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Seed Priming: A Potential Supplement in Integrated Resource Management Under Fragile Intensive Ecosystems

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A majority of agricultural activities are conducted under fragile lands or set-up. The growth and development of crops are negatively affected due to several biotic and abiotic stresses. In the current situation, research efforts have been diverted toward the short-term approaches that can improve crop performance under changing environments. Seed treatment or priming technology is in a transition phase of its popularity among resource-poor farmers. Suitable policy intervention can boost low-cost techniques to implement them on a larger scale in developing countries and to harness the maximum benefits of sustainable food production systems. Primed seeds have high vigor and germination rate that help in seedling growth and successful crop stand establishment under stress conditions. This review is attempted to assess different seed priming techniques in terms of resource use efficiency, crop productivity, cost–benefit balance, and environmental impacts. Moreover, a comprehensive study of the mechanisms (physiological and biochemical) of seed priming is also elaborated. A detailed examination of the applications of priming technology under diverse agroecosystems can improve our understanding of the adaptive management of natural resources.

Keywords: seed treatment, biotic and abiotic stresses, hydropriming, mitigation strategies, crop performance

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INTRODUCTION

Nearly 60% of the Indian population relies upon agriculture and its associated sectors for their livelihood. Enormous improvement in food grain production was achieved through the Green Revolution with the adoption of modern approaches such as high-yielding varieties, agrochemicals and intensified farming (Akhilesh and Kavitha, 2020). Although high-yielding varieties are being promoted, the bulk of the tropical land fails to provide suitable growth conditions for these high-yielding crops; and consequently, low yield is obtained even after the application of necessary agrochemicals. Indiscriminate use of these chemicals causes environmental pollution, soil degradation and economical burden to farmers. Different factors such as rapid growth in population rate, cultivating lands that are ill-suited for agriculture, inappropriate farming practices and eradication of trees for fuel and shelter can render tropical soils to be fragile. Further, the regional agricultural hubs under tropical conditions are highly affected by extreme events of climate change, e.g., heavy rainfall, floods and droughts (González-Orozco et al., 2020; Sarkar et al., 2020a).

Dealing with fragile ecosystems is challenging for agricultural researchers to provide restorative solutions. In this context, to curtail the effects of climate change and continue cultivation practices under fragile ecosystems, the adoption of eco-friendly and economical techniques such as seed priming, low-input sustainable agriculture, conservation agriculture, etc., are imperative (Rakshit and Singh, 2018; Sarkar et al., 2020a). Pre-sowing techniques like seed priming grabbed the attention of researchers and grew into the subject of extensive investigation and interest when it addressed the problems of slow and non-uniform germination, low seed vigor, poor crop stand, biotic and abiotic stresses, poor product quality, etc. (Paparella et al., 2015; Chatterjee et al., 2018; Zulfiqar, 2021). Seed priming eases germination even under adverse conditions, lifts crop performance and enhances yield potential (Ajouri et al., 2004; Ibrahim, 2016; Marthandan et al., 2020). To alleviate the effects of modern agriculture, this technique emerged as a viable strategy that protects plants against both biotic and abiotic stresses (Sarkar et al., 2018). The absolute performance of seed priming is more prominent under adverse conditions (Parera and Cantliffe, 1994) such as fragile ecosystems than favorable conditions.

FRAGILE ECOSYSTEMS

Fragile lands comprise tropics, semi-arid areas, deserts, wetlands, islands, coastal regions and mountains (ENVIS Resource Partner on Biodiversity, 2020). It is projected that over 33% of land resources in the world are degraded owing to intensive agricultural practices, deforestation, desertification, salinization, pollution, industrialization, urbanization, unscientific land-use practices, climate change, etc. (Abhilash, 2021). Globally, drylands are distributed around 6.45 billion hectares, and 70% of these lands are used for cultivation purposes (Karim and Rahman, 2015). Peculiar characteristics of desert soils are drought and aridity circumstances where crop experiences water-deficit conditions. In desert farming, crop strives with water-scarce situations as a result of inadequate rainfall, and rapid land surface evaporation leads to crop failure or reduction in yield. Annual rainfall in semi-arid regions falls in between desert ecosystem and potential evapotranspiration. The major hazards in semi-arid regions are low rainfall, soil erosion and salinity that lead to low soil organic carbon content, available nitrogen and poor soil structure (Garcia-Franco et al., 2018). According to Chivasa et al. (2001), the poor stand establishment of tropical crops in semi-arid regions of Zimbabwe is primarily due to low-quality seeds, poor sowing techniques and low soil moisture. Salinity has affected above 800 million hectares of the global area (Gopalakrishnan and Kumar, 2020). The expansion rate of soil salinization indicates that more than 50% of global arable land will be affected by 2050 (Tisarum et al., 2020). The germination percentage, as well as germination time, decreases with an increase in salt concentration (Ibrahim, 2016).

In India, mountains are sustaining 6% of the population and 18% of the geographical area (Wani, 2011) where the potential of agriculture is extensive. The major constraint in hilly lands is undulating topography, which causes soil erosion and a reduction in soil fertility. Further, low temperature or chilling stress generates reactive oxygen species (ROS), which hampers seed germination (Farooq et al., 2017). Wetlands contribute 4.7% of India's geographical area (Bassi et al., 2014), which are saturated with water throughout the year or differing durations. The main limitations in wetland agriculture are excessive flood and drought damage and nutrient run-off. In small islands, the challenge is to meet people's demands with limited resources. Similar to other categories of fragile lands, small island soils too struggle with complications such as irregular topography, ecosystem instability, soil erosion and loss of fertility. Coastal areas occupy more than 10% of land on the Earth's surface (Ministry of Environment Forest, 2012). Agriculture in coastal areas faces considerable threats such as seawater inundation, soil salinity, and erosion.

INTEGRATION OF RESOURCES IS KEY

Fragile ecosystems are extremely vulnerable to climate change that induces adverse effects on crop production and food security. For example, diffusion and mass flow of nutrients (especially water-soluble ones) decrease due to drought stress (Vurukonda et al., 2016). To meet the nutrient demand of crops and for the finest yields, chemical fertilizers play a key role. Despite several advantages, chemical fertilizers and pesticides are unfriendly to the environment, causing damage to soil, plant, animal, and human health and also placing an economic burden on farmers. Indiscriminate application of synthetic fertilizers interrupts sustainability and environmental quality, while the reduction of organic matter application causes adverse impacts on soil health (Sarkar et al., 2017a; Ferdous et al., 2020). Loss of soil fertility is accompanied by decreased soil aggregation, water-holding capacity (WHC), biodiversity and crop stress tolerance (Sergaki et al., 2018). To minimize these impaired effects of climate change and agrochemicals on soils, agriculture and environment, switching to the integration of fertilizers and naturally available resources that sustain environment and restore nutrients naturally through supporting internal cycling and assuring harmony of ecosystem is an appropriate practice to restore the quality of degraded systems (Singh and Reddy, 2011; Dubey et al., 2021a,b). These are basically practiced with a customized approach. Integration of agrochemicals with organic or natural resources such as farmyard manure (FYM), compost and bio-fertilizers replaces some quantity of fertilizers, supplements a part of energy, improves soil properties and maintains sustainability (**Figure 1**). In a 5-years field experiment on wheat, integrating 50 and 75% of recommended dose of NPK fertilizers with FYM and bio-fertilizer enhanced grain yield significantly in all seasons and also reduced the quantity of chemical fertilizer requirement (Cisse et al., 2019). Further, integration of manure and bio-agent with 50% recommended dose of fertilizers greatly enhanced yield in the long run. Single and combined application of organics, viz. press mud, FYM and vermicompost, in bread wheat revealed the improvement in grain yield by 30–68%, and the highest B:C ratio was recorded in FYM treatments (Ali et al., 2020).

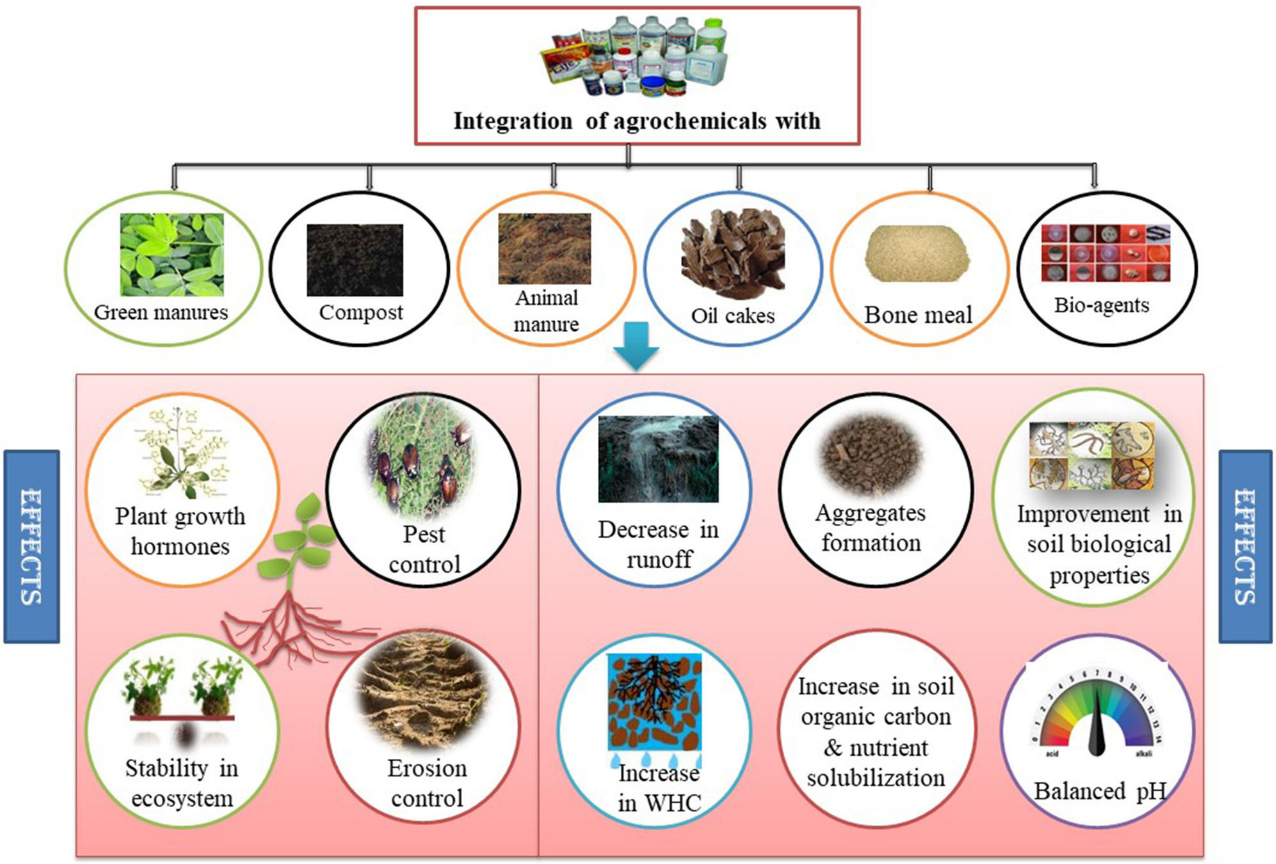

FIGURE 1 | Benefits of integrating agrochemicals with natural resources.

SEED PRIMING—A VIABLE ANSWER

Modern agricultural practices with an intensive approach (e.g., heavy tillage, synthetic agrochemicals, hybrid varieties, and monocropping) may further deteriorate fragile lands by accelerating the loss of organic matter, degradation of soil and environmental damage (e.g., deterioration of water and air quality, loss of biodiversity, and biomagnification); thus, several attempts have been carried out to achieve ecosystem stability. Vital aspects of crop improvement through maintaining sustainability can be accomplished by modulating the metabolism of seed that would be achieved by seed priming technique. Seed priming is a pre-sowing seed treatment that allows controlled hydration of seeds to imbibe water and go through the first stage of germination but does not allow radical protrusion through the seed coat (McDonald, 2000).

Seed priming hastens the germination process and enhances the rate of seedling emergence even under extreme climatic conditions and in problem soils. Seed priming is categorized into different types, viz. hydropriming, osmopriming, halopriming, hormonal priming, and biopriming, and provides extensive crop benefits. Seed priming techniques can deal with detrimental conditions in fragile lands such as drought, heat stress, salinity, nutrient stress and several environmental stresses. Seed soaking in distilled water and osmotic solutions is considered hydropriming and osmopriming, respectively. Hydropriming in paddy crop enhanced resistance against CO_2 stress and oxidative damage (Nedunchezhiyan et al., 2020), while osmopriming with $CaCl_2$ in wheat provided resistance against drought stress (Hussain et al., 2018). Seed imbition using phytohormones to activate seed metabolism is known as hormonal priming. Seed priming with cytokinins (plant growth substance) imparted salt stress in wheat (Iqbal et al., 2006) and drought tolerance in soybean (Mangena, 2020). Beneficial microorganisms or plant growth-promoting microorganisms used for seed treatment are crucial for biopriming. Groundnut seeds treated with *Pseudomonas fluorescens* mitigated salt stress under field conditions (Saravanakumar and Samiyappan, 2007). Enhanced plant stress tolerance against drought was also recorded due to bacterial priming (*Bacillus thuringiensis*) of wheat seeds (Timmusk et al., 2014). Chemical priming is another type of priming where seed treatment is carried using natural substances (organic acids, plant extracts, chitosan, polyamines, mannose, trehalose, etc.) or synthetic compounds (sodium nitroprusside, sodium hypochlorite, etc.) (Jisha et al., 2013; Paparella et al., 2015; Lutts et al., 2016). However, combined application of natural and synthetic substances is also a common practice in seed priming. For example, Bajwa et al. (2018) found that priming wheat seeds with sorghum extracts and benzyl aminopurine improved crop performance under saline soil conditions. Choosing an appropriate priming approach in accordance with the limitations of a fragile land would be pertinent to combat stress.

MECHANISMS OF SEED PRIMING

Priming exposes seed to stimuli, in response to which a set of interlinked biochemical changes occurs such as activation of enzymes, synthesis of growth-promoting substances, metabolism of germination inhibitors and repair of cell damage (Farooq et al., 2010; Chatterjee et al., 2018). The process of seed priming is accomplished in three stages (Ibrahim, 2016; Lutts et al., 2016; Marthandan et al., 2020). Seed imbibition is the first (I) stage, where the seed uptakes water rapidly as the water potential of the seed is low. Stage II is known as the activation phase. This stage is characterized by a series of metabolic and repairing events at the cellular level (**Figure 2**). The moisture content decreases, and the major changes documented during this stage include synthesis of protein, formation of new mitochondria, activation of enzymes and antioxidant system, and DNA repair. Seed imbibition is stopped after this stage. Rehydration during seed priming induce changes at the cellular level such as cell division, synthesis of nucleic acids, protein, ATP production, increase in cell energy, ATP/ADP ratio for energy requirement, accumulation of essential lipids, production of antioxidants and activation of DNA repair mechanism (Varier et al., 2010; Paparella et al., 2015; Lutts et al., 2016). In the cell damage repair system, DNA repair is most crucial because, in case of defective repair, oxidative injury can lead to cell death during germination (Paparella et al., 2015). Studies revealed that proteins, carbohydrates and lipid-mobilizing enzymes are activated during seed priming (Varier et al., 2010; Di Girolamo and Barbanti, 2012; Hameed et al., 2013). For example, α-amylase activity along with total soluble sugars increased in wheat when primed with benzyl aminopurine and sorghum water extract (Bajwa et al., 2018). α-Amylase is known to hydrolyse the starch (polysaccharides) reserves into sugars (simple forms). Priming enhances protein synthesis by increasing the synthesis of rRNA and improving the integrity of ribosomes. Production of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) and maintaining a balance between generation and destruction of ROS such as hydrogen peroxide, superoxide and hydroxyl radicals under stress conditions are important effects of seed priming (Wojtyla et al., 2016; Farooq et al., 2017). In stage III, the uptake of water is rapid, and protrusion of the radicle indicates that the germination process has entered into the growth and cell elongation phase (Marthandan et al., 2020). Metabolic changes of seeds induced by priming are detailed with some research findings in **Table 1**.

PRACTICES AND PERFORMANCES OF SEED PRIMING

The objectives of seed priming related to improved crop performance are achieved by different methods as described in the earlier section. Each priming technique involves restricted hydration to allow imbibition and pre-germinative metabolic changes (**Figure 2**). The efficiency of priming is affected by numerous factors and straightaway depends on treated crop species, particular cultivar and selected priming method. Physical, chemical and biological factors such as nature of solute and water content, primers, time, temperature, existence or non-existence of luminosity, aeration and seed condition also control priming success and decide germination rate and time, seedling vigor and finally plant growth and development. In hydropriming, the soaking of seeds in water for a specific period of time before sowing is ensured, which will finally be dried to a certain moisture content (Singh et al., 2015) and is an effortless, economical and environment-friendly technique. It is a potent approach to combat abiotic stresses such as heat and drought stress to crop. Different chemical solutions are also used as priming agents. Soaking of seeds in the solution with inorganic salts, viz. NaCl, KNO_3, $CaCl_2$, and $CaSO_4$, is known as halopriming (Nawaz et al., 2013). Halopriming stimulates the crop to raise robust even under soil salinity. This is a common observation in hydropriming that due to the high water potential of pure water entry to seed is very fast, which allows abrupt seed imbibition, which may not be congenial for germination metabolic activation and cell elongation under diverse agro-ecologies. To overcome this hurdle, seeds are soaked in an osmotic solution such as sugar, polyethylene glycol (PEG), glycerol, sorbitol and mannitol, followed by air drying. Osmosis controls the excess water entry into the seed during imbibition, hence reducing the ROS accumulation and thus protecting the cell from oxidative injury. Osmopriming improves crop performance in both saline and non-saline conditions. Because of its direct impact on seed metabolism, plant growth regulators in minuscule quantities are also used in pre-sowing seed treatment with different organic compounds, viz. IAA, salicylic acid, ascorbate and kinetin (Nawaz et al., 2013), and not only promotes growth and development but also alleviates the impacts of several environmental stresses. In diverse stressed agro-ecologies, it is a common practice where seeds are soaked in a nutrient solution with certain concentration for a specific time period before being sowed with a resultant positive effect on growth, yield and nutrient uptake (Shivay et al., 2016). Researchers have documented that seed priming with macro- or micronutrients can increase water uptake efficiency, enhance nutrient substances and hasten the seed germination rate and seedling development (Bhowmick et al., 2013; Rakshit et al., 2013, 2014).

The application of beneficial microorganisms (*Trichoderma harzianum*, *Azospirillum lipoferum*, *Pseudomonas fluorescens*, *Rhizobium* spp., *Bacillus* spp., etc.) improves soil properties, enhances plant growth and increases the activity of symbiotic microbes (Javaid, 2010; Sarkar et al., 2017b). Further, they improve plant performance by releasing plant growth hormones, mobilizing nutrients and suppressing pests and diseases. Among all methods of microbial applications, the advanced method is seed biopriming. It is the seed pre-soaking (seed hydration) along with inoculation of beneficial microorganisms. Biopriming promotes microbial colonization at the root zone of the plant

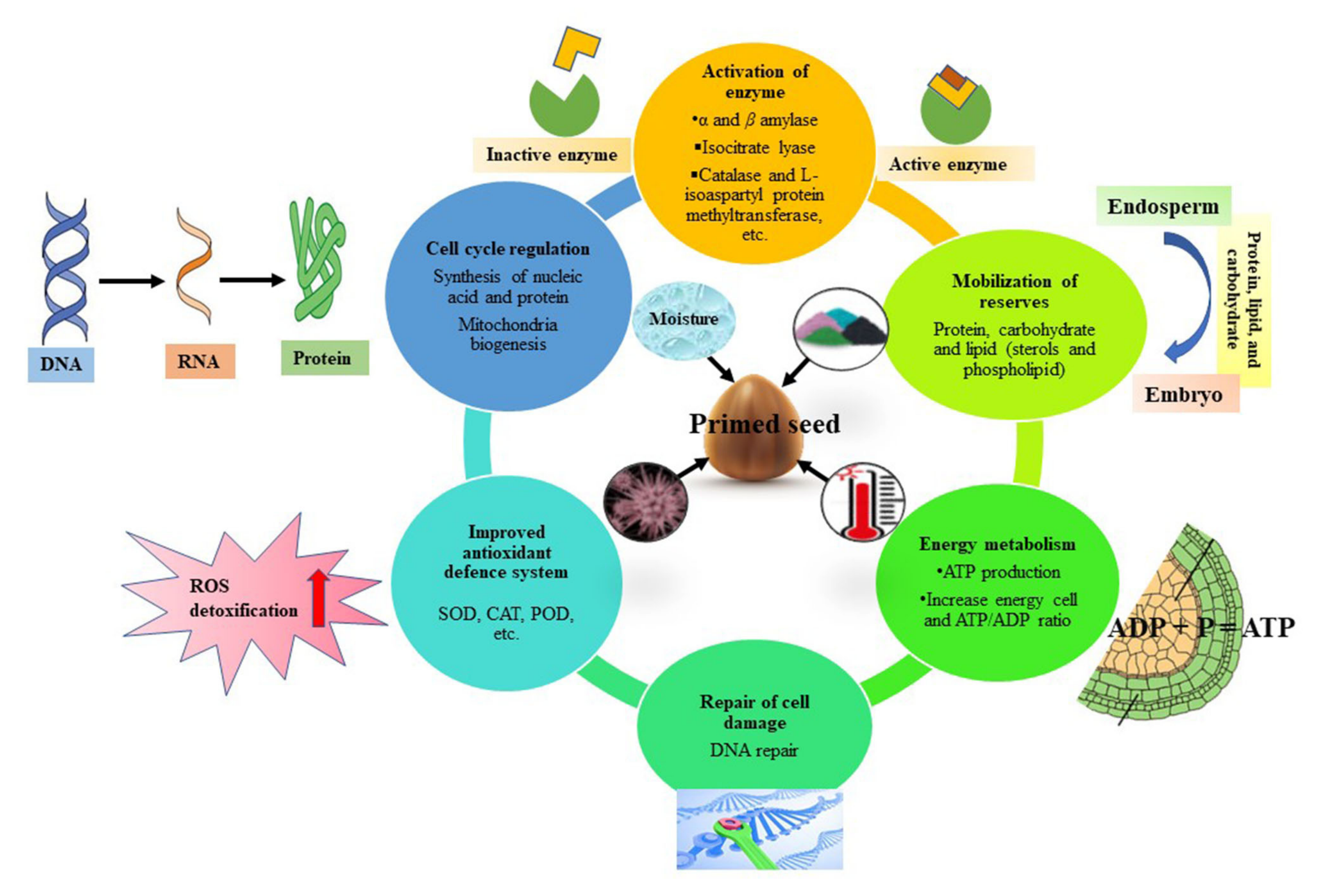

FIGURE 2 | Biochemical and molecular changes influenced by seed priming during stage II.

and thus enhances plant growth (Raj et al., 2004; Sarkar et al., 2020b).

The capability of seed priming to enhance nutrient use efficiency can be an answer for limited mineral reserves of essential nutrients as it is being depleted day by day. Under the current agricultural scenario, ∼50% of applied fertilizers are indeed utilized by crop (Parihar et al., 2019), and the rest is subjected to losses through leaching, soil fixation, low mobility, denitrification, etc., posing threat to the environment and economy, which could be minimized by seed priming that enhances uptake nutrients and minimize losses (Sarkar et al., 2021). Biopriming of wheat seed with *T. harzianum* improved nitrogen use efficiency (agronomic) up to 3.36% when applied with 1/4th N and recommended dose of PK (Meena et al., 2016). Nutrient priming of barley seed with P and Zn individually or in combination enhanced the nutrient uptake and water use efficiency under nutrient (P and Zn)-deficient and drought conditions (Ajouri et al., 2004). In a P-deficient tropical soil, priming of mung bean seeds with 0.01 and 0.02% P enhanced the P uptake (Shah et al., 2012). Kumar et al. (2020) reported maximum P solubilizing activity in a consortium of *Burkholderia gladioli*, *Pseudomonas* sp., and *Bacillus subtilis*, and the application of this consortium through seed biopriming improved the soil available P by 54%.

Seeds priming improves water use efficiency and, hence, suitable in drought-prone areas as well. Seed priming is one of the lifelong practices with new age interventions that proved to be an efficient technology for plants under water stress conditions. Under mild-to-severe drought conditions, priming of sesame seeds with different species of mycorrhizal fungi (*Funneliformis mosseae* and *Rhizoglomus intraradices*) enhanced water use efficiency by 6% to 10% by improving root length and overall root system (Askari et al., 2019). Priming of rice seed with moringa leaf extract increased the water productivity to the highest level (compared with $CaCl_2$ and KCl) when managed under alternate wetting and drying conditions (Rehman et al., 2015). Osmopriming with different molecules (gibberellic acid and ammonium molybdate) improved water use efficiency in summer cowpea seeds sown under limited water availability conditions (Arun et al., 2017).

The economical profit of a crop via any technology can be determined through a benefit–cost (B:C) ratio analysis that can be described as an evaluation of expenditure through comparing economic benefit with the economic cost of an activity (Shively and Galopin, 2013). Seed priming techniques reduce chemical

TABLE 1 | Mechanisms of seed priming involved in improved stress tolerance in crops.

Crop	Priming type (priming agent, concentration, and soaking time)	Changes at physiological, biochemical, and molecular levels	Effect	References
Rice	Biopriming (*Bacillus amyloliquefaciens*, *Serratia marcescens*; 1×10^7 CFU ml^{-1}; 12 h)	Enhanced activities of peroxidase (APX) and polyphenol oxidase (PPO) in rice seedlings	Reduced rice blast (disease) severity caused by *Magnaporthe oryzae* (fungus)	Amruta et al., 2019
	Chemical priming (spermidine + trehalose; 1 mM; 24 h)	(i) Increased proline and soluble sugar contents in leaves (ii) Reduced malondialdehyde (indicator of oxidative damage level) content in rice seedlings (iii) Improved CAT, POD, and APX activities in rice seedlings (iv) Expressions of polyamines biosynthesis-related genes and trehalose-6-phosphate–phosphatase genes	Increased chilling tolerance resulting in better seed vigor and seedling growth	Fu et al., 2020
Wheat	Chemical priming (sodium nitroprusside; 0.1 mM; 12 h)	(i) Increased activities of leaf superoxidase dismutase (SOD), POD, and CAT (ii) Increased contents of leaf proline, ascorbic acid and total phenolics (iii) Decreased leaf malondialdehyde content	Enhanced salt tolerance	Ali et al., 2017
	Osmopriming (aerated $CaCl_2$; 1.5%; 12 h)	(i) Increased leaf area and tissue water contents (ii) Enhanced accumulation of osmolytes (proline and glycine betaine) (iii) Reduced lipid peroxidation (iv) Activation of transcription factors associated with antioxidant enzymes	Increased crop performance under drought stress	Tabassum et al., 2018
	Chemical priming (sorghum water extract; 5% v/v; benzyl aminopurine; 5 mg L^{-1}; 12 h)	(i) Increased chlorophyll (*a* and *b*) and total chlorophyll contents (ii) Improved accumulation of total soluble sugars and total soluble proteins in leaves (iii) Increased α-amylase activity in leaves (iv) Reduced Na^+ content and enhanced K^+ content in leaves (v) Increased total phenolic level in leaves	Improved salt tolerance	Bajwa et al., 2018
Barley	Nutrient priming ($ZnSO_4$; 10 mM of Zn; KH_2PO_4; 50 mM of P; 12 h)	Improved root growth and root biomass	Improved P and Zn uptake and water use efficiency under nutrient (P and Zn)-deficient and drought conditions	Ajouri et al., 2004
Pearl millet	Biopriming (*Pseudomonas fluorescens*; 1×10^8 CFU ml^{-1}; 6 h)	(i) Increased leaf surface area (ii) Rhizobacteria-mediated induced systemic resistance (iii) Production of plant growth-promoting hormones, antimicrobial and antioxidative substances, etc.	Reduced downy mildew (disease) severity caused by *Sclerospora graminicola* (fungus)	Raj et al., 2004
Chickpea	Osmopriming ($CaCl_2$; 18 h)	(i) Increased specific leaf area, CO_2 net assimilation rate and relative water content (ii) Improved accumulation of leaf total soluble phenolics, free proline and ascorbic acid (iii) Increased activities of CAT, SOD, and APX (iv) Increased α-amylase activity and trehalose content in germinating seeds	Enhanced chilling tolerance	Farooq et al., 2017
Rapeseed	Biopriming (hypovirulent *Sclerotinia sclerotiorum* strain DT-8 carrying a DNA virus SsHADV-1; 10 ml 5 g $seed^{-1}$; 18 h)	(i) Induced systemic resistance (ii) Influence on composition and structure of plant microbiome (iii) Secretion of oxalic acid	Reduced stem rot (disease) severity caused by *S. sclerotiorum* (fungus)	Qu et al., 2020
Cotton	Hydropriming (water; 2 h)	(i) Increased activities of CAT, SOD, POD, ascorbate peroxidase (APX), and glutathione reductase (GR) (ii) Decreased lipid peroxidation	Improved germination per cent and reduced deterioration of seeds under accelerated aging	Goel et al., 2003
Tobacco	Chemical priming (putrescine; 0.1 mM; 48 h)	(i) Increased activities of SOD, CAT, POD, and APX in tobacco seedlings (ii) Decrease in the level of malondialdehyde	Enhanced chilling tolerance	Xu et al., 2011

TABLE 2 | Role of priming in improving plant performance.

S. no.	Crop	Priming agent and temperature	Priming duration	Results	References
1	Mung bean	Distilled water	6 h	At chilling stress conditions, i.e., 5°C, primed seeds showed significantly higher germination and seedling growth as compared with the control	Posmyk and Janas, 2007
2	Pyrethrum	Distilled water at 25°C	24 h	Hydropriming reduced the mean germination time, enhanced germination percentage and improved the resistance against salt stress conditions	Li et al., 2011
3	Sunflower	Water at 25°C	18 h	Hydropriming of seeds showed significantly higher mean germination (92%), speed of emergence, vigor index, seed dehydrogenase activity, seedling total DNA content and seedling dry weight (21 mg) as compared with control	Shanthala and Siddaraju, 2013
4	Faba bean	Water at 22–24°C	8 h	Improved mean germination time (5.81 days) and higher seed yield by 12.0%	Damalas et al., 2019
5	Wheat	$CaSO_4$ (50 mM) at 25°C	12 h	Priming with $CaSO_4$ enhanced germination percentage, root length, and fresh and dry weight of seedlings under both saline and non-saline conditions as compared with control. Maximum potassium concentration, total sugars and reducing sugars in seedlings were also found	Afzal et al., 2008
6	Sunflower	KNO_3 (−1.0 MPa) at 30°C	24 h	The results showed that in primed treatments, germination percentage, radical length, seedling height, dry weight, no. of leaves per plant, and sodium and potassium contents in plants were significantly found high as compared with those in control even under saline stress conditions	Bajehbaj, 2010
7	Tomato	KNO_3 (25 mM) at 25°C	24 h	Halopriming with KNO_3 enhanced germination index, final germination percentage, root length, shoot length and seedling fresh weight as compared with other treatments and control	Nawaz et al., 2011
8	Sesame	$CaCl_2$ (2%) at 27°C ± 3°C	6 h	In primed seeds, final emergence per cent, root length, shoot length, seedling fresh weight, dry weight and vigor index were significantly higher than that those of control	Shabbir et al., 2014
9	Spinach	PEG (−0.6 MPa) at 15°C	8 days	Osmopriming enhanced seed germination potential and stress tolerance in germinating seeds by increasing the strength of antioxidant system	Chen and Arora, 2011
10	Soybean	PEG (−1.2 MPa) at 25°C	12 h	Significant impact on germination index, germination percentage and seed vigor	Sadeghi et al., 2011
11	Alfalfa	PEG (−0.6 MPa) at 25°C	24 h	Results of the experiment revealed that seed osmopriming enhanced growth, leaf area and nodulation under drought conditions. Physiologically enhancement in PS-II efficiency, relative water content, stomatal closure, N_2 fixation, and P and K uptake were also observed	Mouradi et al., 2016
12	Wheat	Ascorbic acid (50 ppm) + salicylic acid (50 ppm)	12 h	Seeds primed with salicylic acid and ascorbic acid resulted in germination percentage and reduced the time of germination in both saline and non-saline conditions as compared with remaining treatments. It also significantly improved the shoot length, fresh weight and dry weight of shoots	Afzal et al., 2006
13	Rice	Salicylic acid (20 ppm)	48 h	Results revealed the enhancement in vigor, uniform germination, mean germination time, radical and plumule length, seedling fresh and dry weights as compared with control	Basra et al., 2006
14	Hot pepper	Salicylic acid (0.8 mM) Acetylsalicylic acid (0.2 mM)	48 h	Under saline conditions, both the priming treatments gave significantly better results as compared with control by enhancing seedling vigor, emergence percentage, root and shoot length, seedling fresh weight and dry weight	Khan et al., 2009
15	Wheat	Ascorbic acid (20 ppm)	48 h	In primed treatments, maximum germination and emergence percentage, root length, shoot length and dry weight were noticed as compared with control	Khan et al., 2011
16	Wheat	10^{-4} M of gibberellic acid, salicylic acid	8 h	Both hormonal priming treatments significantly enhanced yield in all genotypes under normal conditions as well as drought-stressed conditions. Salicylic acid priming greatly enhanced the stress tolerance index in crops	Ulfat et al., 2017
17	Barley	50 mM of P + 10 mM of Zn	12 h	Results of the experiment revealed that nutrient priming with Zn and P under the deficiency of these nutrients significantly improved uptake of both P and Zn by plants along with the improved performance of growth parameters	Ajouri et al., 2004
18	Barley	Zn (10 mM) + P (100 mM)	12 h	The growth parameters such as germination percentage, seedling emergence, root dry weight, shoot dry weight, and seedling dry weight were found significantly superior as compared with remaining treatments	Abdulrahmani et al., 2007
19	Maize	Fe (8.5 mM) Zn (4 mM) + Mn (2.5 mM)	24 h	Among the treatments, nutrient-primed treatments showed significantly superior results such as seedling growth, root length, and Zn, Mn, Fe, and P concentrations in shoots and yield	Imran et al., 2013

(Continued)

TABLE 2 | Continued

S. no.	Crop	Priming agent and temperature	Priming duration	Results	References
20	Maize	Zn (4 mM) + Mn (2.5 mM) B (5 mM) P (0.2 M)	24 h	Under controlled conditions, primed nutrient contents in seed were significantly improved than those of control. Nutrient priming with mentioned nutrients significantly increased growth of plants when the nutrient solution was deficient in that particular nutrient	Muhammad et al., 2015
21	Bread wheat	0.5 M of $ZnSO_4$	12 h	Nutrient priming with zinc under zinc-deficient soil conditions enhanced final yield by 27.1%, which was maximum improvement as compared with the rest of the treatments imposed	Rehman et al., 2018
22	Rice	*Trichoderma harzianum*	24 h	Biopriming reduced the deteriorating effect of salinity and significantly increased proline, phenol content and membrane stability as compared with non-primed seeds. It also significantly enhanced the number of leaves, leaf area and chlorophyll content	Rawat et al., 2012
23	Chickpea	*T. harzianum*	12 h	The results revealed that biopriming with *Trichoderma* suppressed *Fusarium* wilt by 53.38–57.99% suppression and also increased the germination and plant growth parameters as compared with those of chemical fungicides and control	Kumar et al., 2014
24	Pea	*Trichoderma asperellum*	24 h	In bioprimed treatments, increase in shoot length, root length, no. of leaves, shoot fresh weight, root fresh weight, shoot dry weight and root dry weight by 35.29, 96.49, 28.13, 36.10, 146.26, 30.17, and 77.2%, respectively, was recorded	Singh M. et al., 2016; Singh V. et al., 2016
25	Maize	*Azospirillum brasilense*	12 h	Biopriming with *Azospirillum* resulted in significantly higher field emergence (96.3%), crop growth, performance and yield than those of control	Madhukeshwara and Sajjan, 2017
26	Wheat	*T. harzianum*	30 min	Biopriming significantly enhanced effective tillers by 59–153%, chlorophyll content by 174–189% and root length by 27% than those of control	Meena et al., 2016

input requirements of the crop by increasing efficiency (Rakshit et al., 2014), which helps in enhancing the B:C ratio. In a 3-years experiment on wheat, the economic returns and B:C ratio were higher in osmopriming compared with hydropriming (Farooq et al., 2020). Enhancement in economic yield per cent by 4–39% was reviewed in wheat, rice, maize, and linola crops through the adoption of different seed priming techniques (Farooq et al., 2019). The seed biopriming technique regulates defense systems of crops to overcome climatic conditions under varied agro-ecologies and showed a higher B:C ratio than that of the recommended dose of fertilizer (Devika and Rakshit, 2019). While comparing the effects of hydropriming, chemical priming and hormonal priming on developing salt tolerance in Indian mustard, Srivastava et al. (2010) concluded that hydropriming is a simple and cost-effective approach to achieve the target.

Seed priming is an economical and trending technique that can resist environmental stresses as well as biotic stresses (pests and pathogens). The benefits of seed priming with the help of research evidence are shown in **Table 2**.

CONCLUSIONS

Seed priming is a viable option to boost the performance of crops under fragile ecosystems. An enhanced understanding of the metabolic events taking place throughout the priming intervention and the subsequent germination should facilitate to use this simple and inexpensive technology for maximizing seed performance in a more resourceful way under varied fragile ecologies. However, many popular technologies failed to reach the farmers' field due to a lack of awareness. Suitable policy intervention to strengthen the extension services moves the targets to the next level. It is desirable to highlight the advantages of seed priming in terms of ecosystem restoration and harness sustainable biomass production from degraded lands.

AUTHOR CONTRIBUTIONS

OSD, SS, PB, and JS: writing. AR: writing, editing, and supervision. DS: writing and editing. All authors contributed to the article and approved the submitted version.

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