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REVIEW ARTICLE

A review on seed priming to combat climate variability in agriculture

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ABSTRACT

Global agriculture faces immense challenges due to climate change, which causes unpredictable weather patterns, decreased agricultural productivity, and decreased food security. Seed priming is critical in combating climate variability because it has emerged as a promising method for improving seed germination and agricultural resilience. This review evaluates the efficiency of several seed priming techniques, including hydro-priming, halo-priming, osmo-priming, bio-priming, chemical priming, and hormone priming. These techniques improve seedling vigor, stress tolerance, and overall crop yield. Seed priming increases germination rates and resistance to biotic and abiotic stresses, such as salinity and drought, while improving agricultural output and disease resistance. Seed priming reduces the demand for chemical pesticides and fertilizers by increasing soil quality and nutrient absorption, which supports sustainable agriculture. This review highlights the potential benefits of seed priming as a practical, affordable, and practical strategy to reduce the negative effects of climatic variability on agriculture. Future studies should focus on developing the best priming techniques for diverse crop varieties and conditions, as well as examining the combined impacts of various priming strategies. Seed priming will be crucial to preserving food security and agricultural sustainability in the face of ongoing climate change.

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INTRODUCTION

Climate change is an impending global challenge that poses significant threats to our planet's ecosystems, human societies, and overall well-being. Extended variations in temperature and meteorological patterns are referred to as climate change (UN). As demonstrated by the abundance of evidence from 2023, climate change is real, and it is primarily due to human activity (Shephali, 2024). The Intergovernmental Panel on Climate Change's report estimates that the global average temperature will be 1.5 to 2.0 °C higher than it was in the late 1800s by the end of this century (Field & Barros, 2014). Extreme weather events, such as heat, cold, droughts, and floods, pose the greatest threats to crop production worldwide (Loreti *et al*., 2016). Climate and agriculture are interconnected phenomena, climate change creates unpredicted weather patterns that pose a risk to agriculture by threatening global food production and security (Reddy, 2015). This change in the agricultural sector can have a detrimental impact on the overall resilience of the agricultural system, create food security risks, and result in unstable incomes for farmers (Urruty *et al*., 2016). The lack of affordable and high-quality seeds for farmers has an impact on agricultural productivity as well (V. K. Singh *et al*., 2020a). Agriculture in fragile areas faces biotic and abiotic stresses (Devika *et al*., 2021a). Drought, salinity, temperature, and heavy metals affect seedling germination and emergence and are responsible for 50% of the yield reduction (Varshney & Tuberosa, 2013). Insect pests and diseases are becoming more frequent as a result of various climatic factors (Skendžić *et al*., 2021). Different management research techniques are being developed to reduce losses and increase production (Li *et al*., 2019). Various approaches are being used to increase agricultural productivity and stress tolerance. Among them, seed priming enhances the germination and growth of crops. Many farmers are unfamiliar with seed priming, which improves crop production and seedling growth (Devika *et al*., 2021b). It is a technique that changes seeds without triggering their germination action, enabling growth conditions (Choudhary *et al*., 2008). This will improve the seed performance. It has been realized that priming interferes with the seed's water content, cell cycle innovation, electron microscope features, oxidative stress tolerance, and reserve mobilization (Raj & Raj, 2019).

Seed priming refers to a pre-sowing treatment that leads to a physiological state that facilitates the seed to germinate more efficiently (Lutts *et al*., 2016). Numerous countries, such as Pakistan, China, and Australia, have adopted the seed priming approach, and thousands of studies have been carried out to determine the way priming works in all kinds of crops (Nawaz *et al*., 2013). It is a vital tool in sustainable agriculture since it improves germination, increases the amount of nutrients in food and seeds, promotes plant growth, increases yield, requires less fertilizer, and gives tolerance to biotic and abiotic stress (Thapa *et al*., 2020). Priming has also been shown to be beneficial for a variety of field crops, including wheat, sugar beet, maize, soybeans, and sunflower (Arif *et al*., 2008). The seeds are first soaked in a treatment solution to gradually absorb water, and then they are dried to return the enlarged seeds to their original state. Throughout this phase, the seeds go through several physiological and biochemical modifications. This technology uses biological, chemical, or physical treatments to improve the quality of the seed (Fu *et al*., 2024). Various techniques of seed priming include water (hydro-priming), inorganic salts (halo-priming), organic solutions (osmo-priming), temperature treatments (thermo-priming), solid materials (solid matrix priming), and biological compounds (bio-priming) (Ashraf & Foolad, 2005). These techniques involve pre-hydration and activating early germination in seeds. However, the effectiveness of the method depends on the specific plant species being treated and the priming techniques chosen (Marthandan *et al*., 2020a).

Seed priming is a profitable approach in sustainable farming, helping crops succeed with minimum pesticides, and aiding in improving their development and tolerance (Thakur *et al*., 2019). Primed seeds are more adaptable to different abiotic and biotic stress than unprimed seeds (Nazir *et al*., 2014). Temperature is a major limiting factor in plant growth. Studies on various crops have shown that seed priming effectively improves germination and early seedling growth. Seed priming also helps crops develop resistance to both biotic and abiotic stresses (Dashtmian & Hosseini, 2014). Seed priming helps seeds emerge faster than untreated seeds, which typically take longer to sprout (Hussian *et al*., 2013). Seeds that have been primed have more growth potential and produce greater yields, whereas unprimed seeds have less growth potential and yield less (Shah *et al*., 2013). Primed seeds are more adaptable to a variety of biotic (from living organisms) and abiotic (from non-living elements) stress conditions than non-primed seeds (Nazir *et al*., 2014). Primed seeds are more disease- and pest-resistant than non-primed seeds (Shah *et al*., 2013; Ullah *et al*., 2019). Research investigating whether seed priming can improve stress tolerance and decrease physiological, biochemical, and cellular effects is necessary due to the impact of environmental uncertainty on crop growth. Currently, there are few studies on the molecular expression of seed priming, and there is insufficient evidence to help us understand the molecular mechanisms behind priming responses in various crop species. This creates a huge gap in discharging the priming technique for commercial utilization (Marthandan *et al*., 2020a).

This review focuses on seed priming as a strategy to ensure constant agricultural production under climatic variability. It addresses gaps in current research and proposes future directions for optimizing seed priming for different crops and environments. This study examines many seed priming techniques to determine their effectiveness in increasing agricultural productivity in various climates.

METHODOLOGY

This review was conducted by consulting many articles and reports regarding seed priming and its applications in agricultural climatic variation management. To be more precise, the data was organized, and its key features were described. The findings are displayed as text and tables under the various headings that denote the study's conclusion.

TYPES OF SEED PRIMING

Seed priming is done in various ways that have been developed to provide the seeds with vitality, enhance germination, and reduce environmental stress. Following are the various priming methods, which have been explained below:

Halo priming: Halopriming is the process of treating the seeds with a salty solution, which helps enhance germination and establishment in the early stages (Mondal & Bose, 2019). Halopriming treatments, particularly with 4000 ppm NaCl, improved the seedling vigor, grain yield, and water use efficiency (WUE) of the maize under water deficit and hence proved that this eco-friendly technique could alleviate drought stress in sensitive crops El-Sanatawy *et al*., 2021). Potassium nitrate (KNO_3) and potassium dihydrogen phosphate (KH_2PO_4) are effective treatments for promoting seed germination and vigor, especially for those with low initial vigor, providing approaches for increasing plant stand establishment and performance (Batool *et al*., 2015). Pre-sowing treatment of tomato seeds in potassium nitrate (KNO_3) solution increases germination percentage and boosts the physiological response. This technique is a prominent tool that provides vital drifts for enhancing seed priming procedures in agricultural practices (Nawaz *et al*., 2011).

Biopriming: Biopriming is the process in which seeds are inoculated with beneficial microorganisms to be able to survive under various environmental conditions. This process may use plant growth-promoting rhizobacteria (PGPR) (Mitra *et al*., 2021). Using beneficial microorganisms in biopriming improves plants' natural defenses against pests and other stresses. Biopriming emerges as an alternative synthetic chemical for all crops worldwide, which aids in coping with various stressors (Fiodor *et al.*, 2023). Biopriming promotes agricultural production and stress tolerance by successfully introducing beneficial bacteria to seeds, consequently improving seed germination, stand establishment, harvest quality, and yield across multiple crops (Mahmood *et al.*, 2016). Seed biopriming is a better method among priming strategies, providing not only improved seed germination and vigor but also effective biotic stress management. This eco-friendly method uses a variety of beneficial microbial organisms to solubilize nutrients (Deshmukh *et al.*, 2020).

Osmopriming: Osmopriming is a seed treatment procedure where seeds are immersed in special solutions to help them start germinating without causing them to sprout yet (Lei *et al.*, 2021). Soaking caraway seeds in polyethylene glycol (PEG) through osmopriming greatly enhances their germination and early growth, suggesting the potential for higher crop results (Mirmazloum *et al.*, 2020). Soaking rice seeds in a mixture of calcium chloride can considerably boost their germination across different rice varieties (Islam *et al.*, 2012).

Chemical priming: Chemical priming is the process of treating plants with chemicals to improve their ability to tolerate environmental stress. This process enables plants to develop natural defenses, both physically and at the molecular level (Sako *et al.*, 2020). Salicylic acid (50 ppm) seed priming increased wheat's resistance to water stress both before and after emergence because of increased seed germination, improved tissue water status, root-shoot ratio, MSI, and chlorophyll levels, all of which improved yield qualities (Razzaq *et al.*, 2013). Treating maize seeds with urea and KNO3 before sowing boosts their germination and growth, even when facing drought or salty conditions. This strategy shows potential for helping maize plants endure stress better (Mondal & Bose, 2014). Treating capsicum seeds with chemicals boosts their germination and helps seedlings survive and grow better in salty or cold environments. This strategy is inexpensive and eco-friendly, encouraging plants to handle stress more successfully (Yadav *et al.*, 2011).

Solid matrix priming: Solid matrix priming is a procedure where seeds are mixed with solid material and water in specified proportions. This helps seeds absorb water to the correct level for germination without starting to sprout (Taylor *et al.*, 1988). SMP improves low-quality cabbage seed emergence and germination, guaranteeing strong transplants and viable seed storage (Ermiş *et al.*, 2016). SMP improves the germination and emergence of okra, especially at low temperatures. When mixed with *Trichoderma viride*, SMP considerably improves field emergence and marketable pod yield, demonstrating its potential for increasing production under difficult conditions (Pandita *et al.*, 2010).

Hydro-priming: Hydropriming is a technique in which seeds are immersed in water to initiate germination without sprouting and then dried to their original weight. This helps plants cope with environmental stress by stimulating their metabolic mechanisms (Nakao *et al.*, 2018). Pre-sowing hydropriming, especially for 48 hours, exhibits significant effectiveness in enhancing bitter gourd germination and seedling growth, offering a promising approach to improving crop establishment and yield (Adhikari *et al.*, 2021). Hydro-priming exhibits potential for enhancing seed parameters in grain sorghum, particularly improving germination percentage and speed at suboptimal temperatures, although longer treatment durations may not yield additional benefits (Moradi & Younesi, 2009). Hydro-priming for 7 and 14 hours improved field performance in pinto bean cultivars, increasing seedling establishment, ground cover, plant biomass, and grain yield per unit area. Ground cover was shown to be an accurate predictor of production potential Ghassemi-Golezani *et al.*, 2010).

Hormonal priming: Hormonal priming involves applying hormones such as ascorbic acid, salicylic acid, gibberellic acid, and abscisic acid to plant seeds to promote germination and seedling growth (Afzal *et al.*, 2005; Kumari *et al.*, 2017). Plant growth is stimulated by phytohormones. Seed priming improves metabolic processes before germination, which increases crop production under biotic and abiotic stress (Rhaman *et al.*, 2020). Ascorbic acid and salicylic acid are examples of phytohormones that promote wheat development in saline environments, underscoring their critical function in plant salt tolerance (Afzal *et al.*, 2006).

IMPACT OF SEED PRIMING IN AGRICULTURE

Seed priming, including both traditional and innovative priming methods, stands out as an essential method for boosting plant resilience against environmental stresses, leading to uniform stand establishment, increased yield potential, and decreased environmental impact (Jisha *et al.*, 2013; Marthandan *et al.*, 2020b; Rajendra Prasad *et al.*, 2016). Seed priming, a widely used method for increasing seed vigor and stress tolerance, provides significant agricultural advantages. A variety of priming methods, improved procedures, and integrative methods are influencing the path of crop cultivation and seed preservation (Paparella *et al.*, 2015). Impact of seed priming on agriculture.

Improvement in germination

Seed priming is a popular strategy for enhancing seed germination and seedling growth in various crop species, leading to better crop establishment and agricultural productivity (Hosseini & Koocheki, 2007). Seed germination and seedling vigor are greatly increased when seeds are treated with 60% concentration solutions of *Trichoderma viride* or *Pseudomonas fluorescens* for three hours or twelve hours, respectively (Ananthi *et al.*, 2014). According to Armin *et al.* (2010), watermelon seed priming improved emergence, emergence rate, and plumule length, with KNO_3 producing the best results when compared to an alternative priming medium. Hydro-priming boosts vigor, synchronization, and germination speed. Hydro-priming boosts vigor, synchronization, and germination speed. Hydro-priming for 8 to 24 hours has the potential to improve faba bean production methods by promoting seedling emergence and productivity, especially in situations where soil moisture is scarce (Damalas *et al*., 2019).

Increased crop resilience

Chemical priming prepares plants to quickly activate their defenses under stress, helping them survive better than untreated plants (Sako *et al*., 2020). The protective properties of priming agents have made them a potential technique in current disease management, preventing plants from infections and abiotic stresses while not influencing performance (Beckers & Conrath, 2007). Biopriming and hormonal priming are the most successful approaches, with signaling molecules like salicylic acid (SA) and jasmonic acids (JA) playing essential roles in disease tolerance mechanisms. Compounds like β-aminobutyric acid and azelaic acid may influence defense-related gene expressions (Mustafa *et al*., 2019). Seed priming techniques offer a promising alternative to chemical pesticides. Hydro-priming, bio-priming, and other seed priming techniques are showing efficiency against a range of plant diseases, including collar rot, yellow mosaic virus, and downy mildew, while also increasing crop resilience against pathogens such as *Alternaria spp.* (Mondal & Bose, 2014).

Reduced input requirements

Seed-priming with *Trichoderma viride* stimulates phosphorus uptake in soybeans, leading to increased soil phosphatase activity, dehydrogenase activity, and fungal colony-forming units, resulting in a 20% reduction in the recommended phosphorus fertilizer dose (Paul & Rakshit, 2021). Bio-priming helps to meet many current production system objectives by utilizing helpful microorganisms in an environmentally acceptable manner. However, it also plays a vital role in enhancing crop nutrient usage efficiency (Sarkar *et al*., 2021). Seed priming methods, especially hydropriming and hormonal priming, show a significant ability to enhance soybean tolerance to water deficit stress, thereby improving germination, biochemical profiles, and yield parameters across a range of moisture regimes (Langeroodi & Noora, 2017).

Enhancement in crop yield

Seed priming significantly increased grain yield in soybeans, with primed seed plots outperforming non-primed plots, likely due to early and improved emergence in the priming treatments (Agawane & Parhe, 2015). Seed priming with micronutrients has great potential to improve crop yield by promoting growth, development, and grain yield (Mondal & Bose, 2019). Seed priming with neem leaf extract enhanced lentil growth and yield, greatly improving seed yield per plant and yield per hectare (Bhateshwar *et al*., 2020). The establishment, yield, and quality of hybrid sunflower seedlings were greatly impacted by seed priming methods; hydropriming and osmopriming with NaCl yielded better outcomes in terms of emergence time, plant population, achene yield, and protein content (Hussain *et al*., 2006). In a variety of crops, including tomato, okra, onion, watermelon, chili, sponge gourd, and ridge gourd, seed priming methods increase seed vigor and seedling growth, increasing yield and nursery quality (Maiti *et al*., 2011). Seed priming with silver nanoparticles (AgNPs) considerably improves seed germination, growth, and yield in watermelon, with AgNP-treated Riverside and Maxima watermelons at Snook yielding 31.6% and 35.6% respectively, as compared to the control (Acharya *et al*., 2020). Rahangdale *et al.* (2022) reported that a combination of 50% poultry manure, 50% vermicompost, and priming with water demonstrated superior growth, yield, and quality parameters in black wheat, highlighting its effectiveness in enhancing crop performance. Wheat priming with plant growth-promoting rhizobacteria (PGPR) colonies produced a significant rise in grain yield, with up to a 53% increase above control in silt loam soil, compared to a 31% increase in sandy loam soil (Akbar *et al*., 2019).

Enhanced food security

It is also necessary to increase global population needs and crop productivity. Plants face various biotic and abiotic stresses, but defense priming poses an eco-friendly solution. By exposing plants to mild stress, seed priming enhances their resilience, making them more responsive to stress. This sustainable practice supports long-term global food security (Tiwari & Singh, 2021). Drought poses a significant challenge for farming in arid and semi-arid regions, which leads to lower seed germination, plant development, and overall production. Furthermore, changes in global climate and current agricultural techniques increase crop production declines. Seed priming is a low-cost and practical approach for increasing drought stress resilience by promoting rapid and advanced seed germination. This mechanism activates the cellular defense system, shortens imbibition time, enhances germination promoters, and regulates osmotic processes (Marthandan *et al*., 2020b).

Impact on soil health

Akbar *et al.* (2019) discovered that applying plant growth-promoting rhizobacteria (PGPR) had significant effects on soil parameters, with silt loam soil experiencing a 205% increase in organic matter compared to sandy loam soil, which increased by 110%. When seeds are primed with gypsum and FYM, soil phosphorus and potassium content increase as soil pH and gypsum requirements decrease (Shah *et al*., 2013).

ROLE OF SEED PRIMING FOR ABIOTIC TOLERANCE

Crop productivity and growth are severely hampered by unfavorable environmental factors and extreme abiotic stressors such as salt, drought, hot or low temperatures, and heavy metal stress (Ullah *et al*., 2019). Plants grown from primed seeds show strong and quick cellular defense responses. The priming process involves a variety of metabolic processes for strengthened protection and enhanced resistance through a dynamic interplay across many pathways (Jisha *et al*., 2013). Seed priming increases stress tolerance by triggering signaling pathways at the molecular, cellular, and biochemical levels. Priming repairs seed damage alters DNA processes, and influences the early stages of germination. It also leads to increased gene activation and reserves food mobilization for better germination and seedling growth (Lal *et al.*, 2018). Crop stress tolerance is enhanced by seed priming. Primed seeds show improved resistance to environmental challenges such as salt, temperature swings, and drought by turning on stress-responsive genes and metabolic pathways.

Drought tolerance

Hydro and osmopriming treatments caused better germination than the control variant under salinity and drought stress (Moghanibashi *et al.*, 2013). Drought-tolerant strains of Trichoderma harzianum enhance drought resistance in wheat by regulating osmotic balance and activating protective physiological mechanisms (Shukla *et al.*, 2015). Osmopriming increased the beneficial responses in plants by significantly reducing lipid peroxidation and boosting drought tolerance (Garcia *et al.*, 2021). The hydropriming treatment maintained lower amounts of malondialdehyde (MDA) and enhanced the enzymatic activity of starch catabolic enzymes, such as α-amylase, improving the breakdown of stored carbohydrates (Antoniou *et al.*, 2016). Furthermore, MDA is thought to be a biomarker of oxidative damage it is generated during the process of lipid peroxidation (Min *et al.*, 2017).

Flooding tolerance

Hydropriming significantly increases the emergence and seedling growth of rice in flooded soils (Garcia *et al.*, 2021). Sarkar (2012) reported that seed priming with water and 2% Jamun (*Syzygium cumini*) leaf extract significantly improves flood tolerance in rice by improving seedling establishment and accelerating growth, as shown by the superior performance of the submergence-tolerant Swarna-Sub1 over the prone Swarna in early flooding conditions.

Salinity tolerance

Soil salinity is another negative factor that causes crop plant losses, particularly in dry and semiarid locations (Tabassum *et al.*, 2018). Salinity stress conditions increase osmotic pressure, ion uptake imbalances, and oxidative stress in sorghum, alter early growth stages, and decrease crop production (Saadat & Homaee, 2015). Under salt stress (150 mmol NaCl solution), a study assessed the germination indices and seedling enhancement of sorghum treated with nanoiron oxide (n-Fe2O3). Through physiological changes, such as photosynthetic rate, chlorophyll index, photosystem II efficiency, and relative water content, to reduce membrane damage, the results showed high salt tolerance in plants treated with nano priming (Maswada *et al.*, 2018). Priming pigeon pea seeds with KNO_3 or $CaCl_2$ enhanced their soluble sugars, proteins, and free amino acids under salinity stress (Verma & Srivastava, 1998). Numerous crops, including tomato (*Solanum lycopersicum* L.) (Pradhan *et al.*, 2014), hot pepper (*Capsicum annuum* var. *acuminatum* L.) (Khan *et al.*, 2009), lettuce (*Lactuca sativa* L.) (Nasri *et al.*, 2011), maize (*Zea mays* L.) (Abraha & Yohannes, 2013), okra (*Abelmoschus esculentus* L.) (Ben Dkhil *et al.*, 2014), and pea (*Pisum sativum* L.) (Naz *et al.*, 2014), have shown a positive effect on salinity stress.

Temperature tolerance

Temperature stress reduces crop yield and affects the security of world food supplies (Bita & Gerats, 2013; Sun *et al.*, 2019). Despite the induction of stress-response proteins and the alteration of metabolic homeostasis, heat priming confers a large degree of thermotolerance, enabling plants to survive subsequent thermal shocks (Hilker *et al.*, 2016; Ibrahim, 2016). Chilling conditions during germination and plant development cause reductions in carbohydrates, lipids, and proteins, resulting in cell damage, and osmopriming treatment in seeds increases the cold tolerance of wheat plants (30 mM NaCl) (Garcia *et al.*, 2021). It has been established that heat priming can successfully increase a variety of plant species' capacity to withstand later recurrent heat stress (Wang *et al.*, 2014). Heat shock proteins (HSPs) have been linked to the development of thermotolerance (Xue *et al.*, 2014). HSPs were reported to be highly increased by heat priming used during seed germination or the vegetative stage, therefore decreasing heat stress during grain filling in wheat (Wang *et al.*, 2014; Zhang *et al.*, 2016). Cold priming has been shown to successfully increase plant resistance to low-temperature stress (Thomashow, 1999). Table 1 demonstrates that seed priming assists crop establishment despite various stresses, including drought, salinity, heat, cold, and heavy metal phytotoxic stress. This shows how seed priming enhances germination, growth, yield, and stress tolerance in many horticultural crops.

ROLE OF SEED PRIMING IN BIOTIC STRESS TOLERANCE

Seed priming helps protect against biotic stressors like fungi and harmful bacteria (Paul *et al.*, 2022). Seed priming has several benefits, such as early emergence, high water usage efficiency, better stand establishment, deeper root growth, and germination at a wide range of temperatures. These benefits help escape greater tolerance to stresses and biotic stress Mustafa *et al.*, 2017).

Systemic acquired resistance

A process of induced defense known as systemic acquired resistance (SAR) provides lasting protection against a wide range of microbes (Durrant & Dong, 2004). Various kinds of non-pathogenic growth-promoting rhizosphere bacteria can colonize plant roots and provide broad-spectrum disease resistance in plants. This type of IR has created systemic resistance (Van Loon *et al.*, 1998). The endophytic basidiomycete *Piriformospora indica* provides systemic resistance against fungal infections and salt stress when it forms a symbiotic relationship with barley roots (Waller *et al.*, 2005). Plants' ability to' recall' antimicrobial defenses is often linked to systemic resistance. Plants that have been infected, colonized, or treated with chemicals are more likely to respond quickly and efficiently to biotic or abiotic stress (Goellner & Conrath, 2008).

Table 1. Impact of seed priming on abiotic stress condition on crop performance.

Abiotic stress	Crop	Observed effects	References
Drought	Wheat (*Triticum aestivum L.)*	Increased osmolytes (13–45%), better growth (5–63%), and less cell damage (3%). With CaCl2 solution improving yield (14–79%), osmolytes (6-48%), hydration (2-47%), and leaf area (9–43%), seed priming improved drought performance.	Tabassum *et al.* (2018)
Salinity	Maize (*Zea mays L.)*	Priming with CaCl2·2H2O improves germination and increases the fresh and dry weight of plumules and radicles. Increased levels of Na+, K+, Ca2+, and Cl−.Most of the Ca2+ was retained in seeds and mesocotyl.	Ashraf & Rauf (2001)
Heat	Garden Pea (*Pisum sativum L.*)	H2O, CaCl2, and salicylic acid priming enhance germination, seedling development, and physiological characteristics. Osmopriming and (hormo priming were the most successful methods.	Tamindžić *et al.* 2023)
Cold	Jatropha (*Jatropha curcas* L.)	Priming with various substances improves cold resistance by raising germination percentage and accelerating leaf emergence. Reduced leaf senescence, higher relative water content (62.0-66.3% vs. 47.8%), and less membrane damage (37.6-49.4% vs. 72.4%).	Yadav *et al.* (2012)
Heavy metal	*Trifolium repens L.*	priming of seeds higher and quicker germination rates when zinc and cadmium are present. improved emergence and development of seedlings in contaminated soil. While polyethylene glycol priming reduced Cd uptake, gibberellic acid priming boosted it. also priming enhanced antioxidant response and photosynthesis during stress.	Galhaut *et al.* (2014)
Heavy metal	Wide range of crops	Metal stress can be minimized by a variety of priming approaches, including hydropriming, chemo priming, osmopriming, redox priming, nutri priming, hormo priming, and biopriming. Increased seedling emergence and vigor. Increased yield and germination on soil harmed by metals.	Saboor *et al.* (2019)

Disease resistance

Seed priming improves plant disease resistance by stimulating pre-germinative metabolic activity and activating defense mechanisms against diseases such as fungi, bacteria, viruses, and nematodes, making it an environmentally acceptable alternative to chemical pesticides. For example, hydro-priming has been proven to minimize collar rot in chickpeas, yellow mosaic virus in mung bean, and downy mildew in pearl millet when bio-priming with Trichoderma harzianum efficiently suppresses cowpea root rot pathogens (Mondal & Bose, 2014). Hormonal priming helps control reactive oxygen species (ROS) generated during disease by inducing the production of genes associated with defense. Enzymes that play key roles in this defense mechanism are peroxidase, superoxide dismutase, and phenylalanine ammonia-lyase (Mustafa *et al.*, 2019).

Weed control

Seed priming with indole acetic acid (IAA) or salicylic acid (SA) can significantly reduce the oxidative stress induced by *Orobanche ramosa* infection in tomato plants. Seed priming not only promotes tomato shoot and root growth under both healthy and infected conditions, but it also greatly lowers 0robanche-induced oxidative damage. This protective effect is related to elevated antioxidant defense indicators, like metabolites and enzymes, in infected tomato seedlings (Madany *et al.*, 2020). The incorporation of plant hormones like gibberellic acid (GA_3) and abscisic acid (ABA) in weed control measures provides new possibilities. GA_3 can promote consistent weed seed germination, increasing the effectiveness of PRE herbicides. While ABA may induce weed seed dormancy, decreasing selection pressure and weed infestations until crop canopy closure (Oliveira *et al.*, 2020).

Induced cross tolerance

Induced cross-tolerance refers to the activation of systemic plant tolerance after exposure to another type of stress. The severity and duration of the main stress can impact tolerance for subsequent stress (Feder & Krebs, 1998). It is possible to have cross-tolerance for biotic stress. For example, NH4+ nutrition may result in the NH4+ syndrome, which shows leaf chlorosis and changes in metabolite levels. On the other hand, when NH_4^+ is the only nitrogen source available, it can protect tomatoes from *Pseudomonas syringae* and lessen the impacts of high salinity on plants like citrus and barley. Changes in hormones, polyamines, and antioxidant enzymes are involved in this resistance, demonstrating the interdependence of plant responses to many stresses (Llorens *et al.*, 2020).

Nematode tolerance

Seed priming has shown potential for increasing plant tolerance to nematode infestations such as Meloidogyne incognita, a pathogen that causes severe production losses. Recent research on bread wheat has shown that seed priming with neem leaf extract is the most effective treatment. According to Arshad *et al.* (2022), laboratory studies demonstrated that neem reduced egg hatching by 30% while increasing juvenile mortality by 72%. Pot studies showed that neem-treated plants had significantly fewer galls, females, eggs, and juveniles (24.01%, 21.16%, 21.21%, and 21.30%, respectively). El-Shafey & Elamawi (2010) reported that seed priming treatments including different salts and sulfur greatly enhanced the mortality rate of white-tip nematodes when compared to typical soaking procedures. The treatments with $NaCO_3$ + NaCl, sulfur 5g, $NaCO_3$, and sulfur + $MgSO_4$ had the highest mortality rates compared to the nematicide Mocap. Furthermore, seed priming treatments resulted in varying amounts of nematode infection, with $NaCO_3$, $NaCO_3$ + NaCl, and sulfur + $MgSO_4$ priming reporting the lowest infection rates. Therefore, there is a close link between nematode mortality, infection rates, and treatment success, indicating seed priming as a feasible strategy for regulating white tip nematode infestation in rice agriculture.

BIO PRIMING: A SUSTAINABLE APPROACH TO COMBAT CLIMATE CHANGE

Bio-priming is an innovative seed treatment technique that uses biological inoculation with beneficial microbes and physical seed hydration to improve disease management against seed- and soil-borne diseases. This ecological technique, which employs specific fungal antagonists, offers a sustainable and effective alternative to conventional chemical treatment (Reddy, 2012). Climate change threatens global agriculture by increasing environmental stress and decreasing crop growth and production. On-farm seed priming, particularly biopriming with beneficial bacteria such as Trichoderma, Pseudomonas, and Bacillus, increases crop resilience and yield. This sustainable strategy eliminates the need for chemical inputs, which helps to mitigate the harmful effects of climate change on agriculture (Rakshit, 2019).

Mechanism of biopriming

Biopriming improves seed performance through several processes, helping to boost crop resilience. Furthermore, it mitigates the impact of climate change by encouraging sustainable agriculture methods and reducing dependency on chemical inputs.

Enhanced germination and seedling vigor

Bio-priming enhances plant growth and productivity, especially in dry circumstances. It improves the plant's ability to fight stress by improving antioxidant defenses, nutrient absorption, and water balance, leading to better resilience and yield (Nawaz *et al.*, 2021). Priming seeds with *Pseudomonas fluorescens* or *Trichoderma viride* enhances germination rates, seedling vigor, and overall growth compared to untreated seeds. These bacteria boost nutrient absorption, hormone control, and plant defense mechanisms, encouraging strong seedling establishment and growth (Ananthi *et al.*, 2014).

Improved nutrient uptake

Seed biopriming increases nutrient uptake, which improves plant growth, productivity, and resilience to stress. It improves the utilization of essential nutrients such as nitrogen and zinc, making it an effective method for sustainable agriculture (Sarkar *et al.*, 2021). Treating rice seeds with *Azospirillum amazonense* considerably increases their ability to absorb and use nitrogen, improving nitrogen absorption by 3.5–18.5%. This leads to healthier plants with better growth and higher yields (Rodrigues *et al.*, 2008). Priming maize seeds with *Trichoderma harzianum* improves nitrogen use, increasing nitrogen content in roots by 8.8–9.76% and in shoots by 3.5%. This allows plants to grow stronger and better tolerate stress (Akladious & Abbas, 2012).

Stress hormone regulation

Adding Rhizobacteria to seeds before planting them helps plants grow and handle stress better by increasing phytohormones like auxins and gibberellic acid and lowering stress hormone ethylene levels through aminocyclopropane-1-carboxylate deaminase (Chakraborti *et al.*, 2022). Bio-priming with *Bacillus pumilus*, *Bacillus licheniformis*, and *Bacillus coagulans* improves crop stress tolerance by increasing antioxidant enzyme activity and modulating microRNA expression, successfully decreasing the effects of salt stress on maize (Aydinoglu *et al.*, 2023).

Induced systemic resistance

Seed biopriming enhances systemic resistance by activating resistance marker genes related to salicylic acid, ethylene, and jasmonic acid pathways. This stimulates the production of phytohormones and secondary metabolites, boosting the plant's immune response. Biopriming with *Trichoderma spp*. also increases proteins like mitogen-activated protein kinase, amplifying signals for a quicker and stronger defense (Mitra *et al.*, 2021). Singh *et al.* (2020) found that seed bio-priming with *Pseudomonas aeruginosa* strain MF-30 induced systemic resistance in maize by increasing the expression of defense-related genes (PR-1 and PR-10), increasing the activity of antioxidative defense enzymes, and significantly reducing disease severity and lesion length caused by *Rhizoctonia solani*.

Climate change mitigation and sustainability benefits

Biopriming contributes substantially to climate change mitigation and sustainability by increasing plant tolerance to climatic shocks, lowering chemical input requirements, and improving soil health through beneficial microbes (Singh *et al.*, 2023). This leads to improved nutrient uptake, more efficient water use, higher agricultural yields, and lower greenhouse gas emissions.

Reduction in chemical use

Biopriming, the process of inoculating seeds with beneficial microbes and hydrating them, has emerged as a viable alternative to chemical disease treatments, lowering reliance on hazardous chemicals and encouraging sustainable agriculture (Bisen *et al.*, 2015). Priming seeds with beneficial microorganisms like *Trichoderma viride* enhances nutrient uptake, lowering chemical fertilizer needs, and enhancing baby corn growth and resistance (Yadav *et al.*, 2018). Treating seeds with beneficial microorganisms enhances agricultural yield by 12–20% while lowering the need for artificial fertilizers (Pérez-Jaramillo *et al.*, 2016).

Improved soil health

Bio-priming with cyanobacteria improves soil health by increasing organic carbon, nitrogen, and microbial activity critical to soil function. In *Grevillea wickhamii*, seedling root length increased by 57%, and in *Tephrosia wiseana*, shoot lengths grew by 54% compared to untreated plants, indicating significant improvements in both soil and plant growth (Chua *et al*., 2020). Plant growth-promoting fungi (PGPFs) improve crop yield, soil health, and plant stress resistance via biofortification and biopriming (Geetha *et al*., 2023). Bioagents like Trichoderma spp. and Pseudomonas fluorescens improve soil health by suppressing plant diseases and controlling diverse stresses, encouraging eco-friendly and sustainable agriculture practices (Pandey, 2017).

Resilience to climate extremes

Biopriming allows agricultural systems to better withstand the negative effects of climate change by guaranteeing continuous stand establishment in stressed conditions. Biopriming is an excellent strategy for alleviating biotic and abiotic pressures while also contributing to long-term crop production in the face of uncertain climate shifts (Singh *et al.*, 2020b). Bio-priming improves crop resilience to climatic extremes by increasing nutrient and water efficiency and reducing the need for chemical fertilizers and pesticides. It stimulates strong root growth, supports yields in dry situations, and fosters sustainable agriculture (Rakshit, 2019).

Sustainable resource use

Biopriming is a sustainable method that promotes plant growth and nutrient efficiency, significantly increasing drought resilience and minimizing fertilizer-related pollution. Biopriming wheat seeds with *Trichoderma harzianum* improves nitrogen utilization. This strategy helps sustainable agriculture by tackling resource scarcity and climate change, ultimately enhancing crop yields and resilience (Devika *et al.*, 2021b). Biopriming promotes resource sustainability by increasing nutrient uptake, reducing fertilizer pollution, and improving drought tolerance. This environmentally friendly strategy, which uses vital bioagents such as *Trichoderma* and *Bacillus*, promotes sustainable agriculture, reduces dependency on pesticides, and boosts crop resilience (Rakshit *et al*., 2015).

Supporting biodiversity

Seed biopriming is a sustainable technology that preserves and enhances biodiversity. It enhances nutrient intake, promotes plant growth, and protects against infection, leading to stronger plants that tolerate environmental challenges. Biopriming also enriches soil biodiversity by increasing microbial activity in the root zone. It helps plants establish themselves on degraded land, speeding up regeneration and reconstructing ecosystems, creating resilient environments that maintain ecological balance (Sarkar & Rakshit, n.d.). Table 2 shows how biopriming can enhance the resistance of crops to some diseases. The following table shows how biopriming can enhance the resistance of crops to some diseases. It shows that various forms of biopriming agents can assist in decreasing disease occurrences and increasing plant health and vigor.

Table 2. Biopriming treatments and developed resistance in different crops. ents and developed resistance in different crops.

Crop	Disease	Biopriming agent	Developed resistance	Reference
Maize (*Zea mays* L.)	Banded Leaf and Sheath Blight (*Rhizoctonia solani*)	*Pseudomonas aeruginosa* MF-30	Protect from *Rhizoctonia solani*, Growth Promotion under Pathogenic Stress Conditions	Singh *et al.* (2020)
Carrot (Daucus carota)	Seed-borne pathogens *Alternaria dauci* and *Alternaria radicina*	*Clonostachys rosea*	Reduced incidence of *A. dauci* and *A. radicina*, improved seedling stand establishment	Jensen *et al.* (2004)
Cowpea (Vigna unguiculata)	Root Rot (Fusarium *solani*, *Macrophomina phaseolina*, and *Rhizoctonia solani*)	*Trichoderma harzianum*	Root rot incidence was reduced by 64.0% and (pre-emergence) and post-emergence root rot incidence decreased by 68.0%, 60.1%, 57.1% after 40 days, and 64.0% (post-emergence) after 60 days.	El-Mohamedy *et al.* (2006)
Rice (Oryza sativa)	Seed, soil, and seedling diseases	*Trichoderma harzianum*, *T. viride*, *T. virens*, *Pseudomonas fluorescens*,	Reduce the incidence of *Rhizoctonia solani*, Pythium seed rot, damping off, and *Helminthosporium oryzae*	Reddy (2012)
Soybean (Glycine max)	Pre and post emergence damping off	*Pseudomonas aeruginosa*	Reduce the incidence of preemergence damping off by 48.6-51.9% and post emergence by 65-97.25%.	Begum *et al.* (2010)
Coconut (*Cocus nucifera*)	Coconut leaf rot	*Bacillus subtilis*, *Pseudomonas fluorescens* (solely and mixed), and *Trichoderma viride*	Enhance the growth and produce the resistance against coconut leaf rot disease	Reddy (2012)
Pea	Fusarium solani, Rhizoctonia solani	*T. harzianum*, *B. subtilis* and *P. fluorescens*	Reduction in pre- and post- emergence stages by 72.7–84.5%, 72.2–82.9% and 67.6–80.0% after 15, 45 and 60 days after sowing, respectively	El-Mohamedy *et al.* (2006)

COST-EFFECTIVENESS OF USING PRIMING-BASED SOLUTION

Seed priming is an easy, low-cost method that stimulates several physiological and metabolic processes to improve germination and seedling establishment. It is also economical because it lowers the energy used under stressful conditions (Johnson & Puthur, 2021). It is a risk-avoidant tool for improving plant acclimatization under both biotic and abiotic stresses, as well as ensuring uniform seed germination, rapid emergence, better stand establishment, improved crop growth, and increased pulse and other crop productivity (Bhowmick, 2018). It is also being used in genetically modified crop varieties to improve their performance under stress conditions, such as low phosphorus and submergence, and as a supplementary tactic to grain biofortification (Farooq *et al*., 2019). Osmo-primed wheat seedlings could be planted in rows separated by 22.5 cm to boost output and economic return (Paparella *et al*., 2015). Since primed seeds have better nutrient and water absorption efficiency, seed priming is also utilized to maximize resource consumption. These uses demonstrate seed priming's adaptability as a useful instrument in environmentally friendly farming methods (Ashraf & Foolad, 2005). Nutrient priming has been considered more affordable and convenient than soil application in low fertile soils, which results in lower expenses on synthetic fertilizers (Slaton *et al*., 2001). There may be some more circumstances where priming does not assist farmers, although negative impacts of seed priming are rare (Bhowmick, 2018).

Conclusion

Seed priming is a very efficient and environmentally friendly method of increasing agricultural output and resilience to climate instability. Different priming techniques were evaluated, including hydro-priming, halo-priming, osmo-priming, bio-priming, chemical priming, and hormone priming. The results showed significant increases in crop yields, stress tolerance, and germination rates. These methods decrease the need for chemical inputs and enhance soil health, which supports sustainable agricultural practices. It will be necessary to adapt these priming techniques for future use with diverse crops and environmental circumstances, as well as look into the potential benefits of combining multiple priming techniques. Seed priming can significantly improve food security and agricultural sustainability in response to the effects of climate change.

DECLARATIONS

Author contribution statement

Conceptualization: JSR and PRC.; Methodology: AM.; Software and validation: JSR.,. PRC. and AM; Formal analysis and investigation: JSR.; Resources: JSR; Data curation: JSR.; Writing—original draft preparation: JSR.; Writing—review and editing: JSR.; Visualization: JSR.; Supervision: JSR.; Project administration: JSR.;. All authors have read and agreed to the published version of the manuscript.

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