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Improving Seed Quality by Seed Priming under Abiotic Stress Condition: A Review

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ABSTRACT: Plants face various environmental stresses such as drought, extreme temperatures, exposure to hazardous compounds, submersion, and high salt levels, all of which significantly impact their growth, development, and yield. To enhance plants' ability to withstand these challenges, seed priming has emerged as a simple and cost-effective technique. In this method, seeds are soaked in solutions containing natural or synthetic chemicals before sowing, which accelerates the germination process and triggers crucial physiological and biochemical changes in plants. Seed priming is a physiological process that enables plants to respond more effectively to impending environmental stresses as part of their defense mechanism. Furthermore, plants grown from primed seeds exhibit enhanced and faster responses to environmental challenges. It is evident that seed priming for improved tolerance to abiotic stresses operates through multiple pathways linked to various metabolic activities. Different types of seed priming techniques are employed, and all have demonstrated the ability to produce seedlings that grow faster, more uniformly, and yield larger harvests. Although primed seeds have limitations in terms of viability when stored at high temperatures, the advantages of seed priming outweigh these drawbacks. For successful seed priming, it is crucial to use high-quality seeds that are uniform in size and maturity. Poor-quality or non-uniform seeds may yield inconsistent priming effects and variable germination rates. This overview aims to provide a comprehensive understanding of the various crop species that benefit from seed priming techniques and the undeniable advantages it offers in terms of increased resistance to environmental challenges.

Keywords: Abiotic stress, salinity, seed germination, seed priming, seedling emergence.

INTRODUCTION

At different stages of their growth and development, plants are naturally subjected to a wide range of environmental challenges (Lal *et al*., 2018). Temperature extremes, drought, and salinity are three frequent abiotic factors that have an impact on plant growth (Zhao *et al*., 2007). Abiotic stressors on field-standing crops in agricultural systems result in enormous economic productivity losses and plant diseases (Jakab *et al*., 2005). Extreme temperatures, salt, and drought cause crop plants to experience osmotic stress, which in turn causes an imbalance at the molecular, physiological, and cellular levels that ultimately results in plant mortality. The complex mechanisms that plants have evolved to sense stimuli and react to their surroundings include modifying plant metabolites, activating hormone signal pathways, and producing free radicals such as salicylic acid, abscisic acid, ethylene, and jasmonate (Farooq *et al*., 2009). Because of the reduced water potential that resulted from the water shortage, seed germination and seedling establishment were impeded (Farooq *et al*., 2009). Another significant issue that plants experience as a result of being exposed to drought stress is oxidative damage, which is caused by the abundant synthesis of reactive oxygen species (Gill & Tuteja 2010).

In order to increase crop yields and lessen the detrimental consequences of water shortage, it has become essential (Ashraf & Rauf 2001). Plants respond to biotic and abiotic environmental challenges by producing a number of volatile organic compounds that are crucial for both signalling and defence processes. The amount of volatile organic compounds emitted under stressful conditions depends on stress resistance, the length of time, and the severity of stresses. Salinity and drought are two examples of environmental stresses that have several facets and are influenced by a diverse range of elements. The majority of plants are affected by salinity and drought, which can result in a variety of physiological, biochemical, and metabolic changes that can induce oxidative stress and ultimately lower yield (Shafi *et al.*, 2009; Xiong & Zhu 2002).

Plants also develop protective enzymes in reaction to environmental challenges, including superoxide dismutase, catalase, ascorbate peroxidase, and proline, which neutralise ROS produced as a result of stresses. Plants create biological volatile organic compounds that are crucial as signalling and defence chemicals (Vickers *et al.,* 2009). Since the beginning of time, various methods have been tried in an effort to increase plants' tolerance to stress. These methods include both traditional ones, such hybridization and selection, as well as more contemporary ones, including polyploidy breeding, genetic engineering, and mutation breeding, among others. These contemporary breeding techniques unavoidably have some drawbacks, such as the high cost, labor-intensive, and significant energy and personnel requirements. Due to the well-understood multigenic or complicated nature of drought and salinity-resistant features, numerous attempts to generate plant varieties with better-quality drought and salinity tolerance using selection-based breeding procedures have proven to be utterly fruitless (Cushman & Bohnert 2000; Flowers *et al*., 2000).

Innovative methods like genetic engineering, plant tissue culture, and seed priming can all significantly increase productivity and yield. Crops of higher quality can be produced by using advanced genetic engineering and genome editing techniques to introduce certain foreign genes into important crop species (Gust & Nürnberger 2010). Studies have revealed that the drawbacks of gene silencing and the impact of pleiotropy make it difficult to incorporate transgenes into breeding programmes. Due to the limitations of current technology, research has focused on a variety of alternative strategies, including seed priming, tissue culture, and mutagenesis, in an effort to provide plants the ability to withstand environmental stress (Lal *et al*., 2018). Seed priming with hormone solutions is referred to as hormonal priming, and hormonal seed priming plays an important role in seed metabolism (Rhaman *et al*., 2020). Currently, hormonal seed priming is a commonly used technique to improve seed germination, seedling growth, and crop yield in adverse conditions (Hasanuzzaman & Fotopoulos2019). These alternative methods must be straightforward, affordable, and simple enough for farmers to use without obvious difficulty. They also need to be effective at reducing stress (Jisha *et al.,* 2013).

SEED PRIMING

One of the crop management strategies for reducing the negative effects of drought stress is seed priming (Sharma *et al*., 2014). It has been demonstrated that priming seeds is an excellent approach for giving plants the ability to withstand stress. In order to impart specific physiological, cellular, and biochemical states inside the seed that increase germination, seedling establishment, and stress tolerance, seed priming involves exposing seeds to solutions of hormones, low osmotic potential, plant nutrients, inorganic salts, and water (Hussain *et al*., 2016; Lal *et al*., 2018). It was Heydecker, Higgins, and Gulliver who initially presented the seed priming notion in 1973. It is a useful strategy that encourages the quick and uniform emergence of seedlings in addition to achieving higher vigour, which improves crop stands and increases output. It is a low-cost and straightforward hydration technique in which seeds are partially soaked in solutions until pre-germination metabolic activities without actual seed germination are initiated, and then dried back to almost their initial dry weight. For rapid, high-quality crop growth and bumper yield in a variety of crops, seed priming is used (Yadav & Tripathi 2018). Priming seeds imparts a cellular condition that makes plants grown from them more resilient to environmental challenges like salinity and drought.

Seed priming increases a plant's resistance to pathogen attacks and its ability to fend off illnesses. Reduced imbibitions lag time, enzyme activation, synthesis of germination-promoting metabolites, imbibitional repair of metabolic processes and osmotic alteration are the key causes of rapid and uniform germination of primed seeds (Farooq *et al* ., 2006).

It has been reported that priming of seeds is advantageous to numerous crops under chilling stressors. Due to the activation of antioxidant defense mechanisms within plant tissues, priming of seeds improved the tobacco plant's ability to withstand cold during the germination and seedling growth stages (Xu *et al.,* 2011). According to (Guan *et al.,* 2009), priming of seeds accelerated germination and encouraged seedling growth in maize under chilling stress. Similar reports claim that osmopriming and hydropriming sped up the germination and growth of chickpea plants when temperatures were low (Elkoca *et al.,* 2007). In comparison to unprimed seeds, (Hussain *et al.,* 2016) found that two indica rice seeds (HHZ-inbred & YLY6-hybrid) that were osmoprimed, hydroprimed, redox primed and chemical primed under chilling stress appeared to have increased and faster germination, rapid seedling growth, higher shoot length, higher root length, and higher fresh weights of shoot and roots. It has also been discovered that hydroprimming and osmoprimming in indica and japonica rice seeds resulted in seedlings with higher levels of soluble sugar, amylase, superoxide dismutase, peroxidase, and catalase activity, as well as higher levels of free proline. Increased proline content and the aforementioned antioxidants' activities are signs of better tolerance to low temperature stress in rice seedlings that have been primed. In comparison to unprimed seeds, priming of seeds has been shown to increase soluble protein, total soluble sugar, and proline under water stress. Crop growers have been heavily advised to use this method to increase their crop yields in unfavorable field conditions (Yuan-yuan *et al*., 2010). As a result, seed firms have given finding suitable priming chemicals that may be utilized to increase plant tolerance to unfavorable circumstances in the field's great attention (Job *et al*., 2000; Jisha *et al*., 2013). Even while priming of seeds is the usual strategy that receives the most attention, plants can also be primed at the seedling stage.

In seed priming, seeds are slightly moistened until the germination process begins, but the radical does not protrude as a result (Coolbear & Mcgill 1990). Viability and storage are the key barriers to the use of primed seeds in real situations (McDonald, 2000). According to studies, prepped seeds kept at high temperatures lose viability when sown (Hussain *et al*., 2016). However, seed re-priming and heat shock are reported to enhance viability of primed seeds which are under storage for long period of time at higher temperatures (Hussain *et al*., 2016). Figure one below shows the mechanisms of seed priming (Rao *et al*., 2022). Physiological, biochemical, and molecular underpinnings are used to explain how rice seed priming causes quick germination, seedling establishment, and economic output.

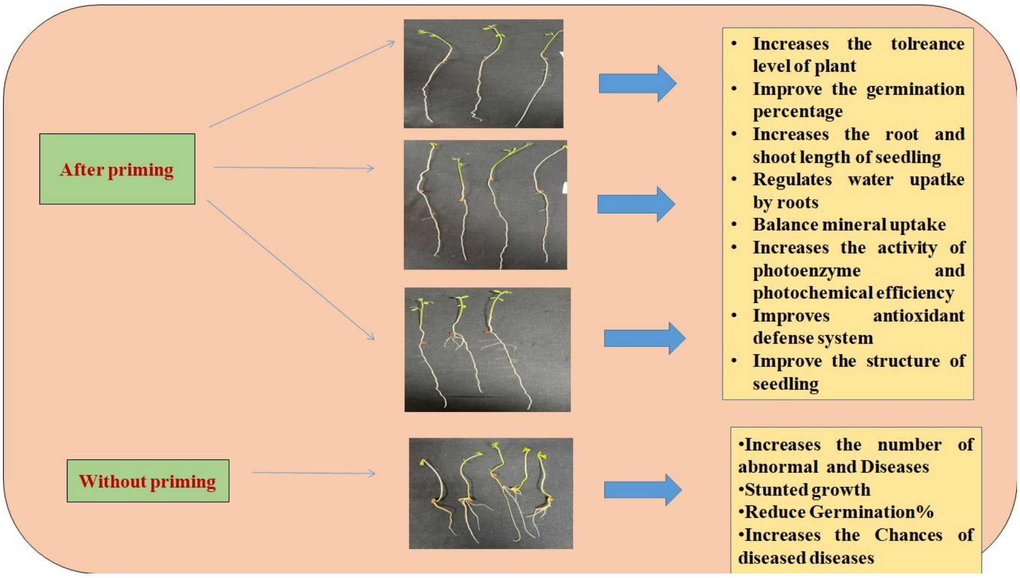

Fig. 1. The Effect on seedling before and after priming (Standardization done by Rao *et al*., 2022).

The Factors Influencing Seed Priming. Farooq *et al*. (2010) Light, aeration, seed quality, drying, storage, and priming temperature and length are the main variables that are evaluated in specific priming experiments. There are several other elements that affect seed priming. In a polyethylene glycol solution, air is thought to play a crucial role in assisting seed respiration, which is essential for seed viability and also helps seedlings emerge uniformly. But the impact of aeration on seed priming varies depending on the species; for example, in onions, air in the PEG solution increased the percentage of seed.

Aerated priming has been favored in the vast majority of the examined literature because it ensures the seed has a secure environment. Air is typically supplied in smaller-scale seed priming tests using aquarium pumps (Di-Girolamo & Barbanti 2012). Some literary works have suggested that light has an impact on seed priming mechanisms. Although celery and lettuce are photoblastic seeds that need light to germinate, the priming procedure for primed lettuce produced superior results when it was conducted in the dark. This is because dormancy was minimized. Osmotic potential and chemical reaction speed are strongly influenced by temperature. According to some reports, priming at a temperature of 15°C significantly improved seed germination in some species; however, low temperatures slowed down the processes, making them take longer to produce the same outcomes (McDonald, 2000). Priming procedures typically take place at a temperature between 15 and 20°C. The type of osmotic solution, temperature, osmotic potential, and crop species all affect how long a treatment lasts when priming seeds. Longer priming times can make seeds more vulnerable to radicle emergence and produce damage that cannot be repaired when the seeds are dried back out (Parera *et al.,* 1993). Lehmann love-grass seeds were imbibed in H_2O_2 in the dark at 10°C, and it was discovered that as priming time was extended from one day to three days, the percentage of germination improved (Watts, 2001). While seeds primed for a longer amount of time at lower H_2O_2 potentials exhibited decreased responsiveness to germination, seeds primed for a shorter period of time at high H_2O_2 potentials generally triggered enhanced germination. Optimum period of priming seeds vary from one species to another (Hardegree & Emmerich 1994) seed Priming Agents There are various inorganic and organic chemicals such as silicon, nano-silicon particles, potassium nitrate, potassium chloride, calcium chloride used in priming of different seeds of plants for improving seed germination and seedling emergence (Yadav *et al*., 2018; Yousof, 2013). For priming seeds, a variety of solutions are utilised, including those containing glycerol, polyethylene glycol, calcium chloride, and sugars with higher osmotic potentials. Plant growth hormones are efficient at converting stress-related signals into changes in gene expression that provide plants the ability to adapt to unfavorable environmental situations. The favorable effects that gibberellic acid, salicylic acid, and kinetin play in inducing plant responses to saline stressors have garnered a lot of attention (Afzal *et al*., 2011). There is a lot of study on the beneficial effects of salicylic acid and kinetin for treating or exogenously applying them to wheat seedlings to induce salt tolerance (Jafar *et al*., 2012).

Table 1: The effect of different type of priming method under different type of abiotic stress.

Crop	Method of priming	Results	Reference	Stress
Cowpea	Osmopriming	OP + BC improved plant biomass, chlorophyll, and sugar accumulation in cowpea under salinity Integrated use of osmopriming with $CaCl_2$ (OP) and biochar (BC) improved seedling emergence	(Farooq *et al.*, 2020)	Salinity
Cucumber	Hydropriming	The best identified temperature would be 25 ± 10 C and the optimum duration of soaking is 48h for hydroprimng in cucumber. It is imperative to conclude that hydropriming is a simple, low cost and eco-friendly technique for improving seed quality attributes in cucumber.	(Sowmya *et al.*, 2020)	Control Hydration and Dehydration
Zea Maize	Halopriming and Hormonal Priming	Soaking of seed with GA3 and NaCl solution is advantageous to obtain healthy seedlings. The second best option for priming is hormonal priming with Salicylic acid and halopriming with $CaCl_2$	(Neha Kumari *et al.*, 2020)	Abiotic stress
All crop	Chemical priming	The use of chemical priming also needs to be combined with a precise prediction and understanding of climate change to mitigate drought and temperature stress tolerance. Although further research is needed, chemical priming represents a feasible approach for improving abiotic stress tolerance to maintain or increase crop yield	Kaori Sako *et al* ., 2019)	Different abiotic condition drought , heat and cold
Wheat	Nutrient priming	Cd stress and its management for aiming to reduce Cd uptake and accumulation in wheat may help to improve wheat growth and grain quality	(Rizan *et al*., 2016)	Heavy metal stress
Radish	Bio priming	Applications of bio-priming with bacteria strains significantly improved the percentage of seed germination under saline conditions. These results suggested that bio-priming with PGPR under saline conditions could be useful to obtain higher seed germination percentages in radish	(Haluk *et al*., 2008)	Salinity stress
Chickpea	Magnetopriming	Two chickpea varieties—Pusa 1053 and Pusa 256—to 100 mT (militesla) for an hour, followed by exposure to varying salinity levels and normal conditions, significantly increased germination percentage, germination rate, as well as seedling growth by improving shoot length, root length, and seedling vigour indices I and II compared to unprimed chickpea seeds	(Thomas *et al.*, 2013)	Salinity stress
Wheat	Magnetopriming	Increased activity of APX and GPX under soil flooding, lower oxidative stress	(Balakhnina *et al.*, 2015)	Flooding
Soyabean	Magnetopriming	Higher germination percentage, seedling biomass and fresh weight; improved light harvesting, Chl fluorescence, leaf photosynthetic efficiency and leaf protein content; reduced ROS production	(Shine *et al*., 2011)	Laboratory, field
Mouse-ear cress (Arabidopsis thaliana)	Gama ray priming	Better germination index, primary root length, seedling growth and fresh weight and antioxidant enzymes; reduced ROS and gene expression at the best dose	(Qi *et al*., 2015)	Cadmium stress

IFFERENT SEED PRIMING METHODS AND THE EFFECTS OF STRESS TOLERANCE

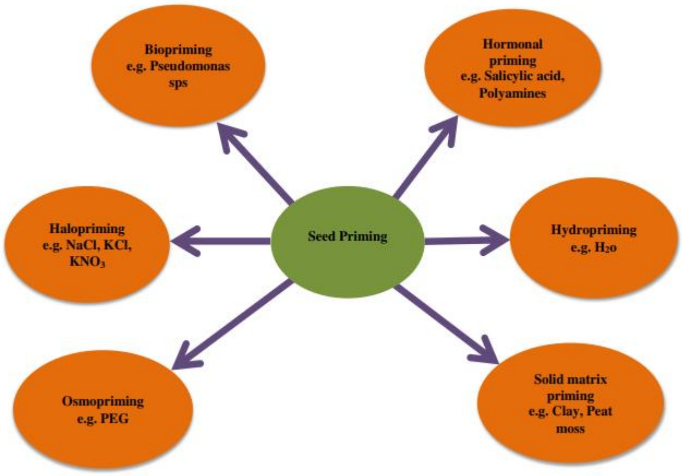

Fig. 2. The types of method of seed priming (Farooq *et al*., 2006).

HYDROPRIMING

Hydropriming is a straight forward, inexpensive, and risk-free method for enhancing seed osmotic adjustment capacity, increasing establishment of seedlings, and increasing crop production under stressful environmental conditions (Kaur *et al*., 2002). Under situations of high temperature and water scarcity, hydropriming of cotton seeds improved seed germination (Casenave & Toselli 2007).

OSMOPRIMING

Osmopriming is the process of treating seeds by soaking them for a set amount of time in low osmotic solutions such polyethylene glycol, sugar, mannitol, and others before drying them and preparing them for sowing. The amount of chlorophyll a, b, and carotenoids in the maize plant decreases simultaneously with the germination percentage and germination index reduction under prevalent stress conditions like salt. Seed priming causes metabolic changes during germination that help sorghum adapt better to salt stress (Aliu *et al*., 2015). Wheat seed germination may be hampered by exposure to high salt chloride concentrations (Akbari *et al*., 2007; Lal *et al.*, 2018). Wheat cultivars with hydrogen peroxide-primed seeds showed increased resistance to salt (Wahid *et al.*, 2007). $CaCl_2$, abscisic acid, and water hydroprimed mustard seeds have demonstrated faster germination, and the crops resulting from the hydroprimed seeds have a high concentration of chlorophyll and dry biomass weight under polyethylene glycol (PEG) and NaCl stressors (Srivastava *et al*., 2010a). Thiourea supplementation promotes tolerance against salinity stress, presumably maintaining water homeostasis, in *Brassica juncea* roots. Under water stress and salinity stress circumstances, potassium nitrate priming and hydropriming greatly improved seed germination and seedling growth (Kaya *et al*., 2006). Although priming had no favorable impact on field emergence, winter wheat seeds primed with KCl, water, and PEG demonstrated faster germination (Giri & Schillinger 2003).

HORMONAL PRIMING

A possible method for reducing the detrimental effects of salt stress on crops is the exogenous application of plant growth agents, osmoprotectants, or osmolytes through seed or foliar applications (Afzal *et al*., 2008). Priming of seed, a regulated soaking technique then followed by drying is a practical approach for counteracting the effect of salinity in several crop species due to its low-cost effectiveness and simplicity (Jafar *et al*., 2012). According to (Chunthaburee *et al*., 2014) study, priming two glutinous rice cultivars (Niewdam & KKU-LLR-039) with spermidine and gibberellic acid increased shoot length, root length, seedling length, seedling fresh weight, and seedling dry weight of seedling from primed seeds of both cultivars compared to seedling of the unprimed seeds, alleviating the inhibitory effect of salinity stress. Similar to this, rice seedlings from primed seeds exhibit much higher levels of anthocyanin and chlorophyll under saline stress, indicating robust photosynthetic activities as compared to unprimed controls.

Primed rice seeds exposed to salt stress gave rise to seedlings with a higher proline content, which is linked to safeguarding plant cellular structures and mediating osmotic adjustment. Salinity stress increased the content of hydrogen peroxide in rice cultivars thereby causing increased lipid peroxidation by inducing higher production of reactive oxygen species, however, spermidine and gibberellic acid primed rice were found to produced seedling with lower content of hydrogen peroxide hence minimal lipid peroxidation compared to untreated seedlings (Chunthaburee *et al*., 2014). The germination percentage, pace, and length of the plumule of primed marigold and sweet fennel were all negatively impacted by increasing salinity stress in the study by Sedghi *et al*. (2010), although seedlings grown from NaCl and GA_3 primed seeds showed no decline. Primed seeds exhibited a higher rate of germination across all salinity levels, and seedlings grown from primed seeds have longer plumules than seedlings from unprimed seeds. Similar to this, primed pot marigold was found to have the maximum fresh and dry radicle weights at a salinity stress level of $7.5dSm^{-1}$. Pot marigold has a faster rate of germination than fennel, which suggests that it is more tolerant of saline. In saline stress conditions, GA_3 and NaCl priming can influence the proper metabolic processes within seeds, enhancing seed germination and seedling emergence.

HALOPRIMING

Halopriming Various seed priming techniques have been shown to boost a variety of plant species' resistance to drought. Using potassium salts and ascorbic acid to prime wheat seeds increased wheat seedlings' ability to withstand drought (Farooq *et al*., 2013). Sugarcane cultivars develop more quickly when exposed to salinity and drought when halopriming is used Patade *et al*. (2009). According to Yan (2015), under drought stress, priming Chinese cabbage seeds with urea, potassium nitrate, and distilled water resulted in seedlings with noticeably higher germination percentages, germination potential, and seed vigour indices. Through modulating higher activities of peroxidase, superoxide dismutase, catalase, and osmoprotectants proline, the priming effect stimulated the germination characteristics that were previously inhibited by the severity of the drought, providing protection against water deficit compared to seedling from unprimed seeds. On the other hand, both seedlings from primed and unprimed seeds had lower soluble sugar content. Halopriming and redox priming of seeds of two rice cultivars with calcium chloride, potassium chloride and hydrogen peroxide grown under salinity stress produced seedling with increased final germination percentage, shoot length, root length and seedling dry biomass while hydropriming did not affect seedling germination (Afzal *et al*., 2012). Similarly, rice seed primed with $CaCl_2$, distilled water, KCl_2 and H_2O_2 significantly reduced the length of time taken by seeds to germinate under different range of salinity stress. In contrast, halopriming with calcium chloride increased K+ in root and leaf but decreased leaf accumulation of Na+ and root uptake while higher Na+ take-up and leaf accumulation were observed in seedling from unprimed and H_2O_2 primed seeds.

Salt stress significantly increased the uptake of Na^+ in rice cultivars with a concurrent increase in concentration of leaf Na^+ at higher levels of salinity. Prior to now, it was reported that rice seedlings raised from $CaCl_2$ and KCl_2 primed rice seeds had higher chlorophyll content than those raised from hydroprimed, H_2O_2 primed, as well as unprimed seeds, which had lower levels of it. This decrease in chlorophyll content was attributed to rising salinity levels (Afzal *et al*., 2012). Under drought stress, priming wheat seeds with $CaCl_2$ increased productivity by promoting seedling emergence, establishment, height, number of grains, tillers, and grain weight (Hussian *et al.*, 2013). According to reports, prepping hybrid maize seeds with KNO_3, urea enhanced germination potential, seedling growth, root length, protein content, and proline amount when exposed to salinity and drought conditions (Anosheh *et al.*, 2011). Rice seeds that have been osmotrimmed or halotrimmed with $CaCl_2$ and KCl exhibit improved seedling vigour as evidenced by quicker germination, seedling emergence, productive tiller number, kernel yield, harvest index, and yield of straw.

CHEMICAL PRIMING

Chemical Priming Seeds from different species of crops are primed using a variety of chemicals. When plants are treated with some natural or synthetic compounds, such as chitosan, choline, selenium, paclobutrazol, putrescine, ethanol, potassium dihydrogen phosphate, zinc sulphate, copper sulphate, and butenolide, they can be given the ability to withstand abiotic stress (Demir *et al.*, 2012; Foti *et al*., 2008). Burned cellulose and smoke made from plants were used to extract the butenolide compound. Faster seedling establishment brought on by butenolide therapy reduces sensitivity to pathogen assault. While there were no obvious observable effects on giant cells, priming rice seeds with silicon significantly reduced rice root attacks by nematode (*Meloidogyne graminicola*) as well as delayed worm development. OsERF1, OsEIN2, and OsACS1 transcript levels within the ethylene pathways were highly connected with improved silicon primed rice plants' resistance to nematode attacks. The silicon priming effect was dependent on the ethylene route since it dramatically reduced the number of nematodes in rice plants while also increasing ethylene signalling. However, there was no such effect in plants with low ethylene signalling (Zhan *et al*., 2018). Rice varieties primed with selenium under arsenic stress were found to have depressive effects on the stress and markedly increased plant height, weight of panicles, number of grain, 1000-grain weight, chlorophyll content as well as above-soil biomass compared to unprimed seedlings (Moulick *et al.*, 2018).

NUTRIENT PRIMING

Nutrient Priming Various initiatives have been made in an effort to identify fresh, efficient priming agents. In priming tests, the use of micro or trace elements like boron and zinc has received attention. Presoaking seeds in a selenium solution before planting is one method for giving plants the element and controlling development (Khaliq *et al*., 2015). An innovative strategy that combines the advantages of increased nutrition availability and seed priming is seed priming with nutrients (Al-Mudaris & Jutzi 1999). Growing research suggests that plant nutrients like iron, manganese, and zinc are crucial for influencing how well plants can withstand biotic and abiotic stressors (Marschner, 2012; Imran *et al*., 2013). Potassium, silicon, and selenium are three mineral nutrients that are particularly important for crop plants to survive in today's severe weather conditions (Amalina *et al.*, 2016; Azeem *et al*., 2015; Wang *et al*., 2016). Zinc solution priming of seeds increases wheat and chickpea grain production (Arif *et al.*, 2007). Because of its antioxidant qualities, the vitamin ascorbic acid, which is necessary, can be utilised to prime seeds.

It has been established in the past that a high level of endogenous ascorbate is crucial for maintaining the antioxidant capacity that shields plants from oxidative damage (Farooq *et al*., 2006). Under salinity stress, pretreatment of wheat grass (*Agropyron elongatum*) with ascorbic acid enhanced its germination properties (Tavili *et al.,* 2010). Imran *et al*. (2013) investigated the effects of nutrition priming and hydropriming on maize with iron and Zn + Mn in both lab and field settings. The findings revealed that nutrient primed maize had significantly improved seedling fresh biomass, shoot, and root length at low root zone temperature. But there was no distinction between unprimed and hydroprimed maize. Similarly, Zn+Mn priming on the field was more effective than Fe priming and hydropriming at promoting maize seedling development and nutrient status.

In a study by (Moulick *et al.,* 2018), selenium (Se) priming of two varieties of rice (Swarna & Satabdi) under arsenic stress was discovered to significantly increase plant height, biomass, panicle weight, number of tillers, and content of chlorophyll a, b, and c at all Se doses (0.5 Mg L, 0.75 Mg L, and 1.0 Mg L). A greater dose of 1.0 Mg L was more successful in boosting these growth parameters; this dose dependence of the enhancement of these growth characteristics. Se priming was also successful in preventing the transfer of arsenic to other plant aerial sections. Wang *et al.* (2016) studied that Selenium and salicylic acid priming of two rice types under chilling stress was found to boost rice seedling growth as evidenced by increases in shoot length, root length, shoot fresh biomass, and root fresh biomass. Similarly, the maximum emergence rates for the Se and SA primed rice types are 81.87% and 80%, respectively, with enhanced germination rates of 87.5% and 82.81%. When two rice cultivars (Super basmati and Shaheen basmati) were primed with concentrations of 15, 30, 45, 60, 75, 90, and 105 mol L Se, (Khaliq *et al.,* 2015) discovered that the mean emergence time and time to attain 50% emergence were significantly shortened and the emergence index was raised in comparison to hydroprimed and control rice seeds. But 60 and 75 mol L Se priming were more successful in reducing these characteristics. Additionally, it was discovered that Se priming boosted the shoot, root, and dry biomass of Super basmati and Shaheen rice seedlings more than hydroprimed and their unprimed control counterparts did.

MAGNETOPRIMING

Magnetopriming, a dry priming technique that involves submerging seeds of various crop species in magnetic flux density to start vital germination processes, has been reported to hasten germination, increase germination rate, and boost seedling vigour of various crop species (Thomas *et al.,* 2013). According to Thomas *et al*. (2013), study, magnetopriming two chickpea varieties—Pusa 1053 and Pusa 256—to 100 mT (militesla) for an hour, followed by exposure to varying salinity levels and normal conditions, significantly increased germination percentage, germination rate, as well as seedling growth by improving shoot length, root length, and seedling vigour indices I and II compared to unprimed chickpea seeds The study also showed that under both normal and salt stress circumstances, primed chickpea genotypes showed increased water imbibition, which promotes quicker germination and seedling growth. It has been noted that seeds of buckwheat (*Fagopyrum esculentum* Moench.), flax (*Linum usitatissimum* L.), field pea (*Pisum sativum* L.), and sunflower (*Helianthus annus* L.) exposed to static magnetic field produced early and quick-growing seedlings (Gubbel, 1982; Thomas *et al.,* 2013).

It has been observed that low-quality seeds subjected to a magnetic field exhibited better quality and germination rate (Carbonell *et al.,* 2008). It was discovered that magnetopriming was helpful in reducing the negative effects of drought stress in maize seedlings (Anand *et al*., 2012). According to Vashisth and Nagarajan (2010), wheat and sunflower seeds subjected to a static magnetic field were shown to have much more amylase activity than the controls.

BIOPRIMING

It was discovered that pretreatment of pea seeds with an aqueous extract of lesser bulrush increased the rate of germination, seedling growth, shoot length, and root length by reducing the negative effects of salinity and increasing the contents of proline, total soluble sugar, chlorophylls a and b, carotenoids, total phenolic, and total flavonoid while lowering the levels of malondialdehyde in the plants from primed seeds from untreated seeds. However, it was shown that seedlings from unprimed pea seeds had less alkaloid content (Ghezal *et al.,* 2016). In the cases of sweet maize (*Zea mais* L.), pea (*Pisum sativum*), cucumber (*Cucumis melo* L.), and soy beans (*Glycine max* L.), biopriming has been shown to be effective in preventing seedling damping off (Girolamo & Barbanti 2012). Singh *et al.* (2016) carried out a field investigation on *Trichoderma asperellum* biopriming pea seeds. The study's findings showed that when compared to unprimed peas, biopriming significantly enhanced the number of pea leaves, shoot length, fresh and dry weight of shoot, fresh and dry weight of root, and root length. In order to protect seedlings from illnesses, pest infestations, and infections, biopriming is crucial.

SOLID MATRIX PRIMING

Solid Matrix Priming Another method of hydrating seeds, solid matrix priming involves simulating natural imbibition processes in the soil environment with semi-solid inorganic or organic components. The following characteristics must be present in substrates for matrix priming: increased seed safety, lower matric potential, higher surface-to-volume ratio, low water solubility, higher water holding capacity, and capacity to adhere to seed surfaces. Materials used in solid matrix seed priming include vermiculite, peat, and commercial substrates like Micro-cel and Celite (Di-Girolamo & Barbanti 2012). The substrates that gradually moisten the seeds must be combined with the seeds in solid matrix priming. It is necessary to replace the clean water with a low-osmotic solution, similar to that used for osmotic priming, in order to improve seed imbibition management (Di Girolamo & Barbanti 2012). Numerous studies have noted the advantages of solid matrix priming for various crop species. It was discovered that solid matrix priming improved soybean germination and seedling vigour in addition to improving carrot field performance (Lutts *et al.*, 2016). According to a study, in both normal and cold temperature circumstances, matrix priming boosted the rate of seed germination, seedling establishment, and onion growth (Kepczynska *et al.*, 2003). According to reports, combining biological, chemical, and solid matrix priming may significantly improve seed performance (Sen & Mandal 2016). In several tropical vegetable species, matriconditioning combined with Bacillus subtilis, fungicide, and gibberellins boosted crop establishment and yield (Andreoli & Andrade 2002). Additionally, it was discovered that GA_3 matri conditioning improved the quality of hot pepper seeds (Ilyas, 2006). Okra grown in freezing temperature settings had higher germination rates, fields of emergence of seedlings, fruits per plant, and productivity when solid matrix priming was mixed with a species of Trichoderma viride (Pandita *et al.*, 2010). The germination percentage, shoot and root lengths, leaf length and width, and germination speed of bamboo (*Dendrocalamus strictus*) were all increased by solid matrix priming and 1% KNO_3 priming for 8 hours, according to Sarkar *et al.* (2018). According to Sen and Mandal (2016) study, matrix-aided chitosan priming of mung bean seedlings under salinity conditions led to higher germination index, germination speed, coefficient germination velocity, low mean germination duration, and higher germination stress resistance indices for plant height and root length compared to unprimed mung bean seedlings. However, there is no discernible impact of priming on these traits under increased salinity stress of above 12 dSm (deci Siemens metre). Seed priming has a number of drawbacks. Compared to unprimed seeds, primed seeds have a much shorter lifespan. Primed seeds have reportedly been known to quickly degrade in storage if the temperature is high. Primed sweet maize seeds showed poor germination as well as growth performance of seedlings after stored for 3 months at 25°C compared to unprimed seeds (Chiu *et al.*, 2002; Hussain *et al.*, 2016). Lower and delayed germination had been observed in primed tomato seeds stored for 6 months at 30°C compared to control seeds. Primed lettuce seeds were reported to have reduced longevity in storage at higher temperature and humidity relative to unprimed seeds. Primed lettuce seeds stored for 14 days in mild conditions of 45°C and 50% relative humidity showed delayed and non-uniform germination than unprimed (Hill *et al.*, 2007; Schwember & Bradford 2005).

Studies have pointed out that the better qualities of primed seeds stored at 25°C could be maintained for the period of only 15 days after which their agronomic performance is less than that of unprimed seeds. It has been reported that priming of onion prior to storage helps in delay of viability loss, after storage priming had no any implication on seed viability. Primed and dried seeds of onion have retained germination improvement potentials even after the period of 18 months stored at 10 °C (Hussain *et al.*, 2016). According to Chiu *et al.* (2002), primed sweet corn seeds were found to be more durable than unprimed seeds and to display greater germination and seedling vigour responses when stored for more than 12 months at 80 or 10°C. The interaction of genetic and environmental factors, such as seed water content, seed storage temperature, and seed quality, is what causes variations in the lifetime of primed seeds. High temperatures and seed water content are known to hasten the rate at which seeds deteriorate (Hussain *et al.*, 2016). Indica rice (HHZ, inbred & YLY6, hybrid) seeds were primed with 10% polyethylene glycol and 0.5 m mol L spermidine for 24 hours at 25 °C, according to Hussain *et al.* (2016). According to reports, post-storage treatments such dehydration, heat shock, priming, and humidification can partially recover the lower durability of primed seeds. After being kept, seeds can benefit from repeated priming to lessen the negative effects that storage has on the viability of the seeds.

GENERAL STEPS OF SEED PRIMING

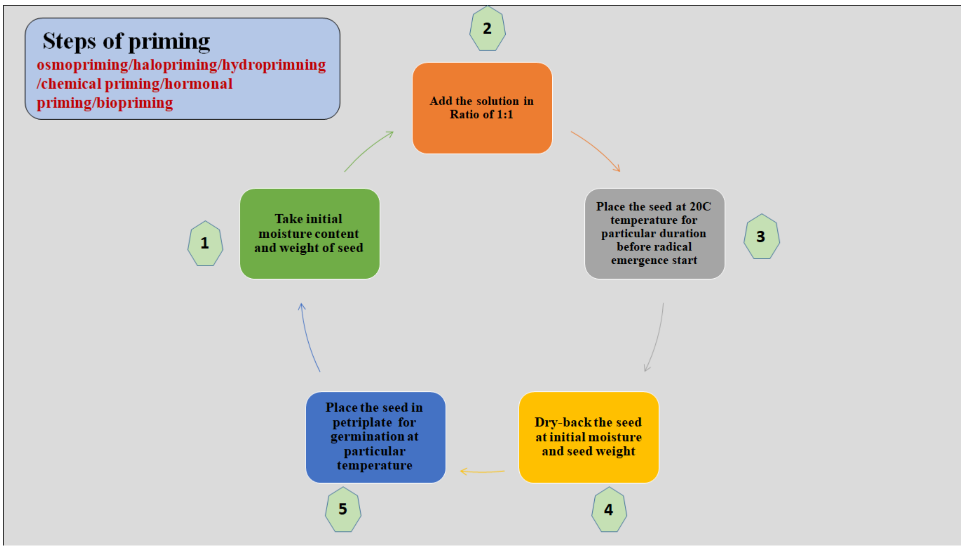

Fig. 3. The general procedure of seed priming by using different method Standardization done by Rao *et al*. (2022)

CONCLUSIONS

In recent years, the practice of priming seeds has come to be recognized as a dependable method for dealing with stress since it helps protect plants from many sorts of stress that could negatively impact their fitness. Additionally, this method provides a practical, sensible, clever, and easy solution for plant protection. Drought, salinity, oxidative stress, and high temperatures are all related and can cause comparable types of damage. As a result, these abiotic stimuli primarily trigger comparable biological signaling pathways and reactions. Early phases of plant development are known to be activated by seed priming, and growth eventually results in rapid defense responses. Although the particular biochemical mechanisms of seed priming are not entirely understood, it is hypothesized that the buildup of inactive proteins in primed cells is to blame. On the effectiveness of seed priming, several opinions were presented. According to (Nascimento & West 1988), primed seeds have improved germination and seedling vigour due of the mobilization of food reserves, activation and synthesis of specific enzymes, as well as increased production of DNA and RNA.

FUTURE SCOPE

Future seed priming studies should aim to deepen our understanding of the underlying mechanisms, explore new priming agents and protocols, evaluate long-term effects, integrate priming with other techniques, and expand the application of seed priming to diverse crops and environments. Such research efforts can contribute to enhancing agricultural productivity, sustainability, and resilience in the face of global challenges.

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