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Seed Priming: The Way Forward to Mitigate Abiotic Stress in Crops

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Abstract

Abiotic stress is a major threat to the farming community, biasing the crop productivity in arid and semi-arid regions of the world. The seed is an important component of agriculture, contributing significantly to the booming production of food and feed crops across the different agro-ecological regions of the world with constant challenges with reference to production, storage, and quality control. Germination, plant growth, and development *via* non-normal physiological processes are detrimentally affected by stress. Seed priming is an alternative, low cost, and feasible technique, which can improve various abiotic stress tolerances through enhanced and advanced seed production. Seed priming is a process that involves imbibing seed with a restricted amount of water to allow sufficient hydration and advancement of metabolic processes but preventing germination. The beneficial influence of priming on the germination performance of diverse species is attributed to the induction of biochemical mechanisms of cell repair: the resumption of metabolic activity that can re-impose cellular integrity, through the synthesis of nucleic acids (DNA and RNA) and proteins and the improvement of the antioxidant defense system metabolic damage incurred by dry seed and thus fortifying the metabolic machinery of the seed. With this background, this chapter highlights the morphological, physiological, biochemical, and molecular responses of seed priming and recent advances in priming methods as a tool to combat abiotic stress in crop plants.

Keywords: abiotic stress, seed priming, crop establishment, physiological changes, biochemical changes

1. Introduction

Crop plants are subjected to multiple abiotic stresses during their life span that significantly reduces productivity and foreshadow global food security. The improvement of crop plants through direct selection-based conventional breeding for drought and salinity stress appears to be quite complex [1]. Abiotic stresses such as salinity, drought, flooding, heat, cold, freezing, excess light, UV radiation, and heavy metal toxicity have a significant impact on seed which reduce germination rate, seedling growth and yield with significant

variations from crop to crop worldwide [2]. Water stress is a key agronomic problem globally and is one of the most important factors reducing crop productivity. Drought is one of the most important environmental component limiting plant growth and productivity. The advancement of crop plants through direct selection-based conventional breeding for drought and salinity stress appears to be quite complex. In agriculture, alternative innovative technologies such as plant tissue culture, seed priming and genetic engineering could play a major role in combating abiotic stresses for increasing yield. The quality of seed in the present time can be accomplished by various means where the basic and applied knowledge of plant physiology, genetics and seed technology all are integrated to improve the criteria of quality of seeds. Seed germination is a dynamic and complex stage of plant ontogeny, with several interactive metabolic processes changing from a storage phase to a mobilization phase [3]. The multitude of simultaneous metabolic processes taking place in germinating seed makes it difficult to explore events related to the initiation of the germination process. The catabolic processes in the storage tissues can confound measurements and interpretation of anabolic and growth processes occurring in the developing embryo in the entire seed. The time from sowing to the seedling establishment is of considerable importance in crop production and has major impacts on plant growth, final yield and post-harvest seed quality [4]. Efficient seed germination is important for agriculture. Successful foundation of early seedling indeed requires an accelerated and uniform emergence and root growth. In nature, plants often face the challenge of severe environmental conditions, which include various biotic and abiotic stresses that exert unfavorable effects on plant growth and development causing considerable losses in crop productivity. Drought, salinity and extreme temperature cause osmotic stress on crop plants which generate an imbalance at cellular, molecular and physiological levels which ultimately lead to plant death [5]. Abiotic stress causes many physiological and biochemical changes in the seedlings, which include the generation of reactive oxygen species (ROS), leading to membrane injury and cell leakage and destruction of photosynthetic components [6]. Seed priming is a simple, safe, cost effective, and effective approach for enhancement of seed germination, early seedling growth, and yield under stressed and non-stressed conditions [7]. Seed priming is a form of seed preparation in which seeds are pre-soaked before planting with a certain solution that allows partial hydration but will not germinate and redried to original moisture content [8].

2. Abiotic stress and its effect on crop growth and development

Abiotic stresses are closely related individually or cohesive; they cause physical, morphological, biochemical and cellular changes that adversely affect plant growth and productivity and ultimately yield. Heat, drought, salinity and cold are major abiotic pressures that cause severe cell damage to a wide variety of plants, including crop plants (**Figure 1**). Water stress or drought is a major challenge for agricultural production worldwide. Excessive wilting causes a change in the ratio of membrane lipids and this may result in increased electrolyte leakage [9]. Drought is known as a prime abiotic factor that limits plant growth and production in arid and semi-arid regions and is the most significant factor in world security and sustainability in agricultural production. Drought slows growth, induces stomatal closure and therefore reduces photosynthesis, growth and yield in a number of plant species [10]. Water stress has been revealed to be one of the factors limiting the productivity of cowpea as it affects not only the production of the grain, but also the whole process of growth of all organs of the plant and its metabolism [11]. Water stress limits the size of individual leaves and leaf number.

Figure 1.
Direct and indirect causes of low productivity of field and horticultural crops.

Physiological disorders occur during seed germination under abiotic stress is a decrease in water uptake by the seed due to the low water potential of the germination medium. Slow or abnormal growth and emergence result in fewer and smaller plants, which are more susceptible to various abiotic stresses [12]. In addition to causing various structural changes at different levels of organization in the seed, slow rate of imbibitions may lead to a series of metabolic changes, including up-regulation or down-regulation of enzyme activities, perturbation in the mobility of inorganic nutrients to developing tissues, disturbance in N metabolism, imbalances in the levels of plant growth regulators, reduction in hydrolysis and utilization of food reserves and accumulation of compatible osmotic such as soluble sugars, free proline and soluble proteins [13]. Stress processes may lead to poor or complete lack of germination under abiotic conditions. Salinity is also considered as substantial abiotic stress and significant factor affecting crop production globally and especially in arid and semi-arid regions [14]. The salinity of soil reduces water availability of plant root via negative (low) osmotic potential as well as decrease of germination dynamics of plant seeds by ionic toxicity of Na^+ and Cl^- [15]. Of the extensive forms of abiotic stress, heat stress has an independent mode of action on the physiology and metabolism of plant cells. Due to high temperatures, various physiological injuries have been observed such as scorching of leaves and stems, leaf abscission and senescence and root and shoot growth inhibition or fruit damage, which as a result lead to decreased plant productivity [16]. The plant growth is reduced by affecting the shoot, net assimilation rates and finally the total dry weight of the plant due to high temperature [17]. The stress is extensively prominent on reproductive development than on vegetative

growth, and the sudden reduction in yield with temperature is mainly associated with pollen infertility in many crop species under effects of high-temperature [18]. Heat stress which causes multifarious, and often adverse, alterations in plant growth, development, physiological processes, and yield is one of the major consequences of high-temperature stress [19]. Due to stress limitation of available technology, we should think of various alternate technologies such as priming, mutagenesis, and tissue culture for combating abiotic stresses. In crop species, seed germination and early development of seedling are the most sensitive stages to salinity stress. Salinity delays the onset, reduce the rate and increase the dispersion of germination phenology, leading to a reduction in plant growth and final crop yield. Thus, if the effect of abiotic stress can be mitigated at the early stages, the chance of establishing a successful crop under stress will be improved [20].

3. Seed priming and its importance

Priming involves prior exposure to elicitors which brings a cellular state that arrest the harmful effects of abiotic stress, and plants raised after priming are more tolerant of abiotic stress. Seed dormancy is an emerging issue related to germination that is common to many plant species. It is a practice that allows a species to estimate the germination period in a population. Some species use an environmental indicator (such as drought, rain or temperatures) to integrate germination of many seeds at a particular time of year. Temperature, humidity, air and light conditions are the main factors for seed germination. The minimum temperature is the minimal temperature at which a seed germinates effectively and the maximum is the highest temperature at which seeds can germinate [21]. At optimal temperatures, germination is rapid and uniform but with meager change in this temperature can damage seeds or make them go into the dormancy condition. Seeds need accurate moisture to initiate internal processes leading up to germination. Osmotic adjustment or priming of seeds before sowing is known as a potent way to increase germination and emergence rate in some species with incremental seed development [22]. Inadequate seed germination and subsequently poor field establishment are a common occurrence at adverse conditions of the environment. Seed germination and early seedling growth are the most sensitive stages of water limitation and the water deficit may impede the onset and reduce the rate and uniformity of germination, leading to poor crop accomplishment and yield in several crops. Seed priming is a water-based approach with low external water potential that restrict hydration (controlled hydration of seed) and permit metabolic processes necessary for enhancing germination rate and seed quality by managing the seed moisture content and temperature in which the seed is taken through the initial biochemical processes within the initial stages of germination but preventing the seed transition towards full germination [23]. This will assure better field emergence and disease resistance under various adverse conditions. The purpose of priming is to reduce the germination time and improve stand and germination percentage under unfavorable environmental conditions. Primed seeds are used instantly but may be dried and stored for a short time for later use. Primed seeds attain the potential to rapidly imbibe and revive seed metabolism thus enhancing the germination rate [24]. These attributes have practical agronomic implications notably under adverse germination conditions. Pre-treatment using a priming induced stimulus like sodium nitroprusside, hydrogen peroxide, melatonin and polyamines results in enhanced cell tolerance and amelioration of stress-induced plant growth inhibition [25]. Therefore, the beneficial effects of priming may be more evident in under favorable rather than unfavorable conditions [26]. Primed seeds generally exhibit an increase germination rate, greater germination uniformity, and,

at times, greater total germination percentage. Abiotic stresses produce oxidative stress and activate similar cell signaling pathways and cellular responses [27]. But, seed priming seems to activate these signaling pathways during the early stages of growth, resulting in faster defense responses [28]. The abiotic stress tolerance generated by seed priming is accorded via the synchronization of divergent physiological, biochemical, systemic, cellular and molecular modulations [29]. The purpose of seed germination is to reduce the germination period and to protect the seed from environmental stress during the critical stage of seedling growth to integrate the growth leading to uniform establishment and improved yields. It minimizes the effect of salinity on the morphological parameter of the plants. One of the priming methods called osmopriming is a commercially available method of improving seed germination and strength. It controls seed imbibition to initiate the germination process followed by the seed drying up to its original weight. Various methods of seed planting such as hormonal priming and support for chemo priming in improving the process of germination, flowering and growth of plants are done for commercial purposes on the farm or on the farm. Planting seed on a farm requires electricity, high-tech seed harvesting, seed hardening or seed-drying process is accessible to farmers to help them with cool farming and horticulture [30]. The effective use of a seed management method depends on the type of test, method of application, crop selection, early performance of the plant, chemical selection, concentration, duration of treatment and the purpose of the application. Priming method in seed management techniques is proven very essential factor for enhancing quality issues, germination rate and establishment. Priming can interfere with some of the degenerative effects of aging, leading to improved seed performance [31]. It has shown an immense effect of priming to activate different processes related to cell cycle and to induce to the synthesis of nuclear DNA in radial tip cells [32]. Seed priming had the most beneficial effect on leaf area indicating the advantage of rapid seedling emergence [33]. The reason attributed may be due to cell division, cell number due to multiplication in various plant tissues, auxin multiplication, cell wall plasticity and permeability of cell membrane, increases photosynthesis, cell enlargement and rapid cell wall elongation [34].

4. Factors affecting seed priming process

Seed priming is controlled by many factors such as aeration, light, temperature, concentration of priming solution, time (duration), and seed quality.

4.1 Aeration

Aeration is considered an important step to assist seed respiration, seed viability and contributes to synchronize the emergence [35]. Germinating seeds respire very actively and need sufficient oxygen. The consequence of aeration varies according to species: in onion aeration of the PEG solution increased the germination process compared to non-aerated treatment [36]. No difference was noticed in the germination of lettuce seeds between aerated and non-aerated K_3PO_4 priming [37].

4.2 Duration

Duration (maximum length of time) of priming is one of the key factors for seed priming. Seed priming for 7 h and 14 h is sufficient to augment seed and seedling vigor, stand establishment, and grain yield contrary to soaking the seeds for 21 h

for optimizing duration of hydro priming in green gram [38]. Seeds primed for 12 h took significantly fewer days to emerge and reach maturity when compared to the untreated dry seed, whereas 36 h primed seeds showed poor germination and 48 h primed seeds inhibited germination. This inhibition may be attributed to the prolonged period of priming that led to excess water in the seeds and greater reduction in the O₂ availability to the embryo [39].

4.3 Temperature

The lower temperatures during priming seem to result in slower imbibition of seeds, increasing the duration of phase II of the triphasic pattern of imbibitions [40]. This would allow the activation mechanisms to repair the membrane systems and prevent destruction caused by rapid imbibition. Hydro priming at 15°C increased synchronization of germination and speed of seedling emergence in *Solanum lycocarpum* [41]. Seed priming at 15°C showed good vigor, mean germination time and growth response in french bean compared to seed primed at 30°C which inhibits germination [42]. Seed priming at low temperature showed the beneficial effects on germination index, speed of germination, length of radical and plumule, fresh weight of seedling and seedling vigor index compared to high temperature in wheat [43]. Priming was effective in reducing the time for 50% germination, mean germination time and increase germination percent and seedling vigor index when primed with potassium di-hydrogen phosphate at low temperature in sunflower [44]. GA₃ (20 ppm) primed seeds at low temperature showed significantly higher germination, root length, shoot length and seedling dry weight over higher temperature in soybean [45]. Seed priming at 15°C showed better percent increase in germination, mean germination time than at higher temperature at 30°C. Seed priming at low temperature associated with a buildup of nucleic acids and protein synthesis and membrane repair [46].

4.4 Concentration

Seedling growth was not proper and subsequent growth of seedling was arrested probably due damage of cell organelles due to higher concentration when seed primed with ethrel. Increasing the concentration of priming solution from 10⁻³ M to 10⁻¹ M at constant temperature decreased the germination to the extent of 21% and 56% when papaya seeds were treated with oxalic acid and mannitol [47]. Soaking of wheat seeds in GA₃ at low concentration not only enhances the speed of germination but also increase the length of radical as well as plumule [48]. Osmopriming with PEG at low concentration in spinach improved the final germination percentage, germination rate and uniformity [49]. Seed priming at lower concentration of growth regulators favors the increase enzymatic activity which leads to the favorable environment for the germination. Growth regulators at higher concentration inhibit the seed germination which might have been due to solute leakage and lipid per oxidation which limit the necessary material for germination and seedling growth [50]. Tomato seeds osmo-primed with PEG 6000 at low concentration improved mean germination time, seedling emergence percentage and cell membrane stability over higher concentration [51]. Seed priming with 1% sodium molybdate reduced the seed germination due to toxic effect on physiological and biochemical processes within the cell [52]. In case of seed priming with higher concentration of ammonium molybdate and magnesium nitrate solution germination was absent. The reason attributed due to higher concentration of chemical which cause detrimental effect on cellular mechanism and mitochondrial; membrane in seed [46].

4.5 Light

Light effect changed widely according to crop species. Illumination during seed priming of celery seeds reduced dormancy [53]. The best germination in lettuce was obtained with seeds primed in the dark [37]. Light played a vital role in maximizing seed germination with guava seeds primed at 12 h of light and 12 h of dark [54].

5. Seed priming and physiological changes during priming

Seed treatment technology is an important link between seed producers and crop production. Seed priming is the technology which is a novel concept of treating seeds using various solvents including water which activates physiological processes of seeds. When dry seeds are immersed in water, water absorption occurs in three stages [55]. Stage I is imbibition where there is a swift initial water uptake due to the seed's low water potential. Proteins are synthesized using existing mRNA and DNA and mitochondria are repaired during stage I phase. In stage II, there is a steady increase in seed water content, but physiological activities associated with germination are initiated, including synthesis of proteins by translation of new mRNAs and new mitochondria. There is a swift uptake of water in stage I where the process of germination is completed culminating in radicle emergence. Stages I and II are the foundations of successful seed priming where the seed is brought to a seed moisture content that is just short of radicle protrusion [56]. The pattern of water uptake during priming is identical to that during slow germination and controlled. Seed hydration triggers germination via three stages: imbibition, lag phase and radicle protrusion through the testa [57]. Seed requires oxygen, water, and a suitable temperature for germination. The time from sowing to the seedling establishment is of considerable importance in crop production and has a major impact on plant growth, yield and post-harvest seed quality [4]. During germination process of orthodox seeds three distinct phases is manifested where in (1) Phase I: seed hydration process related to passive imbibition of dry tissues associated with water movement preliminary occurring in the apoplastic spaces; (2) Phase II: activation phase associated with the rejuvenate of metabolic activities and repairing processes at the cell level; and (3) Phase III: initiation of developing processes associated to cell elongation and leading to radical protrusion. Phases I and III both entail an increase in the water content while hydration remains stable during Phase II. Before the conclusion of Phase II, it is considered that germination remains a reversible process: the seeds may be dried again and remain functioning during storage and able to subsequently re-initiate germination under propitious condition. Water-based seed priming is elucidated as a pre-sowing dressing that partially hydrates seeds without allowing emergence [58]. Different treatments may indeed be applied during the reversible stage of germination (point 3). They broadly differ according to the osmotic potential of the priming solution, the duration, the external temperature, and the existence of specific chemical compounds. The efficient treatments trigger metabolic processes activated during phase II of germination, which are then transitory stopped before a loss of desiccation occurs [59]. Priming is a technique that allows controlled seed hydration to trigger pre-germinative metabolism but does not allow the seed for the transition towards full germination. In the case of primed seed hydration treatment allows regulated imbibition and induction of the pre-germinative metabolism ("activation"), but radicle emergence is prevented, represented by the extended second phase. Final phase (phase III) represents the germination and post-germination phase which is again similar in the case of non-primed seeds. In the case of primed hydration treatment seeds allow regulated imbibition and the introduction

of pre-germinative metabolism (“initiation”), but the emergence of radicle is inhibited, represented by an extended second phase. The final stage (phase III) represents germination and the post-emergence phase which is similar in the case of unprimed seeds. During Phase I Imbibition there is a rapid absorption of water due to the lower seed potential than outside. Initially there is water movement in apoplastic spaces, proteins are synthesized from existing mRNAs and DNA and mitochondria are repaired during Phase I. In phase II, there is the activation of metabolic and repairing activity along with the synthesis of proteins by translation of new mRNAs of new mitochondria, whereas phase III is associated with regaining capacity of rapid water uptake and initiation of growing processes linked with cell elongation that leads to radical protrusion. Priming allows a seed to hydrate up till a seed moisture content involving the entire phase I and before the end of phase II when the germination remains a reversible process just short of the radical protrusion [56]. Thus priming activates ‘pre-germinative metabolism’ that included a wide range of physiological functioning. This activates DNA repair pathways, ROS scavenging systems (that impart for seed repair response) and also helps in preserving genome integrity [60]. Priming solutions can be supplemented with hormones or beneficial micro-organisms. The seed may be dried back for storage, distribution and planting. Priming can induce the germination by improving the speed and synchronization of seed germination [61]; it can improve seed vigor which require very short or no activation time during germination. The advanced germination status of primed seeds contributes to increased germination under stressful conditions [62]. Besides it also facilitates the initiation of many germination-related activities such as enhanced energy metabolism, early reserve mobilization, embryo expansion and endosperm weakening [31]. Priming also enhances the specific stress-responsive systems which include induced accumulation of LEA and heat shock proteins [63], activation of catalase and other antioxidant scavenging enzymes [64] and up-regulation of genes encoding peroxiredoxin [65].

6. Biochemical and molecular basis of stress tolerance

The type of test, method of application, selection of crop, initial performance of the crop, selection of chemical, duration of treatment, its concentration, and the purpose of implication helps in successful application of seed management technique. Priming method in seed management techniques is established, which is very important factor for enhancing quality issues, germination rate and establishment. Priming can improve some of the aging-induced deteriorative events, resulting in improved seed performance [31]. It has shown an immense effect to activate different processes related to cell cycle and to induce synthesis of nuclear DNA in radial tip cells in tomato [32]. Prolonged storage of seeds resulted in a decrease in protein content which led to an increase in oxidation of amino acids, due to increased respiratory function and progression in the process of deteriorating stored seed. Seed degradation results in loss of membrane integrity, changes in enzymatic functions and reduction of protein and nucleic acid synthesis and lesions in DNA [66]. Priming with NaCl and 30% PEG for 24 h of rice seed initiated an increase in the activity of superoxide dismutase (SOD) and peroxidase (POD) which enhance the intensity of respiration of plant and cause an increase in vigourity in germination [67]. Priming is also thought to increase the activity of many enzymes involved in metabolism of carbohydrates (α - and β -amylases), proteins (proteases) and lipids mobilization (iso citratelase) that are implicated in the stored reserves mobilization [68]. These enzymes are vital in the breakdown of macromolecules for the development and growth of the embryo that ultimately result in early and higher seedling emergence

[69]. There are reports that priming facilitates the repair of chromosomal damage [70], permits early DNA replication and repair, increases RNA and de novo protein synthesis and reduces the leakage of metabolites [24]. Thus, total seed protein, peroxidases, polyphenol oxidases, RNA and de novo protein synthesis were enhanced significantly by seed priming. Among the various processes of priming, osmopriming could enhance rapid seed germination by reducing mechanical hindrance on the germinating embryo. The pre-treatment of seeds with priming agents facilitates the active absorption of ionic molecules with greater ATP availability and repair of deteriorated seed parts for reducing leakage of metabolites leading to faster embryo development [71]. It also, reflected in greater cellular membrane integrity, counteraction of lipid peroxidation, and free radical chain reaction often are found to be directly correlated with the maintenance of viability and reduce moisture uptake by hydrated-dehydrated seed [72], repair of biochemical lesions by the cellular enzymatic repair system [73] and metabolic removal of toxic substances [74], counteraction of free radical and lipid peroxidation reactions [75], biochemical changes like enzyme activation [76], and improvement of germination rate particularly in old seeds [77]. Priming provides a 'head-start' of seed transition from quiescent to germinating state, thus increasing the potential to germinate. Seed priming thrust abiotic stress on seeds that represses radicle protrusion but stimulates stress-responsive elements [78].

7. Reversal of seed deterioration by priming

Seed deterioration is defined as the loss of seed viability and vigor due to aging effects and adverse environmental factors distinctly higher temperature, relative air humidity and oxygen/carbon-dioxide ratio [66]. Seed deterioration is associated with several cellular, metabolic and chemical alterations including lipid peroxidation, membrane disruption, and DNA damage, impairment of RNA and protein synthesis and causes several detrimental effects on seeds [79]. The cause of seed deterioration is damage to cellular membranes and other sub cellular components by harmful free radicals generated by peroxidation of unsaturated and polyunsaturated membrane fatty acids. Seed storage causes a decrease in the protein content which may be related to oxidation of the amino acids due to the increase in the respiratory activity and advance in the deterioration process of the stored seeds [80]. Poor storage conditions may accelerate seed deterioration of seeds [81]. As seed deterioration increases, seed performance progressively decreases. Plants that originated from deteriorated seed can reduce growth rate. The aging of seeds, during long term storage deteriorated their vital status which was expressed in change in their moisture content, decreasing of their sowing qualities and development of weaker seedlings with higher water content [82]. The main mechanism for aging of seed is associated with increased peroxidation of lipid membranes [65]. Priming can reverse some of the aging induced deteriorative factors and thus improve seed performance [31]. The beneficial effects of priming are associated with the repair and building up of nucleic acid, increased synthesis of proteins as well as the repair of both mitochondria and membranes [24]. Priming for 24 h with GA₃ and ammonium molybdate in aged seeds showed increase enzyme activity restored almost entire protein profile and esterase and peroxidase isozyme profile as it allowed repair system to combat sub-cellular damage and activated synthesis of enzymes and protein [83]. Under invigorated, metabolic repair processes in deteriorated seeds occur before onset of seed germination process [84]. Seed priming is more useful for enhancing germination of low-quality seed lots than higher-quality ones

which indicates that repair of aging is one of the primary advantages [85]. Significant changes in enzyme activities were observed in primed seeds compared to un-primed seeds. Desiccation and storage of seeds has been suggested to result in progressive loss of integrity of the membrane components of the seeds, which in turn bring about to seed deterioration as measured by loss of seed vigor and viability. Maintenance of the integrity of DNA by repairing the damages incurred naturally is crucial for generating error free template for transcription and replication with fidelity. The damage to DNA which accumulates during the seed aging is repaired by aerated hydration [86]. During imbibition prior to germination the integrity of cell membranes need to be re-established. Rapid imbibitions by the seed at this time probably reverse the damage and cell will attain maximum vigor by repair mechanism. It is thought that hydro priming initiates an oxidative stress, which generates reactive oxygen species, and catalase is synthesized to minimize cell damage. In addition to catalase, levels of superoxide dismutase, another essential enzyme quenching free radicals also increases during priming. Increased levels of these free radical scavenging enzymes due to the oxidative stress during priming might also protect the cell against membrane damage due to lipid peroxidation occurring naturally [68]. Priming with GA₃ and ammonium molybdate allowed repair system to combat sub-cellular damage activated enzyme synthesis due to accelerated aging. The changes in the activation of the enzymes, upon priming advocate that mobilization of storage material may be responsible for increased germination and vigor in primed seeds when compared to unprimed aged seeds [87].

8. Effect of priming on reserve mobilization and management of oxidative status

It is proposed that germination-related processes such as respiration, energy metabolism, and initial reserve mobilization also occur during priming. Higher respiratory activity is required to cover energy pool for speed up germination. Increased respiratory activity has been associated with pre-sowing treatments. Seed priming increased the respiratory activity of seeds and reduced the oxygen-time constant and increased the standard deviation of germination responses [88]. During seed germination, storage proteins, which provide a source of reduced nitrogen and inorganic minerals, need to be mobilized to support seedling growth [89]. Soluble protein content increased in pepper seeds after 12 days of priming in -1.34 MPa NaCl solution [90]. Pepper seedlings developed from primed seed had improved soluble protein [90]. Osmo-priming induced accumulation of stress proteins, such as late embryogenesis abundant (LEA) proteins and heat shock proteins (HSP) [91]. Management of oxidative status is also an important part of primed seed physiology. Priming activates the response of the antioxidant system and modifies the prepared seeds for potential stresses [92]. In the early stages of seed intake and germination, the production of reactive oxygen species (ROS) is primarily due to the respiratory activity of mitochondria, β -oxidative pathway activity, and enzymes such as NADPH oxidase, extra-cellular peroxidase, and oxalate oxidase [93]. Antioxidants, by breaking down high ROS during early endocytosis, play an important role in ensuring successful germination, especially under stressful conditions [94]. Seed priming in tomato seeds revealed enhanced activity of antioxidant enzymes such as ascorbate peroxidase, catalase, peroxidase, glutathione reductase and superoxide dismutase [95]. Free radical scavenging enzymes such as catalase and super dismutase are synthesized during hydro priming to defend the cell from damage due to lipid peroxidation, which occurs due to the oxidative stress induced by hydro priming. Priming synchronizes all the cells

of the germinating embryo in the G2 phase of the cell cycle so that upon further imbibitions, cell division proceeds uniformly in all the cells ensuring uniform development of all parts of the seedlings. Seed priming of pepper (*Capsicum annuum* L.) conducted under temperature stress (low 15° C and high 35°C) for two consecutive runs revealed enhanced germination even in stressful conditions. Priming was found to enhance repair of membranes, the activities of hydrolytic enzymes, and antioxidant system. However, it was noticed that priming decreased sucrose content, whereas the fatty acid composition remained unchanged and increased enzymatic activity of catalase which was enhanced significantly in pepper seeds [96]. Osmopriming with -1.5 MPa PEG 6000 for 6 days of aged seeds of sweet pepper resulted in an improved germination with decreased levels of malondialdehyde (MDA) and total antioxidant activity, total ascorbate, de-hydro ascorbate, and catalase activity in primed seeds enhanced the defense mechanism in protecting the cell membrane damage from reactive oxygen species [29]. Nano priming augmented the performance of seeds by enhancing α -amylase activity, increasing soluble sugar content to support early seedling growth, up-regulating the expression of aquaporin gene in germinating seeds, increased stress tolerance through lower ROS production and creation of nano pores for enhancing water uptake in crops in field [74]. The main obstacle to the practical application of primed seeds is storage and viability. This barrier can be overcome by knowing the genes/markers associated with seed germination and the identified markers can be used to assess the effect of priming on germination efficiency and seed vigor [97]. Genes/markers involved in rice seed priming were identified by comparing differential proteins between the dry and imbibed seed using two-dimensional electrophoresis [98]. Improved germination was reported in polyethylene glycol-6000 (PEG-6000) primed rapeseeds which, on germination, resulted in differential expression of 952 genes and 75 proteins [99].

9. Methods of seed priming and role in improving crop productivity

Seed priming technique such as hydro priming, halo priming, chemical priming, osmopriming, hormone priming, solid matrix priming and nutrient priming are extensively used in crop plants for many environmental stresses. Seed priming increases germination and growth especially under environmental constraints. However, the degree of efficacy of different priming agents varies with plant species and diverse environmental conditions [100]. Different seed priming methods employed to mitigate stress and salt tolerance as reported by many researchers are shown in **Tables 1–5**.

9.1 Hydropriming

Soaking seeds with water overnight and then drying before sowing markedly improved seedling emergence, plant growth establishment, vigor and final yield in field crops [12]. Slow and inconsistent germination of seeds has prompted the need for water-based seed priming. Hydro priming is a very sustainable, cost-effective and environmentally friendly technique, mainly involving soaking the seeds in water for a predetermined time and then drying them back to their initial moisture level [89]. The process of seed germination occurs in three phases, viz., rapid water uptake or imbibition (phase I), lag or plateau phase (phase II), and protrusion of seminal root and resumption of growth (phase III) [55]. Hydro priming reduces the lag period ensures rapid and uniform germination for good stand establishment [127]. Controlled seed hydration as a pre-sowing strategy triggers pre-germination metabolic activities in the form of cellular physiological,

S. no	Priming agent	Crop	Attributed improved	References
1.	Water (12 h)	Rice	Accelerated germination, early emergence time, increased initial growth after emergence, increased dry root weight and dry matter productivity	[101]
		Wheat	Higher germination percent, increased water use efficiency, homogeneity of seedling emergence, increase growth and yield parameters. Aged seeds when primed with water improved induced increase in enzyme activity, improved germination and seedling characteristics	[102]
		Pearl millet	Increased crop emergence and crop yield in arid zone	[103]
		Chickpea	Improved membrane integrity and electrical conductivity of seed leachate. Increased germination indices and seedling growth	[104]
		Sunflower	Increased germination percentage, seed vigor index and seedling growth rate. Reduced time to 50% seedling emergence	[105]

Table 1.
Hydropriming technique and their effectiveness in improving growth of various crops under adverse condition.

S. no	Priming agent	Crop	Concentration	Attributed improved	References
1.	PEG	wheat	−1.0 MPa	Seed germination and grain yield	[106]
		Rape seed	−0.5 MPa	Percentage of germination under saline soil, seedling length, and increased metabolic process in seeds	[107]
		Chickpea	−0.5 MPa	Seed germination, yield and improvement in seed quality attributes	[108]
2.	Mannitol	Broad bean	1%	Percentage of germination, higher seedling length and seed vigor index	[109]
		Rice	1%	Enhanced germination percentage, growth of seedlings and plant survival under salt stress	[110]
3.	Sorbitol	Wheat	1%	Improved seed vigor, plant morphology and upregulation of plant growth regulator	[111]

Table 2.
Osmoconditioning techniques and their effectiveness in improving growth of various crops under adverse condition.

biochemical, and molecular changes [93]. Ameliorated germination of hydro primed seeds is a repercussion of stimulation of enzymes (amylase, protease, phosphatase, lipase, etc.), ATP production, RNA and protein synthesis, DNA replication, detoxification of ROS and lowering of lipid per oxidation by antioxidant enzymes [superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and glutathione reductase (GPx)], accumulation of germination enhancing metabolites (proline, soluble sugars, etc.), higher utilization of seed reserves (proteins, carbohydrates, lipids, and phosphorus compounds), and supplementary metabolic repairing mechanisms. The major limitation associated with hydro priming is uncontrolled water uptake which result in unsynchronized germination [12]. Plants produced from hydro-primed seeds had substantial water uptake which is positively associated with seedling growth. Hydro-priming is a simple method to improve abiotic stress tolerance and improve germination percentage in cauliflower [28]. Seed soaking in water improved germination, seedling establishment and yield in wheat

S. no	Priming agent	Crop	Attributed improved	References
1.	Gibberellic acid (50 ppm)	Rice	Improve crop emergence, crop establishment and yield in direct seeded rice	[112]
2.	Cytokinins (100 ppm)	Soybean	Hasten seed germination rate and seedling development. Improving root length and enhanced nutrient uptake and water use efficiency	[113]
3.	IAA (20 mg L ⁻¹)	Cotton	Improves the germination, root length, seedling height and seedling growth, biomass and leaf photosynthesis capacity and yield	[114]
4.	Auxin (50 ppm)	Wheat	Increased grain filling rate and grain yield and positive effect of photosynthesis	[115]
5.	Salicylic acid (0.9%)	Sesame	Increased germination percent and seedling length and vigorous growth, reduced germination time	[116]

Table 3.
Priming with plant growth regulators and their effectiveness in improving growth of various crops under adverse condition.

S. no	Priming agent	Crop	Attributed improved	References
1.	Potassium nitrate (2%) (50 ppm)	Rice	Improve crop emergence, crop establishment and yield in DSR	[117]
2.	CaCl ₂ (50 mM)	Sorghum	Increased germination rate, root and shoot length under salt stress condition	[112]
3.	KH ₂ PO ₄ (1%)	Maize	Increased field emergence, plant height number of leaves and seed yield	[26]
4.	Mg(NO ₃) ₂ + ZnSO ₄ (2%)	Wheat	Increased plant height, number of leaves, leaf area and chlorophyll content and increased yield under drought stress	[118]
5.	Ammonium molybdate (0.1%)	Common Bean	Improved germination percent, net CO ₂ assimilation rate, chlorophyll content and increased grain yield	[119]
6.	KCl (1%)	Green gram	Enhancing crop stand and increasing yield under drought condition	[120]

Table 4.
Nutrient priming techniques and their effectiveness in improving growth of various crops under adverse condition.

crop under contrasting environmental conditions [128]. Hydro-priming of rice seeds improved the germination rate, speed and uniformity even under less than optimum field condition in upland conditions [129]. Hydropriming of soybean seeds for 12 h was effective to increase number of pods, grain yield and biological yield under drought stress conditions [130]. Hydro-priming for 48 h of naturally aged rice seeds were more efficient in seed germination, emergence and seeding vigor under direct seeded rice [131].

9.2 Osmoconditioning

Osmopriming is known as osmotic priming, osmotic conditioning or osmoconditioning. It is a pre-sowing treatment in an osmotic solution that allows seeds to imbibe water to proceed to the first stage of germination but prevent radicle protrusion through the seed coat [132]. In this methodology, seeds are soaked in osmotic solutions of organic compounds such as polyethylene glycol, mannitol, glycerol, and sorbitol having low water potential so as to regulate the water uptake by seeds and allow the

S. no	Priming agent	Crop	Attributed improved	References
1.	<i>Rhizobium</i> <i>sp</i> + <i>Trichoderma viride</i>	Green gram	Increased germination percentage, synchronized seed germination, growth and yield components.	[121]
2.	<i>Bacillus amyloliquefacians</i>	Rice	Enhanced activities of peroxidase and polyphenol oxidase in seedlings. Improved germination percentage, increased leaf area	[122]
3.	<i>Bacillus</i> sp. (MGW9)	Maize	Improved the germination energy, seedling length, relative water content, field seedling emergence and seedling growth	[123]
4.	<i>Trichoderma asperellum</i> (24 h)	Wheat	Plant growth promoting activities, uniformity in seed emergence, good seedling vigor and establishment under stress conditions	[124]
5.	<i>Azotobacter chroococcum</i>	Chickpea	Implant plant growth, and dry weight and yield	[125]
6.	<i>Azospirillum lipoferum</i>	Barley	Tolerance to stress and improved plant growth and productivity	[126]

Table 5.
Biopriming priming techniques and their effectiveness in improving growth of various crops under adverse condition.

pre-germinative metabolic events to continue, but restrict the seminal root protrusion [20]. Osmohardening with PEG improved seed quality of maize and leading to early germination and better performance under field conditions [133]. Polyethylene glycol (PEG) as an inert material which can prevent embryo toxicity problem during priming. The large size of PEG molecule also prevents its penetration into seed tissues, avoiding lowering the osmotic potential [134]. Seeds primed with PEG were effective in improving seed germination and seedling establishment of sorghum under unfavorable soil moisture conditions. Seed priming with PEG reduced lipid peroxidation and stabilized cell membrane, resulting in elevation of stress tolerance under drought environment [135]. Osmopriming or Osmoconditioning is the seed soaking in solutions with low water potential. In osmopriming, degree and rate of imbibitions is restricted through the exposure of seeds to low external water potential. Osmopriming can maintain the integrity of plasma membrane and gives better germination percentage [28].

Osmopriming of rice seeds enhanced starch to improve sugar availability in embryo and produced strong seedling growth. Osmopriming economically, technically and methodologically is more challenging as it yields easier and faster results than water conservation systems. Osmopriming of spinach seeds with PEG increased germination percentage, stimulated anti-oxidant defense systems and thereby induced tolerance to spinach plants. Osmopriming has advantages which include rapid and uniform germination and emergence, improved seedling growth and better stand establishment under water stress condition [64]. Osmopriming in adequate concentration of PEG improved seedling growth and germination in rice [136]. Seed osmopriming with lower dose of PEG addressed the inhibitory effects of salinity on green gram plants in terms of greater values for osmolytes accumulation, chlorophyll content and better antioxidant defense system and osmotic adjustment [137]. Priming of french bean seeds with PEG 0.1Mpa enhanced germination, emergence time and seedling vigor index [138]. Osmopriming with mannitol mitigated the inhibitory effects of salinity and drought on plant growth in chickpea. Plant produced from seeds soaked in different concentration of mannitol (2–4%) improved biomass and length of shoot and roots under saline conditions [139]. Plants from seeds primed with mannitol had higher activities of antioxidant enzymes and minimal electrolyte leakage and malondialdehyde contents [140]. Osmoconditioning of

cucumber (*Cucumis sativus* L.) seed with 0.7 M mannitol improved the rate of germination at 25°C and 15°C in water. Osmoconditioning stimulated the rate of radical extension, seedling emergence and expansion of the cotyledons and first leaf of cucumber [51].

9.3 Priming with plant growth regulators

Presoaking seeds with optimal concentrations of plant growth regulators has shown to effectively improve germination as well as growth and yield performances of various crop species under environmental stress conditions [141]. Growth regulators normally used for seed priming include auxins (IAA, IBA, and NAA), gibberellins (GA), kinetin, salicylic acid, abscisic acid, ethylene and ascorbic acids. The use of plant hormones and other plant growth regulators as seed pre-sowing treatment can improve plant growth under stressful conditions [28]. Pre-soaking GA₃ in guava seeds at 100 ppm at a temperature range of 32°C/20°C resulted in a significant increase in germination to 84–88% compared to unprimed seeds [54]. Seed priming with GA₃ (100 ppm) for 24 h at low concentration and priming temperature at 15°C in cowpea increased the leaf area index, relative growth rate, crop growth rate and net assimilation rate under limited soil water conditions [142]. Rye seeds soaked with gibberellic acid increased germination percentage under water stress conditions [143].

Seed priming with ethylene minimizes the effect of high temperature on lettuce seed germination [144]. The pre-treated wheat seeds with salicylic acid improved seed germination, rate of germination and total chlorophyll content significantly under salinity levels [145]. Phytohormonal priming can augment seed germination through enhancing some enzymes such as amylase activities and protease that hydrolyzed starch and protein molecules into simple forms available for the embryo to germinate [146]. GA₃ priming has been found to improve seed germination, possibly as a result of nutrients stored inside the seeds, and to make embryos available during germination. Seed endosperm is found in the embryo through the action of other hydrolase enzymes [147]. It is very important that GA₃ promotes the synthesis and production of hydrolases, especially α -amylase, which leads to seed germination. Seed priming is controlled through suppression effects of excess ABA on the expansion of embryo organs caused by inhibition of GA₃ effects on the growth of radical and hypocotyl [148]. Seeds primed with ascorbic acid improved emergence, growth and yield of maize under water deficit [149]. Seed priming with gibberellic acid induced an increase in grain yield of wheat plants, modulation of ion uptake and partitioning and hormone homeostasis under saline conditions [150].

9.4 Nutrient priming

Nutrient priming or nutripriming means soaking of seeds in nutrient solution of a specific concentration, for a certain period of time or duration prior to sowing [151]. Seed priming with nutrients (macro or micro) can increase seed nutrient content and improve seed quality for better germination, seedling establishment, plant growth, nutrient uptake and water use efficiency of several crop species. Nutrient priming is one of the methods of priming practices that includes salts like ammonium molybdate, Mg (NO₃)₂, CaCl₂, CaSO₄, KBr, MgSO₄, KH₂PO₄, ZnSO₄, KNO₃, sodium molybdate, KCl and NaCl in such a way that pre-emergence metabolic functions begin to prevent major outbreaks followed by seed drying at the initial humidity level [24]. In this way, the seeds are immersed in various salts that promote the germination process and subsequent emergence of seedlings even under adverse environmental conditions. Salt priming of hot pepper seed induced salinity tolerance at seedling stage, wherein seed priming improved significantly

the germination percentage and vigor index, plumule and radical length and dry weight of seedling as compared to the non-primed seeds (control) [110]. Nutrient priming in 3% KNO₃ solution for 40 h at normal room temperature increased speed of emergence, seedling vigor index, root length and shoot length over hydro priming, and control in pepper [152]. Pre-sowing seed treatment with ammonium molybdate (10⁻³ M) enhanced germination, improved vigor and growth of root system, increased drought tolerance which helped in higher nutrient uptake in cowpea crop under limited soil moisture [46]. Pepper seeds primed in 1% KNO₃ recorded the highest germination percentage as compared to non-priming [153]. Seed priming with CaCl₂ (2%) and sodium molybdate (100 ppm) increased the harvest index over dry seed under drought stress situation [154]. Nutrient priming is a simple and low cost agro-technique and found suitable to be recommended to the farmers owing to better synchrony of emergence and crop stand under various conditions of environment [7]. Seed ripening with CaCl₂ has been very successful in implanting a high salt tolerance to maize with an improved percentage of germination and biomass of plants. Plants grown from extracted seeds also raised the cellular levels of Ca²⁺, K⁺, and Na⁺. Chloride content was important for maize plants raised from seeds incorporated into NaCl and KCl [155]. Effect of seed priming with KNO₃ and urea increased the seedling growth, germination percentage, germination rate and proline and protein content in maize hybrids under severe and moderate salt and drought stress [156]. Seed priming with ammonium molybdate (10⁻³ M) improved germination, stimulated growth, seed yield, biological yield and water use efficiency in cowpea under limited water supply conditions in cowpea [157]. Seed priming of chickpea seeds in a 0.05% solution of zinc sulphate (ZnSO₄) has been found quite effective to exhibit 19% higher seed yield and 29% more Zn concentration in seeds over that of non-primed seeds [158]. Seed priming with potassium nitrate (0.5%) recorded higher emergence, shoot length, shoot fresh weight, maximum root length and root fresh weight of dry direct-seeded rice compared with non-primed seeds [159]. Seed priming for pepper crop with osmotic solution KCl (10 mM) for 36 h improved the plant biomass, number of leaves per plant, shoot and root length, leaf area and carotenoid content under saline stress [90]. Seed priming sorghum seeds with 50 mM Ca Cl₂ enhanced the germination potential, germination rate, germination index, vigor index, root and shoot length, root and shoot fresh weight and root and shoot dry weight under salt stress condition [26].

9.5 Biopriming

Bio-priming of seeds has diverse process to stimulate morphogenesis and plant immunity, viz., production of phytohormones, induced expression of plant growth-promoting genes, mycoparasitism, increased nutrient status into the plant, antibiosis, trigger phenolic production, activation of antioxidant production, and systemic defense activation. Biopriming plays an important role in improving seed viability, germination, uniformity in emergence, plant vigor, growth and yield [160]. Biopriming agents comprehend plant growth promoting microorganisms (PGPM), Plant growth promoting bacteria (PGPB), plant growth promoting fungi (PGPF) and plant growth cyanobacteria (PGPC). PGPC are responsible for enhancing the crop growth through nitrogen fixation and release of metabolites, improving soil fertility by soil aggregation and enhancing water holding capacity [161]. Rhizosphere microbes play a very crucial role in enhanced uptake of three essential nutrients N, P and K [162]. Application of *Trichoderma* sp. through seed biopriming enhanced the enzyme activity through release of metabolites in maize plants [163]. Application of *Trichoderma harzianum* to cucumber seeds as aqueous slurry and incubated this mixture for 4 days at 20°C increased seedling emergence [164].

Slurry coating of non-primed cucumber (*C. sativus* L.) seeds with *Trichoderma harzianum* and *Trichoderma viridae* or combination of both reduced percentage of damping-off disease and increased the final emergence percentage up to 58.10% and greater seedling fresh weight [165]. Biopriming is recently used as an alternative method for controlling many seed- and soil borne pathogens [166]. Combined effect of *Pseudomonas fluorescens* and *Trichoderma harzianum* as seed biopriming resulted in significant growth of pepper seedlings [167]. Among abiotic stress amelioration by bio priming, *Trichoderma* spp. has been used in controlling salinity and drought stress in maize and wheat which exhibited better physiological and morphological parameters when compared to untreated control [168]. Biopriming with the biofungicide and clove oil 0.06% or 0.1% was an effective seed treatment to improve the vigor and relative speed of germination in hot pepper seeds [169]. Seed priming with Rhizobium + Pseudomonas at 10% for 12 h recorded significantly higher germination percent and speed of germination, and seedling vigor in chickpea [170]. Application of *Pseudomonas aureofaciens* through drum priming system enhanced the stand establishment in tomato [171]. The results showed that seed inoculation with plant growth promoting rhizobacteria had significantly effects on grain yield, grain 1000 weight, number of grains per plant, plant height and all of grain filling parameters such as grain filling period, rate and effective grain filling period in lentil [172]. The technique of biopriming to document using two strains including *Azospirillum brasilense* and *Bacillus amyloliquefaciens* increased drought tolerance in wheat plants through regulation of genes related to stress. Biopriming, an amalgamation of seed priming with application of plant beneficial fungi and bacteria, can remarkably improve seed germination and emergence, seedling establishment, crop growth, and yield parameters under normal and stress conditions [173]. *Thalassobacillus denorans* and *Oceanobacillus kapialis* isolates from salt mine showing halophilic behavior enhanced the growth of fine rice variety under varying salinity concentrations and exhibited improvement in morphological and physiological parameters after 15 and 28 days, respectively, when applied through biopriming [174]. Biopriming of *Medicago truncatula* seeds with *Bacillus* spp. Improved seed germination and seedling biomass and at the molecular level reflected in the up regulation of genes involved in DNA damage repair and antioxidant defense [88].

9.6 Solid matrix priming

In solid matrix priming (SMP) or matrix conditioning, solid or semi solid medium is used as a substitute in place of liquid medium. This technique is accomplished by mixing seeds with a solid or semi solid medium and specified amount of water. In solid matrix priming, a small quantity of seed and solid particles are used. During solid matrix priming, water is slowly delivered to seeds and thus, slow or controlled imbibition occurs, allowing cell repair mechanisms to function [28]. Predominant solid matrices are exfoliated vermiculate, expanded calcined clay, bituminous coal, sodium polypropionate gel or synthetic calcium silicate. Solid matrix priming using saw dust, ground charcoal, green gram seeds responded favorably to shorten incubation periods. The longer incubation periods and higher water levels were harmful to the seeds because they encouraged fungal growth [175].

10. Conclusion and future perspective

Seed priming emerges as a reassuring technology for combating abiotic stress in crops and alleviating the detrimental effects of abiotic stress without much influencing its

fitness. Seed priming technique is innovative, cheap and simple to apply at farmer's field conditions. Oxidative stress, temperature extremes, salinity, and drought are associated and frequently induce similar type of damage. Seed priming stimulates signaling pathways earlier and enhances plant defense responses. Experimental results reveal that improved germination and vigorous growth of seedlings occur in early seed by combining stored nutrients and using genes responsible for the synthesis of essential enzymes. Priming is also capable of repairing damage that occurs inside the seed. Seed priming effects on early stage of germination, and it modulates the DNA replication, transcription, and translation. Storage and short shelf life of the primed seeds are a limitation of this technology. There is a need to standardize suitable priming methods in different crops to combat abiotic stress sustainably. Seed priming may indeed be considered as a valuable strategy to improve stand establishment under detrimental agro-climatic conditions (rainfed, dry farming and dry land farming regions) with enhanced yield, increased tolerance to stress situations, enhanced crop competitiveness against weeds, increased resistance against diseases and increased water use efficiency. In an outline, seed priming acts as an important criterion for the induction of tolerance in plants against a wide range of abiotic stresses. However, more investigation will be needed in unraveling the mechanism of plant growth regulators and their substitutes, especially with stress-responsive genes.

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References

- [1] Kooyers NJ. The evolution of drought escape and avoidance in natural herbaceous populations. *Plant Science*. 2015;**234**:155-162
- [2] Zhao TJ, Liu Y, Yan YB, Feng F, Liu WQ, Zhou HM. Identification of the amino acids crucial for the activities of drought responsive element binding factors (DREBs) of *Brassica napus*. *FEBS Letters*. 2007;**581**:3044-3050
- [3] Bewley JD, Black M. *Seeds: Physiology of Development and Germination*. 2nd ed. New York: Plenum Press; 1994. DOI: 10.1007/978-1-4899-1002-8
- [4] Zhang Y, Pan J, Huang X, Gua D, Lou H, Hou Z, et al. Differential effects of a post-anthesis heat stress on wheat (*Triticum aestivum* L.) grain proteomic determine iTRAQ. *Science Reporter*. 2017;**7**:3468
- [5] Hamidi H, Safarnejad A. Effect of drought stress on alfalfa cultivars (*Medicago sativa* L.) in germination stage. *American-Eurasian Journal of Agricultural and Environmental Sciences*. 2010;**8**(6):705-709
- [6] Jisha KC, Puthur JT. Halopriming of seeds imparts tolerance to NaCl and PEG induced stress in *Vigna radiata* (L.) Wilczek varieties. *Physiology and Molecular Biology of Plants*. 2014;**20**(3): 303-312
- [7] Sedghi M, Nemati A, Amanpour-Balaneji B, Gholipouri A. Influence of different priming materials on germination and seedling establishment of milk thistle (*Silybum marianum*) under salinity stress. *World Applied Sciences Journal*. 2010;**11**(5):604-609
- [8] Ahmad I, Khaliq T, Ahmad A, Basra SMA, Hasnain Z, Ali A. Effect of seed priming with ascorbic acid, salicylic acid and hydrogen peroxide on emergence, vigor and antioxidant activities of maize. *African Journal of Biotechnology*. 2012;**11**:1127-1137
- [9] Liu Y, Li P, Xu GC, Xiao L, Li ZB. Growth, morphological and physiological responses to drought stress in *Bothriochloa ischaemum*. *Frontiers in Plant Science*. 2017;**8**:230
- [10] Alzahrani FO. Metabolic of osmo protectants to elucidate the mechanism of salt stress tolerance in crop plants. *Planta*. 2021;**253**:1-17
- [11] Blum A. Osmotic adjustment is a prime drought stress adaptive engine in support of plant production: Osmotic adjustment and plant production. *Plant Cell Environment*. 2017;**40**:4-10
- [12] Harris D, Joshi A, Khan PA, Gothkar P, Sodhi PS. On-farm seed priming in semi-arid agriculture development and evaluation in maize, rice and chickpea in India using participatory methods. *Experimental Agriculture*. 1999;**35**:15-29
- [13] Ashraf M, Afaf YR, Qureshi MS, Sarwar G, Naqvi MH. Salinity induced changes in amylase and protease activities and associated metabolism in cotton varieties during germination and early seedling growth stages. *Acta Physiologiae Plantarum*. 2002;**24**:37-44
- [14] Khajeh-Hosseini M, Powell AA, Bingham IJ. The interaction between salinity stress and seed vigour during germination of soybean seeds. *Seed Science and Technology*. 2003;**31**:715-725
- [15] Hussian S, Zhang J, Zhong C, Zhu L, Cao X, Yu S. Effect of salt stress on rice growth, development characteristics and

the regulating ways: A review. Journal of Integrative Agriculture. 2017;**16**(11):2357-2374

[16] Vollenweider P, Gunthardt-Goerg MS. Diagnosis of abiotic and biotic stress factors using the visible symptoms in foliage. Environmental Pollution. 2005;**137**:455-465

[17] Wahid A, Gelani S, Ashraf M, Foolad MR. Heat tolerance in plants: An overview. Environmental and Experimental Botany. 2007;**61**(3):199-223

[18] Zinn KE, Tunc-Ozdemir M, Harper JF. Temperature stress and plant sexual reproduction: Uncovering the weakest links. Journal of Experimental Botany. 2010;**61**:1959-1968

[19] Hasanuzzaman M, Nahar K, Fujita M, Ahmad P, Chandna R, Prasad M, et al. Enhancing plant productivity under salt stress: Relevance of poly-omics. In: Salt Stress in Plants. New York, NY: Springer; 2013. pp. 113-156. DOI: 10.1007/978-1-4614-6108-1_6

[20] Ashraf M, Foolad MR. Pre-sowing seed treatment—A shotgun approach to improve germination, plant growth, and crop yield under saline and non-saline conditions. Advance of Agronomy. 2005;**88**:223-276

[21] Nleya T, Ball RA, Vandenberg A. Germination of common bean under constant and alternating cool temperatures. Canadian Journal of Plant Sciences. 2005;**85**(3):577-585

[22] Sivritepe HO. The effects of osmotic conditioning treatments on salt tolerance of Onion seeds. In: 3rd National Symposium on Vegetable Production; Isparta, Turkey. 2000. pp. 475-481

[23] Bradford KJ. Manipulation of seed water relations via osmotic priming to

improve germination under stress conditions. HortScience. 1986;**21**:1105-1112

[24] McDonald MB. In: Bewley MJD, editor. Seed Priming, Black, Seed Technology and Its Biological Basis. Sheffield Academic Press, Sheffield, UK; 2000. pp. 287-325

[25] Savvides A, Ali S, Tester M, Fotopoulos V. Chemical priming of plants against multiple abiotic stresses: Mission possible? Trends in Plant Science. 2016;**21**:329-340

[26] Chen X, Zhang R, Xing Y, Jiang B, Li B, Xu X. The efficacy of different seed priming agents for promoting sorghum germination under salt stress. PLoS One. 2021;**16**(1):e0245505. DOI: 10.1371/journal.pone.0245505

[27] Fujita M, Fujita Y, Noutoshi Y, Takahashi F, Narusaka Y, Yamaguchi-Shinozaki K, et al. Crosstalk between abiotic and biotic stress responses: A current view from the points of convergence in the stress signaling networks. Current Opinion Plant Biology. 2006;**9**:436-442

[28] Jisha KC, Vijayakumari K, Puthur JT. Seed priming for abiotic stress tolerance: An overview. Acta Physiologiae Plantarum. 2013;**35**:1381-1396

[29] Siri B, Vichitphan K, Kaewnaree P, Vichitphan S, Klanrit P. Improvement of quality, membrane integrity and antioxidant systems in sweet pepper (*Capsicum annuum* Linn) seeds affected by osmopriming. Australian Journal of Crop Science. 2013;**7**(13):2068-2073

[30] Harris D, Raghuwanshi BS, Gangwar JS, Singh SC, Joshi KD, Rashid A, et al. Participatory evaluation by farmers of on-farm seed priming in

wheat in India. Nepal and Pakistan. Experimental Agriculture. 2001;37: 403-415

[31] Khan FA, Maqbool R, Narayan S. Reversal of age-induced seed deterioration through priming in vegetable crops—A review. Advance in Plants and Agriculture Research. 2016;4(6):403-411

[32] Sano N, Seo M. Cell cycle inhibitors improve seed storability after priming treatments. Journal of Plant Research. 2019;132:263-271

[33] Arun MN, Bhanuprakash K, Shankara Hebbar S, Senthivel T. Effect of seed priming with various chemicals on germination and vigour in cowpea (*Vigna unguiculata* (L.) Walp). Progressive Research—An International Journal. 2016;11:2113-2117

[34] Salisbury FB, Ross CW. Plant Physiology. Belmont, CA: Wadsworth; 1992. pp. 357-407, 531-548

[35] Hussain A, Rizwan M, Ali Q, Ali S. Seed priming with silicon nano particles improved the biomass and yield while reduced the oxidative stress and cadmium concentration in wheat grains. Environmental Science and Pollution Research. 2019;26(8):7579-7588

[36] Heydecker W, Coolbear P. Seed treatments for improved performance; survey and attempted prognosis. Seed Science and Technology. 1977;5:353-425

[37] Cantliffe DJ. Priming of lettuce seed for early and uniform emergence under conditions of environmental stress. Acta Horticulturae. 1981;122:29-38

[38] Ghassemi-Golezani K, Jabbarpour S, Zehtab-Salmasi S, Mohammadi A. Response of winter rapeseed (*Brassica napus* L.) cultivars to salt priming of

seeds. African Journal of Agricultural Research. 2010;5:1089-1094

[39] Rajpar I, Kanif YM, Memon AA. Effect of seed priming on growth and yield of wheat (*Triticum aestivum* L.) under non-saline conditions. International Journal of Agricultural Research. 2006;1:259-264

[40] Anju BR, Sheeja R. Seed priming: An approach towards agricultural sustainability. Journal of Applied and Natural science. 2019;11(1):227-234

[41] Anese S, Da Silva EAA, Davide AC, Rocha Faria JM, Soares GCM, Matos ACB, et al. Seed priming improves endosperm weakening, germination, and subsequent seedling development of *Solanum lycopersicum* St. Hil. Seed Science and Technology. 2011;39:125-139

[42] Sarika G, Basavaraju GV, Bhanuprakash K, Chaanakeshava V, Paramesh R, Radha BN. Investigation on seed viability and vigour of aged seed by priming in french bean. Vegetable Science. 2013;40:169-173

[43] Yari L, Aghaalikhani M, Khazaei F. Effect of seed priming duration and temperature on seed germination behavior of bread wheat (*Triticum aestivum* L.). ARPN Journal of Agricultural and Biological Science. 2010;5(1):5-8

[44] Kausar M, Mahmood T, Basra SMA, Arshad M. Invigoration of low vigor sunflower hybrids by seed priming. International Journal of Agriculture and Biology. 2009;11:521-528

[45] Assefa MK, Hunje R. Standardization of seed priming duration in soybean [*Glycine max* (L.) Merrill]. Seed Research. 2011;39:1-4

[46] Arun MN, ShankaraHebbar S, Bhanuprakash K, Senthivel T. Effect of

seed priming on phenology, growth and yield of vegetable cowpea (*Vigna unguiculata* (L.) Walp) under different intensities of moisture stress. *Progressive Research—An International Journal*. 2016;**11**:2118-2122

[47] Bhanuprakash K, Yogeesh HS, Arun MN, Naik LB. Effect of priming and ageing on seed germination and vigour in papaya (*Carica papaya*). *Indian Journal of Agricultural Sciences*. 2009;**79**(4):295-297

[48] Parashar A, Verma SK. Effect of pre-sowing seed soaking in gibberellic acid, duration of soaking temperatures and their interaction on seed germination and early seedling growth of wheat under saline conditions. *Plant Physiology and Biochemistry*. 1988;**15**(2):189-197

[49] Chen K. Antioxidants and dehydrin metabolism associated with osmopriming-enhanced stress tolerance of germinating spinach (*Spinacia oleracea* L. cv. Bloomsdale) seeds. In: Graduate Theses and Dissertations, Paper 10471. USA: Iowa State University; 2011. DOI:10.31274/ETD-180810-355

[50] Barthwal P, Prabha D. Effect of ageing and hormonal priming on different physiological attributes on French beans (*Phaseolus vulgaris*). *Advances in Agriculture and Natural Sciences for Sustainable Agriculture*. 2018;**5**:76-79

[51] Amooaghaie R, Vaviland M. The combined effect of gibberellic acid and long time osmopriming on seed germination and subsequent seedling growth of *Klussia odoratissima* Mozaff. *African Journal of Biotechnology*. 2011;**10**(66):14873-14880

[52] Renugadevi J, Natarajan N, Srimathi P. Efficacy of botanicals in improving the seeds and seedling quality

characteristics of cluster bean. *Legume Research—An International Journal*. 2008;**31**:164-168

[53] Khan FA, Maqbool R, Narayan S, Bhat SA, Narayan R, Khan FU. Reversal of age-induced seed deterioration through priming in vegetable crops—A review. *Advances in Plants and Agriculture Research*. 2016;**4**(6):403-410

[54] Bhanuprakash K, Yogeesh HS, Vasugi C, Arun MN, Naik LB. Effect of pre-soaking treatments and temperature on seed germination of guava (*Psidium guajava* L.). *Seed Science and Technology*. 2008;**36**:792-794

[55] Bewley JD. Seed germination and dormancy. *The Plant Cell*. 1997;**9**(7):1055-1066

[56] Bray CM. Biochemical processes during the osmopriming of seeds. In: Kigel J, Galili G, editors. *Seed Development and Germination*. Marcel Dekker: New York; 1995. pp. 767-789

[57] Ibrahim EA. Seed priming to alleviate salinity stress in germinating seeds. *Journal of Plant Physiology*. 2016;**192**:38-46

[58] Chen K, Arora R. Dynamics of the antioxidant system during seed osmopriming, post priming germination, and seedling establishment in spinach (*Spinacia oleracea*). *Plant Science*. 2011;**180**:212-220

[59] Paparella S, Araújo SS, Rossi G, Wijayasinghe M, Carbonera D, Balestrazzi A. Seed priming: State of the art and new prospective. *Plant Cell Reports*. 2015;**34**:1281-1293

[60] Bradford KJ, Bewley JD. Seeds: Biology, technology and role in agriculture. In: Chrispeels MJ, Sadava DE, editors. *Plants, Genes and*

Crop Biotechnology. 2nd ed. Boston: Jones and Bartlett; 2002. pp. 210-239

[61] Bose B, Tandon A. Effect of magnesium nitrate on metabolism in germinating maize seeds. *Indian Journal of Plant Physiology*. 1991;**34**:69-71

[62] Pandita VK, Anand A, Nagarajan S. Enhancement of seed germination in hot pepper following presowing treatments. *Seed Science and Technology*. 2007;**35**:282-290

[63] Catusse J, Meinhard J, Job C, Strub JM, Fischer U, Pestova E, et al. Proteomics reveals potential biomarkers of seed vigor in sugar beet. *Proteomics*. 2011;**11**:1569-1580

[64] Chen Y, Cui J, Li G, Yuan M, Zhang Z, Yuan S, et al. Effect of salicylic acid on the antioxidant system and photosystem II in wheat seedlings. *Biology of Plant*. 2016;**60**:139-147

[65] Li X, Cai J, Liu F, Dai T, Cao W, Jiang D. Cold priming drives the sub-cellular antioxidant systems to protect photosynthetic electron transport against subsequent low temperature stress in winter wheat. *Plant Physiology and Biochemistry*. 2014;**82**:34-43

[66] McDonald MB. Seed deterioration: Physiology, repair and assessment. *Seed Science and Technology*. 1999;**27**:177-237

[67] Sen A, Jos TP. Influence of different seed priming technique on oxidative and antioxidative responses during the germination of *Oryza sativa* varieties. *Physiology and Molecular Biology of Plants*. 2020;**26**(3):551-556

[68] Varier A, Vari AK, Dadlani M. The sub cellular basis of seed priming. *Current Science*. 2010;**99**(4):450-456

[69] Farooq M, Basra SMA, Hussain M, Rehman H, Saleem BA. Incorporation of

polyamines in the priming media enhances the germination and early seedling growth in hybrid sunflower (*Helianthus annuus* L). *International Journal of Agriculture and Biology*. 2007;**9**:868-872

[70] Sivritepe HO, Dourado AM. The effect of priming treatments on the viability and accumulation of chromosomal damage in aged pea seeds. *Annals of Botany*. 1995;**75**:165-171

[71] Dahal P, Bradford KJ, Jones RA. Effects of priming and endosperm integrity on seed germination rates of tomato genotypes. II. Germination at reduced water potential. *Journal of Experimental Botany*. 1990;**41**:1441-1453

[72] Dollypan BRN. Mid-storage and pre-sowing seed treatments for lettuce and carrot. *Scientia Horticulturae*. 1985;**33**:1026-1027

[73] Villiers TA, Edgcumbe DJ. On the cause of seed determination in dry storage. *Seed Science and Technology*. 1975;**3**:761-774

[74] Panda D, Mondal S. Seed enhancement for sustainable agriculture: An overview of recent trends. *Plant Archives*. 2020;**20**(1):2320-2332

[75] Ali M, Hayat M, Ahmad H, Ghani MI, Amin B, Atif MJ, et al. Priming of *Solanum melongena* L. seeds enhancing germination, alters antioxidant enzymes, modulated ROS and improves early seedling growth: Indicating aqueous garlic extract as seed-priming bio-stimulant for egg plant production. *Applied Sciences*. 2019;**9**:1-18

[76] Sananda M, Bose B. Kinetics studies on α -amylase extracted from germinating wheat endosperm of primed and non-primed seeds. *Indian Journal of*

Agricultural Biochemistry.
2012;**25**:137-141

[77] Lee SS, Kim JH, Hong SB, Yun SH, Park EH. Priming effect of rice seeds on seedling establishment under adverse soil conditions. Korean Journal of Crop Science. 1998;**43**:194-198

[78] Chen K, Arora R. Priming memory invokes seed stress-tolerance. Environmental and Experimental Botany. 2013;**94**:33-45

[79] Jyoti MCP. Seed deterioration: A review. International journal of life science botany and pharmaceutical. Research. 2013;(3):374-385

[80] Manonmani V, Ameer Junaithal Begum M, Jayanthi M. Halo priming of seeds. Research Journal of Seed Science. 2014;**7**:1-13

[81] Georghiou K, Thanos CA, Passam HC. Osmoconditioning as a means of counteracting the ageing of pepper seeds during high-temperature storage. Annals of Botany. 1987;**60**:279-285

[82] Panayotov N, Aladjadjiyan A. Effect of long-term storage of pepper (*Capsicum annuum* L.) seeds on their viability measured by selected thermodynamic parameters. Acta Scientiarum Polonorum Hortorum Cultus. 2014;**13**(2):151-162

[83] Arun MN, Shankara Hebbar S, Bhanuprakash K, Senthivel T, Nair AK, Pratima PD. Biochemical investigation on vigour enhancement in fresh and aged seeds upon seed priming in cowpea (*Vigna unguiculata* (L.) Walp). Legume Research—An International Journal. 2021;**44**(12):1497-1505. DOI: 10.18805/LR-4476

[84] Srinivasan K, Jain SK, Saxena S, Radhamani J, Uprety M. Seed priming and fortification. Seed Research. 2009;**37**(1&2):1-13

[85] Ermiş S, Kara F, Özden E, Demir I. Solid matrix priming of cabbage seed lots: Repair of ageing and increasing seed quality. Journal of Agricultural Sciences. 2016;**22**:588-595

[86] Thornton JM, Collins ARS, Powell AA. The effect of aerated hydration on DNA synthesis in embryos of *Brassica oleracea* L. Seed Science Research. 1993;**3**:195-199

[87] Arun MN, Bhanuprakash K, Shankara Hebbar S, Senthivel T. Effect of seed priming on biochemical parameters and seed germination in cowpea (*Vigna unguiculata* (L.) Walp). Legume Research—An International Journal. 2017;**40**(3):562-570

[88] Chiari F, Ajay S, Anjali S, Alma S, Prasad V, Anca M. Hydropriming and biopriming improve *Medicago truncatula* seed germination and upgrade DNA repair and antioxidant genes. Genes. 2020;**11**:1-15

[89] Lutts S, Benincasa P, Wojtyla L, Kubala S, Pace R, Lechowska K, et al. Seed priming: New comprehensive approaches for an old empirica technique, new challenges in seed biology. In: Susana Araújo S, Balestrazzi A, editors. Basic and Translational Research Driving Seed Technology. Open, Rijeka: In Tech; 2016. pp. 1-47

[90] Aloui H, Eymen EM, Cherif H. Seed priming to improve seedling growth of pepper cultivars exposed to salt concentrations. International Journal of Vegetable Science. 2017;**23**:489-507

[91] Gallardo K, Job C, Groot SPC, Puype M, Demol H, Vandekerekhove J, et al. Proteomics of Arabidopsis seed germination and priming. In: Nicholas G, editor. The Biology of Seeds: Recent Advances. CABI: Cambridge; 2002. pp. 199-209

- [92] Kibinza S, Bazin J, Bailly C, Farrant JM, Corbineau F, El-Maarouf-Bouteau H. Catalase is a key enzyme in seed recovery from ageing during priming. *Plant Science*. 2011;**181**:309-315
- [93] Wojtyła Ł, Lechowska K, Kubala S, Garnczarska M. Different modes of hydrogen peroxide action during seed germination. *Frontiers in Plant Science*. 2016;**7**:66. DOI: 10.3389/fpls.2016.00066
- [94] Bailly C. Active oxygen species and antioxidants in seed biology. *Seed Science Research*. 2004;**14**:93-107
- [95] Coolbear P, Slater RJ, Bryant JA. Changes in nucleic acid levels associated with improved germination performance of tomato seeds after low-temperature pre-sowing treatments. *Annals of Botany*. 1990;**65**:187-195
- [96] Kaya G, Demir I, Tekin A, Yasar F, Demir K. The effect of priming application on germination, fatty acids, sugar content and enzyme activity at the temperature of stress of pepper seeds. *Journal of Agricultural Science*. 2010;**16**:9-16
- [97] Job D, Capron I, Job C, Dacher F, Corbineau F, Come D. Identification of germination-specific protein markers and their use in seed priming technology. In: Black M, Bradford KJ, Vazquez-Ramos J, editors. *Seed Biology: Advances and Applications*. Wallingford, UK: CAB International; 2000. pp. 449-459
- [98] Cheng J, Wang L, Zeng P, He Y, Zhou R, Zhang H, et al. Identification of genes involved in rice seed priming in the early imbibition stage. *Plant Biology*. 2017;**19**:61-69
- [99] Kubala S, Garnczarska M, Wojtyła L, Clippe A, Kosmala A, Zmienko A, et al. Deciphering priming-induced improvement of rapeseed (*Brassica napus* L.) germination through an integrated transcriptomic and proteomic approach. *Plant Science*. 2015;**231**:94-113
- [100] Iqbal M, Ashraf M. Seed treatment with auxins modulates growth and ion partitioning in salt-stressed wheat plants. *Journal of Integrative Plant Biology*. 2007;**49**:1003-1015
- [101] Nakao Y, Asea G, Yoshino M, Kojima N, Hanada H, Miyamoto K, et al. Development of hydropriming techniques for sowing seeds of upland rice in Uganda. *American Journal of Plant Sciences*. 2018;**9**:2170-2182
- [102] Bhusal D, Thakur DP. Seed hydropriming technique in cereal crops: A review. *Reviews in Food and Agriculture*. 2020;**1**(2):85-88
- [103] Elisabeth Zida P, James Neya B, Romain Soalla W, Sereme P, Ole Sogaard Lund. Hydropriming of pearl millet in northern and central Burkino Faso applying six hours of soaking and overnight drying of seeds. *African Journal of Agricultural Research*. 2017;**12**(149):3441-3446
- [104] Sharma R, Omvati Verma S. Response to pre-sowing seed treatment on germination indices, seedling growth and enzymatic activities of chickpea (*Cicer arietinum* L.) seed. *International Journal of Ecology and Environmental Sciences*. 2021;**3**(1):405-410
- [105] Catiempo RL, Photchanachai S, Bayogan ERV, Chalermchai W. Impact of hydropriming on germination and seedling establishment of sunflower seeds at elevated temperature. *Plant Soil and Environment*. 2021;**67**:491-498
- [106] Elie Lemmens, Lomme JD, Neils De Brier, Wannes L DeMan, Marice De Proft, Els Primsen, Jan AD. The impact of hydropriming and Osmopriming on

- seedling characteristics, plant hormone concentrations, activity of selected hydrolytic enzymes and cell wall and phytate hydrolysis in sprouted wheat. ACS Omega 2019;4:22089-22100. Available from: <http://pubsacs.org/journal/acsdof>
- [107] Pirosteh-Anosheh H, Hashemi SE. Priming, a promising practical approach to improve seed germination and plant growth in saline soils. Asian Journal of Agriculture and Food Sciences. 2020;8(1):6-10
- [108] Sumar Varshini P, Bayyapu Reddy K, Radhika K, SaidaNaik V. Effect of concentration and duration of osmopriming on germination and vigour of aged seed of chickpea. International Journal of Current Microbiology and Applied Sciences. 2018;7(10):2410-2421
- [109] Cokkizgin A, Girgel U, Cokkizgin H. Mannitol effects on germination of broad bean (*Vicia faba* L.) seeds. Forestry Research and Engineering International Journal. 2019;3(1):20-22
- [110] PiyadaTheerakulpisut NK, BunikaPanwang S. Priming alleviated salt stress effects on rice seedlings by improving Na^+/K^+ and maintaining membrane integrity. International Journal of Plant Biology. 2016;7:53-58
- [111] Shelar A, Singh AV, Maharjan RS, Laux P, Luch A, Gemmati D, et al. Sustainable agriculture through multidisciplinary seed nanoprimer: Prospects of opportunities and challenges. Cell. 2021;10:6-22. DOI: 10.3390/cells10092428
- [112] Dhillon BS, Kumar V, Sagwal P, Kaur N, Singh Mangat G, Singh S. Seed priming with potassium nitrate and gibberellic acid enhances the performance of dry direct seeded Rice (*Oryza sativa* L.) in North-Western India. Agronomy. 2021;11:849. DOI: 10.3390/agronomy11050849
- [113] Mangena P. Effect of hormonal seed priming on germination, growth, yield and biomass allocation in soybean grown under induced drought stress. Indian Journal of Agricultural Research. 2020;54:441. DOI: 10.18805/IJAR.A-441
- [114] Zhao T, Ding X, Xiao Q, Han Y, Zhu S, Chen J. IAA improves the germination and seedling growth in cotton via regularizing the endogenous phytohormones and enhancing the sucrose metabolism. Industrial Crops and Products. 2020;1555:1-9. DOI: 10.1016/j.indcrop.2020.112788
- [115] Khanmdi N, Nabipour M, Roshanfekar H, Rahmana A. Effect of seed priming and application and application of cytokinin and auxin on growth and grain yield of wheat under Alvey climatic condition. Iranian Journal of Crop Science. 2019;21(1):31-44
- [116] Ahmad F, Iqbal S, Khan MR, Abbas MW, Ahmad J, Nawaz H, et al. Influence of seed priming with salicylic acid on germination and early growth of sesame. Pure and Applied Biology. 2019;8(2):1206-1213
- [117] Prasad SR, Kamble UR, Sripathy KV, Udaya Bhaskar K, Singh DP. Seed bio-priming for biotic and abiotic stress management. In: Singh DP, Singh HB, Prabha R, editors. Microbial Inoculants in Sustainable Agricultural Productivity: Vol. 1: Research Perspectives. New Delhi: Springer; 2016. pp. 211-228
- [118] Sathiyarayanan G, Suvarna G, Baradhan G, Prakash G. Effect of various seed halo-priming treatments on seed yield and quality in maize. Plant Archives. 2019;19(1):377-383
- [119] Singhal RK, Pandey S, Bose B. Seed priming with $\text{Mg}(\text{NO}_3)_2$ and ZnSO_4 salts triggers physio-biochemical and antioxidant defense to induce water

stress adaptation in wheat (*Triticum aestivum* L.). Plant Stress. 2021;**2**:1-12.
DOI: 10.1016/j.stress2021.10003

[120] Majda C, Khalid D, Aziz A, Rachid B, Badr A-S, Lotfi A, et al. Nutrient-priming as an efficient means to improve the agronomic performance of molybdenum in common bean (*Phaseolus vulgaris* L.). Science of the Total Environment. 2019;**661**:654-663

[121] Krishnaprabu S. Response of green gram to pre-sowing seed priming chemicals. International Journal of Pure and Applied Biosciences. 2018;**6**(6): 455-458

[122] Bisht N, Mishra SK, Chauhan PS. *Bacillus amyloliquifaciens* inoculation alters physiology of rice (*Oryza sativa* L. var. IR36) through modulating carbohydrate metabolism to mitigate stress induced by nutrient starvation. International Journal of Biological Macromolecules. 2020;**15**(143):935-951

[123] Li H, Yue H, Li L. Seed biostimulant *Bacillus* sp. MGW8 improves the salt tolerance of maize during seed germination. AMB Express. 2021;**11**:74.
DOI: 10.1186/s13568-021-012371

[124] Mahmood A, Kataoka R. Potential of biopriming in enhancing crop productivity and stress tolerance. In: Rakshit A, Singh H, editors. Advances in Seed Priming Singapore. 2018. pp. 127-145. DOI: 10.1007/978-981-13-0032-5_9

[125] Sumbul A, Ansari RA, Rizvi R, Mahmood I. A potential bio-fertilizer for soil and plant health management. Saudi Journal of Biological Sciences. 2020;**27**(12):3634-3640

[126] Fukami J, Cerezini P, Hungria M. Azospirillum: Benefits that go far beyond biological nitrogen fixation. AMB Express. 2018;**8**:73.
DOI: 10.101186/s13568-018-0608

[127] Ahammad KU, Rahman MM, Ali MR. Effect of hydro priming method on maize (*Zea mays*) seedling emergence. Bangladesh Journal of Agricultural Research. 2014;**39**(1):43-150

[128] Patra SS, Mehera B, Rout S, Tomar SS, Singh M, Kumar R. Effect of hydro-priming and different sowing dates on growth and yield attributes of wheat (*Triticum aestivum* L.). Journal of Applied and Natural Science. 2016;**8**(2):971-980

[129] Nakao Y, Asea G, Minoru Y, Nobuki K, Hiroyuki H, Kisho M, et al. Development of hydro priming techniques for sowing seeds of upland rice in Uganda. American Journal of Plant Sciences. 2018;**9**(11):2170-2182

[130] Langeroodi ARS, Noora R. Seed priming improves the germination and field performance of soybean under drought stress. The Journal of Animal and Plant Sciences. 2017;**27**(5):1611-1621

[131] Banjobpudsa S, Sripichitt A, Sarutayophat T. The effect of pre-sowing treatments on germination and vigour of upland rice (*Oryza sativa* L.). International Journal of Agricultural Technology. 2017;**13**:1343-1353

[132] Heydecker W, Higgins J, Gulliver RL. Accelerated germination by osmotic seed treatment. Nature. 1973;**5427**:42-44

[133] Jalal R, Khan AZ, Anwar S, Ahmad J, Safia B, Ahmad F, et al. Influence of different pre-sowing invigoration techniques on early growth of different maize hybrids. International Journal of Biosciences;**15**(2):370-379

[134] Brocklehurst PA, Dearman J. Interaction between seed priming treatments and nine seed lots of carrot, celery and onion. II. Seedling emergence and plant growth. Annals of Applied Biology. 2008;**102**:583-593

- [135] Zhang F, Yu J, Johnston CR, Wang Y, Zhu K, Lu F, et al. Seed priming with polyethylene glycol induces physiological changes in sorghum (*Sorghum bicolor* L. Moench) seedlings under suboptimal soil moisture environments. PLoS One. 2015;**10**(10):e0140620. DOI: 10.1371/journal.pone.0140620
- [136] Sun L, Zhou Y, Wang C, Xiao M, Tao Y, Xu W. Screening and identification of sorghum cultivars for salinity tolerance during germination. Scientia Agricultura Sinica. 2012;**45**(9):1714-1722
- [137] Saha P, Chatterjee P, Biswas AK. NaCl pretreatment alleviates salt stress by enhancement of antioxidant defense system and osmolyte accumulation in mungbean (*Vigna radiate* (L.) Wilczek). Indian Journal of Experimental Biology. 2010;**48**:593-600
- [138] Bhanuprakash K, Yogeesh HS, Arun MN, Naik LB. Studies on seed quality in relation to ageing and priming in french beans cv. Arka komal. In: Proceeding of the Fourth International Food Legume Research Conference—IV New Delhi India. 2005. pp. 771-776
- [139] Kaur D, Grewal S, Kaur J, Singh S. Differential proline metabolism in vegetative and reproductive tissues determine drought tolerance in chickpea. Biology of Plant. 2017;**61**(2):359-366
- [140] Matias JR, Ribeiro RC, Arago CA, Araujo GGL, Dantas BF. Physiological changes in osmo and hydro-primed cucumber seeds germinated in biosaline water. Journal of Seed Science. 2015; **37**(1):7-15
- [141] Bahrani A, Pourreza J. Gibberellin acid and salicylic acid effects on seed germination and seedlings growth of wheat under salt stress condition. World Applied Science Journal. 2012;**18**(5): 633-641
- [142] Arun MN, Shankara Hebbar S, Bhanuprakash K, Senthivel T, Nair AK, Pratima PD. Influence of seed priming and different irrigation levels on growth parameters of cowpea (*Vigna unguiculata* (L.) Walp). Legume Research—An International Journal. 2018;**43**(1): 99-104
- [143] Ansari O, Azadi MS, Sharif-Zadeh F, Younesi E. Effect of hormone priming on germination characteristics and enzyme activity of mountain rye (*Secale montanum*) seeds under drought stress conditions. Journal of Stress Physiology and Biochemistry. 2013;**9**:61-71
- [144] Nascimento WM, Cantliffe DJ, Huber DJ. Ethylene evolution and endo-beta-mannanase activity during lettuce seed germination at high temperature. Scientia Agricola. 2004;**61**(2):156-163
- [145] Azeem M, Qasim M, Abbas MW, Tayyab SB, Yousuf M, Ali H. Salicylic acid seed priming modulates some biochemical parameters to improve germination and seedling growth of salt stressed wheat (*Triticum aestivum* L.). Pakistan Journal of Botany. 2019;**51**(2):1-7
- [146] Miransari M, Smith DL. Plant hormones and seed germination. Environmental and Experimental Botany. 2014;**99**:110-121
- [147] Abu-Muriefah SS. Phytohormonal priming improves germination and antioxidant enzymes of soybean (*glycine max* L.) seeds under lead (Pb) stress. Bioscience Research. 2017;**14**(1):42-56
- [148] Voegelé A, Linkies A, Müller K, Leubner-Metzger G. Members of the GIBBERELLIN receptor gene family GID1 (GIBBERELLIN INSENSITIVEDWARF1) play distinct roles during *Lepidium sativum* and *Arabidopsis thaliana* seed germination.

Journal of Experimental Botany.
2011;155:1851-1870

[149] Farooq M, Hussain M, Wakeel A, Kadambot HMS. Salt stress in maize: Effects, resistance mechanisms and management—A review. *Agronomy for Sustainable Development*. 2015;35:461-448

[150] Iqbal M, Raja NI, Yasmeen F, Hussain M, Ejaj M, Shah MA. Impacts of heat stress on wheat: A critical review. *Advances in Crop Sciences and Technology*. 2017;5(1):01-09

[151] Shivay YS, Singh U, Prasad R, Kaur R. Agronomic interventions for micronutrient biofortification of pulses. *Indian Journal of Agronomy*. 2016;61(4th IAC Special Issue):161-172

[152] Maiti R, Rajkurmar D, Jagan M, Pramanik K, Vidasagar P. Effect of seed priming on seedling vigour and yield of tomato and chilli. *International Journal of Bio-resource and Stress Management*. 2013;4(2):119-125

[153] Dutta SK, Singh AR, Boopathi T, Singh SB, Singh MC, Malsawmzuali. Effects of priming on germination and seedling vigour of bird's eye chilli (*Capsicum frutescens* L.) seeds collected from eastern Himalayan region of India. *The Bioscan*. 2015;10(1):279-284

[154] Manjunath BL, Dhanoji MM. Effect of seed hardening with chemicals on drought tolerance traits and yield in chickpea (*Cicer arietinum* L.). *Journal of Agricultural Science*. 2011;3(3):186-189

[155] Ashraf M, Rauf H. Inducing salt tolerance in maize (*Zea mays* L.) through seedpriming with chloride salts: Growth and ion transport at early growth stages. *Acta Physiologiae Plantarum*. 2001;23(4):407-414

[156] Anosheh HP, Sadeghi H, Emam Y. Chemical priming with urea and KNO₃ enhances maize hybrids (*Zea mays* L.) seed viability under abiotic stress. *Journal of Crop Science and Biotechnology*. 2011;14(4):289-295

[157] Arun MN, Shankara Hebbar S, Bhanuprakash K, Senthivel T. Seed priming improved irrigation water use efficiency, yield and yield components of summer cowpea under limited water conditions. *Legume Research—An International Journal*. 2017;40(5):864-871

[158] Harris D, Rashid A, Miraj G, Arif M, Yunas M. 'On-farm' seed priming with zinc in chickpea and wheat in Pakistan. *Plant and Soil*. 2008;306:3-10

[159] Zheng M, Tao Y, Hussain S, Jiang Q, Peng S, Huang J, et al. Priming in dry direct seeded rice: Consequences for emergence seedling growth and associated metabolic events under drought stress. *Plant Growth Regulation*. 2016;78(2):167-178. DOI: 10.1007/s10725-015-0083-5

[160] Devi K, Barua PK, Barua M. Integrated effect of pre-sowing seed treatment, sowing windows and seasons on seed yield and quality of green gram. *Legume Research*. 2021;44(8):956-961

[161] Shariatmadari Z, Riahi H, Seyed Hashtroudi M, Ghassempour A, Aghashariatmadary Z. Plant growth promoting cyanobacteria and their distribution in terrestrial habitats of Iran. *Soil Science and Plant Nutrition*. 2013;59:535-547

[162] Sarma BK, Yadav SK, Singh S, Singh HB. Microbial consortium mediated plant defense against phytopathogens: Readdressing for enhancing efficacy. *Soil Biology and Biochemistry*. 2015;87:25-33

- [163] Lopez LVP, Rodríguez AR, Coronado MES, Hernandez PEM, Segovia AO. Effects of hydro priming treatments on the invigoration of aged *Dodonaea viscosa* seeds and water-holding polymer on the improvement of seedling growth in a lava field. *Restoration Ecology*. 2016;**24**(1):61-70
- [164] Desmukh AJ, Jaiman RS, Bambharolia RP, Vijay AP. Seed biopriming—A review. *International Journal of Economic Plants*. 2020;**7**(1):38-43
- [165] Pill WG, Collins CM, Goldberger B, Gregory N. Responses of nonprime or primed seeds of “Marketmore 76” cucumber (*Cucumis sativus* L.) slurry coated with *Trichoderma* species to planting in growth media infested with *Pythium aphanidermatum*. *Scientia Horticulturae*. 2009;**121**:54-62
- [166] Reddy PP. Bio-priming of seeds. In: *Recent Advances in Crop Protection*. New Delhi: Springer; 2012. p. 83
- [167] Kumar VV. Plant growth-promoting microorganisms: Interaction with plants and soil. In: Hakeem KR, Akhtar MS, Abdullah SNA, editors. *Plant, Soil and Microbes: Volume 1: Implications in Crop Science*. Springer, Cham; 2016. pp. 1-16
- [168] Pehlivan N, Yesilyurt AM, Durmus N, Karaoglu SA. *Trichoderma* ID11D seed biopriming mitigates dose dependent salt toxicity in maize. *Acta Physiologiae Plantarum*. 2017;**39**:79. DOI: 10.1007/s11738-017-2375-z
- [169] Ilyas S, Asie KV, Sutariati GAK. Bio matricconditioning or biopriming with biofungicides or biological agents applied on hot pepper (*Capsicum annuum* L.) seeds reduced seed borne *Colletotrichum capsici* and increased seed quality and yield. *Acta Horticulturae*. 2015;**1105**:89-96
- [170] Vishwas S, Chaurasia AK, Bara BM, Debnath A, Parihar NN, Brunda K, et al. Effect of priming on germination and seedling establishment of chickpea (*Cicer arietinum* L.) seeds. *Journal of Pharmacognosy and Phytochemistry*. 2017;**6**(4):72-74
- [171] Prachi S, Jyoti S, Shatrupa R, Rahul SR, Anukool V, Rakesh KS, et al. Seed biopriming with antagonistic microbes and ascorbic acid and induce resistance in tomato against *Fusarium* sp wilt. *Microbiological Research*. 2020;**237**:1-13
- [172] Abadeh MR, Sharifi RS, Imani A. Influence of nitrogen and seed biopriming with plant growth promoting rhizobacter (PGPR) on yield and agronomic characteristics of red lentil. *Journal of Applied Environmental and Biological Sciences*. 2013;**3**(11):117-123
- [173] Kasim WA, Osman ME, Omar MN, Abd El-Daim IA, Bejai S, Meijer J. Control of drought stress in wheat using plant-growth-promoting bacteria. *Journal of Plant Growth Regulation*. 2013;**32**:122-130
- [174] Shah G, Jan M, Afrien M, Anees M, Rehman S, Daud MK, et al. Halophilic bacteria mediated phyto remediation of salt-affected soils cultivated with rice. *Journal of Geochemical exploration*. 2017;**174**:59-65
- [175] Sen SK, Mandal P. Solid matrix priming with chitosan enhances seed germination and seedling vigour in mung bean under salinity stress. *Journal of Central European Agriculture*. 2016;**17**(3):749-762