Popular Agriculture **2(5) 203-209(September, 2026)**
Published at popularagriculture.com

Global E-Magazine
ISSN: 3139-7603

POPULAR ARTICLE

Climate-resilient crop varieties in India: scope, status, success stories and the way forward for food security

K.M. Boraiah[1], P.S. Basavaraj[2], H.B. Santosh[3], N.K. Bhojaraja[4], R. Sultana[5], J. Nilesh[6], C.B. Harisha[7], H.M. Hanamant[8], K. Prakash[9]

1 ICAR-National Institute of Abiotic Stress Management (NIASM), Baramati 413115, Maharashtra, India

2 ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad 500059, Telangana, India

3 ICAR-National Institute of Seed Science and Technology Regional Station, Bengaluru 560065, Karnataka, India

Corresponding authors email: bors_km@yahoo.co.in

Manuscript received: August 19, 2026; Decision on manuscript, August 25, 2026; Manuscript accepted: September 1, 2026

Intricacies of the subject

Climate change poses increasing risks to Indian agriculture, particularly rainfed farming, through drought, heat, erratic rainfall, floods and salinity. Climate-resilient crop varieties can reduce these risks and support stable productivity and food security. India has made significant progress in developing varieties tolerant to major abiotic stresses, with successful examples in rice, groundnut and other crops. However, future breeding must focus on multi-trait climate-smart varieties combining stress tolerance with yield stability, quality, disease resistance and farmer acceptance. Emerging tools such as genomics, high-throughput phenotyping and artificial intelligence can accelerate varietal development. Equally important are efficient seed systems, including seed villages, decentralized seed production, farmer-level enterprises and digital platforms, to ensure timely access to quality seed. Integrating breeding innovation with effective seed delivery, farmer awareness and on-farm evaluation will be crucial for strengthening India's climate resilience and food security.

Introduction

Indian agriculture is increasingly exposed to the adverse impacts of climate variability and climate change. Rising temperatures, erratic and uneven rainfall, prolonged dry spells, recurrent floods, salinity, soil degradation and extreme weather events are posing significant challenges to agricultural productivity and farm livelihoods. The impacts are particularly pronounced in rainfed and resource-constrained production systems, where farmers have limited capacity to compensate for climatic uncertainties through irrigation and other external inputs. Under these circumstances, the development and deployment of climate-resilient crop varieties represent one of the most important strategies for sustaining agricultural productivity and ensuring food and nutritional security. Crop varieties possessing tolerance to drought, heat, cold, salinity, submergence, soil acidity and other abiotic stresses can reduce production risks and contribute to greater stability of yield under variable environmental conditions (Boraiah *et al*. 2022). Climate-resilient varieties, therefore, should not be viewed merely as alternatives for stress-prone environments. They constitute an important component of a broader strategy for developing climate-smart and resource-efficient agriculture in India.

India's progress in developing climate-resilient varieties

The Indian agricultural research system has made substantial progress in developing crop varieties adapted to diverse abiotic stresses. The National Agricultural Research System (NARS), comprising the Indian Council of Agricultural Research (ICAR), State Agricultural Universities and other public-sector research institutions, has released a large number of varieties with improved tolerance to drought, salinity, submergence, heat, cold and soil-related stresses. Available institutional information indicates that more than 750 abiotic stress-tolerant crop varieties have been developed and released over the past two decades (Boraiah *et al*. 2021). Drought-tolerant varieties constitute a major proportion of these releases, reflecting the extensive area under rainfed agriculture and the recurring occurrence of moisture stress. Varieties tolerant to salinity and acidity, submergence, heat and low temperature constitute other important components of this portfolio. Major food and agricultural crops, including rice, wheat, chickpea, mustard and groundnut, have received considerable attention because of their contribution to national food security and their large cultivation area. Despite these achievements, the development of a variety does not automatically translate into widespread adoption. Limited availability of quality seed, inadequate awareness among farmers, insufficient demonstrations, lack of region-specific recommendations and concerns regarding performance under non-stress conditions continue to restrict the adoption of several stress-tolerant varieties. Consequently, future breeding programmes must focus not only on stress tolerance but also on yield potential, stability, quality, profitability and farmer acceptability.

Climate-resilient crop varieties: performance and success stories

Drought-tolerant rice varieties

Rice production in eastern and central India is highly dependent on the onset and distribution of monsoon rainfall. Delayed rainfall and prolonged dry spells during crop establishment and reproductive development can cause substantial yield losses. Drought-tolerant and drought-escaping varieties such as Sahbhagi Dhan have demonstrated the potential of genetic improvement to reduce the impact of intermittent drought. Short-duration varieties such as Sahbhagi Dhan, Anjali, and Birsa Vikas Dhan 109 are particularly valuable in rainfed production systems because they can complete their life cycle within a shorter period and thereby reduce exposure to terminal moisture stress (Boraiah *et al*. 2023 and 2021). Such varieties demonstrate how appropriate genetic adaptation can complement agronomic and water-management interventions in drought-prone environments.

Submergence-tolerant rice varieties

Flooding represents another major climatic risk to rice production, particularly in eastern India. Conventional rice varieties may suffer severe yield losses following prolonged complete submergence. The incorporation of the SUB1 gene into widely cultivated rice backgrounds resulted in the development of varieties such as Swarna-Sub1, which possess substantially improved tolerance to complete submergence. Such varieties can survive approximately 10–14 days of complete submergence and subsequently recover when floodwaters recede. The successful deployment of SUB1 rice represents an important example of how molecular genetics and conventional breeding can be integrated to address a clearly defined climatic constraint while retaining desirable characteristics of popular varieties (Boraiah *et al*. 2023).

Salt-tolerant crops

Soil and water salinity constitute major constraints to agricultural productivity in several regions of India. Salinity affects seed germination, plant growth, nutrient uptake and reproductive development, ultimately reducing crop productivity. The ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI, Karnal) and collaborating institutions have contributed substantially to the development and evaluation of salt-tolerant crop varieties. Salt-tolerant rice varieties, wheat varieties such as those belonging to the KRL series, and tolerant mustard materials have provided opportunities for crop production in salt-affected environments. Traditional and locally adapted genetic resources also provide valuable sources of resilience. Pokkali rice, traditionally cultivated under saline coastal conditions in Kerala, is a prominent example of adaptation to salinity. Similarly, Kharchia wheat has long been recognized for its ability to perform under saline conditions. These examples highlight the importance of both modern crop improvement and systematic utilization of traditional genetic resources in developing climate-resilient agriculture.

Groundnut: A rainfed crop that requires continuous breeding for climate resilience

Groundnut is an important oilseed crop of India's semi-arid and dryland regions, where crop production is frequently challenged by drought, high temperature and erratic rainfall. Classical breeding has played a major role in developing varieties adapted to rainfed conditions. For instance, TMV 2 became highly popular among farmers because of its good adaptation to rainfed environments, drought tolerance and desirable seed and oil quality. However, the long-term cultivation of widely grown varieties can also lead to increased vulnerability to emerging diseases, pests and changing climatic conditions, highlighting the need for continuous varietal improvement. Recent breeding efforts have resulted in varieties such as Kadiri Lepakshi, Dharani, DH-256 and ICGV 91114, which have contributed to groundnut production under environments where moisture availability is uncertain (Boraiah *et al*. 2021). Nevertheless, climate resilience in groundnut cannot be judged simply by the plant's ability to survive drought or maintain vegetative growth. Successful pod formation and filling under stress, stable yield, suitable maturity duration, seed and oil quality, disease resistance and market acceptability are equally important for farmers. Therefore, future groundnut breeding programmes need to adopt a multi-trait approach, combining drought and heat tolerance with high and stable productivity, quality, disease resistance and other farmer- and market-preferred traits. Continuous generation and evaluation of new genetic variability will remain essential to ensure that groundnut varieties remain productive and profitable under the increasingly unpredictable climate.

From stress-tolerant to climate-smart varieties

Conventional breeding has played a fundamental role in developing varieties adapted to specific environmental stresses. Traits such as early maturity, deep rooting,

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improved water-use efficiency and tolerance to salinity or temperature extremes have been successfully incorporated into several crop varieties. However, climate change is characterized by increasing variability and simultaneous occurrence of multiple stresses (Boraiah et al. 2024). A crop may experience drought accompanied by high temperature, salinity combined with heat stress, or flooding followed by disease outbreaks. This necessitates a strategic shift from varieties designed for a single stress towards climate-smart varieties capable of maintaining stable performance under multiple and fluctuating environmental conditions.

Future climate-smart varieties should ideally possess:

- Stable and high yield potential under both stress and non-stress environments;
- Tolerance to multiple abiotic stresses;
- Appropriate maturity duration and adaptability;
- Efficient water and nutrient utilization;
- Resistance to major pests and diseases;
- Desirable grain, seed, fodder or fruit quality; and
- Strong market and consumer acceptance.
- Emerging technologies for accelerating crop improvement

Genomics-assisted breeding

Advances in genomics have considerably expanded the possibilities for identifying and utilizing genetic variation for stress tolerance. Molecular markers, quantitative trait locus (QTL) mapping, genome-wide association studies and genomic selection can facilitate the identification and utilization of genomic regions associated with complex traits. Marker-assisted selection can improve the efficiency of breeding programmes, while genome editing technologies such as CRISPR-based approaches provide opportunities for targeted modification of genes associated with important traits. The integration of these technologies with conventional breeding can significantly accelerate the development of climate-resilient varieties.

High-throughput phenotyping

Phenotyping remains a major bottleneck in crop improvement, particularly for complex traits such as drought, waterlogging, salinity and heat tolerance. High-throughput phenotyping platforms provide opportunities to quantify plant responses to stress through measurements of canopy temperature, biomass accumulation, plant architecture, root characteristics, water-use efficiency and other physiological parameters. Such approaches enable breeders to identify superior genotypes more accurately and efficiently under controlled as well as field environments.

Integrated omics approaches

The mechanisms underlying abiotic stress tolerance involve complex interactions among genes, proteins, metabolites and physiological processes. Integration of genomics with transcriptomics, proteomics and metabolomics can provide deeper insights into these mechanisms (Boraiah et al. 2024). The incorporation of artificial intelligence and advanced data analytics into these datasets has further potential to identify key regulatory pathways, candidate genes and superior genotypes for climate adaptation. Thus, the future of crop improvement will increasingly depend on the integration

of genetics, genomics, phenomics, physiology, bioinformatics and artificial intelligence.

Strengthening the link between research and farmers

The ultimate success of climate-resilient crop varieties depends on their performance and acceptance under farmers' field conditions.

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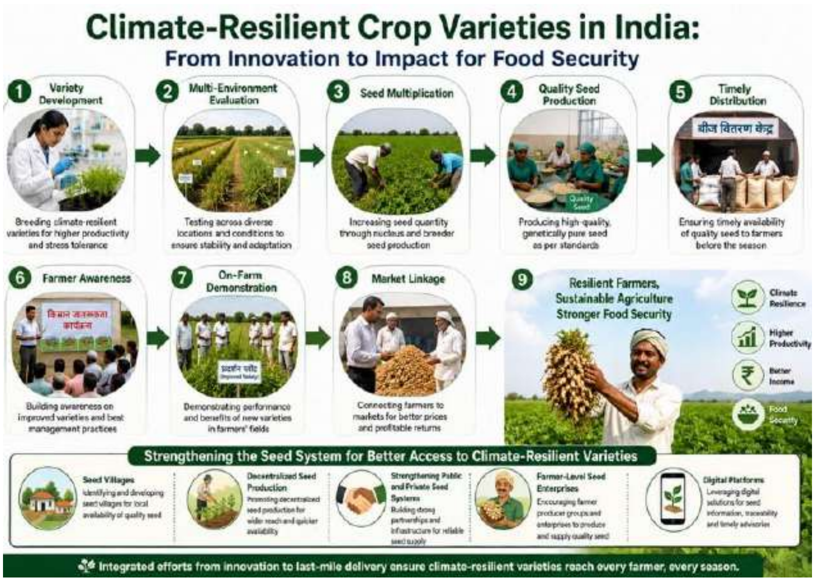
Varieties developed under controlled experimental conditions must therefore undergo rigorous multilocation testing and on-farm evaluation across representative agro-ecological environments. Participatory approaches involving farmers in variety evaluation can provide valuable information on traits that determine adoption. Depending on the production system, farmers may prioritize early maturity, yield stability, grain quality, fodder production, disease resistance, market price or other characteristics. Accordingly, climate-resilient breeding programmes should establish stronger linkages among breeders, physiologists, agronomists, seed producers, extension agencies and farmers.

The Importance of a strong seed delivery system

One of the major constraints in realizing the benefits of climate-resilient varieties is the limited availability of quality seed. Even a superior variety cannot contribute substantially to climate adaptation if farmers are unable to obtain genetically pure and high-quality seed at the appropriate time. A comprehensive strategy was illustrated in figure 1. Seed villages, decentralized seed production, strengthening of public and private seed systems, farmer-level seed enterprises and digital platforms can play important roles in improving access to climate-resilient varieties.

Figure 1. A comprehensive strategy to develop and disseminate the climate-resilient varieties



Policy and institutional priorities

Mainstreaming climate-resilient varieties requires coordinated support from research institutions, government agencies, seed organizations, extension systems and markets.

Priority areas should include:

- Strengthening research investment in drought-, heat-, salinity-, submergence- and multiple-stress tolerance.
- Establishing dedicated seed production and distribution systems for climate-resilient varieties.
- Increasing multilocation and on-farm evaluation under representative stress environments.
- Strengthening farmer awareness and extension programmes through demonstration and digital advisory systems.

- Integrating climate-resilient varieties with crop insurance, water management and other climate adaptation programmes.
- Promoting conservation and utilization of traditional varieties, landraces and crop wild relatives as sources of climate-resilience traits.
- Strengthening interdisciplinary breeding programmes integrating conventional breeding with genomics, phenomics and advanced computational approaches.

The road ahead: breeding for a changing climate

India's agricultural future will be determined not only by how much food can be produced but also by the ability to maintain production under increasingly uncertain climatic conditions. The breeding priorities for the coming decades must therefore extend beyond individual stress tolerance. Greater emphasis should be placed on yield stability, multiple-stress tolerance, resource-use efficiency, nutritional quality and economic value. India possesses extensive genetic resources and a strong network of agricultural research institutions. These resources provide a valuable foundation for developing varieties adapted to future climatic conditions. Systematic characterization and utilization of germplasm, creation of new genetic variability and integration of advanced breeding technologies can further expand the available genetic options. The goal should be to develop crop varieties that are productive under favourable conditions and resilient under adverse conditions.

Conclusion

Climate change presents a fundamental challenge to the sustainability of Indian agriculture and food security. Climate-resilient crop varieties provide an important genetic foundation for reducing production risks associated with drought, heat, flooding, salinity and other environmental stresses. India has made significant progress in developing stress-tolerant varieties, but the next phase requires a more integrated approach. The emphasis must shift from developing varieties tolerant to individual stresses towards climate-smart varieties with stable yield, multiple-stress tolerance, superior quality and broad farmer acceptance. Achieving this objective will require the convergence of modern breeding technologies, high-throughput phenotyping, genomics, omics, artificial intelligence, conventional breeding and farmer participation, supported by efficient seed systems and enabling policies. Ultimately, climate resilience begins with the seed, but it does not end there. The real measure of success will be the extent to which improved varieties reach farmers' fields, perform reliably under variable climates and contribute to sustainable incomes, nutritional security and national food security. For a climate-uncertain future, breeding the right crop varieties today is an investment in India's food security tomorrow.

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