

BIOPRIMING AND ITS APPLICATION TO AGRICULTURE: A SUSTAINABLE APPROACH TO ENHANCING SEED GERMINATION AND STRESS TOLERANCE

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Abstract

Biopriming is a promising pre-sowing seed treatment in which seeds are partially hydrated in a solution containing beneficial microorganisms and subsequently re-dried to their original moisture content. This technique enhances seed vigor by protecting against soil- and seed-borne pathogens that often compromise germination and yield. Beneficial microbes introduced during biopriming contribute to plant growth through mineral solubilization, nutrient mobilization, and the release of plant growth regulators, thereby improving crop establishment and productivity. Extensive research demonstrates the efficiency of biopriming in enhancing seedling emergence, yield stability, and tolerance to diverse abiotic stresses such as drought, salinity, and temperature extremes. The approach is particularly valuable for smallholder farmers and resource-limited regions due to its low cost, scalability, and adaptability across crop species. By reducing dependence on chemical fertilizers, fungicides, and synthetic seed treatments, biopriming supports sustainable intensification and climate-resilient agriculture. It minimizes re-sowing costs, improves crop performance in marginal soils, and aligns with global strategies for environmentally responsible farming. This chapter provides mechanistic insights, crop-specific applications, and field-based evidence highlighting biopriming's role in sustainable agriculture. Future prospects include integrating biopriming with micronutrient enrichment, bio-stimulants, and precision agriculture frameworks to further enhance productivity and resilience in the face of global climate challenges.

Keywords: Abiotic stress, Biopriming, Seed germination, Seed priming, Seedling vigour, Seed quality

Introduction

The agriculture sector faces unprecedented constraints posed by climate change, soil degradation, and increasing pressure to produce more food for an increasing population and awareness of health, leading in producing quality foods on less arable land with minimal environmental footprint. Abiotic stresses, particularly salinity, drought, temperature extremes, and nutrient imbalances, are responsible for yield reductions exceeding 50% in many crop species, directly threatening food security in vulnerable regions. In this context,

seed-based pre-sowing strategies have emerged as low-cost, scalable interventions to improve germination and early vigour under stress conditions. Different seeds used are named as hydro priming, halo priming, osmopriming, hormonal priming and biopriming.

The mechanistic basis of biopriming is multifaceted. Bio-priming is a treatment of seeds with beneficial microorganisms under controlled hydration, which enhances the preparatory processes before germination without the emergence of the radicle. It improves the seedling vigor, germination percentage, speed of germination, growth and development. Bio-priming agents directly release growth-promoting hormones viz., indole acetic acid, gibberellin, and cytokinin or stimulate their production in the plant. They also improve the availability of minerals viz., nitrogen, phosphorous, potassium, and Iron whereby enhance the plant growth and development. Importantly, primed seeds often exhibit stress tolerance, a physiological state in which transcriptional and metabolic changes persist beyond germination, thereby improving seedling resilience to salinity, drought, or chilling stress. Extensive studies have documented the use of beneficial microorganisms to control the proliferation of the disease during priming. Germination was expressed as a percentage of the ratio of normal seedlings to the sum of normal, abnormal, and unsold seeds, that is, total sown seeds. The reduction of growth under stress conditions is a beneficial state in several species of species, such as rice, barley, maize, and wheat. When compared to unprimed seeds, primed seeds usually appear faster with better, uniform, and vigorous vegetation cover and remain stable even under conditions that do not correspond to optimal fields.

From a sustainability perspective, bio priming aligns with circular bioeconomy principles: waste valorisation, sustainable, resource efficiency and environmental alternatives to synthetic agrochemicals (Ferraz & Pyka, 2023). However, optimization of salt type, concentration, priming duration, and post-priming seed storage conditions remains critical for maximizing benefits while minimizing potential negative effects such as ion toxicity or reduced shelf life of treated seeds. Given the accelerating environmental challenges confronting global agriculture, biopriming presents a scientifically and operationally feasible intervention to support both productivity and climate resilience. This review synthesizes current advancements in the physiological, biochemical, and molecular underpinnings of biopriming, examines crop-specific successes, and identifies research gaps to facilitate its broader adoption as a pillar of sustainable agriculture.

Mechanism of Biopriming

Biopriming is a pre-sowing seed enhancement technique involving treating seeds by combining partial hydration, also called controlled imbibition, with helpful biological agents like plant-growth-promoting bacteria, fungi, or groups of microbes (*Trichoderma*, *Pesudomonas*, *PSB*) and then re-dried before sowing. This treatment triggers an array of pre-germinative metabolic activities without radicle protrusion, enabling seeds to germinate faster and perform better under abiotic stresses such as salinity, drought, and temperature extremes, with resistance to seed and soil-borne diseases. This leads to physiological and molecular changes in the seed that speed up germination and make it more uniform. It also improves seedling health in both good and bad environments.

Furthermore, the overview of different mechanisms of seed biopriming for plant stress tolerance was displayed in **Figure 12.1**.

1. Osmotic Regulation and Controlled Imbibition

A part of biopriming is controlling water absorption through controlled imbibition. This is done by using osmotic agents like PEG or salts with low water potential, or by limiting hydration time and then drying. Controlled hydration allows specific metabolic pathways to start again, like enzymes that fix damage and selective translation, but it stops the radical from pushing through. At the same time, seeds collect osmoprotectants like proline, soluble sugars, and trehalose. They also balance ions inside cells, which helps more germination under osmotic or salinity stress. When helpful microbes are added, their metabolites can also affect osmotic responses. Microbial exopolysaccharides improve water retention near seed surfaces, and microbial signals can increase the host's production of osmoprotectants. Osmotic control with the effect of microbes creates a stable moisture environment and balanced intracellular conditions. This reduces shock from hydration and improves germination in dry or saline conditions.

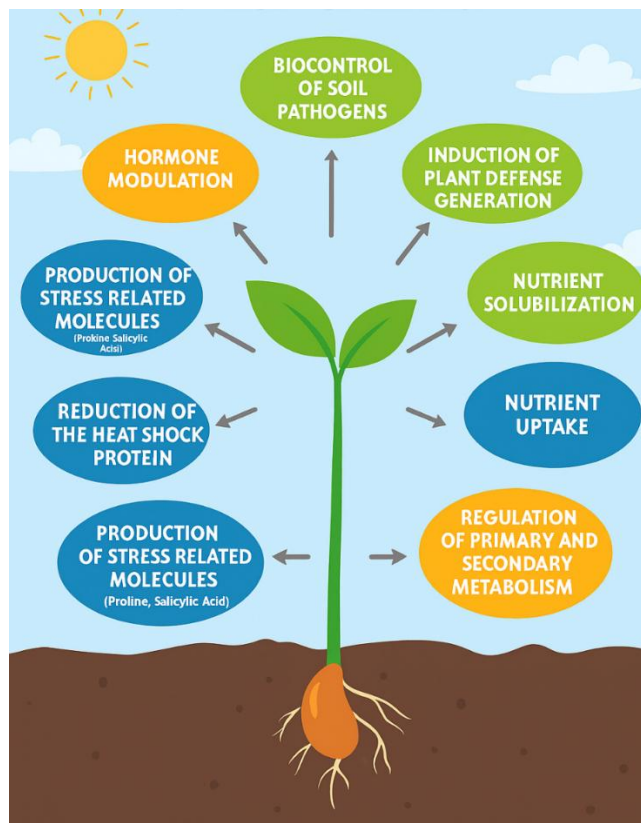


Figure 12.1. Different Mechanisms of Seed Biopriming for Plant Stress Tolerance.

2. Ion Homeostasis and Nutrient Signaling

Biopriming changes the seeds take up and balance ions during germination by (1) pre-activating membrane transporters and ion pumps and (2) adding microbes that change

nutrient availability in the rhizosphere, like phosphate-solubilising bacteria and moving iron through siderophores. Primed seeds often begin to express ion-transporting genes earlier to create the membrane potential needed for nutrient uptake faster to help seedlings keep a balance between K^+ and Na^+ during salinity, and get nutrients stored in the endosperm more easily. Microbial partners make signaling chemicals, like small peptides and organic acids, that start nutrient-signalling pathways in the host. These pathways coordinate energy use and nutrient uptake. The result is better ionic resilience, less toxic Na^+ buildup, better K^+ retention, improved early nutrient uptake, and a stronger start for root growth.

3. Activation of Antioxidant Defence Systems

Biopriming helps in faster antioxidant defenses so seeds and young seedlings can quickly neutralize reactive oxygen species (ROS) that are produced during germination and stress. Partial imbibition increases the levels of antioxidant enzymes like SOD, CAT, APX, and peroxidases, as well as non-enzymatic antioxidants like glutathione and ascorbate. Microbial inoculants can cause systemic expression of antioxidant enzymes through signaling and induce systemic resistance. Studies show that bioprimered seeds and seedlings have higher activities of SOD, CAT, and APX, which help in the reduction of lipid peroxidation and improve membrane integrity under drought, salinity, or pathogen stress (Figure 12.2). This early preparation for ROS cleanup reduces oxidative damage during rapid metabolic activity, helping bioprimered seedlings survive and grow better under oxidative stress.

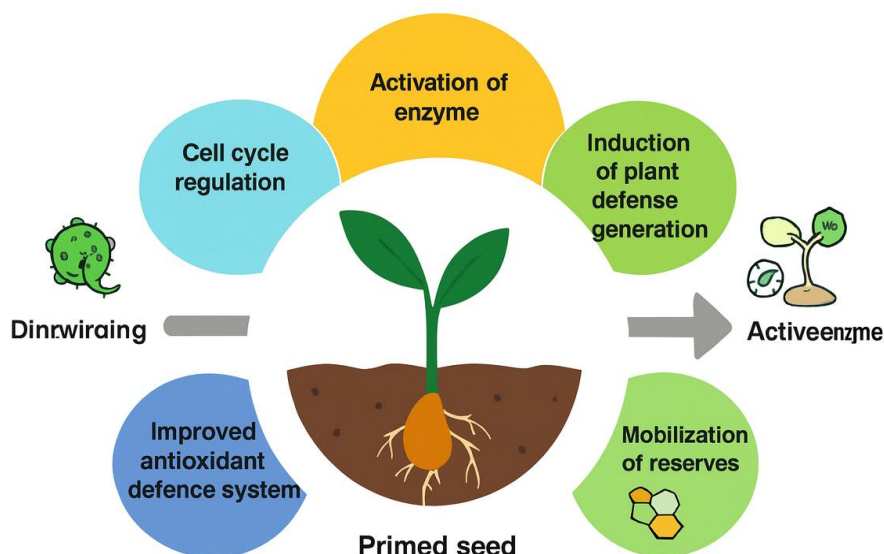


Figure 12.2. Schematic Representation of Seed Biopriming in Activation of the Antioxidant Defense System

4. Hormonal Variation

Biopriming changes the balance and dynamics of important plant hormones that control dormancy, germination, and early growth.

Biopriming often reduce response to abscisic acid (ABA) and increase activity of gibberellins (GA), making it easier for the radicle to come out. Microbes change levels of auxins, cytokinins, ethylene (through ACC deaminase), and brassinosteroids, which support root growth and stress adaptation. Lower ABA/GA ratio speeds up germination, while auxins from microbes encourage root hair growth to improve early nutrient uptake. Studies on hormone treatments and biopriming that involve microbe-induced changes in hormone signaling show long-lasting effects, sometimes lasting multiple seasons, showing that the biopriming can change hormonal sensitivity during early growth and affect long-term plant structure and stress responses.

5. Stress Resistance and Epigenetic Modifications

Besides immediate physiological changes, seed biopriming create a type of stress memory through epigenetic modifications, like DNA methylation and changes in histone structure. These changes affect stress responsive genes expressed during germination and later growth. Research from drought-priming and seed-priming shows specific methylation changes and chromatin marks at genes related to ROS detoxification, osmoprotection, and hormone signaling. These modifications continue into the seedling stage and sometimes across generations, improving the plant's ability to handle recurring stress. The microbial signals from biopriming also interact with the plant's epigenetic system. Microbial elicitors can cause chromatin changes that get defense genes ready for faster activation. So, epigenetic reprogramming connects a onetime priming process with resilience that lasts longer. The conceptual diagram of mechanism of seed biopriming in stress resistance and epigenetic modifications were presented in **Figure 12.3**.

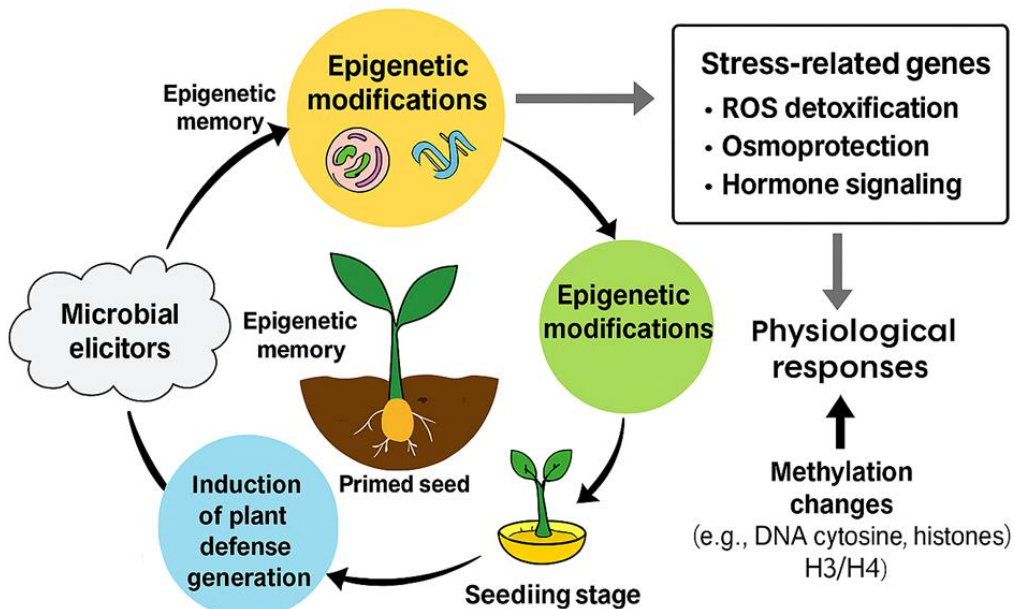


Figure 12.3. Schematic Representation of Seed Biopriming in Stress Resistance and Epigenetic Modifications.

6. Enhanced Metabolic Readiness

Biopriming increases metabolic readiness by restarting respiration, increasing ATP production, and breaking down stored reserves like starch to sugars and storage proteins to amino acids during the controlled imbibition phase. This partial reprogramming prepares enzymatic systems like amylases and proteases, so when germination begins, energy and building processes happen faster and more efficiently, leading to healthy seedlings. Microbial inoculants further increase metabolic activity by giving growth-promoting molecules like vitamins and siderophores and by starting host genes involved in carbohydrate metabolism and energy sensing. This help seedlings quickly set up their own food production and root systems that are needed for continued growth. Measurements often show higher ATP levels, better mitochondrial function, and faster reserve breakdown in bioprimered seeds compared to control seeds.

7. Microbiome Interactions

A main benefit of biopriming compared to abiotic priming is managing the seed microbiome on purpose. Helpful microbes added during biopriming colonize the rhizosphere and the area around the seed, outcompeting pathogens, creating antibiotics and siderophores, dissolving phosphorus, fixing nitrogen, and shaping host immunity through induced systemic resistance. Recent researches show that microbes delivered with seeds can consistently affect the plant's developing microbiome and its interactions with soil. This leads to lasting helpful changes that improve nutrient cycling and disease resistance. Technologies for seed coating and carrier materials like peat, polymers, and biochar are important for delivering viable microbial inoculants and making sure they take hold.

Agricultural Applications

Halopriming is a salt-based seed pre-treatment that enhances crop performance, particularly under challenging environmental conditions. By soaking seeds in carefully selected inorganic salt solutions (e.g., KNO_3 , NaCl , CaCl_2) and then redrying them before sowing, halopriming triggers early metabolic activation, strengthens antioxidant defense systems, and improves nutrient uptake. These physiological adjustments translate into faster germination, better seedling vigor, and greater tolerance to stresses such as salinity, drought, and temperature extremes. As a simple, low-cost, and eco-friendly technique, halopriming holds significant promise for improving crop establishment, yield stability, and sustainability in modern agriculture. The summary of agricultural applications of halopriming was given in **Table 12.1**.

1. Seed Germination and Seedling Development

Bio-priming is a method of introducing microbes to pre-hydrated seeds under controlled conditions. This helps in both germination and seedling development. Microorganisms such as *Trichoderma harzianum*, *Pseudomonas fluorescens*, and *Azospirillum brasilense* colonize the seed, initiate metabolism, and promote uniform germination is used during biopriming and plant growth regulators are also used in biopriming for inducing seedling development.

Biopriming in rice and tomato enhanced the rate of seed germination, length of root and shoot, and vigor due to increased enzyme activity and nutrient availability. Raj et al. (2021) and Singh & Prasad (2020), revealed that tomato seeds treated with *T. harzianum* had better germination and early growth than untreated seeds, which indicates that bio-priming is an effective enhancer (Kumar et al., 2019).

Table 12.1. Effect of biopriming on germination level in crop plants

Crop / Plant	Biopriming Germination level	Mechanistic Insights	Observed Benefits	References
Carrot (<i>Dacus carota sp sativus</i>)	Seed germination between 15.28 and 56.88%.	Seeds soaked in bacterial suspension	80% capable of synthesizing IAA	Fiodor et al. (2023)
Tomato (<i>Solanum lycopersicum</i>)	<i>Enterobacter</i> (P-39, P-41 and P-46)	Osmotolerant plant growth-promoting bacterial strains (genus <i>Enterobacter</i>)	Higher germination percentage and germination rate	Bhatt et al. (2015)
Radish	<i>Agrobacterium rubi</i> , <i>Burkholderia gladii</i> , <i>P. putida</i> , <i>B. subtilis</i> , <i>B. megaterium</i>	Improved seed germination under saline conditions	Increase in seed germination and seedling vigor	Kaymak, et al. (2009)
Kale	142.0% (<i>Bacillus subtilis</i>) 40.0% (<i>Serratia nematodiphila</i>) 7-31 mM NaCl	Bio-priming with <i>Bacillus subtilis</i> and <i>Serratia nematodiphila</i>	The germination percentage was significantly increased by bio-priming	Murunde, & Wainwright (2018)
Onion	42.0% (<i>Bacillus subtilis</i>) 40.0% (<i>Serratia nematodiphila</i>)	Bio-priming with <i>Bacillus subtilis</i> and <i>Serratia nematodiphila</i>	The germination percentage was significantly increased by bio-priming	Murunde, & Wainwright (2018)
Soyabean	Inoculum rate 2×10^9 CFUs/g	Indigenous <i>B. megaterium</i> strains from soil, for seed bio-priming	The highest increase in final germination in cold-treated seeds	Miljaković, et al (2022).
Chilli (<i>Capsicum annuum</i> L.)	<i>T. viride</i> or <i>P. fluorescens</i> at 40, 60, or 80%	Bio-priming with the bio-control agents <i>Trichoderma viride</i> or <i>Pseudomonas fluorescens</i>	Bio-priming with <i>T. viride</i> at 60% (w/v) for 3 h gave the highest values	Ananthi, et al. (2014)
Sunflower (<i>Helianthus annuus</i>)	0.01 % of <i>pseudomonas</i>	<i>Pseudomonas fluorescens</i> UTPf76 and UTPf86	enhancement of seed indices and improvement of seedling growth.	Kaya et al. (2006); Tripti et al. (2022)
Canola (<i>Brassica napus</i> L.)	Plant growth-promoting microorganism (PGPM), including bacterium <i>Bacillus subtilis</i> strain Ham and fungus <i>Trichoderma harzianum</i> strain bp4	The plant growth promotion due to inoculation with fungi was higher than that of bacteria	Increased Germination %, seedling biomass; Decreased oxidative stress	Ataei et al. (2017)

Zarrin-giah (<i>Dracocephalum kotschyi</i> Boiss.)	10 and 20 min seed soaking in <i>Azotobacter chroococcum</i> and <i>Bacillus polymixa</i>	<i>Azotobacter chroococcum</i> and <i>Bacillus polymixa</i> suspension	<i>B. polymixa</i> improved seedling length and vigour index more than those of <i>A. chroococcum</i> suspension culture soaking seeds	Biswas et al. (2018); Mishra et al. (2017)
Rice (<i>Oryza sativus</i>)	Seven isolates, namely IRRI 1, TH 28, TH 21, TH 30, TH 3, TH 26, and TH 7, were selected	<i>Trichoderma harzianum</i>	<i>T. harzianum</i> strains IRRI-1, TH-28, TH-30, and TH-21 showed the greatest reduction in leaf rolling	Singh, et al. (2023)
Garden pea	<i>Bacillus</i> isolates possessed biosynthetic genes for endoglucanase (B42, B43, B50), surfactin (B43, B44, B46), fengycin (B44, B46), bacillomycin D (B42, B50), and iturin (B42), and were able to produce indole-3-acetic acid (IAA), siderophores, and cellulase	<i>B. velezensis</i> (B42), <i>B. subtilis</i> (B43), <i>B. mojavensis</i> (B44, B46), <i>B. amyloliquefaciens</i> (B50), and <i>B. halotolerans</i> (B66)	Two isolates, <i>B. subtilis</i> B43 and <i>B. amyloliquefaciens</i> B50, had the highest effect on final germination, shoot length, root length, shoot dry weight, root dry weight, and seedling vigor index	Miljaković (2024)
Minor millets	<i>Acetobacter</i> @ 10% and 20%, <i>Phosphobacteria</i> @ 10% and 20%, <i>Azophos</i> @ 10% and 20%, <i>Pseudomonas fluorescens</i> @ 10% and 20% (liquid formulation), <i>Pseudomonas fluorescens</i> @ 10% and 20% (dry formulation)	<i>Acetobacter</i> @ 10% and 20%, <i>Phosphobacteria</i> , <i>Azophos</i> , and <i>Pseudomonas fluorescens</i>	Seeds bio-primed with <i>fluorescens</i> 20% (dry formulation) for 6 h recorded higher seed qualities	Balaji & Narayana, (2019)
Wheat	18%, 23% and 14% in alluvial, red and black soils	Application of <i>Trichoderma</i> sp. with chemical nitrogenous (N) fertilization	The root infection was significantly increased, and higher seedling vigour	Meena et al. (2017).
Green gram and Cowpea	TNAU <i>Rhizobium</i> at 15%, 20%, and 25% concentrations and GRI laboratory isolated <i>Rhizobium</i> at 15%, 20%, and 25%	<i>Rhizobium</i> -based bio-priming	Seed bio-priming with <i>Rhizobium</i> strains at optimal concentrations significantly enhanced seedling biomass	Ashokkumar et al. (2025)

2. Improved Nutrient Uptake and Plant Growth

Bio-priming imparts PGPR to seeds for nitrogen fixation, phosphate solubilization, and production of plant hormones.

Application of bacteria such as *Azotobacter*, *Bradyrhizobium*, and *phosphate-solubilizing bacteria* enhances root growth and nutrient uptake in the early stages by forming root nodules through which the plant growth is enhanced. Recent studies conducted on soybean and maize have reported increased chlorophyll content, biomass, nitrogen-phosphorus uptake, and overall growth with the use of inoculated seeds (Fatima et al., 2022; Alori & Babalola, 2018). In the case of wheat, bio-priming based on PSB enhanced phosphorus use efficiency and grain yield (Jat et al., 2020). The effect of biopriming on nutrient uptake in crop plants were presented in **Table 12.2**.

Table 12.2. Effect of biopriming on nutrient uptake in crop plants

Crop / Plant	Nutrient uptake level	Mechanistic Insights	Observed Benefits	References
Fenugreek (<i>Trigonella foenum-graecum</i>)	The main and interaction effects of seed priming and fertilization were significant on the Na of leaves	PGPB fertigation and nutrients foliar application	The highest leaf nitrogen was observed in PGPB bio-priming, and foliar application was greater than the control.	Solouki et al. (2023)
Wheat (<i>Triticum aestivum</i>)	The growth and yield, and nutrient uptake showed an increase with an increase in nitrogen dose up to 150 kg /ha	no seed priming, seed priming with water, seed priming with water + <i>Azotobacter</i> , seed priming with water + AM fungi, seed priming with water + Biomix	Priming with biofertiliser inoculations significantly improves yield and nutrient uptake	Patra, & Singh (2018)
Red cabbage [Brassica oleracea L. var. capitata L. f. rubra (L.)	Significant relationship of Fe and Mn uptake with chlorophyll (SPAD) and between Zn uptake and the earliness of the crop	<i>Trichoderma harzianum</i> , <i>Pseudomonas fluorescens</i> , and <i>Bacillus subtilis</i>	↑ Pod number, seed weight, and improved emergence	Sarkar et al. (2022)
Okra (<i>Abelmoschus esculentus</i>)	<i>Enterobacter hormaechei</i> sp. with multiple plant beneficial traits is a great approach for the enhancement of soil fertility and	<i>Enterobacter</i> spp. significantly improved overall germination parameters and vigor index	All <i>Enterobacter</i> spp. shared common plant growth-promoting traits, namely nitrogen (N ₂) fixation, indole-3-acetic acid production and	Roslan et al. (2020).

	P and K uptake of plants.		siderophore production	
Maize (<i>Zea mays</i> L.)	Seed biopriming is an easy, commercially feasible way to cope with drought stress during reproductive growth to enhance crop productivity	Seeds were inoculated with bacteria culture (<i>Rhizobium phaseoli</i> -RS-1 + <i>Pseudomonas</i> spp.) at the ratio of 1:5.	Seed biopriming considerably ameliorated the drought-induced deterioration in nutrient uptake	Nawaz et al. (2020)
Chick pea	The application of biopriming with Zn spray mitigated the negative effects on grain yield	Zn absorbance in pulses enhanced through biopriming with moringa leaf extract (MLE ₃₀)	The biopriming with Zn spray prominently improved its bioavailability for obtaining the nutrient-rich biofortified grains production.	Nawaz et al. (2025)
Soyabean	Enhance phosphorus (P) uptake in soybean.	Bio-priming with <i>Trichoderma viride</i> Strain BHU-2953.	Higher P-recoveries of bio-primed soybeans, received 90% and 80% RDF	Paul & Rakshit, (2021).
Baby corn	Yield attributes were significantly higher in <i>Trichoderma viride</i> + <i>Glomus intraradices</i> + 75% RDF-treated pots.	Seed bio-priming increased root length and chlorophyll content of baby corn.	Faster germination, improved vigor	Yadav et al. (2018)
Rice (<i>Oryza sativa</i>)	The isolates displayed beneficial capabilities like extracellular enzyme production, IAA, hydrogen cyanide, phosphate solubilisation,	Microbial consortium, prepared from the bacterial and fungal associates of the epiphytic endemic orchid <i>Dendrobium ovatum</i>	increased biomass, enhanced accumulation of photosynthetic pigments and photochemistry, metabolite production, and yield	Raj et al (2024)

	and ammonia production			
Mung bean (<i>Vigna radiata</i>)	Bio-priming was effective in alleviating the detrimental effects of drought stress.	bio-priming (mixture of strains of <i>Pseudomonas fluorescens</i> + <i>Rhizobium phaseoli</i>)	The bio-priming technique increased the grain yield by having a strong antioxidant defense system and better nutrient uptake behaviour under terminal drought stress.	Nawaz et al. (2021)

3. Biocontrol of Seed and Soil Pathogens

Bio-priming is significantly needed for enhancing immunity in young plants. *Trichoderma viride* and *Bacillus subtilis* are antagonistic against Fusarium wilt, *Rhizoctonia solani*, *Alternaria*, etc. These microbes typically produce antibiotics, activate lytic enzymes, and enhance plant defences against infection, thereby reducing disease incidence and promoting healthy root development in crops such as chickpea, maize, and cucumber (Sharma et al., 2021; Harman, 2006). Application of *Bacillus*-based biocontrol agents in chickpea reduced Fusarium wilt and thereby improved seed vigour (Soni et al., 2020). Furthermore, the summary of effect of biopriming on biocontrol in crop plants were presented in **Table 12.3**.

Table 12.3. Effect of Biopriming on Biocontrol in Crop Plants

Crop/ Plant	Biocontrol Level	Mechanistic Insights	Observed Benefits	References
Faba bean	The inhibitor effect of <i>Trichoderma viride</i> , <i>T. harzianum</i> , <i>Bacillus subtilis</i> and <i>Pseudomonas fluorescens</i> was higher against the root rot pathogen	Inhibitory effect of antagonistic fungi and bacteria against the linear growth of root rot pathogenic fungi	Under field conditions, the antagonistic agents could protect seeds against infection by root rot pathogens at both pre- and post-emergence stages.	El-Mougy et al. (2008)
Tomato	<i>B. aryabhatai</i> Z-48 was able to antagonize the mycelial growth of <i>Fusarium oxysporum</i> f.sp. <i>lycopersici</i> in vitro	biopriming with <i>Bacillus aryabhatai</i> Z-48, to suppress <i>Fusarium wilt</i> disease	The seed coating with <i>B. aryabhatai</i> Z-48 significantly reduced the disease index (>60%)	Akram et al. (2024)
Rapeseed (<i>Brassica napus</i>)	Rapeseed bio-priming with strain DT-8 could significantly decrease the disease severity of SSR and increase yield in the field.	Hypovirulent strain DT-8 of <i>S. sclerotiorum</i> , infected with <i>Sclerotinia sclerotiorum</i> hypovirulence-associated DNA virus 1 (SsHADV-1), has	Bio-priming treatment could reduce the total abundance of possible plant pathogens and enhance the connectivity and robustness of the	Qu et al. (2020).

		the potential to control stem rot	interaction network at the genus level.	
Rice (<i>Oryza sativa</i>)	<i>Bacillus amyloliquefaciens</i> strain UASBR9 and <i>Serratia marcescens</i> strain UASBR4 were found to be most effective in reducing disease severity (84.28%)	different bacterial strains through seed priming in reducing the blast disease severity under in vitro, in vivo and field conditions.	The least disease severity and highest seed germination were recorded in seeds bio-primed with <i>B. amyloliquefaciens</i> UASBR9 (0.96 and 98.00%)	Amruta, et al. (2019)
Chilli	Biopriming with 102 spores/mL of <i>T. asperellum</i> suppressed disease by <i>F. solani</i> .	<i>T. asperellum</i> have antagonistic properties against <i>F. solani</i> and <i>P. ultimum</i> .	<i>T. asperellum</i> showed >60 % growth inhibition towards <i>Fusarium solani</i> and <i>Pythium ultimum</i>	Chin et al. (2022).

4. Increased Resistance to Environmental Stresses

Bio-primed seeds resist diseases and cope with drought, salinity, and cold by enhancing antioxidant activities, raising osmolyte concentration, and increasing the expression of stress-related genes (Table 12.4). Microbes such as *Trichoderma*, *Bacillus megaterium*, and *Pseudomonas putida* have been known to help plants utilise water and reduce oxidative stress. Bio-priming maize seeds with *T. Harzianum* improved their cold tolerance via changes in the roots and increased antioxidant enzyme activities (Ghao et al., 2022). Bio-priming of wheat seeds with halotolerant PGPR helped in better growth and more consistent germination in saline soils (Khan et al., 2020).

Table 12.4. Effect of biopriming on resistance to stresses in various crop plants

Crop / Plant	Stress / Context	Observed Yield Benefits	Mechanistic Insights	References
Barley (<i>Hordeum vulgare</i>)	The fungal strain showed an ameliorated response to salt stress	CSR3 alleviated the salt stress and significantly increased root/shoot length and weight	Biopriming of <i>H. vulgare</i> seeds with CSR3 enhanced the germination ratio both in control and salt-treated conditions.	Khan, et al. (2024)
cumin (<i>Cuminum cyminum</i>)	Coating improves the physical properties, as well as its mechanized cropping.	Biopriming of coated cumin increased the protein and antioxidant enzyme activity.	Inoculation of coated seed with <i>Pseudomonas</i> improved the establishment of cumin.	Piri et al. (2019)
Wheat (<i>Triticum aestivum</i>)	<i>Aspergillus fumigatus</i> , as a biological biopriming tool, can positively	The total biomass of stressed wheat plants that had been bio-primed rose by more than 40% to unprimed	Biopriming <i>Triticum aestivum</i> grains affected by the effects of inoculating endophytic fungi <i>Aspergillus fumigatus</i> ON307213	George et al. (2024)

	impact wheat plants experiencing drought stress			
Maize (<i>Zea mays</i>)	The total antioxidant enzyme activities of the salt-stressed bioprimes maize plants were increased by 4.7–5.3%	The chlorophyll and carotenoid contents were significantly increased in the salt-stressed maize upon bioprimes with <i>A. fumigatus</i> .	The fungal-bioprimes plants displayed an improvement in the shoot density, fibrous roots, root length, shoot length, and leaf numbers and areas under salt stress	Yassin, et al. (2024)
Finger millet (<i>Eleusine coracana</i> L.)	Salinity tolerant	Use of <i>Trichoderma</i> isolates thus, has been found to provide a sustainable approach to alleviate salt stress	seed bioprimes with four salinity tolerant <i>Trichoderma</i> isolates (TRU-21, TRU-14, TRU-33 and TRU-176)	Rawat, et al. (2022)

5. Enhancing Crop Yield and Productivity

These advantages therefore translate to higher yields and improved crop performance. Field tests on rice, wheat, soybean, and maize showed that bio-primed seeds resulted in more tillers, more biomass, and bigger harvests. Treatment with *Bradyrhizobium japonicum* on soybean seeds enhanced the nodulation, nitrogen fixation, and yield of soybean plants (Bashir et al., 2021). Use of microbes as seed priming agents in rice improved panicle length and grain number through better nutrient uptake (Choudhary et al., 2019). Hence, bio-priming can be an economical way to achieve maximum output from crops.

Importance of Bioprimes in Sustainable Agriculture

Bioprimes has emerged as a vital strategy in sustainable agriculture, offering an eco-friendly alternative to conventional chemical inputs. By inoculating seeds with beneficial microbes, farmers can reduce reliance on synthetic fertilizers, fungicides, and seed treatments, thereby minimizing environmental pollution and safeguarding soil health. Microbial inoculants enhance nutrient recycling and improve soil fertility, ensuring that crops receive essential nutrients without the negative consequences of chemical overuse. Studies have shown that bioprimes seeds often require fewer pesticide and fertilizer applications while maintaining comparable yields, making this approach highly suitable for organic and resource-efficient farming systems (Meena et al., 2020; Shil et al., 2025).

Beyond reducing chemical dependency, bioprimes contributes to improved plant resilience against biotic and abiotic stresses. Beneficial microbes such as endophytes and mycorrhizal fungi colonize the rhizosphere, strengthening plant defense mechanisms and enhancing tolerance to drought, salinity, and pathogen attacks. This resilience is particularly

important in the context of climate change, where unpredictable weather patterns and resource scarcity challenge agricultural productivity. Recent research highlights that biopriming with endophytes can foster climate-smart crops, aligning with global Sustainable Development Goals (SDGs) by promoting food security and reducing environmental footprints (Tiwari et al., 2025; Gohari et al., 2025).

Another significant advantage of biopriming lies in its role in promoting soil-microbe interactions that sustain long-term agricultural productivity. The inoculated microbes establish symbiotic relationships with plants, improving nutrient uptake efficiency and stimulating root growth. This not only enhances crop yield but also contributes to the restoration of degraded soils. As a result, biopriming supports regenerative agricultural practices that prioritize soil health, biodiversity, and ecological balance. Such practices are increasingly recognized as essential for transitioning toward sustainable food systems (Prasanth et al., 2024).

In summary, biopriming represents a transformative approach to sustainable agriculture by reducing chemical inputs, enhancing crop resilience, and fostering soil health. Its integration into farming systems can help achieve resource-efficient production while addressing global challenges such as climate change, food insecurity, and environmental degradation. As evidence continues to accumulate, biopriming stands out as a promising tool for advancing sustainable and climate-resilient agriculture.

Conclusion

Halopriming has emerged as a promising, sustainable, and low-cost pre-sowing strategy that strengthens seed germination, seedling vigor, and resistance against a wide spectrum of abiotic stresses, including salinity, drought, flooding and chilling conditions. By leveraging controlled salt-based treatments to trigger osmotic adjustment, antioxidant defense, hormonal regulation, and stress conditions, halopriming equips plants with a biochemical and physiological “head start” that sustains performance throughout the growth cycle. Its versatility extends to improving crop establishment in marginal lands, reducing dependence on chemical growth regulators and excessive irrigation, and enhancing overall grain or biomass yield, aligning directly with the principles of climate-smart agriculture. Furthermore, its accessibility and scalability make it particularly suitable for smallholder farmers, enabling resource-efficient production while contributing to global food security goals. As agriculture faces mounting challenges from climate variability and resource constraints, integrating halopriming into seed management programs offers a pathway towards climate-resilient, productive, and environmentally responsible cropping systems. Future research should focus on refining crop-specific protocols, exploring synergistic combinations with biological and nano-priming agents, and assessing long-term impacts on soil health and agroecosystem sustainability to fully harness halopriming’s potential as a basis of sustainable intensification.

Disclosure Statement

The authors reported no potential conflict of interest.

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