



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(6): 195-204
Received: 16-03-2026
Accepted: 23-04-2026

Mohd Amanuddin

M.Sc. (Ag.) Agronomy, School of
Agriculture, SR University,
Hasanparthy, Telangana, India

Vangala Siva Nagi Reddy

Assistant Professor, Department of
Agronomy, College of Agriculture,
Annamacharya University,
Rajampet, Kadapa, Andhra
Pradesh, India

Nitin Singh

Ph.D. Scholar, Department of
Agronomy, Acharya Narendra
Deva University of Agriculture
Technology, Kumarganj, Ayodhya,
Uttar Pradesh, India

KVS Jahnvi

Microbiologist, Biofertilizer
Production Unit, Supreme
Chemicals Ventures, Hyderabad,
Telangana, India

S Glory Madhuri

M.Sc. (Ag), Department of
Agronomy, S. V. Agricultural
College, Tirupati, Acharya N G
Ranga Agricultural University,
Guntur, Andhra Pradesh, India

Neppala Divya

M.Sc. (Agri.) Agronomy,
Department of Agronomy, Naini
Agricultural Institute, Sam
Higginbottom University of
Agriculture, Technology and
Sciences, Prayagraj, Uttar
Pradesh, India

Sonali Sangwan

Assistant Professor, Department of
Biotechnology, Guru Nanak
Khalsa College, Yamuna Nagar,
Haryana, India

Corresponding Author:

Mohd Amanuddin

M.Sc. (Ag.) Agronomy, School of
Agriculture, SR University,
Hasanparthy, Telangana, India

Agronomic innovations for enhancing productivity under abiotic stress conditions

**Mohd Amanuddin, Vangala Siva Nagi Reddy, Nitin Singh, KVS Jahnvi, S
Glory Madhuri, Neppala Divya and Sonali Sangwan**

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i6c.5686>

Abstract

Abiotic stresses including drought, salinity, heat, cold, waterlogging and heavy metal toxicity are among the most devastating constraints on global crop productivity, collectively responsible for yield losses exceeding 50% in major staple crops. With the accelerating pace of climate change, the frequency and intensity of these stresses are projected to increase substantially, posing a serious threat to food security for a growing global population. Agronomic innovations offer practical, scalable and cost-effective strategies to mitigate the adverse effects of abiotic stresses without requiring extensive genetic modification. This review synthesizes current knowledge on key agronomic interventions, including seed priming techniques, soil amendments (biochar, silicon, organic matter), optimized irrigation and water management, mulching, crop geometry adjustments, exogenous application of osmoprotectants and plant growth regulators and the use of plant growth-promoting rhizobacteria (PGPR). The physiological and biochemical mechanisms underlying these interventions - such as enhanced antioxidant activity, osmotic adjustment, improved water-use efficiency and modulation of stress-responsive gene expression - are discussed in detail. Evidence from field and greenhouse studies demonstrates that integrated agronomic approaches can significantly improve crop resilience and sustain productivity under stress conditions. The review also identifies research gaps and future directions for developing climate-smart agronomic packages tailored to specific stress environments. Adoption of these innovations, particularly in developing countries, holds immense potential for ensuring food security under changing climatic scenarios.

Keywords: Abiotic stress, agronomic management, seed priming, biochar, PGPR, osmoprotectants, crop productivity, climate change, drought tolerance, salinity stress

1. Introduction

Global agriculture faces an unprecedented challenge: feeding a projected population of nearly 10 billion people by 2050 while simultaneously confronting the escalating impacts of climate change ^[1]. Abiotic stresses - environmental factors that negatively affect plant growth, development and productivity without involving living organisms - represent the single largest category of constraints on crop production worldwide ^[2]. Drought, salinity, extreme temperatures (heat and cold), waterlogging and heavy metal toxicity collectively account for yield losses of more than 50% in major food crops such as wheat, rice, maize and soybean ^[3]. The Intergovernmental Panel on Climate Change (IPCC) has projected that global mean temperatures will rise by 1.5-4.5 °C by the end of the 21st century, accompanied by altered precipitation patterns, increased frequency of extreme weather events and expanding areas of saline and degraded soils ^[4]. These changes are expected to intensify the severity and geographic spread of abiotic stresses, further threatening agricultural sustainability. In South Asia and sub-Saharan Africa - regions already vulnerable to food insecurity - the consequences are expected to be particularly severe ^[5].

While genetic and biotechnological approaches to developing stress-tolerant crop varieties have received considerable attention, their translation into farmers' fields remains slow due to regulatory hurdles, high development costs and socio-economic barriers ^[6]. In contrast, agronomic innovations - encompassing modifications in crop management practices, soil amendments, water management and the use of biostimulants - offer immediate, accessible and

economically viable solutions that can be deployed across diverse farming systems ^[7].

Agronomic strategies work by modulating the plant's physiological and biochemical responses to stress, improving soil physical and chemical properties, optimizing resource-use efficiency and creating a more favorable microenvironment for crop growth ^[8]. These approaches are not mutually exclusive; rather, their integration into comprehensive stress management packages often yields synergistic benefits that exceed the sum of individual interventions ^[9].

This review aims to provide a comprehensive synthesis of recent advances in agronomic innovations for managing major abiotic stresses in crop production. Specifically, it covers: (i) seed priming technologies, (ii) soil amendments including biochar and silicon, (iii) water management and irrigation strategies, (iv) mulching and crop geometry, (v) exogenous application of osmoprotectants and plant growth regulators and (vi) the use of plant growth-promoting rhizobacteria (PGPR). The underlying mechanisms, practical applications and limitations of each strategy are discussed, along with future research priorities for developing integrated, climate-smart agronomic systems.

2. Abiotic Stresses and Their Impact on Crop Productivity

2.1 Drought Stress

Drought is the most widespread abiotic stress globally, affecting approximately 40% of the world's agricultural land ^[10]. It impairs plant growth by disrupting water relations, reducing turgor pressure, inhibiting stomatal conductance and decreasing photosynthetic efficiency. At the cellular level, drought induces the accumulation of reactive oxygen species (ROS), leading to oxidative damage to membranes, proteins and nucleic acids ^[11]. Yield losses due to drought can range from 20% to 90% depending on the crop species, growth stage and stress intensity. Cereals such as maize and wheat are particularly vulnerable during the reproductive stage, where even brief water deficits can cause irreversible yield penalties ^[12].

2.2 Salinity Stress

Soil salinity affects approximately 900 million hectares worldwide, with an estimated 1-2 million hectares of irrigated land becoming saline each year due to poor irrigation management and inadequate drainage ^[13]. High salt concentrations in the root zone cause osmotic stress, ion toxicity (particularly Na^+ and Cl^-) and nutritional imbalances, collectively impairing germination, vegetative growth and reproductive development ^[14]. Salinity reduces crop yields by 10-25% in moderately saline soils and by more than 50% in severely saline conditions ^[15]. The physiological effects include reduced water uptake, disruption of ion homeostasis, inhibition of enzyme activity and impairment of photosynthesis.

2.3 Heat Stress

Heat stress occurs when temperatures exceed the threshold for normal plant function, typically above 35°C for most temperate crops ^[16]. It disrupts protein conformation, membrane fluidity and photosynthetic apparatus, particularly Photosystem II. Heat stress during anthesis and grain filling is especially damaging, causing pollen sterility, reduced grain set and accelerated grain filling that results in shriveled, low-weight grains ^[17]. Global warming is projected to reduce wheat yields by 6% and maize yields by 7.4% for each degree Celsius rise in temperature ^[18].

2.4 Cold and Waterlogging Stress

Cold stress (chilling below 15°C and freezing below 0 °C)

impairs membrane function, disrupts metabolic processes and causes ice crystal formation in plant tissues ^[19]. Waterlogging creates anaerobic conditions in the root zone, inhibiting aerobic respiration, nutrient uptake and root growth. Both stresses are increasingly erratic due to climate variability, making them difficult to predict and manage ^[20].

2.5 Heavy Metal Toxicity

Contamination of agricultural soils with heavy metals such as cadmium (Cd), lead (Pb), arsenic (As) and chromium (Cr) - arising from industrial effluents, mining activities and excessive use of phosphatic fertilizers - poses a growing threat to crop productivity and food safety ^[21]. Heavy metals interfere with enzyme activity, disrupt mineral nutrition, induce oxidative stress and inhibit photosynthesis, leading to stunted growth and reduced yields ^[22].

3. Seed Priming Technologies

3.1 Concept and Mechanisms

Seed priming is a pre-sowing treatment that partially hydrates seeds to a level that allows pre-germinative metabolic activity but prevents radicle protrusion ^[23]. The technique activates DNA repair mechanisms, enhances antioxidant enzyme activity, promotes the synthesis of stress-protective proteins and accelerates the mobilization of seed reserves, resulting in faster and more uniform germination under stress conditions ^[24]. Primed seeds exhibit improved seedling vigor, better stand establishment and enhanced tolerance to subsequent abiotic stresses - a phenomenon known as 'stress memory' or 'priming memory' ^[25].

3.2 Hydropriming and Osmopriming

Hydropriming involves soaking seeds in water for a defined period followed by re-drying to the original moisture content. It is the simplest and most cost-effective priming method, particularly suitable for resource-poor farmers ^[26]. Osmopriming uses osmotic solutions such as polyethylene glycol (PEG), potassium nitrate (KNO_3), or sodium chloride (NaCl) to control water potential during imbibition. PEG-based osmopriming at -0.5 to -1.5 MPa has been widely reported to improve germination and early seedling growth under drought and salinity stress in wheat, rice and maize ^[27]. Marthandan *et al.* ^[28] demonstrated that osmopriming with PEG-6000 significantly enhanced drought tolerance in rice by upregulating the expression of stress-responsive genes including OsDREB and OsLEA.

3.3 Chemical Priming

Chemical priming involves treating seeds with specific chemical compounds that trigger stress tolerance pathways. Commonly used chemicals include hydrogen peroxide (H_2O_2), ascorbic acid, salicylic acid (SA), nitric oxide (NO) and zinc sulfate ^[29]. Salicylic acid priming has been shown to enhance antioxidant enzyme activities (superoxide dismutase, catalase, peroxidase) and reduce malondialdehyde (MDA) content - a marker of lipid peroxidation - in wheat under heat stress ^[30]. Nitric oxide priming improves salt tolerance in maize by modulating Na^+/K^+ homeostasis and enhancing the activity of H^+ -ATPase in root cells ^[31].

3.4 Biopriming

Biopriming combines seed hydration with the inoculation of beneficial microorganisms, particularly plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi. This approach not

only improves germination and seedling vigor but also establishes a beneficial microbial community in the rhizosphere from the earliest stages of plant development [32]. Biopriming with *Bacillus subtilis* and *Pseudomonas fluorescens* has been reported to significantly improve drought tolerance in chickpea and wheat by producing indole-3-acetic acid (IAA), solubilizing phosphate and synthesizing volatile compounds that induce systemic tolerance [33].

3.5 Nano-priming

Nano-priming is an emerging technology that uses nanoparticles (NPs) - including zinc oxide (ZnO), titanium dioxide (TiO₂), silicon dioxide (SiO₂) and carbon-based NPs - to enhance seed germination and stress tolerance [34]. Nanoparticles improve water and nutrient uptake through seed coats, activate antioxidant defense systems and modulate gene expression related to stress responses. ZnO nanoparticle priming at 25-50 mg/L has been shown to improve germination rate, seedling biomass and chlorophyll content in wheat under salinity stress [35]. However, the phytotoxicity of nanoparticles at high concentrations and their long-term environmental fate require careful evaluation before large-scale adoption.

4. Soil Amendments for Abiotic Stress Mitigation

4.1 Biochar

Biochar is a carbon-rich, porous material produced by the pyrolysis of organic biomass (crop residues, wood, manure) under limited oxygen conditions at temperatures of 300-700°C [36]. Its application to agricultural soils has gained considerable attention as a multi-functional amendment that simultaneously improves soil physical, chemical and biological properties while mitigating abiotic stresses [37]. In drought-prone soils, biochar's high porosity and surface area increase soil water-holding capacity, reduce bulk density and improve soil aggregation, thereby maintaining soil moisture availability to plants during dry periods [38]. Under salinity stress, biochar application reduces Na⁺ uptake by crops through ion exchange and adsorption mechanisms, improves soil cation exchange capacity (CEC) and promotes the leaching of excess salts from the root zone [39]. Biochar also enhances the activity of beneficial soil microorganisms, including mycorrhizal fungi and nitrogen-fixing bacteria [40]. A meta-analysis by Haider *et al.* [41] found that biochar application increased crop yield by an average of 25% under drought stress and 20% under salinity stress. Combined application of biochar with arbuscular mycorrhizal fungi (AMF) has shown synergistic effects, resulting in significantly greater improvements in biomass production, chlorophyll content and nutrient uptake [43].

4.2 Silicon (Si) Application

Silicon, though not classified as an essential plant nutrient, is the second most abundant element in the Earth's crust and is increasingly recognized as a 'quasi-essential' element that confers significant benefits to crops under abiotic stress [44]. Silicon is taken up by plant roots as monosilicic acid [Si(OH)₄] and deposited in cell walls, where it forms a physical barrier that reduces water loss, limits ion uptake and provides mechanical support [45]. Under drought stress, Si application improves water-use efficiency by reducing transpiration through the deposition of silica in the cuticle and stomatal guard cells [46]. Under salinity stress, Si reduces Na⁺ accumulation in shoots, maintains K⁺/Na⁺ homeostasis and alleviates oxidative stress by enhancing superoxide dismutase (SOD) and catalase (CAT) activities [47]. Under heat stress, Si stabilizes cell membrane integrity, protects

photosynthetic pigments and upregulates the expression of heat shock proteins (HSPs) [48]. Mir *et al.* [49] reported that Si application at 1-2 mM significantly improved photosynthetic rate, chlorophyll content and grain yield in rice, wheat and maize under multiple abiotic stresses.

4.3 Organic Matter and Compost

The addition of organic matter - through compost, farmyard manure, green manures and crop residue incorporation - improves soil structure, water retention, nutrient availability and microbial diversity, all of which contribute to enhanced crop resilience under abiotic stress [51]. Organic matter increases soil CEC, buffers soil pH and provides a slow-release source of nutrients that sustains crop growth during stress periods. Compost application has been shown to reduce the negative effects of salinity on tomato and pepper by improving soil osmotic potential and stimulating the production of plant growth hormones [52].

5. Water Management and Irrigation Strategies

5.1 Deficit Irrigation and Regulated Deficit Irrigation

Deficit irrigation (DI) involves applying water below full crop evapotranspiration requirements, deliberately allowing mild water stress during less sensitive growth stages to conserve water while minimizing yield penalties [53]. Regulated deficit irrigation (RDI) restricts water supply during specific phenological stages when crops are least sensitive to water stress, while maintaining full irrigation during critical periods such as flowering and grain filling [54]. Studies on wheat in arid regions have demonstrated that RDI can reduce water use by 20-30% with yield reductions of less than 10%, significantly improving water productivity [55].

5.2 Partial Root-Zone Drying

Partial root-zone drying (PRD) is an innovative irrigation technique in which alternate sides of the root zone are wetted and dried in cycles. This approach exploits the plant's ability to produce abscisic acid (ABA) from drying roots, which signals stomatal closure and reduces transpiration, while the wet side of the root zone maintains adequate water supply for growth [56]. PRD has been shown to reduce water use by 30-50% in fruit trees and vegetables with minimal yield losses, making it particularly valuable in water-scarce environments [57].

5.3 Micro-irrigation and Fertigation

Drip irrigation and micro-sprinkler systems deliver water directly to the root zone, minimizing evaporation losses and reducing the risk of soil salinization associated with surface irrigation [58]. When combined with fertigation - the application of soluble fertilizers through the irrigation system - micro-irrigation enables precise nutrient management that optimizes crop growth under stress conditions. Drip-fertigated crops under salinity stress have shown 20-40% higher yields compared to conventionally irrigated crops [59].

5.4 Rainwater Harvesting and Conservation Tillage

In rainfed systems, rainwater harvesting techniques such as tied ridges, contour bunds and in-situ moisture conservation measures can significantly improve soil water availability during dry spells [60]. Conservation tillage practices - including no-till, minimum tillage and strip tillage - reduce soil evaporation, improve soil structure and enhance water infiltration, thereby increasing the resilience of rainfed crops to drought stress [61]. A long-term study in semi-arid India demonstrated that no-till

combined with residue retention increased soil moisture by 15-20% and improved wheat yield stability under variable rainfall conditions ^[62].

6. Mulching and Crop Geometry

6.1 Mulching

Mulching - the application of organic or inorganic materials to the soil surface - is one of the most effective and widely practiced agronomic strategies for mitigating drought and heat stress ^[63]. Organic mulches (straw, crop residues, compost) reduce soil evaporation, moderate soil temperature fluctuations, suppress weed growth and gradually improve soil organic matter content as they decompose ^[64]. Plastic mulches, particularly black polyethylene film, are highly effective in conserving soil moisture, raising soil temperature in cold climates and reducing soil salinity in the root zone by limiting capillary rise of saline water ^[65]. Research in arid and semi-arid regions has consistently demonstrated that straw mulching at 4-6 t/ha can reduce soil evaporation by 30-50%, increase soil moisture content by 10-20% and improve crop yields by 15-35% under drought conditions ^[66].

6.2 Crop Geometry and Planting Density

Optimizing row spacing, plant density and planting direction can significantly influence the crop microclimate and its response to abiotic stresses. Wider row spacing improves air circulation and reduces canopy temperature under heat stress, while closer spacing can improve canopy cover and reduce soil evaporation under drought conditions ^[68]. East-west row orientation has been shown to reduce canopy temperature by 1-2°C compared to north-south orientation in wheat and maize, with corresponding improvements in grain yield under heat stress ^[69]. Adjusting sowing dates to avoid the coincidence of critical growth stages with peak stress periods is another powerful agronomic tool. Early sowing of wheat in South Asia has been widely recommended to allow grain filling to occur before the onset of terminal heat stress, with studies reporting yield improvements of 10-25% compared to normal sowing dates ^[70].

6.3 Intercropping and Crop Diversification

Intercropping - growing two or more crops simultaneously in the same field - can enhance system-level resilience to abiotic stresses by improving resource-use efficiency, reducing soil temperature and creating a more stable microclimate ^[71]. Cereal-legume intercrops are particularly effective, as the legume component improves soil nitrogen status and provides ground cover that reduces soil evaporation, while the cereal component provides structural support and shade that moderates temperature extremes ^[72]. A meta-analysis of 226 intercropping studies found that intercropping systems produced 22% more yield per unit land area than sole crops, with greater advantages under stress conditions ^[73].

7. Exogenous Application of Osmoprotectants and Plant Growth Regulators

7.1 Osmoprotectants

Osmoprotectants are low-molecular-weight, highly soluble organic compounds that accumulate in plant cells under stress conditions to maintain osmotic balance, stabilize proteins and membranes and scavenge ROS ^[74]. The exogenous application of osmoprotectants - including proline, glycine betaine, trehalose and mannitol - has emerged as a practical agronomic strategy to enhance crop tolerance to drought, salinity and heat stress ^[75]. Proline application at 10-50 mM has been shown to improve

germination, photosynthesis and grain yield in wheat, rice and maize under drought and salinity stress by stabilizing cellular structures, maintaining redox balance and acting as a molecular chaperone ^[76]. Glycine betaine protects the photosynthetic apparatus under heat and salinity stress and has been shown to improve cotton and sorghum yields by 10-20% when applied as a foliar spray at 50-100 mM ^[77]. Exogenous trehalose application at 25 mM improved drought tolerance in maize by enhancing antioxidant enzyme activities and maintaining higher relative water content in leaves ^[78].

7.2 Plant Growth Regulators

Plant growth regulators (PGRs) - including auxins, cytokinins, gibberellins, abscisic acid (ABA), brassinosteroids and salicylic acid - play central roles in mediating plant responses to abiotic stresses and can be applied exogenously to modulate stress tolerance ^[79]. Abscisic acid is the primary stress hormone that triggers stomatal closure, reduces water loss and activates stress-responsive gene expression under drought and salinity stress. Exogenous ABA application at 10-100 µM has been shown to improve water-use efficiency and maintain grain yield in wheat and barley under terminal drought stress ^[80]. Brassinosteroids (BRs) enhance stress tolerance by activating antioxidant defense systems, improving membrane stability and modulating the expression of stress-responsive genes. Foliar application of 24-epibrassinolide at 0.1-1.0 µM has been reported to significantly improve photosynthetic efficiency, chlorophyll content and grain yield in rice and wheat under heat and salinity stress ^[81]. Salicylic acid (SA) application at 0.5-1.0 mM has been shown to enhance antioxidant enzyme activities, reduce oxidative damage and improve yield in tomato, wheat and maize under drought, salinity and heat stress ^[82].

7.3 Polyamines

Polyamines - including putrescine, spermidine and spermine - are small, positively charged molecules that stabilize nucleic acids and membranes, scavenge ROS and modulate ion channels under stress conditions ^[84]. Exogenous application of spermidine at 0.5-1.0 mM has been shown to improve drought and salinity tolerance in wheat and rice by enhancing antioxidant defense, maintaining photosynthetic activity and reducing Na⁺ accumulation in shoots ^[85].

8. Plant Growth-Promoting Rhizobacteria (PGPR)

8.1 Mechanisms of PGPR-Mediated Stress Tolerance

Plant growth-promoting rhizobacteria are beneficial soil bacteria that colonize the rhizosphere and plant roots, promoting plant growth and enhancing stress tolerance through a diverse array of direct and indirect mechanisms ^[86]. Direct mechanisms include the production of phytohormones (IAA, cytokinins, gibberellins), biological nitrogen fixation, phosphate solubilization and the synthesis of volatile organic compounds (VOCs) that trigger induced systemic tolerance (IST) ^[87]. Under abiotic stress conditions, PGPR contribute to stress tolerance through: (i) production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which reduces ethylene levels and prevents stress-induced growth inhibition; (ii) synthesis of exopolysaccharides (EPS) that improve soil aggregation and water retention; (iii) production of osmolytes that contribute to osmotic adjustment; and (iv) activation of antioxidant defense systems in host plants ^[89].

8.2 PGPR under Drought Stress

Inoculation with *Bacillus subtilis*, *Pseudomonas putida* and

Azospirillum brasilense has been shown to improve root architecture, increase root hair density and enhance water uptake in wheat, maize and sorghum under water deficit conditions ^[90]. A meta-analysis of 144 studies found that PGPR inoculation increased crop yield by an average of 20% under drought stress ^[91]. *Bacillus velezensis* inoculation has been shown to upregulate the expression of drought-responsive genes including DREB, LEA and P5CS in wheat under water deficit ^[93].

8.3 PGPR under Salinity Stress

Salinity stress significantly alters rhizosphere microbial communities, reducing the abundance and diversity of beneficial microorganisms. PGPR inoculation can partially restore rhizosphere microbial diversity and provide direct benefits to salt-stressed crops ^[94]. *Pseudomonas fluorescens* and *Rhizobium* spp. inoculation has been shown to improve salt tolerance in legumes by maintaining K⁺/Na⁺ homeostasis, enhancing proline accumulation and reducing Na⁺ uptake through the modulation of HKT₁ transporter expression ^[95].

8.4 PGPR under Heat Stress

Thermotolerant PGPR strains - including *Bacillus cereus*, *Pseudomonas aeruginosa* and *Serratia marcescens* - have been shown to produce heat shock proteins, volatile compounds and phytohormones that enhance heat tolerance in wheat and tomato ^[96]. Inoculation with heat-tolerant *Bacillus* strains improved wheat grain yield by 15-20% under terminal heat stress by maintaining higher photosynthetic rates and reducing membrane electrolyte leakage ^[97].

8.5 Consortium Inoculation

The use of multi-strain PGPR consortia - combining bacteria with complementary mechanisms - has shown greater efficacy than single-strain inoculation in improving crop performance under abiotic stress ^[98]. Consortia combining nitrogen-fixing bacteria, phosphate solubilizers and ACC deaminase producers have demonstrated synergistic effects on crop growth and stress tolerance, with yield improvements of 25-40% under combined drought and salinity stress ^[99].

9. Integrated Agronomic Approaches

9.1 Rationale for Integration

Individual agronomic interventions, while effective, often provide incomplete protection against the complex and multifaceted nature of abiotic stresses. Integrated agronomic approaches that combine multiple complementary strategies can provide synergistic benefits that exceed the sum of individual interventions ^[100]. The integration of seed priming, soil amendments, optimized irrigation and PGPR inoculation creates a multi-layered defense system that addresses stress at multiple levels - from seed germination to crop maturity ^[101].

9.2 Examples of Integrated Packages

Several integrated agronomic packages have been developed and validated for specific stress environments. In drought-prone areas of South Asia, the combination of hydropriming + biochar application (10 t/ha) + deficit irrigation + PGPR inoculation has been shown to improve wheat yield by 30-45% compared to conventional management under water-limited conditions ^[102]. In saline soils of coastal Bangladesh, the integration of salt-tolerant varieties + gypsum application + biochar + PGPR inoculation + drip irrigation has enabled profitable rice cultivation in soils with electrical conductivity up to 8 dS/m ^[103].

For heat stress management in wheat, the combination of early sowing + east-west row orientation + foliar application of salicylic acid + silicon + PGPR inoculation has been shown to reduce canopy temperature by 2-3°C and improve grain yield by 20-30% compared to conventional management under terminal heat stress conditions ^[104].

9.3 Precision Agriculture and Digital Tools

The integration of precision agriculture technologies - including remote sensing, geographic information systems (GIS), soil sensors and decision support systems - with agronomic innovations enables site-specific stress management that optimizes resource use and maximizes productivity ^[105]. Satellite-based vegetation indices (NDVI, EVI) can identify stress hotspots within fields, enabling targeted application of soil amendments and irrigation. Soil moisture sensors and weather-based irrigation scheduling tools can optimize water application timing and quantity, reducing water use while maintaining crop productivity ^[106]. Artificial intelligence (AI) and machine learning algorithms are increasingly being applied to analyze large datasets from sensors, satellites and field experiments to develop predictive models for stress occurrence and recommend optimal agronomic interventions ^[107].

10. Challenges and Future Perspectives

10.1 Current Challenges

Despite the demonstrated efficacy of agronomic innovations for abiotic stress management, several challenges limit their widespread adoption. First, the effectiveness of many interventions is highly context-dependent, varying with soil type, climate, crop species and stress intensity, making it difficult to develop universally applicable recommendations ^[108]. Second, the economic viability of some interventions - particularly biochar production and application, micro-irrigation systems and commercial PGPR formulations - may be prohibitive for smallholder farmers in developing countries ^[109]. Third, the stability and shelf life of PGPR formulations under field conditions remain a significant challenge, as bacterial viability can be compromised by high temperatures, UV radiation and desiccation during storage and application ^[110]. Fourth, the regulatory frameworks for biostimulants and PGPR products vary widely across countries, creating barriers to commercialization and adoption ^[111]. Fifth, the long-term effects of repeated biochar application on soil microbial communities and nutrient cycling are not fully understood and require further investigation ^[112].

10.2 Research Gaps

Several important research gaps need to be addressed to advance the field. There is a need for more long-term, multi-location field trials that evaluate the performance of integrated agronomic packages under realistic farming conditions and across diverse agro-ecological zones ^[113]. The molecular mechanisms underlying the beneficial effects of many agronomic interventions - particularly the interactions between soil amendments, rhizosphere microbiome and plant stress signaling pathways - are not fully elucidated ^[114]. The development of stress-specific, crop-specific PGPR consortia with demonstrated efficacy under field conditions is a priority research area. Similarly, the optimization of biochar production parameters (feedstock, pyrolysis temperature, particle size) for specific soil types and stress conditions requires further investigation ^[115].

10.3 Future Directions

Future research should focus on developing climate-smart agronomic packages that are tailored to specific stress environments, crop systems and socio-economic contexts. The use of high-throughput phenotyping platforms, omics technologies (genomics, transcriptomics, metabolomics) and computational modeling can accelerate the identification of optimal agronomic interventions and their underlying mechanisms^[117]. Participatory research approaches that involve farmers in the co-design and evaluation of agronomic innovations are essential for ensuring their relevance, acceptability and adoption. Extension services and digital advisory platforms can play a crucial role in disseminating knowledge about agronomic innovations to farmers, particularly in remote and resource-poor areas^[118]. Policy support - including subsidies for biochar production, PGPR inoculants and micro-irrigation systems - is needed to make these innovations economically accessible to smallholder farmers who are most vulnerable to abiotic stresses^[119].

11. Conclusion

Abiotic stresses pose a formidable and growing challenge to global food security and their management requires a multi-pronged approach that combines genetic, biotechnological and agronomic strategies. This review has demonstrated that agronomic innovations - encompassing seed priming, soil amendments (biochar, silicon, organic matter), optimized water management, mulching, crop geometry, exogenous application of osmoprotectants and plant growth regulators and PGPR inoculation - offer practical, scalable and cost-effective solutions for enhancing crop productivity under stress conditions.

The evidence reviewed here clearly shows that these interventions work through diverse but complementary mechanisms: improving soil physical and chemical properties, enhancing plant antioxidant defense systems, maintaining osmotic balance, optimizing water and nutrient use efficiency and modulating stress-responsive gene expression. When integrated into comprehensive agronomic packages, these strategies can provide synergistic benefits that significantly exceed the performance of individual interventions.

The successful translation of these innovations from research to practice requires addressing key challenges related to context-specificity, economic viability, regulatory frameworks and knowledge dissemination. Investment in long-term, multi-location field trials, participatory research, digital advisory services and supportive policy frameworks is essential for scaling up agronomic innovations and making them accessible to the farmers who need them most. As climate change continues to intensify abiotic stresses worldwide, agronomic innovations will play an increasingly critical role in sustaining crop productivity, ensuring food security and supporting the livelihoods of farming communities.

References

- Food and Agriculture Organization of the United Nations. The State of Food and Agriculture 2023: Revealing the True Cost of Food. Rome: Food and Agriculture Organization of the United Nations; 2023.
- Kopecka R, Kameniarova M, Cerny M, Brzobohaty B, Novak J. Abiotic stress in crop production. *International Journal of Molecular Sciences*. 2023;24(7):6603. doi:10.3390/ijms24076603.
- Zandalinas SI, Mittler R, Balfagon D, Arbona V, Gomez-Cadenas A. Plant adaptations to the combination of drought and high temperatures. *Physiologia Plantarum*. 2020;162(1):2-12. doi:10.1111/ppl.12540.
- Intergovernmental Panel on Climate Change. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report. Cambridge (UK): Cambridge University Press; 2022.
- Lobell DB, Schlenker W, Costa-Roberts J. Climate trends and global crop production since 1980. *Science*. 2011;333(6042):616-620. doi:10.1126/science.1204531.
- Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X, Lv Y, *et al*. Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. *Plants*. 2019;8(2):34. doi:10.3390/plants8020034.
- Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development*. 2009;29(1):185-212. doi:10.1051/agro:2008021.
- Hasanuzzaman M, Nahar K, Alam MM, Roychowdhury R, Fujita M. Physiological, biochemical and molecular mechanisms of heat stress tolerance in plants. *International Journal of Molecular Sciences*. 2013;14(5):9643-9684. doi:10.3390/ijms14059643.
- Lal R. Integrating animal husbandry with crops and trees. *Journal of Soil and Water Conservation*. 2020;75(1):6A-11A. doi:10.2489/jswc.75.1.6A.
- Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, *et al*. Global warming and changes in drought. *Nature Climate Change*. 2014;4(1):17-22. doi:10.1038/nclimate2067.
- Mittler R. Abiotic stress, the field environment and stress combination. *Trends in Plant Science*. 2006;11(1):15-19. doi:10.1016/j.tplants.2005.11.002.
- Daryanto S, Wang L, Jacinthe PA. Global synthesis of drought effects on maize and wheat production. *PLOS ONE*. 2016;11(5):e0156362. doi:10.1371/journal.pone.0156362.
- Food and Agriculture Organization of the United Nations, Intergovernmental Technical Panel on Soils. Status of the World's Soil Resources (SWSR): Main Report. Rome: Food and Agriculture Organization of the United Nations; 2015.
- Ahmed M, Toth Z, Decsi K. The impact of salinity on crop yields and the confrontational behavior of transcriptional regulators, nanoparticles and antioxidant defensive mechanisms under stressful conditions: A review. *International Journal of Molecular Sciences*. 2024;25(5):2654. doi:10.3390/ijms25052654.
- Ondrasek G, Rathod S, Gireesh C, Anantha MS, Sakhare AS, Parmar B, *et al*. Salt stress in plants and mitigation approaches. *Plants*. 2022;11(5):717. doi:10.3390/plants11050717.
- Wahid A, Gelani S, Ashraf M, Foolad MR. Heat tolerance in plants: An overview. *Environmental and Experimental Botany*. 2007;61(3):199-223. doi:10.1016/j.envexpbot.2007.05.011.
- Hasanuzzaman M, Nahar K, Fujita M. Extreme temperature responses, oxidative stress and antioxidant defense in plants. In: Vahdati K, Leslie C, editors. *Abiotic Stress - Plant Responses and Applications in Agriculture*. Rijeka: InTech; 2013. p. 169-205.
- Asseng S, Ewert F, Martre P, Rotter RP, Lobell DB, Cammarano D, *et al*. Rising temperatures reduce global wheat production. *Nature Climate Change*. 2015;5(2):143-147. doi:10.1038/nclimate2470.

19. Yadav SK. Cold stress tolerance mechanisms in plants. A review. *Agronomy for Sustainable Development*. 2010;30(3):515-527. doi:10.1051/agro/2009050.
20. Voeselek LACJ, Bailey-Serres J. Flood adaptive traits and processes: An overview. *New Phytologist*. 2015;206(1):57-73. doi:10.1111/nph.13209.
21. Shahid M, Dumat C, Khalid S, Schreck E, Xiong T, Niazi NK. Foliar heavy metal uptake, toxicity and detoxification in plants. *Journal of Hazardous Materials*. 2017;325:36-58. doi:10.1016/j.jhazmat.2016.11.063.
22. Nagajyoti PC, Lee KD, Sreekanth TVM. Heavy metals, occurrence and toxicity for plants: A review. *Environmental Chemistry Letters*. 2010;8(3):199-216. doi:10.1007/s10311-010-0297-8.
23. Paparella S, Araujo SS, Rossi G, Wijayasinghe M, Carbonera D, Balestrazzi A. Seed priming: State of the art and new perspectives. *Plant Cell Reports*. 2015;34(8):1281-1293. doi:10.1007/s00299-015-1784-y.
24. Canizares E, Giovannini L, Gumus BO, Fotopoulos V, Balestrini R. Seeds of change: Exploring the transformative effects of seed priming in sustainable agriculture. *Physiologia Plantarum*. 2025;177(3):e70226. doi:10.1111/ppl.70226.
25. Savvides A, Ali S, Tester M, Fotopoulos V. Chemical priming of plants against multiple abiotic stresses: Mission possible? *Trends in Plant Science*. 2016;21(4):329-340. doi:10.1016/j.tplants.2015.11.003.
26. Harris D, Joshi A, Khan PA, Gothkar P, Sodhi PS. On-farm seed priming in semi-arid agriculture: Development and evaluation in maize, rice and chickpea in India. *Experimental Agriculture*. 1999;35(1):15-29. doi:10.1017/S0014479799001027.
27. Farooq M, Basra SMA, Wahid A, Cheema ZA, Cheema MA, Khaliq A. Physiological role of exogenously applied glycinebetaine to improve drought tolerance in fine grain aromatic rice. *Journal of Agronomy and Crop Science*. 2008;194(5):325-333. doi:10.1111/j.1439-037X.2008.00323.x.
28. Marthandan V, Geetha R, Kumutha K, Renganathan VG, Karthikeyan A, Ramalingam J. Seed priming: A feasible strategy to enhance drought tolerance in crop plants. *International Journal of Molecular Sciences*. 2020;21(21):8258. doi:10.3390/ijms21218258.
29. Jisha KC, Vijayakumari K, Puthur JT. Seed priming for abiotic stress tolerance: An overview. *Acta Physiologiae Plantarum*. 2013;35(5):1381-1396. doi:10.1007/s11738-012-1186-5.
30. Hayat Q, Hayat S, Irfan M, Ahmad A. Effect of exogenous salicylic acid under changing environment: A review. *Environmental and Experimental Botany*. 2010;68(1):14-25. doi:10.1016/j.envexpbot.2009.08.005.
31. Fancy NN, Bahlmann AK, Loake GJ. Nitric oxide function in plant abiotic stress. *Plant, Cell & Environment*. 2017;40(4):462-472. doi:10.1111/pce.12707.
32. Basu A, Prasad P, Das SN, Kalam S, Sayyed RZ, Reddy MS, *et al.* Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: Recent developments, constraints and prospects. *Sustainability*. 2021;13(3):1140. doi:10.3390/su13031140.
33. Ilangumaran G, Smith DL. Plant growth promoting rhizobacteria in amelioration of salinity stress: A systems biology perspective. *Frontiers in Plant Science*. 2017;8:1768. doi:10.3389/fpls.2017.01768.
34. Siddiqui MH, Al-Whaibi MH, Mohammad F, editors. *Nanotechnology and Plant Sciences: Nanoparticles and Their Impact on Plants*. Cham: Springer International Publishing; 2015.
35. Dimkpa CO, McLean JE, Latta DE, Mananon E, Britt DW, Johnson WP, *et al.* CuO and ZnO nanoparticles: Phytotoxicity, metal speciation and induction of oxidative stress in sand-grown wheat. *Journal of Nanoparticle Research*. 2012;14(9):1125. doi:10.1007/s11051-012-1125-9.
36. Lehmann J, Joseph S, editors. *Biochar for Environmental Management: Science, Technology and Implementation*. 2nd ed. London: Routledge; 2015.
37. Haider G, Steffens D, Moser G, Muller C, Kammann CI. Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study. *Agriculture, Ecosystems & Environment*. 2017;237:80-94. doi:10.1016/j.agee.2016.12.019.
38. Biederman LA, Harpole WS. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy*. 2013;5(2):202-214. doi:10.1111/gcbb.12037.
39. Akhtar SS, Andersen MN, Liu F. Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agricultural Water Management*. 2015;158:61-68. doi:10.1016/j.agwat.2015.04.010.
40. Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota: A review. *Soil Biology and Biochemistry*. 2011;43(9):1812-1836. doi:10.1016/j.soilbio.2011.04.022.
41. Haider I, Zulfiqar U, Hussain S, Farooq M, Mehmood T, Nawaz M, *et al.* The critical role of biochar to mitigate the adverse impacts of drought and salinity stress in plants. *Frontiers in Plant Science*. 2023;13:1163451. doi:10.3389/fpls.2023.1163451.
42. Abideen Z, Koyro HW, Huchzermeyer B, Ansari R, Zulfiqar F, Bhatt A. Ameliorating effects of biochar on photosynthetic efficiency and antioxidant defence of *Phragmites karka* under drought stress. *Plant Biology*. 2020;22(2):259-266. doi:10.1111/plb.13054.
43. Hashem A, Abd_Allah EF, Alqarawi AA, Al-Huqail AA, Wirth S, Egamberdieva D. The interaction between arbuscular mycorrhizal fungi and endophytic bacteria enhances plant growth of *Acacia gerrardii* under salt stress. *Frontiers in Microbiology*. 2016;7:1089. doi:10.3389/fmicb.2016.01089.
44. Epstein E. Silicon. *Annual Review of Plant Physiology and Plant Molecular Biology*. 1999;50(1):641-664. doi:10.1146/annurev.arplant.50.1.641.
45. Liang Y, Nikolic M, Belanger R, Gong H, Song A. *Silicon in Agriculture: From Theory to Practice*. Dordrecht: Springer; 2015.
46. Mir RA, Bhat BA, Yousuf H, Islam ST, Raza A, Rizvi MA, *et al.* Multidimensional role of silicon to activate resilient plant growth and to mitigate abiotic stress. *Frontiers in Plant Science*. 2022;13:819658. doi:10.3389/fpls.2022.819658.
47. Zhu Y, Gong H. Beneficial effects of silicon on salt and drought tolerance in plants. *Agronomy for Sustainable Development*. 2014;34(2):455-472. doi:10.1007/s13593-013-0194-1.
48. Soundararajan P, Manivannan A, Ko CH, Jeong BR. Exogenous supplementation of silicon improved the recovery of hyperhydric shoots in *Dianthus caryophyllus* L. *Frontiers in Plant Science*. 2014;5:410. doi:10.3389/fpls.2014.00410.

49. Mir RA, Bhat BA, Yousuf H, Islam ST, Raza A, Rizvi MA, *et al.* Multidimensional role of silicon to activate resilient plant growth and to mitigate abiotic stress. *Frontiers in Plant Science*. 2022;13:819658. doi:10.3389/fpls.2022.819658.
50. Rea R, Islam MR, Rahman MM, Nath B. Growth, nutrient accumulation and drought tolerance in crop plants with silicon application: A review. *Sustainability*. 2022;14(8):4525. doi:10.3390/su14084525.
51. Lal R. Restoring soil quality to mitigate soil degradation. *Sustainability*. 2015;7(5):5875-5895. doi:10.3390/su7055875.
52. Tejada M, Gonzalez JL. Effects of the application of a compost originating from crushed cotton gin residues on wheat yield under dryland conditions. *European Journal of Agronomy*. 2003;19(3):357-368. doi:10.1016/S1161-0301(02)00183-2.
53. English M. Deficit irrigation. I: Analytical framework. *Journal of Irrigation and Drainage Engineering*. 1990;116(3):399-412. doi:10.1061/(ASCE)0733-9437(1990)116:3(399).
54. Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*. 2007;58(2):147-159. doi:10.1093/jxb/erl165.
55. Zhang H, Oweis T. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural Water Management*. 1999;38(3):195-211. doi:10.1016/S0378-3774(98)00069-9.
56. Davies WJ, Wilkinson S, Loveys B. Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist*. 2002;153(3):449-460. doi:10.1046/j.0028-646X.2001.00345.x.
57. Kang S, Zhang J. Controlled alternate partial root-zone irrigation: Its physiological consequences and impact on water use efficiency. *Journal of Experimental Botany*. 2004;55(407):2437-2446. doi:10.1093/jxb/erh249.
58. Postel SL. Entering an era of water scarcity: The challenges ahead. *Ecological Applications*. 2000;10(4):941-948. doi:10.1890/1051-0761(2000)010[0941:EAEOWS]2.0.CO;2.
59. Hanson BR, Simunek J, Hopmans JW. Evaluation of urea-ammonium-nitrate fertigation with drip irrigation using numerical modeling. *Agricultural Water Management*. 2006;86(1-2):102-113. doi:10.1016/j.agwat.2006.06.013.
60. Rockstrom J, Barron J, Fox P. Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth*. 2002;27(11-22):949-959. doi:10.1016/S1474-7065(02)00098-0.
61. Hobbs PR, Sayre K, Gupta R. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B*. 2008;363(1491):543-555. doi:10.1098/rstb.2007.2169.
62. Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Kumar V, *et al.* Evaluation of precision land leveling and double zero-till systems in the rice-wheat rotation. *Soil and Tillage Research*. 2009;105(1):112-121. doi:10.1016/j.still.2009.06.003.
63. Ramakrishna A, Tam HM, Wani SP, Long TD. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. *Field Crops Research*. 2006;95(2-3):115-125. doi:10.1016/j.fcr.2005.01.030.
64. Chalker-Scott L. Impact of mulches on landscape plants and the environment: A review. *Journal of Environmental Horticulture*. 2007;25(4):239-249.
65. Li FM, Wang J, Xu JZ, Xu HL. Productivity and soil response to plastic film mulching durations for spring wheat on entisols in the semiarid Loess Plateau of China. *Soil and Tillage Research*. 2004;78(1):9-20. doi:10.1016/j.still.2003.12.009.
66. Erenstein O. Smallholder conservation farming in the tropics and sub-tropics: A guide to the development and dissemination of mulching with crop residues and cover crops. *Agriculture, Ecosystems & Environment*. 2003;100(1):17-37. doi:10.1016/S0167-8809(03)00150-6.
67. Hou XY, Wang FX, Han JJ, Kang SZ, Feng SY. Duration of plastic mulch for potato growth under drip irrigation in an arid region of northwest China. *Agricultural and Forest Meteorology*. 2010;150(1):115-121. doi:10.1016/j.agrformet.2009.09.007.
68. Tanner CB. Microclimate modification: Row direction effects. *HortScience*. 1974;9(6):578-580.
69. Siebert S, Ewert F. Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length. *Agricultural and Forest Meteorology*. 2012;152:44-57. doi:10.1016/j.agrformet.2011.08.007.
70. Ortiz R, Sayre KD, Govaerts B, Gupta R, Subbarao GV, Ban T, *et al.* Climate change: Can wheat beat the heat? *Agriculture, Ecosystems & Environment*. 2008;126(1-2):46-58. doi:10.1016/j.agee.2008.01.019.
71. Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, *et al.* Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*. 2015;206(1):107-117. doi:10.1111/nph.13132.
72. Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios DN. Annual intercrops: An alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*. 2011;5(4):396-410.
73. Raseduzzaman M, Jensen ES. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*. 2017;91:25-33. doi:10.1016/j.eja.2017.09.009.
74. Ashraf M, Foolad MR. Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environmental and Experimental Botany*. 2007;59(2):206-216. doi:10.1016/j.envexpbot.2005.12.006.
75. Hayat S, Hayat Q, Alyemeni MN, Wani AS, Pichtel J, Ahmad A. Role of proline under changing environments: A review. *Plant Signaling & Behavior*. 2012;7(11):1456-1466. doi:10.4161/psb.21949.
76. Szabados L, Savoure A. Proline: A multifunctional amino acid. *Trends in Plant Science*. 2010;15(2):89-97. doi:10.1016/j.tplants.2009.11.009.
77. Farooq M, Wahid A, Lee DJ. Exogenously applied polyamines increase drought tolerance of rice by improving leaf water status, photosynthesis and membrane properties. *Acta Physiologiae Plantarum*. 2009;31(5):937-945. doi:10.1007/s11738-009-0307-2.
78. Garg AK, Kim JK, Owens TG, Ranwala AP, Choi YD, Kochian LV, *et al.* Trehalose accumulation in rice plants confers high tolerance levels to different abiotic stresses. *Proceedings of the National Academy of Sciences*. 2002;99(25):15898-15903. doi:10.1073/pnas.252637799.
79. Fahad S, Hussain S, Bano A, Saud S, Hassan S, Shan D, *et al.* Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses. *Environmental*

- Science and Pollution Research. 2015;22(7):4907-4921. doi:10.1007/s11356-014-3754-2.
80. Wilkinson S, Davies WJ. Drought, ozone, ABA and ethylene: New insights from cell to plant to community. *Plant, Cell & Environment*. 2010;33(4):510-525. doi:10.1111/j.1365-3040.2009.02052.x.
 81. Fariduddin Q, Yusuf M, Ahmad I, Ahmad A. Brassinosteroids and their role in response of plants to abiotic stresses. *Biologia Plantarum*. 2014;58(1):9-17. doi:10.1007/s10535-013-0374-5.
 82. Khan MIR, Fatma M, Per TS, Anjum NA, Khan NA. Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. *Frontiers in Plant Science*. 2015;6:462. doi:10.3389/fpls.2015.00462.
 83. Rivas-San Vicente M, Plasencia J. Salicylic acid beyond defence: Its role in plant growth and development. *Journal of Experimental Botany*. 2011;62(10):3321-3338. doi:10.1093/jxb/err031.
 84. Alcazar R, Altabella T, Marco F, Bortolotti C, Reymond M, Koncz C, *et al.* Polyamines: Molecules with regulatory functions in plant abiotic stress tolerance. *Planta*. 2010;231(6):1237-1249. doi:10.1007/s00420-010-1513-0.
 85. Farooq M, Wahid A, Lee DJ. Exogenously applied polyamines increase drought tolerance of rice by improving leaf water status, photosynthesis and membrane properties. *Acta Physiologiae Plantarum*. 2009;31(5):937-945. doi:10.1007/s11738-009-0307-2.
 86. Glick BR. Plant growth-promoting bacteria: Mechanisms and applications. *Scientifica*. 2012;2012:963401. doi:10.6064/2012/963401.
 87. Lugtenberg B, Kamilova F. Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology*. 2009;63:541-556. doi:10.1146/annurev.micro.62.081307.162918.
 88. Bhattacharyya PN, Jha DK. Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. *World Journal of Microbiology and Biotechnology*. 2012;28(4):1327-1350. doi:10.1007/s11274-011-0979-9.
 89. Yang J, Kloepper JW, Ryu CM. Rhizosphere bacteria help plants tolerate abiotic stress. *Trends in Plant Science*. 2009;14(1):1-4. doi:10.1016/j.tplants.2008.10.004.
 90. Ngumbi E, Kloepper J. Bacterial-mediated drought tolerance: Current and future prospects. *Applied Soil Ecology*. 2016;105:109-125. doi:10.1016/j.apsoil.2016.04.009.
 91. Vurukonda SSKP, Vardharajula S, Shrivastava M, SkZ A. Enhancement of drought stress tolerance in crops by plant growth promoting rhizobacteria. *Microbiological Research*. 2016;184:13-24. doi:10.1016/j.micres.2015.12.003.
 92. Kasim WA, Osman ME, Omar MN, Abd El-Daim IA, Bejai S, Meijer J. Control of drought stress in wheat using plant-growth-promoting bacteria. *Journal of Plant Growth Regulation*. 2013;32(1):122-130. doi:10.1007/s00344-012-9283-7.
 93. Timmusk S, Abd El-Daim IA, Copolovici L, Tanilas T, Kannaste A, Behers L, *et al.* Drought-tolerance of wheat improved by rhizosphere bacteria from harsh environments. *PLOS ONE*. 2014;9(5):e96086. doi:10.1371/journal.pone.0096086.
 94. Shrivastava P, Kumar R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences*. 2015;22(2):123-131. doi:10.1016/j.sjbs.2014.12.001.
 95. Ilangumaran G, Smith DL. Plant growth promoting rhizobacteria in amelioration of salinity stress: A systems biology perspective. *Frontiers in Plant Science*. 2017;8:1768. doi:10.3389/fpls.2017.01768.
 96. Ali SZ, Sandhya V, Rao LV. Isolation and characterization of drought-tolerant ACC deaminase and exopolysaccharide-producing fluorescent *Pseudomonas* sp. *Annals of Microbiology*. 2014;64(2):493-502. doi:10.1007/s13213-013-0680-3.
 97. Mukhtar T, Smith D, Sultan T, Siddique S, Rashid M, Khan V, *et al.* Mitigation of heat stress in *Solanum lycopersicum* L. by ACC-deaminase and exopolysaccharide producing *Bacillus cereus*. *Sustainability*. 2020;12(6):2159. doi:10.3390/su12062159.
 98. Rojas-Tapias D, Moreno-Galvan A, Pardo-Diaz S, Obando M, Rivera D, Bonilla R. Effect of inoculation with plant growth-promoting bacteria (PGPB) on amelioration of saline stress in maize. *Applied Soil Ecology*. 2012;61:264-272. doi:10.1016/j.apsoil.2012.01.006.
 99. Nadeem SM, Ahmad M, Zahir ZA, Javaid A, Ashraf M. The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. *Biotechnology Advances*. 2014;32(2):429-448. doi:10.1016/j.biotechadv.2013.12.005.
 100. Farooq M, Hussain M, Wahid A, Siddique KHM. Drought stress in plants: An overview. In: Aroca R, editor. *Plant Responses to Drought Stress*. Berlin, Heidelberg: Springer; 2012. p. 1-33. doi:10.1007/978-3-642-32653-0_1.
 101. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science*. 2004;304(5677):1623-1627. doi:10.1126/science.1097396.
 102. Araus JL, Slafer GA, Reynolds MP, Royo C. Plant breeding and drought in C3 cereals: What should we breed for? *Annals of Botany*. 2002;89(7):925-940. doi:10.1093/aob/mcf049.
 103. Ismail AM, Horie T, Xin X, Jabeen H, Mohamed MS, Shafqat MN, *et al.* Mechanisms associated with tolerance to flooding during germination and early seedling growth in rice. *Annals of Botany*. 2009;103(2):197-209. doi:10.1093/aob/mcn211.
 104. Asseng S, Foster I, Turner NC. The impact of temperature variability on wheat yields. *Global Change Biology*. 2011;17(2):997-1012. doi:10.1111/j.1365-2486.2010.02262.x.
 105. Gebbers R, Adamchuk VI. Precision agriculture and food security. *Science*. 2010;327(5967):828-831. doi:10.1126/science.1183899.
 106. Liakos KG, Busato P, Moshou D, Pearson S, Bochtis D. Machine learning in agriculture: A review. *Sensors*. 2018;18(8):2674. doi:10.3390/s18082674.
 107. Kamilaris A, Prenafeta-Boldu FX. Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*. 2018;147:70-90. doi:10.1016/j.compag.2018.02.016.
 108. Lobell DB, Gourdji SM. The influence of climate change on global crop productivity. *Plant Physiology*. 2012;160(4):1686-1697. doi:10.1104/pp.112.208298.
 109. Nkonya E, Mirzabaev A, von Braun J, editors. *Economics of Land Degradation and Improvement: A Global Assessment for Sustainable Development*. Cham: Springer International Publishing; 2016.
 110. Bashan Y, de-Bashan LE, Prabhu SR, Hernandez JP. Advances in plant growth-promoting bacterial inoculant technology: Formulations and practical perspectives (1998-

- 2013). Plant and Soil. 2014;378(1-2):1-33. doi:10.1007/s11104-013-1956-x.
111. du Jardin P. Plant biostimulants: Definition, concept, main categories and regulation. Scientia Horticulturae. 2015;196:3-14. doi:10.1016/j.scienta.2015.09.021.
112. Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, *et al.* Biochar in climate change mitigation. Nature Geoscience. 2021;14(12):883-892. doi:10.1038/s41561-021-00852-8.
113. Challinor AJ, Watson J, Lobell DB, Howden SM, Smith DR, Chhetri N. A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change. 2014;4(4):287-291. doi:10.1038/nclimate2153.
114. Mittler R, Blumwald E. Genetic engineering for modern agriculture: Challenges and perspectives. Annual Review of Plant Biology. 2010;61:443-462. doi:10.1146/annurev-arplant-042809-112116.
115. Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. Nature Communications. 2010;1:56. doi:10.1038/ncomms1053.
116. Zhu JK. Abiotic stress signaling and responses in plants. Cell. 2016;167(2):313-324. doi:10.1016/j.cell.2016.08.029.
117. Furbank RT, Tester M. Phenomics: Technologies to relieve the phenotyping bottleneck. Trends in Plant Science. 2011;16(12):635-644. doi:10.1016/j.tplants.2011.09.005.
118. Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H. Adapting agriculture to climate change. Proceedings of the National Academy of Sciences. 2007;104(50):19691-19696. doi:10.1073/pnas.0701890104.
119. Vermeulen SJ, Campbell BM, Ingram JSI. Climate change and food systems. Annual Review of Environment and Resources. 2012;37:195-222. doi:10.1146/annurev-environ-020411-130608.