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Climate-Smart Plant Breeding: Developing Resilient Crops for Future Agriculture

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INTRODUCTION

Agriculture is highly dependent on climatic conditions, and changes in temperature, rainfall, humidity, solar radiation and the frequency of extreme weather events directly influence crop growth and productivity. Climate change is therefore not simply an environmental problem but a major agricultural challenge with direct implications for food availability, farm income, rural employment and national food security. Increasing global temperatures, changing rainfall patterns, prolonged droughts, floods, heat waves, soil salinity and the changing geographical distribution of pests and diseases are creating increasingly unpredictable production environments. Crops that were developed under historical climatic conditions may not perform satisfactorily when exposed to the environmental conditions expected during the coming decades. Consequently, the development of crop varieties capable of maintaining stable yields under climate variability has become an important objective of contemporary plant breeding.

Plant breeding has traditionally focused on increasing yield potential, improving resistance to diseases and insects, modifying maturity duration, improving plant architecture and enhancing product quality. These objectives remain important, but climate change has added a new dimension to breeding. A variety that performs exceptionally well under optimum irrigation and moderate temperature may suffer severe yield losses when exposed to drought or extreme heat. Consequently, breeders must increasingly select varieties not only for high yield under favorable conditions but also for stable

performance under unfavorable conditions. This shift represents a transition from conventional productivity-oriented breeding toward resilience-oriented and climate-smart breeding.

2. Climate Change and Emerging Challenges for Crop Production

Climate change affects crops through both long-term changes and short-term extreme events. Increasing temperatures can accelerate crop development and shorten grain-filling periods, while extreme heat can damage pollen, reduce fertilization and cause reproductive failure. Drought can reduce plant water status, stomatal conductance, photosynthesis and biomass production. Excessive rainfall can cause waterlogging and flooding, leading to oxygen deficiency in the root zone and nutrient imbalance. Salinity can reduce water uptake and cause ion toxicity, while changing climatic conditions can alter pest and pathogen populations. These stresses may occur independently, but in farmers' fields they frequently occur simultaneously.

Heat stress is becoming one of the most important constraints to crop productivity. Plants have specific temperature ranges for optimum growth, and temperatures above these ranges can cause substantial physiological damage. High temperature can increase respiration, reduce photosynthesis, destabilize cellular membranes and accelerate crop development. The reproductive stage is particularly vulnerable because pollen formation, pollen viability, fertilization and grain or fruit development can be severely affected. In wheat, rice, maize and many vegetable crops, heat stress during flowering may cause significant yield

reductions. Therefore, breeding for heat tolerance should focus not only on vegetative growth but also on reproductive stability. Traits such as canopy temperature, membrane stability, pollen viability, heat-shock protein activity, antioxidant capacity and maintenance of photosynthetic activity can serve as useful indicators of heat tolerance.

3. Concept and Importance of Climate-Smart Plant Breeding

Climate-smart plant breeding differs from conventional stress breeding because it considers the expected future production environment during the design of breeding objectives. Instead of selecting varieties only on the basis of historical yield performance, breeders attempt to predict the environmental conditions in which varieties will be grown in the future. This requires collaboration among plant breeders, climatologists, physiologists, agronomists, soil scientists, data scientists and farmers.

Table 1: Major climate stresses and breeding strategies

Climate stress	Major breeding objective	Important traits	Suitable approaches
Drought	Maintain yield under water deficit	Root depth, WUE, stay-green, early maturity	MAS, GWAS, GS
Heat	Protect reproductive development	Pollen viability, canopy cooling, membrane stability	GS, HTP, genome editing

Flooding	Improve survival under excess water	Submergence tolerance, adventitious roots	MAS, GS
Salinity	Maintain growth under saline conditions	Na ⁺ exclusion, K ⁺ /Na ⁺ ratio	QTL, MAS, editing
Cold	Maintain growth under low temperature	Cold acclimation, membrane stability	MAS, GS
Emerging diseases	Develop durable resistance	Resistance genes, quantitative resistance	GWAS, pangenomics
Nutrient deficiency	Improve nutrient-use efficiency	Root traits, NUE	GS, phenotyping
Combined stresses	Maintain productivity under multiple stresses	Stress resilience and stability	AI, GS, multi-environment testing
Erratic rainfall	Improve adaptability	Early maturity, plasticity	G × E analysis
Heat + drought	Maintain reproductive and physiological performance	Canopy temperature, pollen fertility	GS, HTP, editing

4. Genetic Resources for Climate-Smart Breeding

Genetic diversity is the foundation of plant breeding. Without sufficient genetic variation, breeders cannot develop varieties with improved tolerance to environmental stresses. Modern high-yielding cultivars often possess a relatively narrow genetic

base because intensive selection has focused on yield and market traits. Consequently, landraces, traditional varieties, wild relatives, obsolete cultivars and germplasm collections are extremely important sources of novel climate-adaptive genes.

5. Conventional Breeding and Climate Resilience

Conventional breeding remains a fundamental component of climate-smart crop improvement. Hybridization, pedigree selection, backcrossing, recurrent selection and population improvement continue to be widely used. Conventional breeding has the advantage of allowing breeders to combine multiple traits simultaneously under field conditions. For example, a drought-tolerant donor may be crossed with a high-yielding elite variety. Progeny can subsequently be selected for drought tolerance, yield, disease resistance, maturity and quality. However, conventional breeding can require many years because several generations are often needed to identify superior lines. Environmental variability can also reduce selection accuracy.



6. Marker-Assisted Selection and QTL Mapping

Marker-assisted selection involves using molecular markers associated with genes or quantitative trait loci controlling important traits. The approach is particularly useful when a strong relationship exists between a marker and the target trait.

Marker-assisted selection has been used extensively for disease resistance, submergence tolerance, quality traits and abiotic stress tolerance. It allows breeders to select plants at the seedling stage, thereby reducing the time and resources required for conventional phenotyping.

7. Genome-Wide Association Studies

Genome-wide association studies use naturally occurring genetic variation among diverse germplasm collections to identify associations between molecular markers and phenotypic traits. GWAS has become increasingly useful because modern sequencing technologies provide large numbers of genetic markers.

GWAS has been applied to identify loci associated with drought tolerance, heat tolerance, disease resistance, nutrient-use efficiency, root traits and flowering time. However, GWAS results need to be validated because associations may vary among populations and environments. Candidate genes identified through GWAS can subsequently be investigated using functional genomics or genome editing.

8. Genomic Selection

Genomic selection is an important approach for improving complex traits controlled by many genes.

Instead of selecting individuals solely on the basis of measured phenotypes, genomic selection uses genome-wide molecular marker information to predict breeding values.

A training population is first developed in which both genotype and phenotype information are available. Statistical models are then developed to establish relationships between genetic markers and phenotypic performance. These models can be used to predict the performance of individuals that have been genotyped but not extensively phenotyped.

9. Speed Breeding

Speed breeding is a technique for reducing generation time by optimizing environmental conditions such as photoperiod, light intensity, temperature and nutrition. Traditional crops may require several months to complete one generation, whereas optimized controlled environments can allow breeders to produce several generations annually.

The combination of speed breeding with genomic selection provides an especially powerful strategy. Breeders can genotype young plants, predict their breeding values and rapidly advance selected individuals to the next generation. This reduces the time required to develop genetically improved populations.

10. High-Throughput Phenotyping

Phenotyping is one of the most important bottlenecks in modern crop breeding. Climate-resilience traits are often complex and difficult to measure. Traditional measurements such as plant height, biomass and yield provide useful information but may not adequately describe plant responses to stress.

High-throughput phenotyping uses cameras, sensors, drones, robotics, thermal imaging, multispectral imaging and automated data analysis to measure plant characteristics rapidly. Canopy temperature can be measured using thermal cameras, while multispectral sensors can estimate vegetation indices and detect changes in plant health.

11. Artificial Intelligence and Machine Learning

Artificial intelligence is becoming increasingly important because modern breeding programmes generate very large genomic, phenotypic and environmental datasets. Machine-learning methods can identify complex relationships that may not be captured by conventional statistical models.

AI can be used to predict genomic breeding values, classify stress responses, identify disease symptoms, analyze UAV images, characterize environments and predict genotype $\times$ environment interactions. Machine-learning models can also help breeders select promising parental combinations and prioritize traits.

12. Genome Editing and CRISPR-Based Breeding

Genome editing has introduced a new dimension to plant breeding by allowing targeted modification of specific genes. CRISPR/Cas systems are particularly attractive because they can be programmed to target specific genomic sequences.

Genome editing can be used to knock out genes associated with susceptibility to diseases, modify genes controlling stress responses, alter plant architecture, change flowering time and improve nutrient-use efficiency. More advanced technologies such as base editing and prime editing allow increasingly precise genetic modifications.

13. Breeding for Drought Tolerance

Drought tolerance is one of the most important objectives of climate-smart breeding. Drought affects crops through reduced soil moisture, increased atmospheric demand and disruption of plant water balance. The severity of drought depends on its timing, duration and intensity.

Drought-resilient varieties may possess deeper roots, improved water-use efficiency, efficient stomatal regulation, osmotic adjustment and delayed senescence. Early maturity is another important strategy because it allows plants to complete their reproductive phase before severe terminal drought develops.



14. Breeding for Heat Tolerance

Heat tolerance is becoming increasingly important as average temperatures and the frequency of heat waves increase. The effects of heat are particularly severe during reproductive development. High temperatures can reduce pollen viability, impair fertilization and shorten grain-filling periods.

Heat-tolerant genotypes may possess effective canopy cooling, stable membranes, efficient antioxidant systems and heat-shock protein responses. In cereal crops, maintaining grain filling under high temperature is particularly important. In horticultural crops, stable flowering and fruit set are major breeding targets.



15. Breeding for Salinity Tolerance

Salinity reduces plant growth through osmotic stress and accumulation of toxic ions. Sodium and chloride can interfere with cellular processes and nutrient uptake. Climate-smart breeding for saline environments therefore requires identification of genotypes capable of maintaining ion balance.

16. Breeding for Flooding and Waterlogging

Flooding and waterlogging are becoming increasingly important in regions experiencing intense rainfall. Crops adapted to drought may not necessarily tolerate flooding because the physiological mechanisms are different.

Rice has provided an important model for genetic improvement of submergence tolerance. The incorporation of the SUB1 locus into elite rice

varieties demonstrates how molecular breeding can provide farmers with varieties capable of surviving prolonged submergence.

17. Breeding for Nutrient-Use Efficiency

Climate-smart crops should use fertilizers and soil nutrients efficiently. Nitrogen-use efficiency is particularly important because excessive nitrogen fertilizer application contributes to environmental pollution and greenhouse-gas emissions.

Breeding for nitrogen-use efficiency involves improving nutrient uptake, assimilation and utilization. Root architecture is an important component because improved root systems can increase access to nutrients.

18. Breeding for Water-Use Efficiency

Water scarcity is becoming increasingly important in many agricultural regions. Water-use-efficient varieties can help farmers maintain productivity with less irrigation.

Traits such as root depth, canopy temperature, stomatal regulation, transpiration efficiency and early maturity are associated with water-use efficiency. However, breeders must avoid excessive reduction in transpiration because this may reduce photosynthetic carbon assimilation.

19. Breeding for Emerging Pests and Diseases

Climate change can alter pest and pathogen distribution and may allow some species to expand into areas where they were previously absent. Warmer temperatures can increase pest development rates, while altered humidity and rainfall can influence pathogen epidemics.

Climate-smart breeding must therefore incorporate durable resistance to both existing and emerging pests and diseases. Quantitative resistance is particularly valuable because it can provide more durable protection than resistance controlled by a single gene.

20. Breeding for Combined Environmental Stresses

One of the greatest limitations of traditional breeding is that stress tolerance is often evaluated one stress at a time. However, crops in farmers' fields frequently experience multiple stresses simultaneously. Drought and heat may occur together, while flooding may be followed by disease outbreaks. Salinity may occur simultaneously with high temperature, and drought may be accompanied by nutrient deficiency.

Combined stresses can produce physiological responses different from those produced by individual stresses. Therefore, future breeding programmes must increasingly evaluate plants under realistic combinations of stresses. This will require controlled-environment facilities, field-based stress screening and advanced phenotyping technologies.

21. Genotype × Environment Interaction

Genotype × environment interaction is a central issue in climate-smart breeding because different genotypes respond differently to environmental conditions. The performance of a variety can be represented conceptually as the combined effect of genetic factors, environmental factors and their interaction.

A variety that performs well under irrigation may perform poorly under drought, while another variety may show moderate performance across both environments. Therefore, multi-environment trials are essential for identifying stable genotypes.

22. Pangenomics and Climate-Resilient Breeding

Pangenomics is emerging as an important approach for exploring genetic diversity. Instead of relying on one reference genome, pangenomics examines genomic information from multiple accessions.

This approach can identify genes and structural variants that are absent from the reference genome. Some of these variants may provide adaptation to drought, heat, salinity or disease.

23. Climate-Smart Breeding in India

India has highly diverse agricultural environments ranging from arid and semi-arid regions to humid tropical and mountainous systems. Indian agriculture is exposed to drought, heat, flooding, salinity, irregular monsoon rainfall and changing pest and disease pressures. Consequently, climate-resilient crop breeding has become an important research priority.

The Indian Council of Agricultural Research has developed numerous varieties with tolerance to drought, flooding, salinity, heat, cold and other environmental stresses. ICAR reports that the National Agricultural Research System released 1,956 high-yielding stress-tolerant field crop varieties and hybrids during 2014–2022.

24. Climate-Smart Breeding in Horticultural Crops

Horticultural crops are particularly sensitive to temperature and water stress because flowering, fruit set and fruit development can be strongly influenced by environmental conditions. Heat stress can cause

flower abortion and poor fruit setting in vegetables, while drought can reduce fruit size and quality.

Future horticultural breeding should focus on heat-tolerant tomato, pepper and other vegetables, drought-tolerant crops, salinity-tolerant rootstocks and fruit crops capable of maintaining reproductive performance under variable temperatures.

25. Climate-Smart Breeding of Millets and Underutilized Crops

Millets are important candidates for climate-resilient agriculture because many millet species are naturally adapted to drought, high temperature and low-input conditions. Pearl millet, finger millet, sorghum and other dryland crops can contribute to agricultural diversification.

Future breeding should combine their inherent climate resilience with high yield, nutritional quality, biofortification, processing quality, mechanized harvesting suitability and consumer acceptance.

26. Participatory Breeding and Farmer Involvement

The success of climate-smart breeding ultimately depends on farmer adoption. Farmers evaluate varieties not only according to yield but also according to maturity, grain quality, fodder value, market price, taste, storage ability and suitability to local farming systems.

Participatory breeding allows farmers to become involved in variety evaluation and selection. This approach can improve the relevance of breeding objectives and increase the likelihood of adoption.

27. Integration of Breeding and Agronomic Management

Climate-smart varieties should not be considered independent of crop management. Genetic resilience is most effective when combined with appropriate agronomic practices.

Drought-tolerant varieties can perform better when combined with moisture conservation, mulching and efficient irrigation. Heat-tolerant varieties can be complemented with adjusted planting dates. Flood-tolerant varieties may require appropriate drainage and water management.

28. Role of Digital Agriculture

Digital technologies can provide breeders with detailed information about environmental conditions and crop responses. Remote sensing, drones, GIS, GPS, IoT sensors and satellite imagery can characterize breeding environments at high spatial and temporal resolution.

Thermal cameras can measure canopy temperature, while multispectral sensors can identify stress responses before visible symptoms appear. Automated weather stations can provide information about temperature, rainfall, humidity and solar radiation.

29. Multi-Omics Approaches

Climate resilience involves complex molecular pathways. Genomics identifies genetic variants, transcriptomics reveals gene-expression responses, proteomics identifies stress-responsive proteins and metabolomics detects changes in metabolites.

Integrating these different omics layers can help identify the biological mechanisms responsible for stress tolerance. Candidate genes discovered

through multi-omics approaches can subsequently be validated through functional studies or genome editing.

30. Root System Architecture and Climate Resilience

Roots play a fundamental role in drought tolerance and nutrient-use efficiency. Root depth, root length, branching pattern, root thickness and root distribution determine the plant's ability to explore soil resources. Deep-rooted plants may access water from deeper soil layers during drought. Efficient root systems can also improve nutrient uptake under low-fertility conditions.

32. Economic Importance of Climate-Smart Varieties

Climate-resilient varieties can provide significant economic benefits to farmers. Stable yields can reduce production risk and income variability. Drought-tolerant crops can reduce irrigation requirements, while nutrient-efficient varieties can reduce fertilizer expenditure.

Improved resistance to pests and diseases can reduce crop protection costs. Early-maturing varieties can allow farmers to escape terminal drought and provide opportunities for additional cropping.

33. Major Constraints and Challenges

Despite significant advances, climate-smart plant breeding faces several challenges. Many climate-resilience traits are quantitatively inherited and strongly influenced by environmental conditions, making selection difficult. Reliable phenotyping under field conditions remains a major bottleneck.

Combined stresses are difficult to reproduce consistently, and genotype $\times$ environment interactions can complicate selection.

34. Future Prospects

The future of climate-smart plant breeding will depend on the integration of multiple technologies. A future breeding programme may begin with climate modelling to identify future target environments and prioritize traits. Genetic resources can then be screened using genomic tools to identify useful alleles. Crosses can be developed using elite and climate-adapted parents, while genomic selection and marker-assisted selection can accelerate early-generation selection.

CONCLUSION

Climate change is transforming the environmental conditions under which agriculture must operate. Drought, heat, flooding, salinity, irregular rainfall and emerging pests and diseases are increasingly threatening crop productivity and farm income. Conventional breeding has provided enormous benefits to agriculture, but the complexity and speed of climate change require breeding programmes to become faster, more precise and more closely aligned with future production environments.

Climate-smart plant breeding provides an integrated solution by combining conventional breeding with molecular markers, GWAS, genomic selection, pangenomics, speed breeding, high-throughput phenotyping, artificial intelligence, multi-omics and genome editing. These technologies can accelerate the discovery and utilization of genetic variation and improve the prediction of genotype performance under stressful environments.