

Harnessing Speed Breeding and Genomic Selection for rapid development of climate- smart crops

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Introduction:

Agriculture is entering an era of unprecedented challenges driven by rapid climate change, population growth, depletion of natural resources, and the increasing demand for food. The global population is projected to reach nearly 9.7 billion by 2050, requiring agricultural production to increase substantially despite shrinking arable land and growing environmental constraints (United Nations, 2022). Conventional crop improvement has played a vital role in increasing food production over the past century; however, traditional breeding methods generally require 8–12 years to develop and release a new crop variety. This lengthy breeding cycle limits the ability of breeders to respond quickly to emerging climate threats, evolving pests and diseases, and changing market demands (Hickey et al., 2019).

Recent advances in plant genetics, genomics, and controlled - environment

technologies have transformed modern crop improvement by providing innovative approaches that accelerate breeding while maintaining high selection accuracy. Among these innovations, **speed breeding** and **genomic selection** have emerged as two complementary technologies capable of dramatically shortening breeding cycles and improving genetic gain. Speed breeding accelerates plant generation turnover through optimized environmental conditions, whereas genomic selection uses genome-wide molecular markers to predict the breeding value of plants before phenotypic evaluation. Together, these technologies enable breeders to develop improved crop varieties more rapidly than conventional breeding methods (Watson et al., 2018; Crossa et al., 2017).

The integration of speed breeding and genomic selection offers a promising pathway for developing climate-smart crops with enhanced tolerance to drought, heat, salinity,

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flooding, and emerging diseases while simultaneously improving yield, nutritional quality, and resource-use efficiency. As agriculture faces increasing climatic uncertainty, these modern breeding approaches are expected to play a central role in ensuring sustainable food production and global food security during the coming decades (Varshney et al., 2021).

Climate Change and the Need for Rapid Crop Improvement

Climate change has become one of the greatest threats to global agricultural sustainability. Rising temperatures, erratic rainfall, prolonged droughts, floods, soil salinity, and frequent extreme weather events are reducing crop productivity across many agricultural regions. Simultaneously, changing climatic conditions are accelerating the evolution and distribution of insect pests, pathogens, and weeds, creating additional challenges for crop production. According to the Intergovernmental Panel on Climate Change (IPCC), agricultural systems worldwide are becoming increasingly vulnerable to climate variability, emphasizing the urgent need for resilient crop varieties capable of maintaining stable yields under diverse environmental conditions (IPCC, 2023).

Traditional breeding approaches have successfully improved crop productivity for

many decades, but their relatively long breeding cycles limit their effectiveness in responding to rapidly changing climatic conditions. Developing a new cultivar through conventional methods often requires multiple generations of crossing, selection, field evaluation, and seed multiplication before commercial release. By the time a variety reaches farmers, environmental conditions or disease pressures may already have changed substantially (Hickey et al., 2019).

Rapid crop improvement has therefore become an essential component of climate-smart agriculture. Modern breeding programmes aim to accelerate the development of cultivars possessing tolerance to heat, drought, flooding, salinity, and major diseases while maintaining high yield and nutritional quality. The integration of genomics, high-throughput phenotyping, artificial intelligence, speed breeding, and genomic prediction provides unprecedented opportunities to shorten breeding cycles and increase genetic gain, enabling breeders to respond more effectively to future agricultural challenges (Voss-Fels et al., 2019).

Understanding Speed Breeding

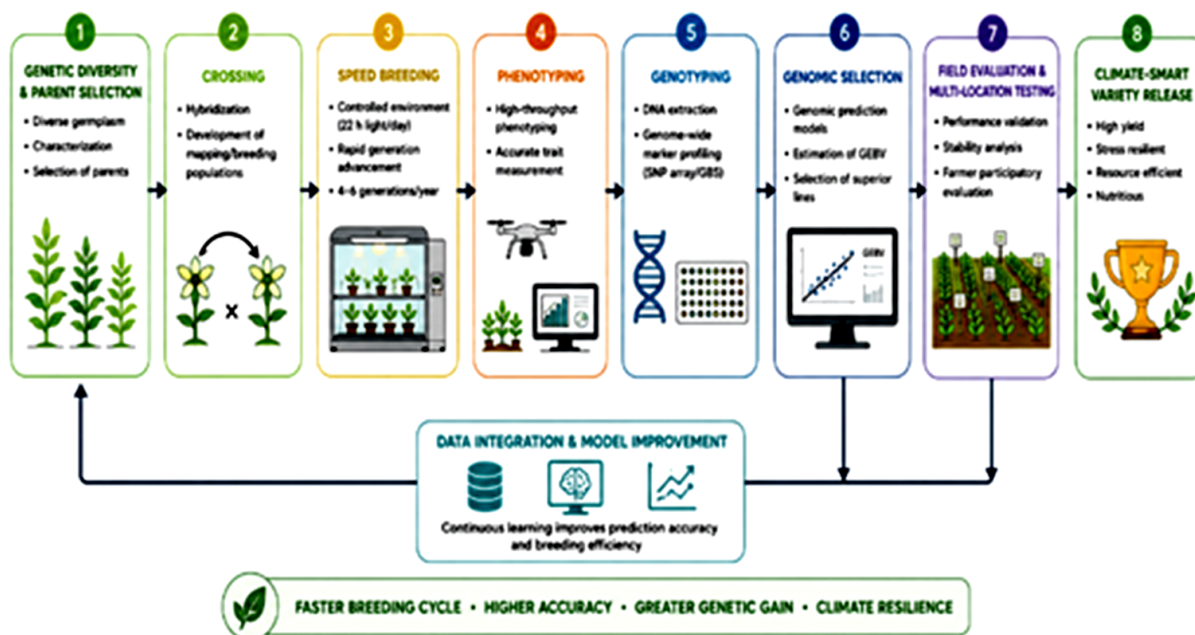
Speed breeding is an advanced plant breeding technique that accelerates crop development by manipulating environmental conditions such as photoperiod, light intensity, temperature, and humidity under controlled

growth environments. By extending daily light exposure to approximately 22 hours and optimizing growing conditions, plants flower earlier, mature faster, and complete multiple generations within a single year. Whereas conventional breeding generally allows only one or two generations annually, speed breeding can produce four to six generations depending on the crop species, thereby substantially reducing the time required for cultivar development (Watson et al., 2018).

growth chambers, and LED lighting systems are commonly used to maintain optimal conditions throughout the crop life cycle. This approach has been successfully applied in wheat, barley, chickpea, pea, canola, rice, and several horticultural crops, demonstrating remarkable reductions in breeding duration while maintaining seed viability and genetic stability (Ghosh et al., 2018).

Beyond accelerating generation advancement, speed breeding enhances

INTEGRATION OF SPEED BREEDING AND GENOMIC SELECTION FOR RAPID DEVELOPMENT OF CLIMATE-SMART CROPS



The principle of speed breeding is based on maximizing photosynthetic activity and minimizing developmental delays without compromising normal plant growth. Controlled-environment facilities, glasshouses,

research efficiency by facilitating rapid gene validation, marker development, mutation studies, and pre-breeding activities. When combined with molecular breeding technologies, it significantly shortens the

interval between crossing and variety release, allowing breeders to respond more rapidly to climate-related challenges and emerging production constraints. Consequently, speed breeding has become an indispensable component of next-generation crop improvement programmes aimed at developing climate-resilient cultivars.

complex traits controlled by numerous genes, including yield, drought tolerance, disease resistance, grain quality, and nutritional composition (Meuwissen et al., 2001; Crossa et al., 2017).

The genomic selection process begins by developing a training population with both phenotypic and genotypic data. Statistical

Table 1. Comparison between conventional breeding and speed breeding

Parameter	Conventional breeding	Speed breeding
Generations per year	1–2	4–6
Variety development	8–12 years	3–6 years
Growing environment	Natural field conditions	Controlled environment
Light duration	Natural photoperiod	Up to 22 hours/day
Selection efficiency	Moderate	High
Suitability for climate-resilient breeding	Limited	Excellent

Principles and Applications of Genomic Selection

Genomic selection (GS) is a modern breeding approach that predicts the genetic potential of breeding lines using genome-wide molecular marker information rather than relying exclusively on observable traits. Unlike marker-assisted selection, which targets only a limited number of major genes or quantitative trait loci (QTLs), genomic selection simultaneously utilizes thousands of molecular markers distributed across the entire genome to estimate genomic estimated breeding values (GEBVs). This comprehensive approach enables accurate selection of

prediction models establish relationships between genome-wide markers and target traits, after which breeding populations are genotyped and their breeding values predicted without extensive field evaluation. This allows breeders to identify superior genotypes at early developmental stages, substantially reducing breeding costs and shortening selection cycles (Voss-Fels et al., 2019).

Genomic selection has been successfully applied in major crops including wheat, maize, rice, barley, soybean, and chickpea for improving complex traits with low heritability. Its ability to increase selection accuracy while reducing breeding time makes

it particularly valuable for developing climate-smart crop varieties capable of performing consistently under changing environmental conditions. Furthermore, integration with high-throughput phenotyping, artificial intelligence, and machine learning is expected to further improve the predictive accuracy and efficiency of future breeding programmes (Varshney et al., 2021).

variability. Successive generations are then rapidly advanced under speed breeding conditions while genome-wide marker data are simultaneously collected from breeding populations. Genomic prediction models identify superior individuals at early growth stages, allowing breeders to select the best lines before extensive field testing. This integrated strategy substantially reduces

Table 2. Applications of genomic selection in crop improvement

Crop	Target trait	Major outcome
Wheat	Heat tolerance	Faster identification of superior breeding lines
Rice	Drought tolerance	Improved prediction accuracy
Maize	Grain yield	Increased genetic gain
Barley	Disease resistance	Early selection of resistant genotypes
Chickpea	Early maturity	Accelerated breeding programme
Soybean	Seed quality	Improved breeding efficiency

Integration of Speed Breeding and Genomic Selection

The integration of speed breeding with genomic selection represents one of the most significant advances in modern plant breeding. While speed breeding accelerates generation turnover, genomic selection enhances the accuracy of selecting superior breeding lines. Together, these technologies reduce both the biological and analytical constraints associated with conventional breeding, enabling the rapid development of improved crop varieties.

In an integrated breeding programme, parental lines are first crossed to create genetic

breeding cycle duration while increasing the rate of genetic gain per year (Watson et al., 2018; Hickey et al., 2019).

The combined application of these technologies is particularly valuable for breeding climate-smart crops with enhanced tolerance to drought, heat, salinity, flooding, and emerging diseases. It also facilitates the rapid pyramiding of favourable alleles controlling yield, nutritional quality, and resource-use efficiency. As advances in genomics, artificial intelligence, phenomics, and automation continue to evolve, the integration of speed breeding and genomic

selection is expected to become a standard breeding strategy for developing resilient crop varieties capable of sustaining global food production under changing climatic conditions.

quality. Genomic selection further enhances breeding efficiency by accurately predicting yield performance and stress tolerance before extensive field testing (Watson et al., 2018). In

Table 3. Advantages of integrating speed breeding with genomic selection

Component	Speed breeding	Genomic selection	Integrated benefit
Generation advancement	Rapid	Moderate	Very rapid breeding cycle
Selection accuracy	Phenotypic	Genome-wide prediction	Highly accurate selection
Variety development	Faster	Faster	Maximum genetic gain
Cost efficiency	Moderate	High	Reduced overall breeding cost
Climate-smart breeding	Good	Excellent	Highly efficient development of resilient varieties

Applications in Major Crops

The combined use of speed breeding and genomic selection has transformed crop improvement programmes across numerous field and horticultural crops. These technologies have significantly reduced the time required to develop improved cultivars while increasing the efficiency of selecting superior genotypes for complex traits. Their application is particularly valuable in crops where rapid adaptation to changing climatic conditions is essential for maintaining food security (Watson et al., 2018; Crossa et al., 2017).

In wheat, speed breeding has enabled the production of up to six generations per year, allowing rapid incorporation of genes associated with heat tolerance, drought resistance, rust resistance, and improved grain

rice, genomic selection has been successfully applied for improving drought tolerance, submergence tolerance, grain yield, and nutritional quality, while speed breeding accelerates the development of elite breeding lines. Similarly, maize breeding programmes increasingly integrate these technologies to improve resistance against major diseases, enhance grain yield, and develop hybrids adapted to heat and water stress (Hickey et al., 2019).

Legume crops such as chickpea, soybean, lentil, and pea have also benefited considerably from accelerated breeding approaches. Speed breeding enables rapid generation advancement, while genomic prediction facilitates early identification of superior genotypes possessing disease resistance, early maturity, and enhanced seed

quality. Oilseed crops including canola and mustard are similarly being improved for drought tolerance, oil quality, and disease resistance through integrated breeding strategies. The successful implementation of these technologies across diverse crops demonstrates their broad applicability in modern crop improvement programmes.

provide an effective platform for accelerating the development of climate-resilient crop varieties capable of addressing these challenges (IPCC, 2023).

Speed breeding enables breeders to rapidly advance segregating populations carrying genes for tolerance to drought, heat, salinity, flooding, and nutrient deficiencies.

Table 4. Applications of speed breeding and genomic selection in major crops

Crop	Target traits	Technology applied	Major outcome
Wheat	Heat tolerance, rust resistance	Speed breeding + Genomic selection	Faster development of climate-resilient cultivars
Rice	Drought tolerance, grain quality	Genomic selection + Speed breeding	Accelerated breeding cycle
Maize	Disease resistance, grain yield	Integrated breeding	Improved hybrid performance
Chickpea	Early maturity, wilt resistance	Speed breeding	Multiple generations per year
Soybean	Seed yield, disease resistance	Genomic selection	Increased selection accuracy
Barley	Salinity tolerance	Integrated breeding	Improved stress adaptation
Canola	Oil quality, drought tolerance	Speed breeding	Rapid cultivar development

Role in Developing Climate-Smart Crops

Climate-smart crops are varieties capable of maintaining high productivity under adverse environmental conditions while efficiently utilizing natural resources and reducing agriculture's environmental footprint. Developing such cultivars has become a global priority due to increasing temperatures, erratic rainfall, emerging pests and diseases, and degradation of agricultural ecosystems. Speed breeding and genomic selection together

Simultaneously, genomic selection identifies superior individuals possessing favourable combinations of alleles for multiple complex traits before phenotypic expression. This combined strategy substantially increases genetic gain per unit time and enables breeders to respond quickly to newly emerging climatic stresses (Voss-Fels et al., 2019).

Beyond stress tolerance, these technologies facilitate the development of varieties with improved water-use efficiency,

nutrient-use efficiency, disease resistance, lodging resistance, and enhanced grain quality. Such improvements reduce dependence on irrigation, fertilizers, and pesticides, thereby supporting environmentally sustainable agriculture. Consequently, the integration of speed breeding and genomic selection has become a key component of climate-smart breeding programmes designed to ensure stable crop production under future climatic uncertainty (Varshney et al., 2021).

Challenges and Future Prospects

Despite their enormous potential, the widespread adoption of speed breeding and genomic selection faces several scientific, technical, and economic challenges. Establishing controlled-environment facilities for speed breeding requires substantial investment in infrastructure, artificial lighting systems, temperature regulation, and automation. Likewise, genomic selection depends on high-density molecular markers, reliable phenotypic datasets, advanced computational resources, and specialized expertise in quantitative genetics, bioinformatics, and statistical modelling (Crossa et al., 2017).

The predictive accuracy of genomic selection models may decline when breeding populations differ genetically from the training population or when strong genotype × environment interactions occur. Similarly,

speed breeding protocols require optimization for individual crop species because photoperiod responses and growth requirements vary considerably among plants. Developing standardized protocols for diverse crops remains an active area of research (Watson et al., 2018).

Future prospects for these technologies are highly promising. Artificial intelligence, machine learning, high-throughput phenotyping, unmanned aerial vehicles (UAVs), robotics, digital imaging, and automated data analytics are expected to further improve breeding efficiency. The integration of genome editing, pangenomics, predictive breeding, and precision phenotyping with speed breeding and genomic selection will likely revolutionize crop improvement by enabling rapid development of superior cultivars adapted to future climatic challenges. Increased collaboration among research institutions, governments, and the private sector will further accelerate the translation of these technologies into practical agricultural solutions.

India's Progress in Speed Breeding and Genomic Selection

India has made significant progress in adopting modern breeding technologies to strengthen national food and nutritional security. Research institutions under the **Indian Council of Agricultural Research**

(ICAR), together with State Agricultural Universities, have increasingly incorporated genomic tools into breeding programmes for cereals, pulses, oilseeds, and horticultural crops. Marker-assisted breeding and genomic selection are now being applied in wheat, rice, maize, chickpea, pigeon pea, and several other economically important crops to improve yield potential, disease resistance, and climate resilience (Varshney et al., 2021).

Indian researchers have also initiated speed breeding programmes in crops such as wheat, rice, chickpea, and mustard using controlled-environment growth chambers and optimized lighting systems. These programmes have demonstrated considerable reductions in breeding cycle duration while facilitating rapid evaluation of breeding populations and gene validation studies. Institutions such as the **Indian Agricultural Research Institute (IARI)**, **Punjab Agricultural University (PAU)**, the **Indian Institute of Wheat and Barley Research (IIWBR)**, the **Indian Institute of Millets Research (IIMR)**, and the **International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)** are actively integrating genomics, phenomics, and accelerated breeding approaches into crop improvement programmes.

Looking ahead, India's expanding investments in genomics, artificial intelligence, digital agriculture, precision

phenotyping, and controlled-environment agriculture provide a strong foundation for integrating speed breeding and genomic selection into routine breeding pipelines. Continued investment in infrastructure, skilled human resources, and international collaborations will enable India to accelerate the development of climate-smart crop varieties capable of supporting sustainable agricultural production under changing environmental conditions.

Conclusion

The increasing impacts of climate change demand crop improvement strategies that are faster, more precise, and capable of addressing multiple complex traits simultaneously. Speed breeding and genomic selection have emerged as two of the most transformative technologies in modern plant breeding, significantly reducing breeding cycle duration while improving the accuracy of selecting superior genotypes. Their integration enables breeders to accelerate the development of crop varieties possessing enhanced yield potential, climate resilience, disease resistance, nutritional quality, and resource-use efficiency.

The successful application of these technologies across major food crops demonstrates their immense potential for strengthening global food security and supporting climate-smart agriculture.

Nevertheless, maximizing their benefits will require continued investment in research infrastructure, genomic resources, phenotyping platforms, computational tools, and human capacity development. As these technologies become increasingly integrated with genome editing, artificial intelligence, and digital agriculture, they are expected to redefine the future of crop improvement. Harnessing speed breeding and genomic selection will therefore play a pivotal role in developing resilient agricultural systems capable of meeting the food demands of a growing global population while ensuring environmental sustainability and long-term agricultural resilience.

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