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Breeding 4.0: Convergence of AI, CRISPR and Speed Breeding for Next-Generation Climate-Resilient Crops

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INTRODUCTION

Agriculture is entering a new era in which crop improvement must respond to climate change, increasing food demand, declining natural resources and the growing complexity of agricultural production systems. Rising temperatures, prolonged droughts, irregular rainfall, soil salinity, flooding and emerging pests and diseases threaten crop productivity across many regions. Conventional plant breeding has made substantial contributions to food security, but developing new varieties with multiple desirable traits can require many years of crossing, selection and field evaluation. The need to accelerate genetic improvement has therefore encouraged integrating digital technologies, molecular biology and controlled-environment cultivation into modern breeding programmes.

The concept of Breeding 4.0 describes an emerging, data driven approach to crop improvement that combines artificial intelligence (AI), genome editing, genomic selection, high throughput phenotyping, advanced genomics and speed breeding. Rather than operating as independent technologies, these tools can form a coordinated pipeline in which AI identifies promising genetic targets, CRISPR based genome editing modifies selected sequences, speed breeding accelerates generation advancement and genomic prediction helps identify superior plants for further evaluation.

AI can process large volumes of genomic, phenotypic, environmental and historical breeding data to identify patterns that may be difficult to detect through conventional statistical approaches. CRISPR based genome editing enables targeted modification of selected DNA sequences, while speed breeding uses controlled environmental conditions to accelerate flowering and seed production. The combination of these approaches creates opportunities to shorten breeding cycles and improve selection precision (Watson *et al*., 2018; Krishnappa *et al*., 2021). Recent research has also highlighted the potential of integrating genomic selection and genome editing to improve complex traits such as drought tolerance, water use efficiency and yield.

Understanding the Concept of Breeding 4.0

Breeding 4.0 can be understood as the transition from predominantly observation based and marker-assisted selection towards a connected, predictive and increasingly precise breeding system. It uses digital information and biological technologies to improve the efficiency of identifying, developing and evaluating crop varieties. Traditional breeding depends heavily on repeated field observations, controlled crossing, phenotypic selection and multi season testing. Although these methods remain essential, they can be slow when traits are strongly influenced by the environment or controlled by many genes. Breeding 4.0 supplements conventional approaches with automated measurements, predictive algorithms, genome wide information and accelerated generation turnover.

Artificial Intelligence in Modern Plant Breeding

Artificial intelligence is becoming an important tool for managing the complexity of modern crop improvement. Breeding programmes generate extensive information through DNA sequencing, field experiments, remote sensing, weather stations, laboratory analyses and high throughput phenotyping. AI and machine learning can integrate these datasets to support faster and more informed decisions.

1. AI-based genomic prediction

Genomic prediction estimates the breeding value of plants using information from markers distributed across the genome. Machine learning methods can be used to identify relationships between genetic markers and observed traits, particularly when combined with sufficiently large and representative training datasets. This approach can help breeders rank candidate plants before conducting extensive field testing.

For example, genomic prediction may assist in identifying wheat lines with potential drought tolerance, rice lines with improved yield stability or maize lines adapted to heat stress.

The accuracy of predictions depends on the quality of the training population, genetic diversity, trait heritability, environmental representation and model selection. AI does not automatically outperform conventional statistical methods. Its usefulness must be established through independent validation and comparison with appropriate baseline models.

2. Computer vision and high throughput phenotyping

High throughput phenotyping involves collecting plant measurements rapidly using imaging systems, drones, sensors, automated platforms and remote sensing technologies. Computer vision can analyse images to estimate plant height, canopy cover, leaf area, flowering time, biomass, disease symptoms and visible stress responses.

Thermal imaging can help identify differences in canopy temperature associated with water stress, while multispectral and hyperspectral imaging can provide information about vegetation condition and physiological responses. These tools allow breeders to evaluate many plants more efficiently than manual measurements alone.

3. Predicting genotype by environment interactions

Crop performance depends on the interaction between genotype and environment. A variety that performs well under favourable conditions may fail under heat, drought or nutrient limitation. AI models can integrate genomic information with environmental variables such as temperature, rainfall, soil properties and management practices to estimate performance across locations.

These predictions can support the identification of broadly adapted varieties and varieties specifically suited to particular production environments. However, models trained in one region may not predict performance reliably in another region if the environmental and genetic conditions differ substantially.

CRISPR Based Genome Editing for Precision Crop Improvement

CRISPR based genome editing has expanded the possibilities for modifying crop traits by allowing researchers to target selected DNA sequences. The CRISPR associated protein system uses a guide RNA to direct the editing machinery to a specified genomic region. Depending on the system and experimental design, editing can produce targeted mutations, modify gene regulation or introduce particular genetic changes. Unlike conventional crossing, which combines many genetic regions from parental plants, genome editing can focus on selected genes or regulatory sequences. This may be useful when a well characterized genetic target is associated with an important agronomic trait.

Chen *et al*. (2019) discussed the potential of CRISPR based technologies for precision plant breeding, including crop improvement through targeted genetic modification. The practical success of an edit nevertheless depends on the biological function of the target, the crop genotype, editing efficiency and subsequent plant regeneration.

1. Improving drought and heat tolerance

Drought and heat tolerance are complex traits involving root development, stomatal regulation, flowering time, photosynthesis, osmotic adjustment and cellular protection. CRISPR can be used to investigate genes associated with these processes and to develop targeted modifications where the biological evidence is sufficiently strong. For example, modifying a regulatory gene may influence water use efficiency or flowering time.

2. Improving disease and pest resistance

Genome editing can support the development of disease resistant crops by modifying susceptibility genes or strengthening selected defence pathways. It can also help researchers investigate plant pathogen interactions and identify genetic mechanisms underlying resistance. Resistance should be evaluated against diverse pathogen populations and under realistic field conditions.

3. Improving nutritional quality and resource efficiency

CRISPR based approaches may help modify genes involved in nutrient composition, antinutritional factors, grain quality, plant architecture and nutrient use efficiency. Such improvements could support food quality and sustainable crop production.

Speed Breeding: Accelerating Generation Advancement

Speed breeding is a controlled environment approach that accelerates plant development by optimizing factors such as photoperiod, light intensity, temperature, nutrition and growing conditions. Its primary purpose is to reduce the time required to advance generations and obtain seed from selected plants. Watson *et al*. (2018) demonstrated the value of speed breeding as a tool for accelerating crop research and breeding. By adjusting environmental conditions, some crops can complete substantially more generations annually than under conventional field schedules, although the achievable rate varies by species, genotype and protocol.

1. Accelerating conventional crosses

Speed breeding enables breeders to advance segregating populations rapidly. After crossing selected parents, successive generations can be

grown under controlled conditions, allowing the recovery and selection of plants carrying desirable combinations of traits. This is particularly valuable for crops with relatively long generation times. Faster generation advancement can reduce the time needed to develop lines with improved disease resistance, plant architecture, grain quality or adaptation to specific environments.

2. Speed breeding after genome editing

Genome editing does not automatically produce a finished variety. Edited plants must be regenerated, characterized, evaluated and where necessary, advanced through subsequent generations to establish the desired genetic characteristics. Speed breeding can accelerate this process by allowing selected edited plants to produce seed more rapidly.

Integrating AI, CRISPR and Speed Breeding

The greatest potential of Breeding 4.0 lies in the integration of these technologies rather than their isolated use. Each component addresses a different limitation in conventional breeding. AI helps identify useful patterns and prioritize candidates. CRISPR enables targeted investigation or modification of selected genetic regions. Speed breeding reduces the time required for generation advancement. Genomic selection helps predict the performance of breeding material based on genome wide information, while high throughput phenotyping provides rapid measurements of plant characteristics.

A coordinated breeding pipeline may begin with identifying a target problem, such as heat induced yield loss in rice. Researchers collect genomic, phenotypic and environmental data and use statistical models to identify promising genetic regions. Functional studies then help determine whether specific targets are suitable for editing. Edited or conventionally bred plants are advanced through speed breeding, followed by genomic screening, controlled stress evaluation and field testing. The resulting data can be fed back into the prediction models, improving future selection decisions. This feedback system creates a continuous cycle of discovery, prediction, breeding and validation.

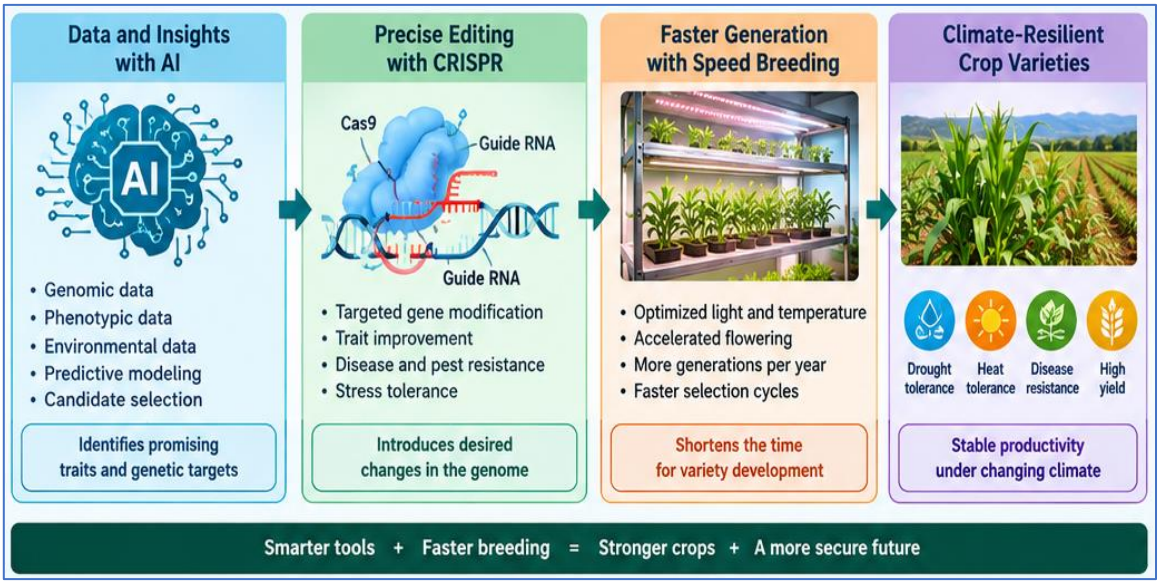


Fig. 1: Integrated Breeding 4.0 framework combining AI, CRISPR genome editing and speed breeding to develop climate-resilient crops.

Table 1: Roles of AI, CRISPR and speed breeding in next-generation climate-resilient crop improvement

Technology	Primary function	Potential application	Major limitation
Artificial intelligence	Analyses complex genomic, phenotypic and environmental datasets	Predicting yield, stress tolerance and adaptation	Model accuracy depends on data quality and validation
CRISPR based genome editing	Targets selected DNA sequences or gene regulation	Improving disease resistance, stress responses and quality traits	Editing efficiency, biological trade offs and regulatory requirements
Speed breeding	Accelerates plant development and generation advancement	Rapid advancement of breeding populations and edited lines	Requires suitable controlled environments and crop specific protocols
Genomic selection	Predicts breeding value using genome wide markers	Selection for complex traits such as yield and drought tolerance	Prediction accuracy may decline across populations or environments
High throughput phenotyping	Collects plant trait measurements rapidly	Screening large populations under stress conditions	Requires calibration and reliable interpretation
Integrated breeding pipeline	Combines prediction, editing, rapid generation advancement and validation	Faster development of climate-resilient cultivars	Requires coordination, expertise, funding and field testing

Breeding Climate Resilient Crops for Future Agriculture

Climate resilience should be treated as a central breeding objective rather than a secondary trait. Future varieties must maintain acceptable productivity under changing climatic conditions while supporting efficient use of land, water and nutrients.

1. Drought resilience

Drought-tolerant crops may combine deeper rooting, improved water use efficiency, appropriate flowering time and effective recovery after water stress. AI can identify genetic and environmental patterns associated with drought performance, while genome editing can help investigate specific genes and accelerated breeding can accelerate the advancement of promising material. The final selection must consider grain or fruit yield under both water limited and favourable conditions. Survival alone is not sufficient if economic productivity remains low.

2. Heat tolerance

High temperatures can impair pollen viability, flowering, grain filling and photosynthesis. Heat-resilient varieties may possess improved reproductive stability, membrane protection and temperature appropriate developmental timing. AI-assisted analysis of canopy temperature, flowering time and yield under contrasting temperature regimes can help breeders identify promising candidates. Genetic modification may contribute where specific targets are well established, but field validation remains necessary because heat stress interacts with humidity, soil moisture and crop development.

3. Flooding and salinity tolerance

Flooding can cause oxygen deficiency in roots, while salinity disrupts water uptake and ion balance. Both stresses involve multiple physiological and genetic mechanisms. Integrated breeding approaches can support the identification of useful traits and the

development of improved varieties. However, tolerance is often specific to the duration, intensity and timing of stress. Testing should therefore reproduce realistic production conditions and include more than one environment.

4. Resistance to emerging pests and diseases

Climate change can alter the distribution, seasonal activity and severity of crop pests and pathogens. Breeding programmes must therefore consider resistance durability, pathogen diversity and the possibility that resistance genes may lose effectiveness over time. AI based disease detection, genomic analysis and precision genome editing may contribute to identifying and improving resistance. Nevertheless, crop rotation, surveillance, biological control and other integrated management practices remain necessary to reduce selection pressure and maintain durable protection.

Benefits of Breeding 4.0

- First, it can shorten the interval between identifying a useful trait and advancing promising breeding material. Speed breeding reduces generation time, while AI and genomic selection can help prioritize plants for further evaluation.
- Second, targeted genome editing can facilitate the investigation and modification of selected genes. When the genetic basis of a trait is sufficiently understood, this may reduce the need for repeated crossing to introduce a particular change.
- Third, high throughput phenotyping can improve the scale and consistency of plant measurements. More detailed observations may help breeders distinguish varieties that perform well under different environmental conditions.
- Fourth, integration of genomic and environmental data may improve the selection of varieties suited to specific agroecological zones. This is important because climate resilience is not a single universal characteristic. Varieties must be adapted to local temperature patterns, rainfall, soil conditions, pests and farming systems.

CONCLUSION

Breeding 4.0 represents a promising approach to developing climate-resilient crops by integrating artificial intelligence, CRISPR based genome editing, speed breeding and genomic selection. These technologies can accelerate crop improvement, enhance stress tolerance and improve yield stability under changing climatic conditions. However, their success depends on reliable data, careful field validation, responsible application and accessibility to farmers. Integrating these innovations with conventional breeding and local agricultural knowledge can contribute to sustainable agriculture and long term global food security.

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