et al., 2022).

9. Nano priming

Nano priming is a revolutionary technology for seed priming that employs nanoparticles (NPs) such as zinc oxide, iron oxide, titanium dioxide, silver nanoparticles, and others. Plants are unable to utilisefertilisers or nutrients that have been applied to them because they drain or degrade when exposed to light and water. Delivery of nutrients and nanoparticulate materials to plants allows for appropriate and controlled utilisation of macromolecules and nutrients at a particular spot needed to promote plant development (Alamet al., 2015).

The following are the primary advantages of priming

1. Priming has a constant and quick germination rate, seedling vigour, and crop establishment under adverse situations.
2. Priming is used to combat thermoodormancy. High temperatures (35° C) that limit the development of free amino acids and esterase activity required for radicle protrusion may be overcome when seeds are primed with kinetin, resulting in germination (Cantliffeet al., 1984).
3. Crop production can be increased and negative impacts of stress (drought and salt) can be reduced by seed priming.
4. Age-related chromosomal damage is lessened by priming.
5. It lessens the damaging illnesses carried by the soil.
6. Low vigour seeds' viability is also improved by priming.

3. CONCLUSION AND FUTURE PERSPECTIVES

Seed priming has been demonstrated to improve stand establishment, boost yield, and accelerate seedling emergence. Priming has been demonstrated to be beneficial for a variety of field crops. It is the finest remedy for germination-related issues, particularly when crops are produced in unfavourable circumstances. Numerous priming methods have developed and are currently used in a wide variety of crops. It can increase germination rates and percentages as well as seedling emergence, ensuring adequate stand establishment in a variety of environmental circumstances. Seed priming, which improves tolerance to harmful environmental circumstances, undoubtedly activates a number of metabolic pathways. The seedlings that grew from prepped seeds had uniformly early germination. Additionally, seed priming treatments enhance the general growth of seedlings and plants, thus farmers or other crop producers should practise and implement the science of seed priming to maximise crop production in any challenging environmental conditions.

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2. Rephraser

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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