



REVIEW ARTICLE

Microbial seed biopriming: A promising approach for enhancing crop performance under abiotic stress

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Abstract

Abiotic stresses such as drought, salinity, heat and heavy metal toxicity are major constraints limiting global agricultural productivity and posing a serious threat to food security. Therefore, the development of sustainable and eco-friendly strategies to enhance crop resilience under adverse environmental conditions is imperative. Biopriming, a novel strategy for enhancing the physiological and biochemical activities of seeds through the use of beneficial microbes such as fungi, bacteria and yeast, has gained significant attention for its potential to improve plant tolerance under different abiotic stresses. This review explores the underlying mechanisms by which biopriming enhances stress resilience, including modulation of phytohormonal balance, activation of antioxidant defence systems, osmolyte accumulation and improved nutrient acquisition. In addition, the contributions of plant growth-promoting rhizobacteria (PGPR), endophytes and fungal inoculants in inducing systemic stress tolerance are critically evaluated. Evidence from recent studies demonstrates that biopriming can improve seed germination by 10–15 %, seedling vigour by 10–20 %, root and shoot growth by 10–15 %, chlorophyll retention by 10–20 % and grain or biomass yield by 5–10 % under various stress conditions, depending on crop species, microbial strain and severity of stress. Thus, seed biopriming has the potential to bridge the gap between potential and actual yield and serves as a valuable approach to improve crop performance and productivity under adverse environments. By unlocking the potential of bioinoculants, agricultural production systems can become more resilient to climate change.

Keywords: abiotic stress; beneficial microbes; phytohormones; plant growth regulation; seed quality enhancement

Introduction

The current global population is estimated approximately 7.6 billion and expected to increase to 9.8 billion by 2050 (1). Due to the increase in population, human activities such as deforestation, excessive use of chemicals and pesticides have significantly contributed to environmental pollution. In addition, the rapid industrialisation and overuse of fossil fuels have increased the greenhouse gas emissions causing global warming (2). Global climate change is expected to intensify as rising temperatures and increasing atmospheric CO₂ levels alter rainfall patterns and distribution. Depending upon the environmental conditions, plants face various abiotic stresses that affect their growth and development (3, 4). Plants exposed to abiotic stresses, change their morphology, cell structure, physiological and biochemical reactions. Abiotic stresses are estimated to cause significant yield losses in crops, often exceeding 50 % under severe conditions, depending on the crop species, stress intensity and duration (5, 6). Among the

various abiotic stresses, drought stress has a negative impact on agriculture. While approaches viz., genetic improvement, organic and chemical inputs have been widely employed to mitigate stress effects, they are often associated with high costs, environment risk and limited adaptability across diverse agroecosystems. In these perspectives, one of the biggest challenges is the sustainability of agriculture, which means reducing the stress induced crop losses to maintain the agricultural productivity for the world population without leaving negative impacts on the environment (7). In recent years, seed priming techniques have emerged as a cost-effective and ecofriendly approach to improve crop establishment and enhance stress tolerance. Among various priming approaches, seed biopriming using beneficial microorganisms has gained considerable attention for its potential to promote plant growth under adverse climatic conditions. Biopriming activates the plant defense mechanisms and stress responsive pathways at the early stages of plant development. Beneficial microbes play a vital role by inducing antioxidant system, promote osmolyte accumulation and

regulates the expression of stress responsive genes. Furthermore, biopriming improves seed germination, vigour and seedling establishment, which are crucial determinants of crop yield, particularly under stress prone environments (8).

Despite its considerable advantages, the large-scale adoption of biopriming remains limited due to a lack of understanding of seed microbe interaction, selection of effective microbial strain and optimising their concentration for different crops and stress conditions. Therefore, a comprehensive synthesis of current knowledge is essential to fully exploit the potential of biopriming as a sustainable strategy for improving abiotic stress tolerance in crops (9).

A systematic approach was adopted to collect and analyse the relevant literature for this review. This review focuses on the effects of various abiotic stresses on crop plants, including their physiological, biochemical and molecular responses; evaluates the role of beneficial microbes in enhancing stress tolerance; and critically assesses the feasibility and effectiveness of seed biopriming across different stress conditions. In addition, the review identifies

key knowledge gaps, discusses existing limitations and inconsistencies in reported findings and outlines future research directions for the practical application of biopriming in climate-resilient agriculture.

Effect of abiotic stress on plants

Abiotic stress such as drought, salinity, temperature and heavy metal stress are major constraints to crop productivity, significantly reducing crop growth and yield (10, 11). At the physiological level, these stresses impair photosynthetic efficiency, reduce leaf area and alter stomatal behaviour by limiting carbon assimilation and plant development (12, 13). A common consequence of abiotic stress is the induction of osmotic balance and excessive accumulation of reactive oxygen species (ROS) resulting in oxidative damage to cellular components such as proteins, lipids and nucleic acids (14, 15). Therefore, it is essential to examine the specific effects of major abiotic stresses individually to better understand their mechanisms and plant responses. The plant response to these abiotic stresses is discussed in detail in the following sections and Fig. 1.

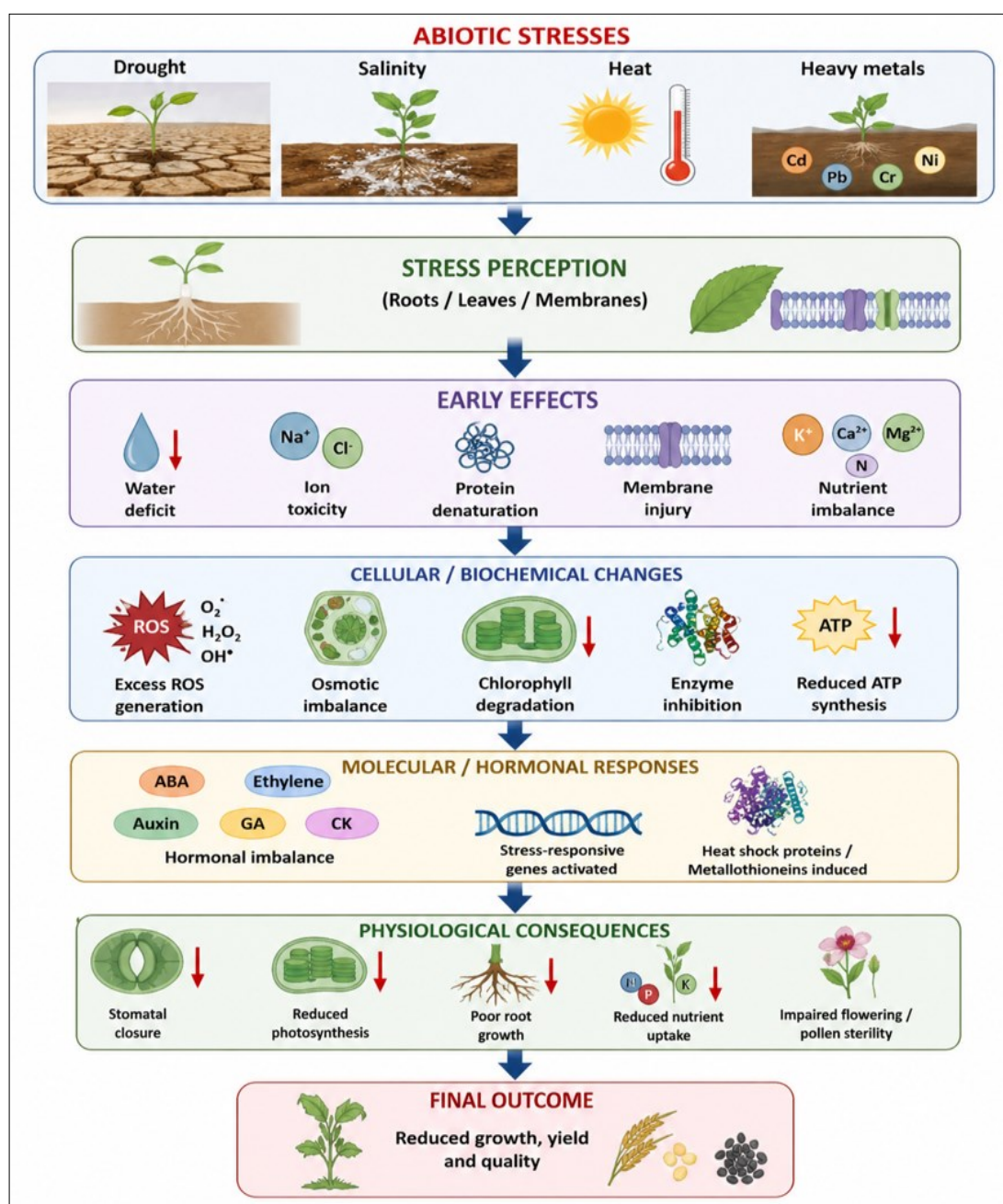


Fig. 1. Overview of plant responses to abiotic stresses.

Effect of drought stress on crop growth

Drought stress occurs due to lack of water availability in the rhizosphere region due to excessive transpiration, where plants demand more water than it can absorb and restrict root water absorption (16). During seed germination, water stress affects the initiation of metabolic activities, as water is essential for enzyme activation and reserve mobilisation. Drought stress reduces cell division and cell elongation leading to impaired structural integrity. Drought stress affects the photosystem and electron transport chain, leading to decreased ATP production and increased ROS accumulation, which damage the structure of the chloroplast (17). Increased ROS production affects the cellular homeostasis (18). Drought stress impacts the production of primary and secondary metabolites. Primary metabolites are essential for energy production and growth. Secondary metabolites are essential for the plant defense, stress response and adaptation. Closure of stomata due to drought stress inhibits the CO₂ uptake and limits the photosynthesis, thereby decreasing the availability of primary metabolites (19). Secondary metabolites such as carotenoids, flavonoids and isoprenoids act as antioxidants to protect against oxidative damage and enhance stress tolerance (20). Drought stress alters the plant metabolism and affects the crop growth and yield.

Effect of salinity stress on crop growth

Salinity induces osmotic stress by reducing the soil water potential due to high concentrations of Na⁺ and Cl⁻ ions. It limits the uptake of water by roots, leading to reduced cell turgor and suppressed growth in roots and young leaves (21, 22). Prolonged exposure of Na⁺ and Cl⁻ in plant cells results in ion toxicity. This reduces the uptake of essential nutrients such as potassium and calcium leading to physiological disorders including leaf burn, chlorosis and premature senescence (23, 24). During generative stage of plant growth, salinity affects the flowering, fertilisation, seed development and pollen viability (25, 26). Salinity stress lowers the photosynthetic activity by closure of stomata and inhibits the stomatal enzyme like PEP carboxylase (27).

Effect of heat stress on crop growth

Heat stress is a major environmental constraint that disturbs the key physiological processes such as photosynthesis, water relation, membrane stability and reproductive development leading to reduced growth and yield losses. Photosynthesis is highly sensitive to elevated temperature, which reduces the photosystem efficiency, electron transport and CO₂ assimilation (28–30). Heat stress affects the chloroplast, particularly thylakoid membrane and disturbs the key proteins. Prolonged exposure to high temperature results in the decline of photosynthetic rate in maize approximately 47 % after 7 days at 38 °C and up to 73 % after 28 days (31). Early developmental stages such as germination and seedling establishment are highly sensitive, with reports indicating germination reductions of up to 95 % under extreme heat stress (32, 33). The reproductive phase is the most heat-sensitive stage. Elevated temperatures affect the pollen viability, anther dehiscence, stigma receptivity, fertilisation and grain filling processes. These impairments result in reduced grain number, poor seed set and decreased grain size in major crops such as cereals and legumes (34, 35). At the molecular and hormonal levels, heat stress triggers extensive regulatory changes. Phytohormones such as abscisic acid (ABA), auxins, gibberellins and ethylene undergo significant alterations, influencing stomatal behaviour, senescence and stress signalling pathways (36).

Effect of heavy metal stress on crop growth

Heavy metal stress impairs crop growth and development, starting from germination to yield. Metals such as cadmium, lead, chromium, nickel, copper and zinc at higher concentrations have a toxic effect on the root and plant system. The excessive accumulation of heavy metals such as mercury, cadmium, lead and chromium primarily due to anthropogenic activities can severely impair plant health. These metals disrupt photochemical processes, inhibit growth and may ultimately lead to plant death (37). Common symptoms of toxicity include leaf chlorosis, reduced nutrient uptake, impaired nitrogen fixation and significant yield losses (38, 39). The effect of heavy metals is more critical during the reproductive phase, resulting in yield loss. Reduction in vegetative growth and reduced photosynthesis leads to decreased formation of grains or pods and reduced seed size. In some cases, heavy metals can completely inhibit reproductive success (40, 41). Male reproductive structures such as pollen grains and anthers, are highly sensitive to heavy metals such as cadmium, resulting in poor pollen viability, impaired fertilisation and poor seed set (42, 43).

Beneficial microbes in agriculture

Beneficial microbes act as natural biofertilisers and biostimulants that improve plant growth and productivity under adverse environmental conditions. Among these, plant growth promoting rhizobacteria, Arbuscular mycorrhizal fungi, endophytes and consortia represent the most widely studied. The different microbial groups and their mechanism are listed in Table 1. These beneficial microbes can be incorporated into the seed through the process of seed priming. Microbes' relationship to the host can be classified as rhizospheric and endophytic. Endophytic microbes can able to colonise the inner tissues of the plant parts. These microbes can be applied individually or as a microbial consortium for wider benefits in sustainable agriculture.

Biopriming

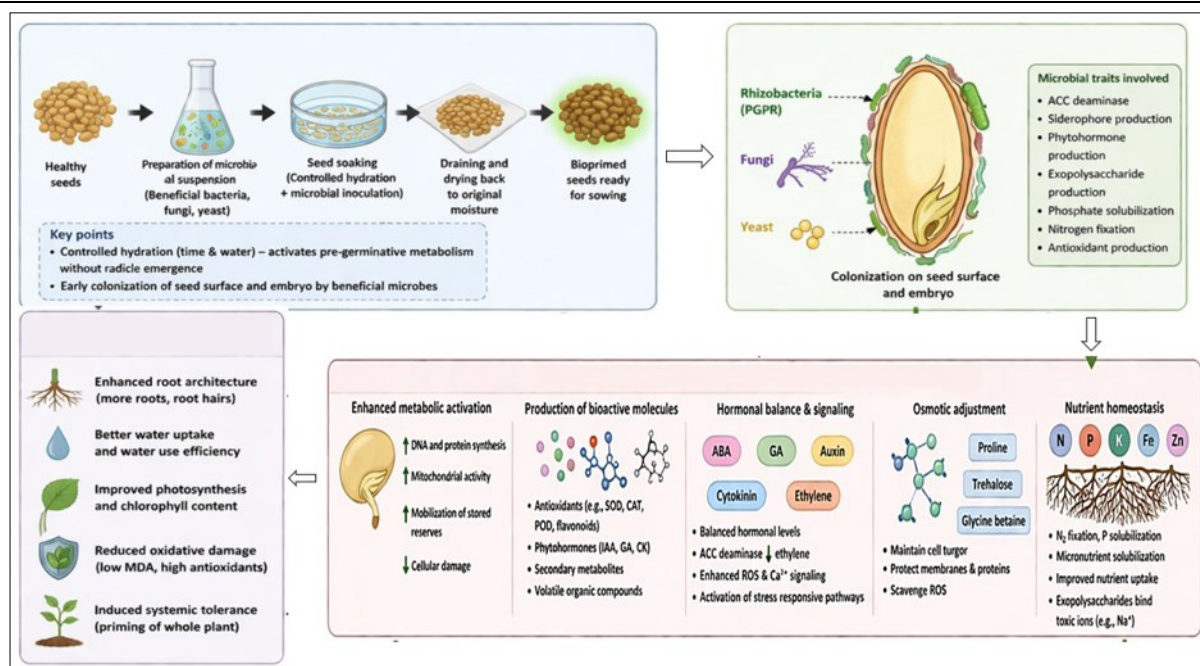
Biopriming has emerged as an efficient seed quality enhancement technique combining the physiological benefits of seed hydration with the biological advantages of beneficial microorganisms. Seed biopriming is achieved through controlled hydration of seeds followed by inoculation with selected beneficial microbes under regulated conditions (44). The duration of soaking and the amount of water used during priming are critical to prevent radicle emergence while activating pre-germinative metabolic processes (45).

Several crops such as wheat, rice, maize, pearl millet, tomato, chilli, capsicum, brinjal, cucumber, greengram, chickpea, blackgram, soybean and sunflower have demonstrated positive responses to seed biopriming with bacterial and fungal inoculants (46, 47). Bio-primed seeds generally exhibit improved seed germination, faster and uniform field emergence, enhanced seedling vigour, reduced dormancy and greater tolerance to abiotic stresses such as drought, salinity and heat (44). The overview of the biopriming process is illustrated in Fig. 2.

One of the major objectives of promoting seed biopriming is to reduce dependency on chemical inputs and ensure eco-friendly delivery of beneficial microorganisms into the crop environment (48). Microorganisms play key roles in nutrient cycling, phytohormone production, stress resilience and overall plant growth. In seed biopriming, either single microbial strains or multiple compatible strains are used depending on the target crop and stress condition. Their crop-wise effects are discussed in Table 2.

Table 1. Beneficial microbes and their mechanism in mitigating abiotic stresses

Microbial group	Key genera	Targeted abiotic stresses	Mechanism	Impact on plant system	Reference
Plant Growth Promoting Rhizobacteria	<i>Azotobacter</i> , <i>Azospirillum</i> , <i>Rhizobium</i> , <i>Bacillus</i> and <i>Pseudomonas</i>	Drought, salinity, heavy metal and heat stress	ACC deaminase activity, Phytohormone production, Nitrogen fixation and Phosphorus, potassium solubilization	Improved root structure, reduced ethylene levels, enhanced nutrient uptake and better water retention	(84–86)
Arbuscular Mycorrhizal Fungi	<i>Rhizophagus</i> , <i>Funneliformis</i>	Drought and salinity	Hyphal extension increases root surface area, osmotic adjustment and improved water and Phosphorus uptake	Osmotic balance, enhanced nutrient uptake and increased stress tolerance	(87, 88)
Endophytes (bacterial and fungal)	<i>Pseudomonas</i> , <i>Serendipita indica</i>	Drought, salinity and heat	Enhancement of antioxidant system, modulation of melatonin related response	Reduce oxidative damage and enhance stress signalling	(89)
Microbial Consortia	PGPR + AMF combination	Multiple stresses	Hormonal regulation, antioxidant defense and osmotic balance	Improved growth and yield under multiple stresses	(90, 91)

**Fig. 2.** Mechanism of microbial seed biopriming under abiotic stress.**Table 2.** Mechanistic Role of Microbial Communities in Abiotic Stress Mitigation

Sl.No	Microbial strain	Dose / Inoculum level	Method	Priming duration	Abiotic stress	Crop	Mechanism / Activity	Major response	Reference
1	<i>Bacillus pumilus</i> SH-9	10 ⁸ CFU mL ⁻¹	Seed biopriming	8 hr	Drought	Rice	Production of IAA, ABA, sucrose, exopolysaccharides, siderophores	Improved germination, vigour and drought tolerance	(92)
2	<i>Pseudomonas fluorescens</i> + <i>Trichoderma harzianum</i>	10 ⁷ –10 ⁸ CFU mL ⁻¹	Seed treatment	6–8 hr	Drought	Cumin	Antioxidant enhancement and growth promotion	Increased seed germination, shoot length and leaf soluble proteins	(93)
3	<i>Rhizobium tropici</i> + <i>Paenibacillus polymyxa</i>	Standard inoculum	Seed inoculation	6 hr	Drought	Common bean	Regulation of stress-responsive genes	Enhanced drought tolerance and gene upregulation	(94)
4	<i>Pseudomonas putida</i> H-2-3	10 ⁸ CFU mL ⁻¹	Seed biopriming	8 hr	Drought	Soybean	Antioxidant metabolism and radical scavenging	Improved growth and oxidative stress protection	(95)
5	<i>Bacillus</i> sp. MGW9	10 ⁸ CFU mL ⁻¹	Seed biopriming	12 hr	Salinity	Maize	Increased CAT, POD, SOD and proline accumulation	Improved germination and seedling vigour under	(96)
6	<i>Paraburkholderia phytofirmans</i>	Bacterial suspension	Seed inoculation	6 hr	Heat	Tomato	Chlorophyll retention and osmoprotectant synthesis	Increased chlorophyll, sugars and amino acids	(97)
7	<i>Azospirillum brasilense</i>	Standard inoculum	Seed treatment	6–8 hr	Heavy metal	Chickpea	Root growth promotion and chromium	Improved growth and chromium stress tolerance	(98)

Single species priming

The process of inoculation of a single microorganism during seed priming. This biopriming uses specified microbes to maximise the plant growth and defence without competition from other microbes. Single inoculation of *Trichoderma harzianum* increases the seed physiology, 100 seed weight, field emergence and yield compared to control seeds in maize (49).

Consortium seed priming

The process of inoculation of multiple microorganism such as bacteria, yeast and fungi for the higher benefits in the plant system compared to single inoculation (50). By priming seeds with microbial consortia, it enhances the seed germination, seedling growth and resistance against abiotic stresses. Compatible microbes show synergistic effect on plant growth and development. Seed biopriming with nodule associated plant probiotics augmented several yield attributes of green gram including dry matter accumulation, thousand seed weight, harvest index, biological yield and grain yield (51).

Mechanism of seed biopriming in context of abiotic stress management

Seed priming involves controlled hydration of seeds and improves seed germination and uniform crop establishment. In coriander, hydropriming for 6 hr significantly increased the germination percentage over the control by 25 % (52). Seed biopriming improves seed germination and seedling growth under salinity and drought stress (53, 54). The process involves early microbe colonisation on the seed surface and embryo. As a result, bio-primed seeds exhibit enhanced DNA and protein synthesis, improved mitochondrial activity, mobilisation of stored reserves and cellular damage for rapid and uniform establishment of seedlings under stress conditions (55). Microbes in the seeds stimulate the production and release of signalling molecules like antioxidants, phytohormones and secondary metabolites. These molecules are essential for seed germination, enzyme activity and stress tolerance response (56). Biopriming modulates the hormonal balance and signalling networks by regulating abscisic acid (ABA), gibberellins (GA), auxins, cytokinin and ethylene, often mediated through microbial traits such as ACC deaminase activity, which reduces stress induced ethylene levels and promotes root growth. Additionally, ROS and calcium signalling pathways are enhanced to activate stress responsive mechanism (57, 58) (Fig. 2).

Reactive oxygen species accumulation, osmotic imbalance and antioxidant defence are common responses across different abiotic stresses; however, their regulation under biopriming is more coordinated and efficient. Biopriming enhances the plant's ability to maintain redox homeostasis by modulating both enzymatic (superoxide dismutase, catalase, peroxidase) and non-enzymatic antioxidants. Unlike stress-induced ROS, which causes cellular damage, controlled ROS signalling in bio-primed seeds acts as a regulatory mechanism for stress adaptation. Similarly, osmotic adjustment is improved through the accumulation of compatible solutes such as proline, glycine betaine and trehalose, which stabilise cellular structures and maintain water balance. Importantly, microbial-mediated priming integrates these responses with hormonal signalling and gene expression, providing a more robust and sustained tolerance compared to non-primed plants.

Furthermore, biopriming plays an essential role in maintaining homeostasis and nutrient balance under stress conditions. Microbial exopolysaccharides can bind toxic ions such as sodium, thereby reducing their toxicity and uptake, while microbes enhance nitrogen fixation, phosphorous solubilisation and improve nutrient availability in stressed or degraded soil. In addition, sustained colonisation of the rhizosphere by beneficial microbes enhances the root architecture and promotes induced systemic tolerance (59, 60). Biopriming stimulates plant growth by improving the nutrient uptake efficiency of plant growth promoting bacteria. It improves crop establishment by releasing compounds that are involved in mineral solubilisation (61). Most of the fertilisers applied to the soil are lost due to leaching and are not available for plant growth and development. Phosphate solubilising microorganism such as *Enterobacter*, *Bacillus* and *Pseudomonas* produces crystal dissolving compounds and produces phosphate solubilising enzymes that make phosphorus available to the plants (62). Plant growth promoting rhizobacteria produce more auxin and gibberellin during biopriming to enhance uniform plant growth (63). Microbial inoculants play a vital role in the osmotic adjustment under salinity and drought stress by promoting the accumulation of proline, trehalose and Glycine betaine. These osmolytes help in maintaining the cell turgor and protect the plant from oxidative damage. Inoculation of strains like *Actinobacteria*, *Bacillus*, *Brevibacterium* and *Sphingomonas* increases the level of trehalose, proline and glycine betaine in crops like rice, soybean and groundnut resulting in improved plant growth and water retention. The Fig. 3 represents the benefits of the biopriming.

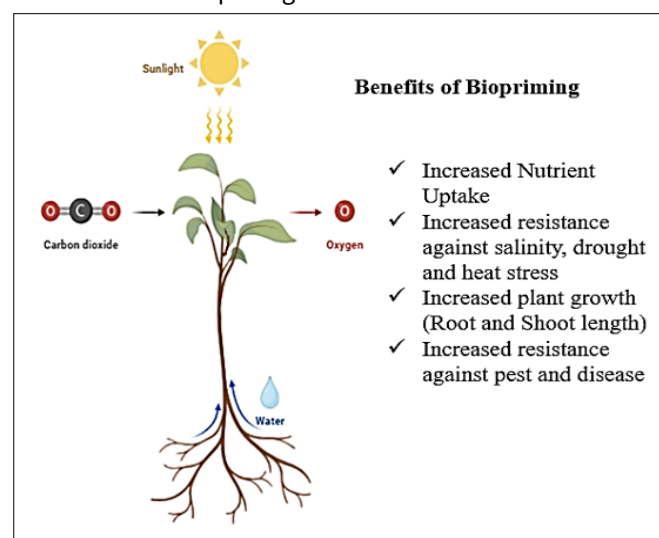


Fig. 3. Benefits of biopriming under abiotic stress conditions.

Although numerous studies report positive effects of biopriming, the magnitude of response varies widely depending on microbial strain, crop genotype and environmental conditions. For instance, single-strain inoculations often show inconsistent performance under field conditions compared to controlled environments, whereas microbial consortia may provide more stable results due to functional complementarity. However, contradictory findings also exist where high inoculum densities or incompatible microbial combinations lead to reduced plant performance. Furthermore, most studies are short-term and conducted under controlled conditions, limiting the understanding of long-term field-level sustainability and scalability. These inconsistencies highlight the need for standardised protocols and multi-location validation trials.

Molecular mechanism and gene expression in bio-primed seeds

Seed biopriming alters early seed metabolism and induces a primed physiological state that enhances germination and stress tolerance. At the molecular level, biopriming triggers coordinated reprogramming of DNA repair mechanisms, hormonal signalling pathways, antioxidant defence systems and photosynthetic processes (Fig. 4). For instance, studies in *Medicago truncatula* Gaertn. have shown upregulation of DNA repair genes such as *FPG* and *OGG1*, along with antioxidant genes including *APX*, *SOD* and *MT2*, contributing to improved seed quality and stress resilience (64). Similarly, in maize, biopriming with *Bacillus* consortia under salinity stress enhances the expression of antioxidant genes (*ZmAPX1.2*, *ZmBADH1*, *ZmCAT*) and signalling-related genes such as mitogen-activated protein kinases (*ZmMPK5*, *ZmMPK7*) and calcium-dependent protein kinases (*ZmCPK11*), which are key components of stress signal transduction pathways (65).

Beyond individual gene activation, biopriming influences higher-level regulatory networks involving transcription factors such as DREB (Dehydration-Responsive Element Binding), WRKY, NAC and MYB families, which play central roles in coordinating stress-responsive gene expression. These transcription factors are activated through signalling cascades involving ROS, calcium signalling and MAPK pathways, enabling rapid perception and response to environmental stress. Furthermore, cross-talk between phytohormonal pathways, particularly ABA, ethylene and auxin signalling, modulates downstream gene expression related to osmotic balance, ion transport and cellular protection. For example, PGPR-mediated priming in tomato induces a transcriptionally reprogrammed state involving ABA and ethylene signalling, ion homeostasis and antioxidant metabolism, thereby enhancing salinity tolerance (66).

In biopriming establishes a “molecular memory” in seeds, allowing faster and more efficient activation of stress-responsive pathways upon exposure to adverse conditions. However, the precise regulatory networks and their interactions under field conditions remain insufficiently understood, highlighting the need for integrative multi-omics approaches to fully elucidate these mechanisms.

Factors determining the efficiency of biopriming

Biopriming efficiency is highly influenced by the combination of microbial traits, crop genotype, inoculum parameters and environmental conditions. The success of biopriming depends on the compatibility between these factors, which determine microbial establishment and plant response under abiotic stress (Fig. 5).

Microbial strain selection and colonisation efficiency

The appropriate selection of microbial strain is crucial for successful biopriming experiment. The effective strain should possess strong plant growth promoting traits, including phytohormone production, Indole-3-acetic acid, ACC deaminase activity, nutrient solubilisation (P, K and Zn) and Siderophore production (67, 68). However, beyond the promoting traits, the ability of strain to effectively colonise to the seed surface and root system is more important. Microbial characteristic such as growth rate, competitiveness and stress tolerance play a major role than simply increasing inoculum concentration (69). Furthermore, native or well adapted strains and consortia generally exhibit superior colonisation efficiency and consistent field performance compared to non-native or single strain inoculants (70,71).

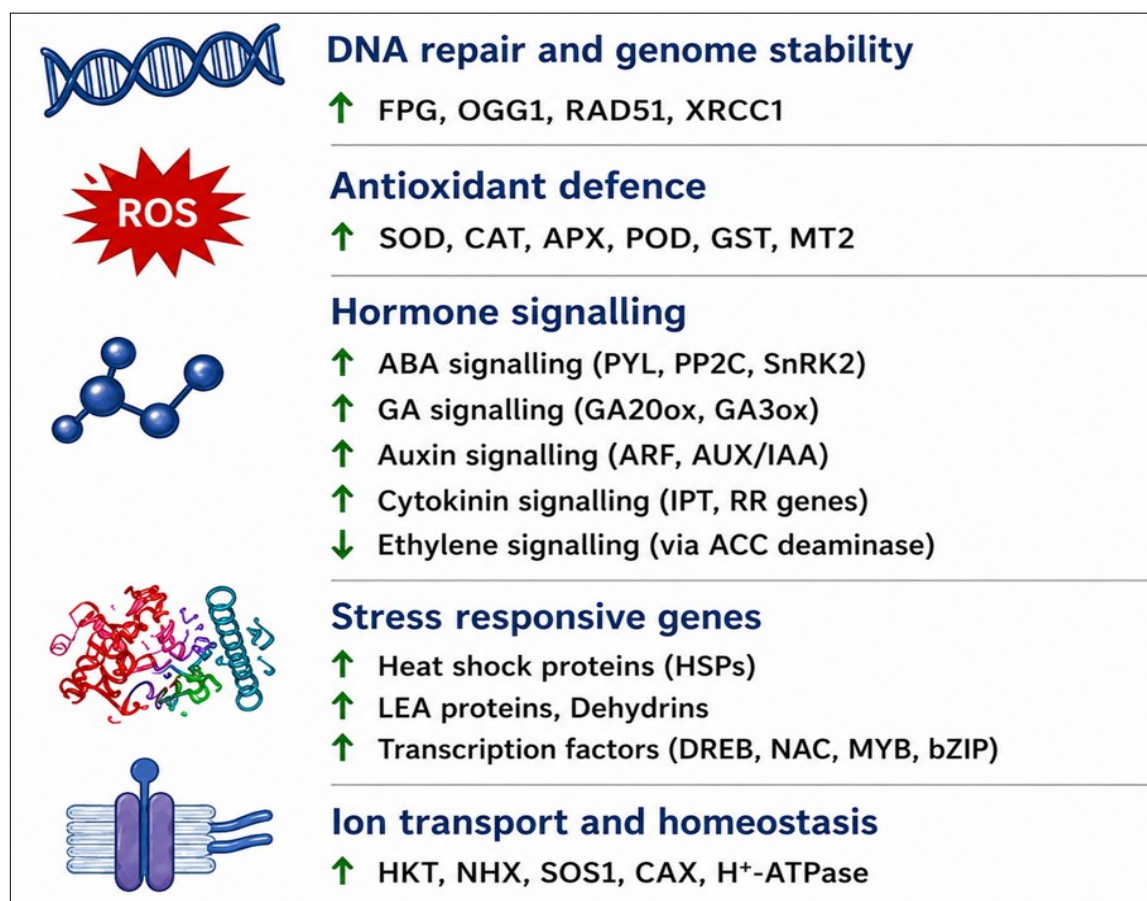


Fig. 4. Molecular mechanism of microbial seed biopriming under abiotic stress.

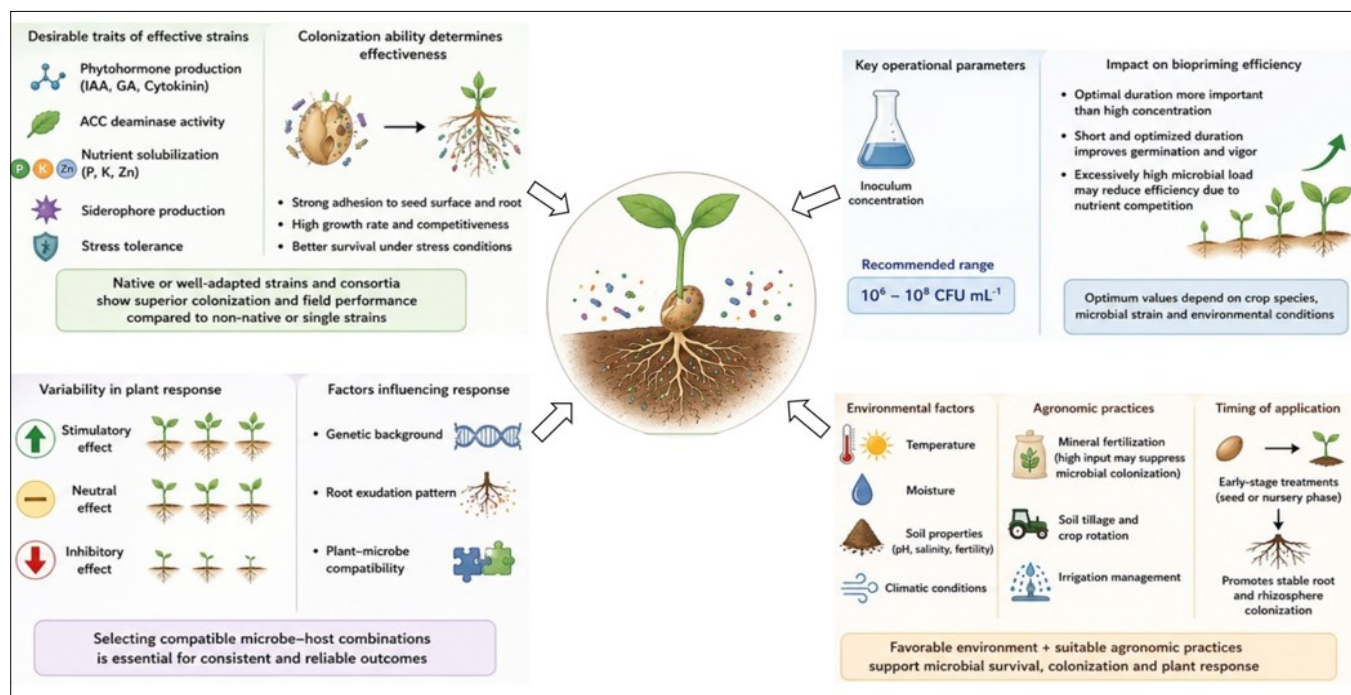


Fig. 5. Factors influencing the efficiency of microbial seed biopriming and plant response under abiotic stress.

Inoculum concentration and priming duration

Inoculum density and seed exposure time are key operational parameters influencing biopriming experiment outcomes. Studies indicate that priming duration is often more critical than initial microbial concentration, with shorter and optimised durations promoting better germination and seedling vigour (72). Excessively high microbial loads do not necessarily enhance plant performance and may even have adverse effects by increasing competition for nutrients or reducing colonisation efficiency, particularly under fertilised conditions (73). Typically, optimal inoculum concentrations fall within the range of 10^6 – 10^8 CFU mL⁻¹; however, these values are highly dependent on the crop species, microbial strain and environmental conditions, necessitating empirical standardisation (74,75).

Crop and genotype specificity

The effectiveness of biopriming is strongly influenced by crop species and genotype. Plant responses to microbial inoculation vary significantly, with the same treatment producing stimulatory, neutral, or even inhibitory effects across different cultivars (76–78). This variability highlights the importance of selecting compatible microbe–host combinations to achieve consistent and reliable outcomes. Tailoring biopriming strategies at the cultivar level can significantly enhance their effectiveness in improving stress tolerance and crop performance (75, 79).

Environmental and agronomic conditions

Environmental factors and crop management practices play a significant role in determining biopriming efficiency. Soil properties such as fertility, pH, salinity and moisture, along with climatic conditions, directly influence microbial survival, colonisation and plant response (80, 81). Additionally, agronomic practices such as mineral fertilisation can modulate microbial activity; for instance, high fertiliser inputs may suppress endophytic colonisation and alter optimal inoculum requirements (82). The timing of application is also crucial, as early-stage treatments during seed or nursery phases promote more stable root and rhizosphere colonisation compared to later-stage applications (83).

Conclusion and future perspectives

Biopriming represents a promising and sustainable strategy to enhance crop resilience against diverse abiotic stresses including drought, salinity, heat and heavy metal toxicity. For effective field-level application, biopriming protocols should be standardised with optimised inoculum concentrations typically ranging between 10^6 – 10^8 CFU mL⁻¹ and priming durations of 6–24 hr, depending on crop species and microbial strain. Under optimised conditions, biopriming has been reported to improve seed germination by 10–20 %, seedling vigour by 15–25 % and yield by 5–15 % under abiotic stress conditions. However, these outcomes require validation across diverse agroecological regions through multi-location trials.

Integration of biopriming with emerging tools such as genomics, transcriptomics, proteomics and metabolomics can provide deeper insights into plant–microbe interactions and stress adaptation mechanisms. In addition, the use of bioinformatics tools, microbial consortia design and precision agriculture technologies (such as sensor-based monitoring and data-driven decision support systems) can enhance the consistency and scalability of biopriming applications. Furthermore, advancements in formulation technologies, including nano-carriers and encapsulation methods, may improve microbial survival and delivery efficiency under field conditions.

Future research should focus on developing crop-specific microbial consortia, standardising protocols across environments and integrating biopriming with climate-smart agricultural practices to achieve sustainable and resilient crop production systems.

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Authors' contributions

VSK participated in conceptualisation and writing the original draft. KS, MVK, KM, CV, MG and VBRP participated in conceptualisation, supervision, review and editing. KS, MV, KM, CV, RV and SR reviewed and edited the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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