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# Climate-Resilient Crop Breeding: The Future of Indian Agriculture

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Indian agriculture is entering an era in which productivity cannot be judged only by the yield obtained under favourable conditions. Rising temperatures, irregular monsoon rainfall, droughts, floods, salinity, heat waves, unseasonal rainfall, and changing pest and disease pressures are increasing production risks. These stresses interact with declining water availability and pressure on land and natural resources. Climate change therefore creates a dual challenge: India must continue increasing food production while making crops capable of performing under increasingly variable environments. The Intergovernmental Panel on Climate Change has identified agriculture as highly vulnerable to climate-related hazards, particularly through heat and water stress (IPCC, 2022). For India, climate-resilient crop breeding is consequently becoming a central strategy for long-term food, nutritional and livelihood security.

## Meaning and Importance of Climate-Resilient Crop Breeding

Climate-resilient crop breeding is the systematic development of crop varieties that maintain acceptable yield, quality and stability under environmental stresses and changing climatic conditions. Unlike conventional breeding that may emphasize maximum yield in favourable environments, climate-resilient breeding targets performance across stressful and variable environments. Important breeding objectives include drought tolerance, heat tolerance, flood and waterlogging tolerance, salinity tolerance, cold tolerance, resistance to emerging pests and diseases, efficient use of water and nutrients, early maturity, and stable yield. The objective is not to create a variety that survives one stress alone. Future cultivars should combine several desirable traits without sacrificing grain quality, market value or farmer profitability. This requires understanding genotype × environment interaction because a genotype performing well in one environment may not be stable elsewhere. Multi-location testing, stress-screening nurseries and climate-representative breeding environments are therefore essential.

## Major Climate Threats to Indian Crops

Temperature stress is one of the most important threats. High temperature can shorten crop duration, reduce pollen viability, disturb grain filling and decrease yield, particularly in wheat, rice, maize and several horticultural crops. Heat during wheat grain filling can accelerate maturity and reduce grain weight. In rice, high night temperature can affect respiration and spikelet fertility. Increasing temperature also changes the geographical suitability of crops and can favour some insect pests and pathogens. Water-related stresses are equally important. Drought reduces germination, root growth, photosynthesis and reproductive success, while excessive rainfall and flooding restrict oxygen availability around roots. Coastal and irrigated regions additionally face increasing salinity problems. These stresses may occur together or sequentially, making breeding for complex stress combinations more important than breeding for isolated stresses.

## Indian Examples of Resilient Crop Varieties

India already provides strong evidence that breeding can convert climate risk into manageable production opportunities. Swarna-Sub1 rice carries the SUB1 locus and can tolerate prolonged submergence, making it valuable in flood-prone lowlands. Its development demonstrates the importance of using useful genes from diverse germplasm and transferring them into farmer-preferred varieties. Marker-assisted backcrossing played a major role in developing submergence-tolerant versions of the widely grown Swarna variety (Neeraja *et al.*, 2007). Drought-tolerant rice provides another important example. Sahbhagi Dhan, developed through collaborative breeding, is a short-duration drought-tolerant variety suited to rainfed environments. Field evidence from eastern India has shown advantages over conventional varieties during drought years, demonstrating that genetic improvement can protect yield when irrigation is limited (Anantha *et al*., 2016; Dar *et al*., 2020). Climate resilience is also relevant to wheat, pulses, millets, oilseeds and horticultural crops. Short-duration pulses can escape terminal drought; heat-tolerant wheat can protect grain filling; pearl millet naturally offers strong adaptation to heat and water scarcity; and improved groundnut and chickpea lines can be selected for drought and disease resilience. Thus, breeding should be crop- and region-specific rather than based on a single national ideotype.

## Genetic Resources: The Foundation of Resilience

The success of climate-resilient breeding depends on genetic diversity. Landraces, traditional cultivars, wild relatives, obsolete varieties, germplasm collections and breeding populations contain alleles for adaptation to drought, salinity, heat, flooding, disease and nutrient stress. Conservation of these resources in national and international genebanks is therefore not merely a biodiversity activity; it is an investment in future crop improvement. Pre-breeding is especially important because useful genes in wild relatives may be linked with undesirable traits. Through crossing, backcrossing and selection, breeders can transfer valuable alleles into agronomically useful backgrounds. Participatory approaches can further identify locally adapted materials and farmer-preferred traits, increasing the probability that resilient varieties will be adopted.

## Modern Breeding Technologies

Climate-resilient breeding is increasingly supported by molecular and computational tools. Marker-assisted selection can accelerate the transfer of major genes or quantitative trait loci associated with stress tolerance. Marker-assisted backcrossing has already been valuable for incorporating traits such as submergence tolerance into elite rice backgrounds. Genomic selection offers an additional advantage for complex traits controlled by many genes, such as yield stability, drought tolerance and heat adaptation. Instead of waiting for complete phenotypic evaluation of every breeding line, genomic prediction can estimate breeding values using genome-wide markers and a training population. This can shorten breeding cycles and increase genetic gain when supported by reliable phenotypic and environmental data. Genomic selection is particularly useful for complex traits for which conventional marker-assisted selection is less effective (Jannink *et al*., 2010; Heffner *et al*., 2010). Genome-wide association studies, haplotype analysis, pangenomes and high-throughput genotyping are helping breeders discover useful alleles and understand genetic diversity. Gene editing, particularly CRISPR-based technologies, provides another precision approach. It can modify specific genes controlling stress responses, plant architecture, flowering, nutrient use or water-use efficiency. India's recent development of genome-edited rice varieties, including DRR Dhan 100 (Kamala) and Pusa DST Rice 1, illustrates the growing role of precision breeding in national crop improvement. These technologies should complement, rather than replace, conventional breeding and field evaluation.

## High-Throughput Phenotyping and Climate-Smart Selection

A major limitation in breeding for climate resilience is the difficulty of measuring complex stress responses. Traditional visual scoring is often slow, subjective and labour-intensive. High-throughput phenotyping can address this limitation through drones, spectral cameras, thermal imaging, sensors and automated image analysis. Traits such as canopy temperature, vegetation indices, plant height, biomass, root architecture and disease severity can be measured rapidly. Phenotyping should be conducted in environments that represent future climate conditions. Controlled drought, heat, salinity and flooding screens can identify tolerant materials, but field testing remains essential because real farms contain interacting stresses. Combining phenotyping with weather data, soil information and genomic prediction can improve selection for genotype × environment interaction and yield stability.

## Role of Artificial Intelligence and Digital Agriculture

Artificial intelligence and machine learning are emerging as important components of future breeding. Large datasets containing genotype, phenotype, soil, weather and management information can be analysed to predict promising parents and breeding lines. Machine learning may also help identify nonlinear relationships among genes, traits and environmental variables. Climate-informed modelling can simulate how candidate varieties may perform under future temperature and rainfall scenarios before expensive multi-location testing. However, AI is only as reliable as the data used to train it. Indian breeding programmes therefore need standardized phenotyping, high-quality environmental records, interoperable databases and collaboration between breeders, geneticists, physiologists, data scientists and climatologists.

## Breeding Strategies for Indian Agriculture

India requires a portfolio-based breeding strategy. In drought-prone regions, priority should be given to early maturity, deep rooting, efficient water use and stable reproductive performance. In flood-prone eastern and northeastern regions, submergence and waterlogging tolerance should receive greater attention. In coastal areas, salinity tolerance and combined salinity–heat tolerance is increasingly important. In wheat-growing regions, heat tolerance and short-duration adaptation are priorities. For rainfed farming, resilience should be combined with low-input performance. Breeding programmes should also prioritize nutritional quality, cooking quality, market traits and resistance to pests and diseases. A variety that survives climate stress but has poor grain quality or limited market demand is unlikely to be adopted. Therefore, resilience must be defined as agronomic, nutritional and economic resilience.

## Institutional and Policy Support

Climate-resilient breeding cannot succeed through genetics alone. India needs strong public breeding programmes, long-term investment in agricultural research, modern phenotyping facilities, seed systems and effective extension. The ICAR National Innovations in Climate Resilient Agriculture programme has assessed climate vulnerability across agricultural districts and promoted location-specific resilient technologies and varieties. In 2026, the Government reported that 310 of 651 assessed predominantly agricultural districts were categorized as vulnerable, highlighting the scale of climate risk and the need for targeted adaptation. Seed multiplication and timely distribution are as important as variety development. Farmers need access to quality seed at affordable prices, reliable information and demonstrations under local conditions. Breeding targets should therefore be developed with farmers, processors, consumers and markets in mind.

## Future Direction: From Stress Tolerance to Climate Readiness

Future breeding must also move from "stress tolerance" toward "climate readiness." This means breeders should consider not only average temperature or rainfall but the timing, duration, intensity and sequence of stresses. For example, a crop may experience heat during flowering followed by drought during grain filling, or waterlogging followed by high temperature. Such combinations can produce responses that cannot be predicted from single-stress experiments. Breeding trials should therefore use managed-stress environments and realistic climate scenarios. Another priority is yield stability. Farmers generally prefer a variety that produces a dependable harvest across difficult seasons rather than one that gives an exceptionally high yield only in a favourable year. Statistical tools for stability analysis, environmental characterization and genomic prediction can help identify broadly adapted genotypes. At the same time, breeding should strengthen regional adaptation. India's diverse agro-climatic zones require decentralized testing and breeding targets suited to local soils, rainfall patterns, cropping systems and market preferences. Such an approach can make climate-resilient varieties practical, affordable and farmer-centred rather than technology-driven.

## Challenges and Future Priorities

Several challenges remain. Climate change is producing new combinations of stresses, while breeding programmes often evaluate traits separately. Genotype × environment interaction can make selection difficult. Resilient traits may sometimes carry yield or quality penalties. Advanced technologies can also be expensive and require specialized expertise. Regulatory frameworks, biosafety considerations and public acceptance must be addressed responsibly, particularly for genome-edited crops. Future breeding should focus on stress combinations, dynamic adaptation, root traits, water-use efficiency, nutrient-use efficiency and yield stability. Multi-parent populations, speed breeding, genomic selection, gene editing and AI-assisted prediction can be integrated into a single breeding pipeline. Crop wild relatives and underutilized crops should receive greater attention because they can broaden the genetic base and strengthen diversification.

## Conclusion

Climate-resilient crop breeding is not simply an alternative branch of plant breeding; it is becoming a fundamental requirement for Indian agriculture. The future crop must produce well not only when rainfall, temperature and soil conditions are favourable, but also when farmers face drought, heat, floods, salinity and emerging biological threats. India already has successful examples such as Swarna-Sub1 and Sahbhagi Dhan, while genomics, high-throughput phenotyping, genomic selection, gene editing and artificial intelligence are opening new possibilities. The most effective approach will combine genetic diversity, modern breeding technologies, rigorous multi-environment testing, farmer participation, strong seed systems and supportive public policy. Climate resilience should ultimately be measured by stable productivity, profitability, nutritional value and resource efficiency under real farming conditions. By investing today in resilient varieties and precision breeding, India can strengthen food security, protect farmer livelihoods and build an agricultural system capable of meeting the uncertainties of the future.

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