

Pan-Genomics and AI: The New Toolbox for Breeding Super Crops for Drought and Heat

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INTRODUCTION

Climate change is creating new challenges for agriculture across the world. Rising temperatures and irregular rainfall are increasing the frequency of drought and heat stress which can reduce crop growth and productivity. Farmers need crop varieties that can survive under stressful conditions while maintaining stable yields and good nutritional quality. Traditional breeding has made significant contributions to crop improvement but developing climate-resilient varieties requires a deeper understanding of the genetic diversity hidden within crop species. Two emerging technologies — pan-genomics and artificial intelligence (AI) — are opening new opportunities for crop improvement. Pan-genomics helps scientists explore the complete genetic diversity of a crop species while AI helps analyse enormous amounts of biological and environmental data to identify useful genes and predict crop performance. Together they can accelerate the development of climate-smart crops suited to the changing needs of agriculture (Huang *et al.*, 2012; Varshney *et al.*, 2021).

What is pan-genomics?

Every crop variety has a genetic blueprint called its genome. However different varieties of the same crop do not possess exactly the same genes. Some varieties contain unique genes that help them tolerate drought resist diseases or survive high temperatures. If scientists study only one reference genome they may miss important genes present in other varieties or wild relatives.

Pan-genomics is the study of the complete genetic repertoire of a species by combining genomic information from multiple varieties and related genetic resources. Instead of relying on a single reference genome it captures both shared genes and genetic sequences that occur only in certain varieties.

For example, a drought-tolerant rice variety may possess genetic variants associated with deeper roots or improved water-use efficiency. A heat-tolerant wheat variety may carry useful genes that help maintain pollen fertility and

grain development during high temperatures. Pan-genomics can help identify such differences and make them available for targeted breeding.

Table 1: Major components of pan-genomics

Component	Meaning	Importance in crop breeding
Core genome	Genes shared by most or all studied varieties	Supports essential plant growth and development
Variable genome	Genes present in some varieties but absent in others	Reveals differences in stress tolerance and adaptation
Structural variations	Large changes such as insertions deletions or gene rearrangements	Helps identify useful genetic diversity missed by conventional analysis
Wild-relative genes	Genetic resources from wild ancestors and related species	Provides new sources of drought and heat tolerance

Pan-genomics therefore gives plant breeders a broader picture of crop diversity and helps them identify valuable genetic resources that might otherwise remain undiscovered.

How does artificial intelligence help crop breeding?

Modern crop research generates huge amounts of data from DNA sequencing satellite images weather records soil sensors field experiments and crop phenotyping. Analysing these data manually is time-consuming and may not reveal complex relationships between genes and environmental conditions.

Artificial intelligence can identify patterns in these datasets and help researchers make faster and more informed decisions. Machine learning models can examine genetic markers and field observations to estimate which plants are more likely to perform well under drought or heat stress. Computer vision can analyse images to measure plant height leaf area canopy temperature and signs of stress. AI does not replace plant breeders or field experiments. Instead it helps scientists narrow down promising candidates so that limited research time and resources can be directed towards the most useful plants.

Table 2: Applications of AI in climate-resilient crop breeding

AI application	How it works	Potential benefit
Genomic prediction	Uses genetic markers and past performance data to predict breeding value	Identifies promising parents and breeding lines
Image-based phenotyping	Analyses photographs and drone images of crops	Detects early signs of heat and drought stress
Gene discovery	Identifies patterns linking genetic variation with important traits	Prioritises candidate genes for validation
Climate and yield modelling	Combines weather soil and crop data	Predicts how varieties may perform under future conditions
Precision selection	Integrates genomic and field data	Helps breeders select plants more efficiently

These applications can make crop improvement more precise and support the selection of varieties suited to different agro-climatic regions (Crossa *et al.*, 2017).

Combining pan-genomics and AI: A powerful partnership

Pan-genomics and AI are most effective when they work together. Pan-genomics provides a broad catalogue of genetic variation while AI helps identify which variations are most likely to contribute to desirable traits. This combination can improve the efficiency of

selecting plants for complex characteristics such as drought tolerance and heat resilience (Bayer *et al.*, 2021). Consider a breeding programme aimed at developing drought-tolerant chickpea. Researchers may first analyse the genomes of hundreds of cultivated varieties and wild relatives to identify genetic differences. They can then combine these data with field measurements of root growth, plant water status and grain yield under limited water availability. AI models can help predict which genetic combinations are most promising for further testing.

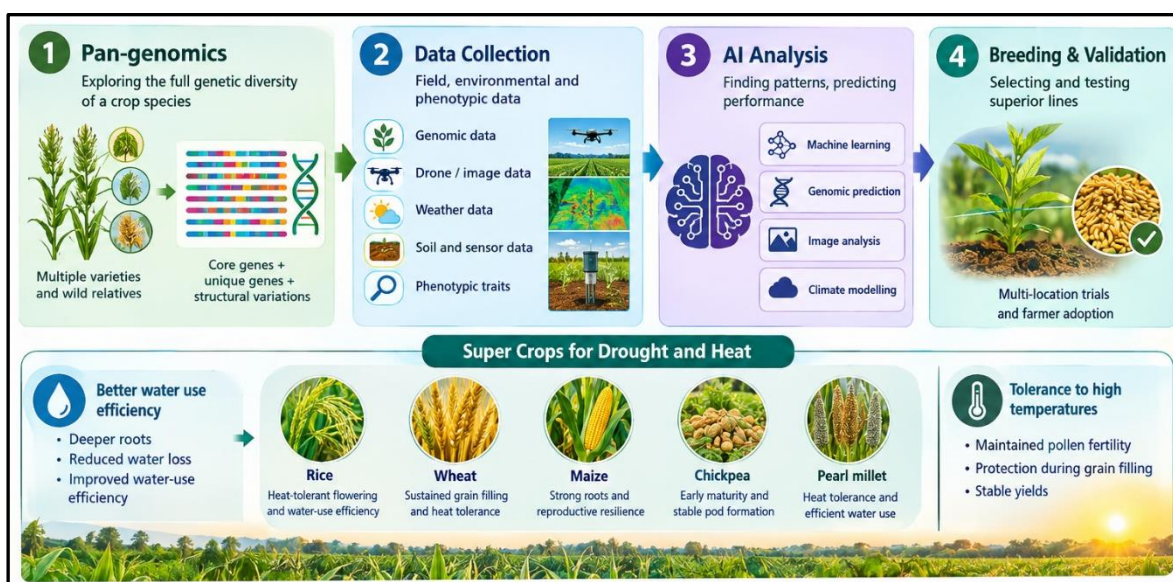


Figure: Integration of pan-genomics and artificial intelligence for developing drought- and heat-resilient crop varieties through genetic diversity analysis, AI-based prediction and field validation.

❖ Integration of pan-genomics and artificial intelligence for developing climate-resilient crop varieties.

1. Explore crop diversity

Pan-genomics identifies useful genes and genetic variations in cultivated crops and wild relatives.

2. Collect field and environmental data

Researchers measure yield, root traits, canopy temperature and performance under drought and heat.

3. Apply AI-based predictions

Machine learning identifies promising genes, breeding lines and genetic combinations.

4. Validate and select superior crops

Field trials confirm performance before promising varieties are advanced towards release.

Breeding super crops for drought and heat

The term super crops refer here to improved crop varieties that combine several desirable traits rather than a single characteristic. These crops should maintain productivity under stress while meeting farmers' needs for yield, quality and profitability.

1. Crops that use water more efficiently

Drought-tolerant crops may develop deeper or more extensive root systems to access water from deeper soil layers. Other useful traits include reduced water loss through leaves, improved water-use efficiency and the ability to maintain growth during temporary water shortages. Genomic information and AI-assisted prediction can help breeders select plants with favourable combinations of these characteristics (Mir *et al.*, 2012).

2. Crops that withstand high temperatures

High temperatures can damage pollen development and fertilisation and shorten the

grain-filling period in cereals. In pulses and oilseeds heat stress may also affect flowering, pod formation and seed development. Breeders can use genomic diversity to search for genetic variations associated with heat tolerance. AI can help analyse temperature records and crop responses to identify plants that maintain reproductive success and grain yield under hot conditions.

3. Crops that maintain stable yields

A variety that performs well in one location may not perform equally well in another. Soil type, rainfall patterns, sowing dates and the timing of heat waves all influence crop performance. AI-based genomic prediction can help breeders estimate how different varieties may perform across multiple environments. However, these predictions must be tested under real field conditions before reliable recommendations can be made (Crossa *et al.*, 2017).

Table 3: Potential climate-resilient crops and breeding priorities

Crop	Major challenge	Important traits to target
Rice	Water scarcity and heat during flowering	Improved water-use efficiency and heat-tolerant flowering
Wheat	Terminal heat and drought	Sustained grain filling and stable grain yield
Maize	Irregular rainfall and high temperatures	Strong root systems and improved reproductive resilience
Chickpea	Terminal drought and heat	Early maturity and stable pod and seed formation
Pearl millet	Severe drought and extreme temperatures	Heat tolerance and efficient water use

These are breeding priorities rather than guarantees that pan-genomics or AI alone will deliver all the desired traits.

Importance for Indian agriculture

India's agricultural production spans diverse climatic zones and farming systems. Rainfed regions face particular challenges from unpredictable monsoon rainfall while wheat-growing areas in northern India can experience terminal heat during grain development. Pulses and millets are also important for improving

nutritional security and strengthening farming systems in water-limited environments.

Integrating pan-genomics and AI into Indian crop improvement programmes could help researchers:

- Identify useful genes from indigenous landraces and crop wild relatives.
- Develop locally adapted varieties for rainfed and drought-prone regions.
- Select breeding lines with better heat tolerance and yield stability.

- Use drone imagery and field sensors to monitor crop stress more efficiently.
- Improve the selection of varieties suited to different soil and climatic conditions.

India's genetic resources are particularly valuable for chickpea, pigeonpea, pearl millet, rice and other crops. Protecting these resources and combining them with modern genomic technologies can support long-term agricultural resilience (Varshney *et al.*, 2021).

Challenges and limitations

Despite their potential, these technologies face several practical challenges. High-quality genomic data and reliable field observations are essential for building useful AI models. Generating pan-genomes requires specialised sequencing facilities, bioinformatics expertise and financial investment. AI predictions can also become unreliable when they are applied to crops or environments that differ substantially from the training data. Another challenge is that drought and heat tolerance are complex traits influenced by many genes and environmental factors. A gene that benefits a crop under one set of conditions may provide little advantage under another. Improving stress tolerance must also be balanced with yield potential, nutritional quality and resistance to pests and diseases. For farmers to benefit, promising varieties must undergo rigorous multi-location testing and be supported by affordable seed systems and appropriate agronomic practices. Traditional breeding knowledge remains essential throughout this process.

The future of climate-smart crop breeding

The future of crop improvement will depend on integrating multiple technologies rather than relying on a single solution. Pan-genomics can expand the range of genetic variation available to breeders while AI can accelerate the analysis of genomic, phenotypic and environmental data. Genomic selection, speed breeding and gene editing may further support the

development of improved crop varieties when used appropriately. In the coming years researchers may be able to predict which genetic combinations are most suitable for specific agricultural regions and climate scenarios. Such approaches could make breeding programmes more targeted and efficient. Nevertheless, the success of these technologies will depend on accurate predictions, careful field validation and collaboration among plant breeders, geneticists, agronomists, data scientists and farmers.

CONCLUSION

Pan-genomics and artificial intelligence represent an important advance in the search for climate-resilient crops. By uncovering hidden genetic diversity and improving the prediction of crop performance these technologies can help breeders develop varieties that use water efficiently, tolerate high temperatures and maintain more stable yields. For India and other regions vulnerable to climate change this integrated approach offers promising opportunities to strengthen food security and support sustainable agriculture. The real achievement will not simply be developing technologically advanced crops but ensuring that resilient and productive varieties reach farmers and perform reliably under the challenging conditions of real agricultural fields.

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