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PGPR for Climate-Resilient Vegetable Production

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Vegetable production is increasingly challenged by climate variability, including irregular rainfall, prolonged drought, soil salinity, heat waves and low temperature. These stresses interfere with root growth, nutrient acquisition, photosynthesis, reproductive development and ultimately yield and quality. Plant growth-promoting rhizobacteria (PGPR) represent an important biological approach for strengthening vegetable crop resilience under such fluctuating environments. PGPR are beneficial bacteria that colonize the rhizosphere or root surface and promote plant performance through diverse mechanisms, including biological nitrogen fixation, phosphate solubilization, potassium mobilization, siderophore production, phytohormone modulation, 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity, exopolysaccharide production and induction of antioxidant defence. Under abiotic stress, these microorganisms can improve root architecture, water relations, nutrient-use efficiency, osmotic adjustment, reactive oxygen species detoxification and ion homeostasis. Research in tomato, pepper, cucumber, cabbage and eggplant demonstrates the potential of PGPR to improve plant survival and physiological performance under drought, salinity and temperature stress. However, inconsistent field performance caused by strain–genotype interactions, poor rhizosphere colonization, formulation instability and environmental variability remain a major challenge. Future PGPR research should therefore move from single-strain laboratory screening towards stress-specific microbial consortia, genomic selection, robust formulations and multi-location field validation. PGPR-based bioinoculants, when integrated with irrigation management, organic matter management and climate-resilient cultivars, could become an important component of climate-smart vegetable production.

Keywords: PGPR, rhizobacteria, vegetable crops, climate resilience, drought, salinity, heat stress, biofertilizer, abiotic stress, sustainable horticulture

Introduction: Why Do Vegetables Need Microbial Allies?

Vegetable crops are generally high-value and nutrient-dense crops, but many vegetables have relatively shallow or sensitive root systems and high water and nutrient requirements. Consequently, fluctuations in soil moisture, temperature and salinity can rapidly affect vegetative growth, flowering, fruit set and marketable yield. Drought reduces leaf water status and stomatal conductance, salinity imposes both osmotic and ionic stress, while high temperature can disturb photosynthesis, membrane stability, pollen viability and reproductive development. Climate-resilient vegetable production therefore requires approaches that do more than simply supply nutrients. The plant must be able to acquire resources efficiently, maintain physiological activity during stress and recover rapidly after stress. This is where PGPR become important. PGPR are beneficial rhizosphere-associated bacteria capable of stimulating plant growth directly or indirectly. Their functions include nutrient mobilization, hormone regulation, pathogen suppression and induction of plant defence and stress tolerance. Recent reviews specifically identify PGPR as promising biological tools for climate-smart vegetable production.

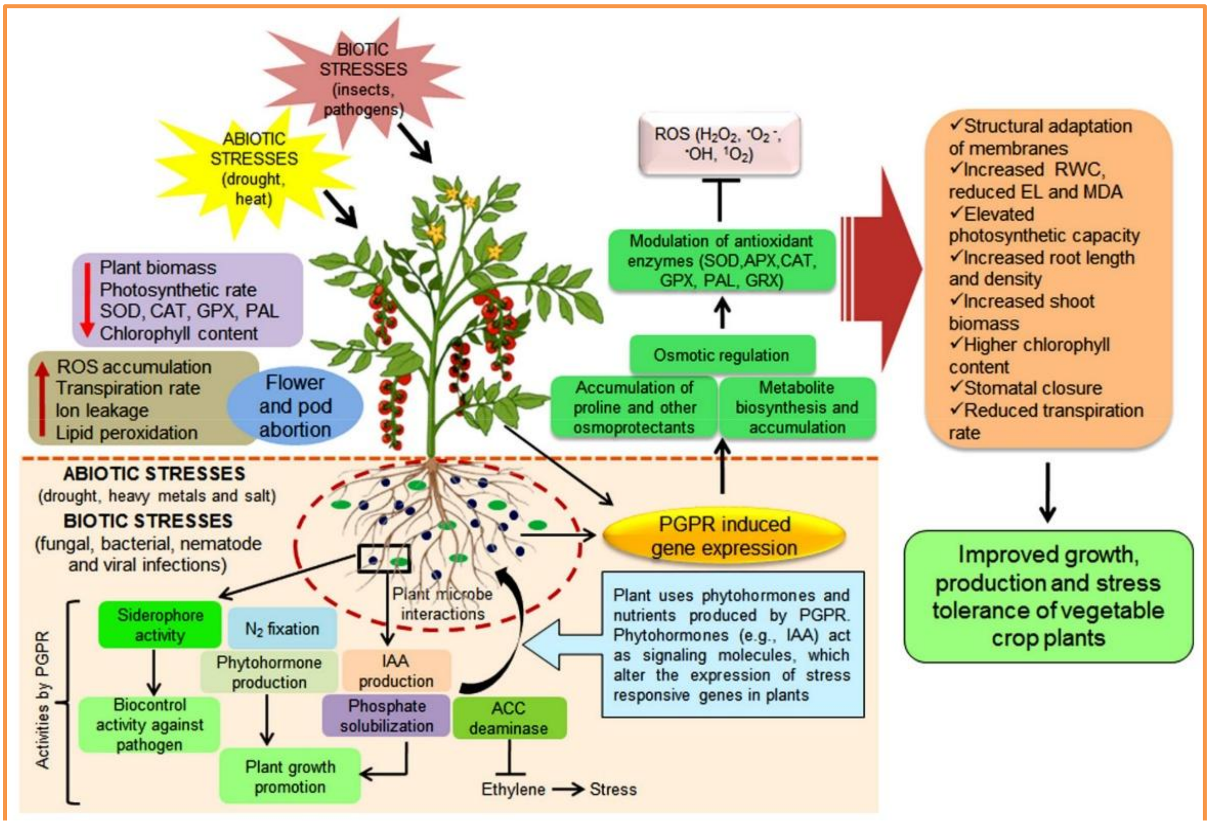


Fig.1. PGPR emerging as an effective bioinoculant to improve growth, production and stress tolerance

How PGPR Make Vegetable Crops More Climate Resilient

PGPR do not simply act as conventional biofertilizers. Their importance under climate stress arises from a network of biochemical, physiological and molecular interactions.

Table 1. Major PGPR mechanisms contributing to climate resilience in vegetable crops

PGPR mechanism	Major effect on plant	Relevance under climate stress
Nitrogen fixation	Improves N availability	Supports growth when nutrient uptake is restricted
Phosphate solubilization	Releases unavailable P	Maintains energy metabolism and root development
Potassium mobilization	Improves K acquisition	Helps stomatal regulation and water balance
IAA production	Stimulates root development	Greater root exploration improves water and nutrient capture
ACC deaminase	Reduces stress-induced ethylene	Prevents excessive growth inhibition
Siderophore production	Improves Fe acquisition	Supports chlorophyll formation and metabolism
Exopolysaccharides	Improves rhizosphere aggregation and water retention	Particularly useful under drought and salinity
Antioxidant stimulation	Enhances SOD, CAT, APX and related systems	Limits oxidative damage
Osmolyte accumulation	Promotes proline, sugars and related compounds	Maintains cellular water balance
Ion regulation	Restricts Na^+/Cl^- accumulation or improves K^+ balance	Important under salinity
Induced systemic tolerance	Activates stress-responsive pathways	Provides broader physiological protection

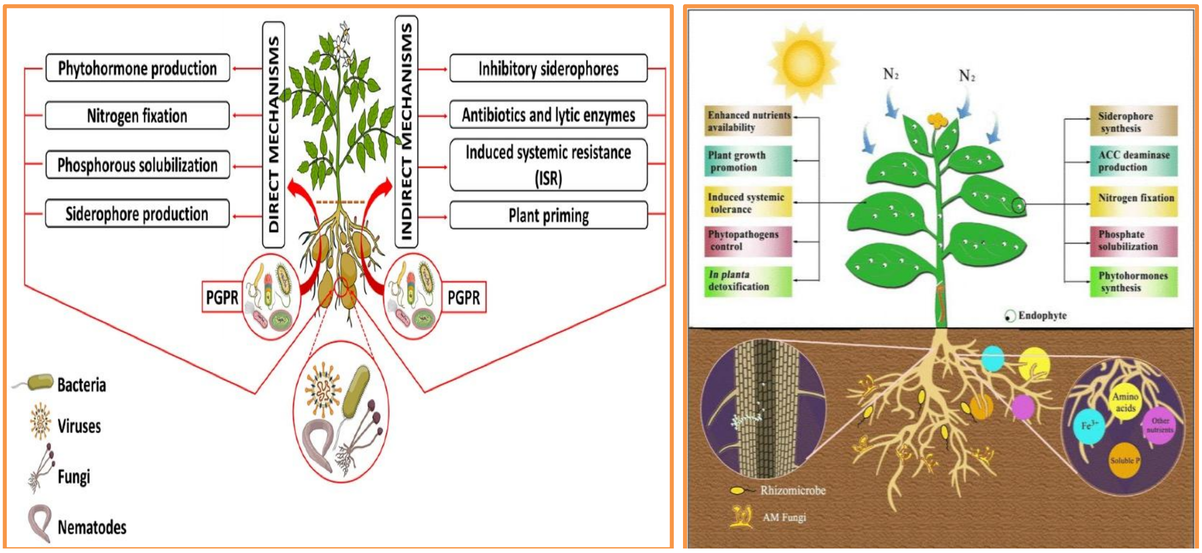
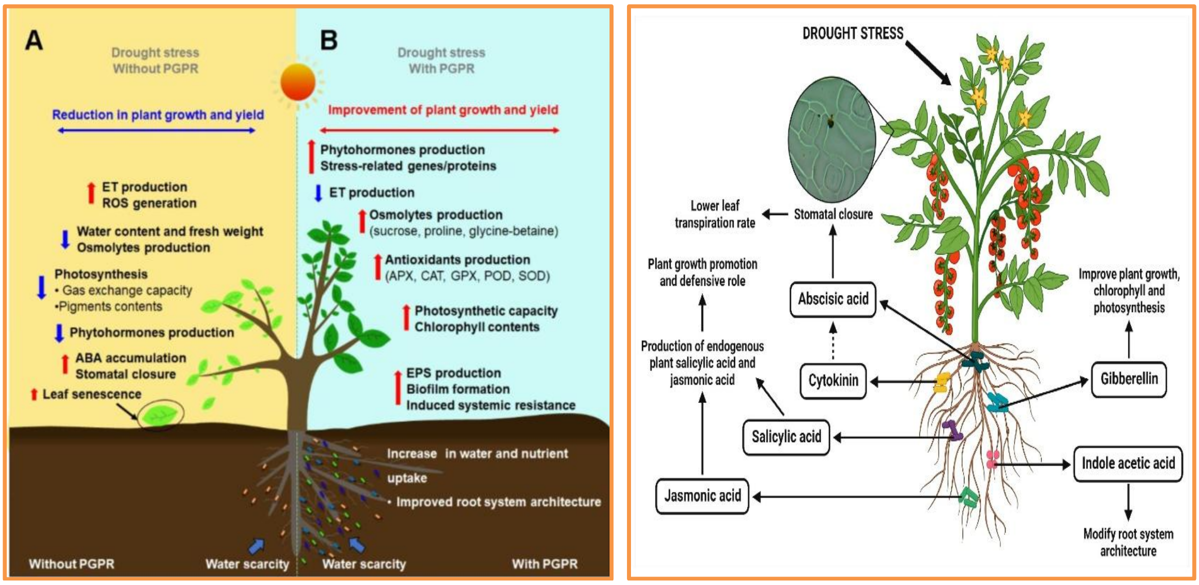


Fig.2. PGPR mechanisms contributing to climate resilience in vegetable crops

PGPR-mediated stress tolerance is therefore a multilayered phenomenon rather than a single biochemical response. Recent research highlights hormone regulation, antioxidant defence, osmoprotection, ion regulation and rhizosphere microbiome restructuring as interconnected components of PGPR-mediated stress tolerance.

PGPR and Drought Resilience

Drought causes cellular dehydration, stomatal closure, reduced carbon dioxide assimilation, impaired nutrient uptake and oxidative stress. In vegetables, prolonged water deficit can reduce leaf area, root growth, flowering and fruit development. PGPR can counter these effects by modifying root architecture and regulating plant hormones. IAA-producing bacteria can stimulate lateral roots and root hairs, increasing the soil volume explored by the plant. Some PGPR also produce ACC deaminase, which lowers the concentration of stress-induced ethylene and prevents excessive inhibition of root and shoot growth. A particularly illustrative experiment was reported in pepper using *Bacillus licheniformis* K11. Under progressive drought, inoculated plants showed substantially better root and shoot growth and approximately 80% survival after 15 days, whereas the uninoculated drought-stressed plants did not survive. The bacterium also altered stress-related protein and gene expression, demonstrating that PGPR-mediated drought tolerance can extend from root colonization to molecular regulation. It further indicates that drought-tolerant PGPR can improve root elongation, phytohormone production, volatile organic compound signalling and antioxidant protection.



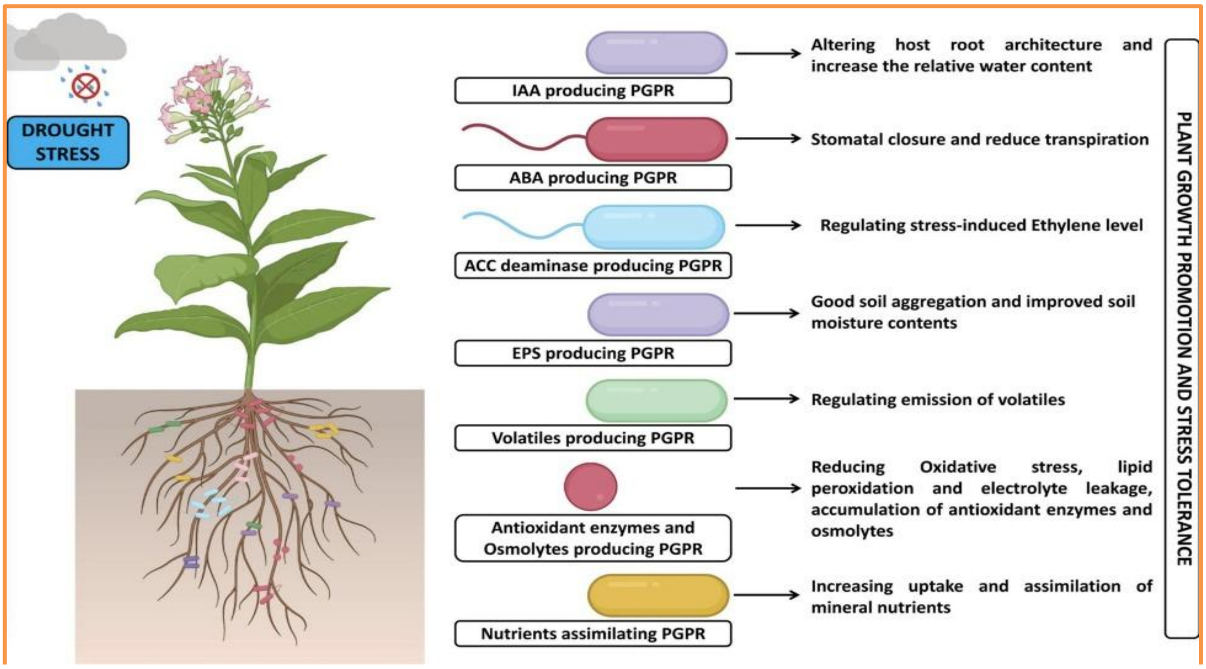


Fig.3. PGPR and Drought Resilience

PGPR Against Salinity Stress

Salinity represents a dual challenge: **osmotic stress** restricts water uptake, while excessive Na^+ and Cl^- cause ionic toxicity and nutritional imbalance. Sensitive vegetables such as tomato, chilli, cucumber and eggplant can show reduced germination, root growth, leaf expansion and yield under saline conditions.

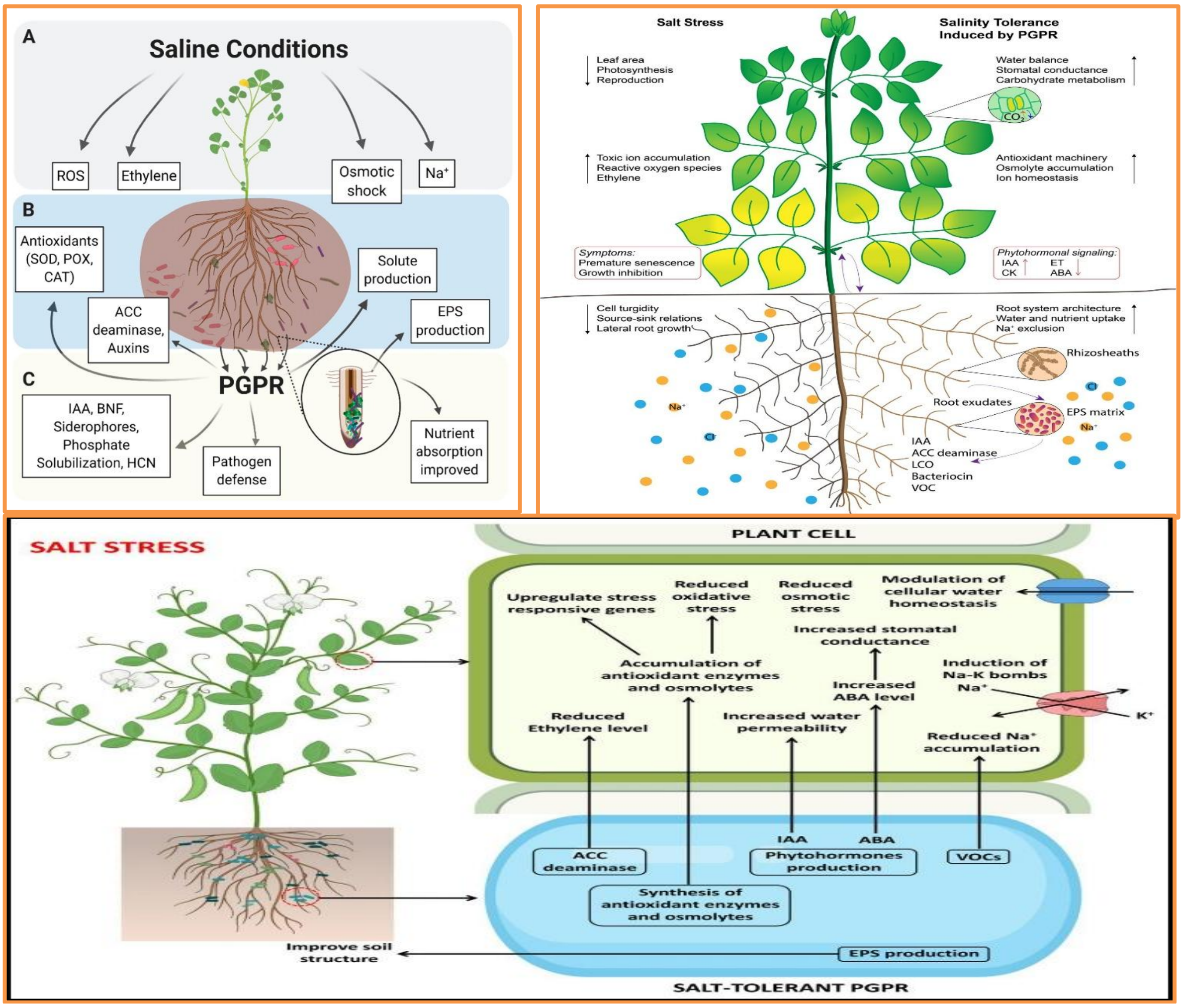


Fig.4. PGPR against salinity stress

PGPR may reduce salt injury through several mechanisms. Exopolysaccharides can modify the rhizosphere environment, while improved root development facilitates resource acquisition. PGPR can also stimulate antioxidant enzymes and influence ion homeostasis. For example, recent synthesis of vegetable research reports that PGPR treatment in eggplant under 50 mM NaCl increased antioxidant defence and reduced root Na^+ accumulation; SOD and glutathione reductase activities increased by approximately 38.7% and 22.9%, respectively, while root Na^+ concentration decreased by approximately 38.4%. This demonstrates an important principle: "salt tolerance is not simply a matter of excluding sodium; it involves maintaining cellular redox balance, nutrient status and water relations simultaneously".

PGPR for Heat and Temperature Stress

High temperature is becoming increasingly important in vegetable cultivation. Heat stress can impair photosynthetic machinery, destabilize membranes, accelerate respiration and reduce pollen viability and fruit set.

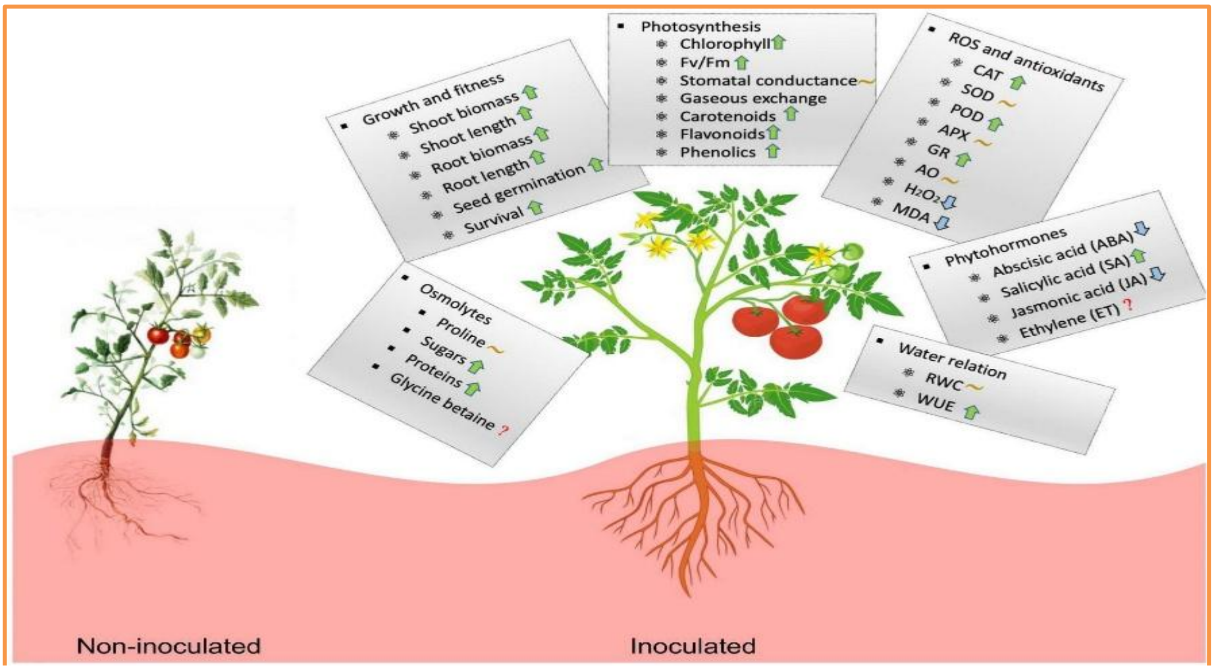


Fig.5. Mechanism of PGPR against heat stress

PGPR may improve thermotolerance by enhancing antioxidant defence, regulating phytohormones, stimulating osmoprotectants and modifying stress-responsive gene expression. An interesting example is *Bacillus zanthoxyli* HS1 in cucumber. Recent literature reports that this bacterium can influence stomatal behaviour, callose deposition and antioxidant enzymes such as superoxide dismutase and catalase under heat and salt stress. Such responses are important because heat resilience depends not on a single trait but on the ability of the plant to maintain photosynthesis, membrane integrity, water balance and reproductive function simultaneously.

PGPR and Nutrient-Use Efficiency

Climate resilience is closely connected with nutrient-use efficiency. Drought and salinity can reduce nutrient diffusion and root uptake, making fertilizer application less effective. PGPR can mobilize nutrients through phosphate solubilization, potassium release, siderophore production and biological nitrogen fixation. They may also improve root surface area and root physiological activity. Thus, the role of PGPR should not be viewed simply as "replacing fertilizer." A more scientifically appropriate concept is improving nutrient acquisition and utilization within an integrated nutrient management system. For vegetable production, this approach can potentially reduce unnecessary nutrient losses while maintaining crop productivity. Recent reviews identify improved nutrient- and water-use efficiency as major components of PGPR-mediated climate resilience.

PGPR, Root Architecture and the Rhizosphere

The root is the first interface between the crop and a changing soil environment. A vigorous root system is therefore fundamental to climate resilience. PGPR can influence root length, lateral root formation, root hair development and root biomass through IAA and other signalling molecules. Some bacteria also produce extracellular polymers that contribute to biofilm formation and rhizosphere aggregation. The result is a more biologically active rhizosphere in which plants and microorganisms exchange signals and resources.

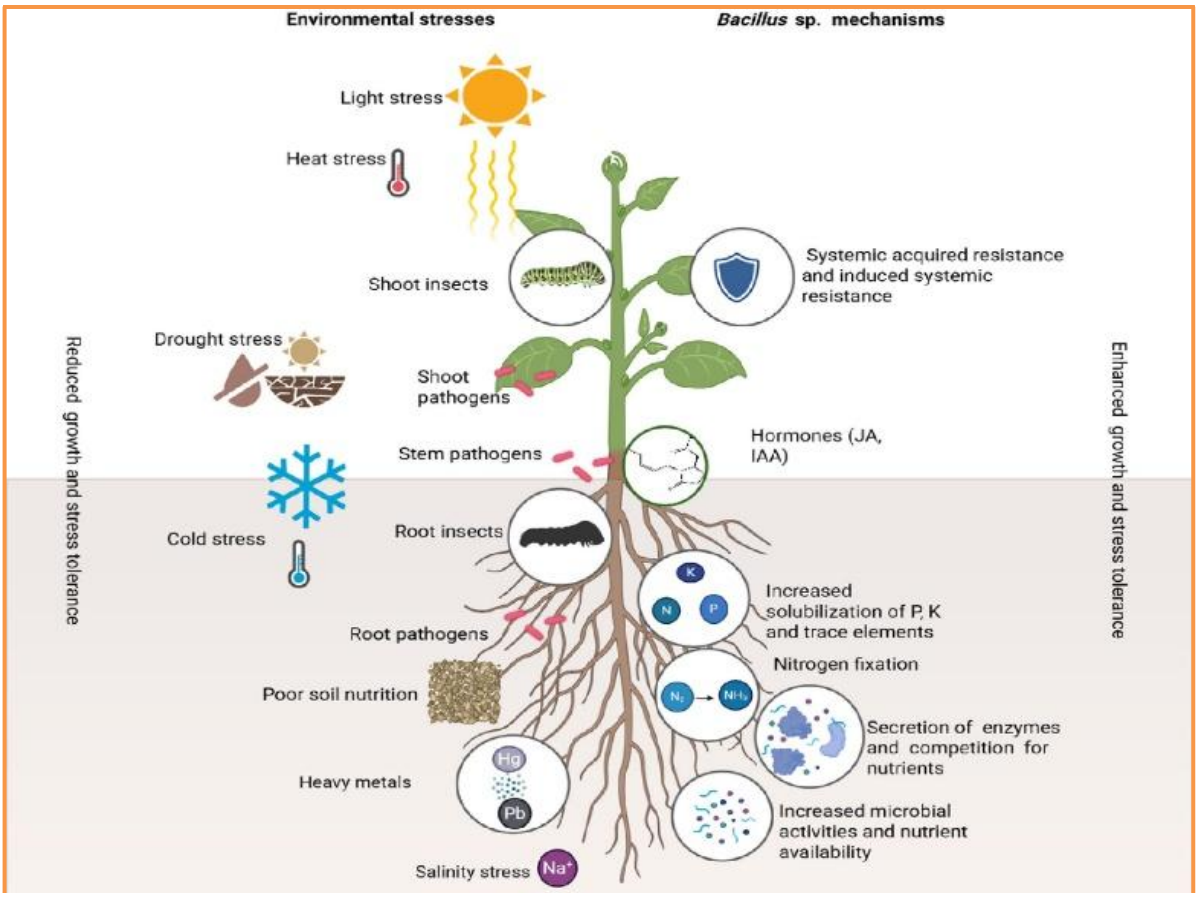


Fig.6. PGPR-mediated stress tolerance in vegetable crops

Table 2. Examples of PGPR-mediated stress tolerance in vegetable crops

Vegetable crop	PGPR/example	Stress	Reported response
Pepper	*Bacillus licheniformis* K11	Drought	Improved root/shoot growth and survival; altered stress-related proteins
Cabbage	*Flavobacterium* sp. GJW24	Drought	Regulation of stomatal closure and drought-responsive genes
Cucumber	*Bacillus zanthoxyli* HS1	Heat + salinity	Antioxidant and stomatal responses
Eggplant	PGPR strains	Salinity	Enhanced antioxidant defence and reduced Na^+ accumulation
Tomato	Various PGPR	Drought/salinity	Improved osmotic adjustment, nutrient acquisition and stress tolerance
Chilli/ pepper	Various PGPR	Drought	Improved hormonal regulation and stress responses

From Laboratory Success to Farmer's Field

One of the most important issues in PGPR research is the difference between controlled-environment performance and field performance. A strain that performs exceptionally well in a Petri plate, pot or greenhouse may fail in the field because of competition with indigenous microorganisms, unsuitable soil pH, temperature fluctuations, moisture variability, poor root colonization or incompatibility with the crop genotype.

A 2024 systematic review noted that much of the PGPR literature on drought and salinity has been generated under laboratory or greenhouse conditions and emphasized the need for more field-level validation. Therefore, future PGPR research should evaluate:

- Root colonization efficiency
- Survival and persistence of inoculants
- Compatibility with vegetable genotypes
- Interaction with native microbiomes
- Shelf life and formulation stability
- Dose and application method
- Compatibility with fertilizers and pesticides
- Yield and marketable quality
- Economic returns
- Multi-location performance

Recent research also identifies low rhizosphere colonization and ecological instability as major barriers to large-scale PGPR implementation.

The Next Generation: PGPR Consortia and Precision Microbial Agriculture

The future of PGPR technology is unlikely to depend exclusively on single bacterial strains. Different microorganisms perform different functions: one may solubilize phosphate, another may produce ACC deaminase, while another may enhance stress signalling or suppress pathogens. Therefore, designed microbial consortia containing compatible strains could provide broader and more stable benefits. Emerging research directions include:

1. Stress-specific PGPR screening.
2. Microbial consortia designed for drought, salinity or heat.
3. Genomic and metagenomic identification of elite strains.
4. Biofilm engineering to improve root colonization.
5. Encapsulation and advanced formulations for longer shelf life.
6. Integration of PGPR with drip irrigation and fertigation.
7. PGPR × genotype interaction studies.
8. Microbiome-assisted breeding.
9. Precision application according to soil and climate conditions.
10. Life-cycle assessment of microbial inputs.

Practical Framework for PGPR-Based Climate-Resilient Vegetable Production

PGPR should be incorporated as one component of an integrated production system rather than considered a standalone solution.

Table 3. Practical PGPR strategy for climate-resilient vegetable cultivation

Production stage	Recommended approach
Nursery	Seed treatment or root-zone inoculation with compatible PGPR
Transplanting	Root dipping or soil application where recommended
Soil preparation	Combine PGPR with adequate organic matter and good soil structure
Irrigation	Integrate with efficient irrigation such as drip irrigation
Fertilization	Use within integrated nutrient management rather than indiscriminately replacing fertilizers
Stress period	Maintain appropriate soil moisture and monitor salinity/temperature
Evaluation	Record plant growth, root traits, physiological responses, yield and quality
Long-term strategy	Select locally adapted strains and validate under field conditions

PGPR can therefore become most effective when combined with stress-tolerant cultivars, organic matter management, mulching, efficient irrigation, balanced nutrition and appropriate crop scheduling.

Conclusion

Climate change is transforming vegetable production from a question of simply achieving maximum yield into a challenge of maintaining stable productivity under environmental uncertainty. PGPR offer a biologically based strategy for strengthening this resilience. Their importance lies in their multifunctionality. By improving root architecture, nutrient acquisition, hormone regulation, antioxidant defence, osmotic adjustment and ion homeostasis, PGPR can help vegetables withstand drought, salinity and temperature extremes. Evidence from pepper, cabbage, cucumber, eggplant and other vegetable systems demonstrates considerable promise, although field-level consistency remains a major research challenge. The future should therefore move beyond the concept of PGPR as simple biofertilizers. They should be developed as climate-responsive microbial technologies tailored to particular vegetable crops, soils and stress environments. The most promising pathway is an integrated model in which climate-resilient genotypes + efficient irrigation + balanced nutrition + healthy soils + precision PGPR inoculation works together. Such an approach can transform the invisible microbial community around vegetable roots into a practical biological resource for sustainable and climate-resilient horticulture.

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