



POPULAR ARTICLE

The 5G revolution in plant breeding and variety evolution: From field selection to AI-driven crop improvement

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Intricacies of the subject

The story of plant breeding is a story of speed. Early farmers selected the best plants they could see. Scientific breeding later added controlled crossing, replicated trials and statistical selection. Molecular markers then allowed breeders to track useful genomic regions without waiting for every trait to become visible. Today, high-throughput phenotyping, genomics, cloud computing and artificial intelligence are pushing breeding towards an even faster and more data-rich era. The term '5G revolution' in this article is used as a simple way to describe five broad waves of progress in crop improvement: field selection, hybrid breeding and quantitative genetics, molecular breeding, genomics and high-throughput phenotyping, and finally AI-driven integrated breeding. These stages overlap rather than replace one another. Modern breeding programmes use tools from several stages at the same time.

Generation 1: Breeding begins with the field

The earliest form of plant breeding was farmer selection. Plants with better yield, seed size,

taste, maturity, disease escape or adaptation were saved as seed for the next season. Over generations, this simple process changed crop populations and contributed to domestication. Scientific breeding transformed this process by making selection more systematic. Breeders began maintaining defined varieties, making controlled crosses and evaluating progenies in replicated experiments. Statistical methods helped separate genetic differences from environmental variation. Field selection remains the foundation of breeding even today. No matter how advanced a laboratory technology becomes, a new variety must eventually perform in farmers' fields. Yield, stability, quality and adaptation are ultimately biological and agricultural outcomes.

Generation 2: Quantitative genetics and hybrid breeding

Many important crop traits are controlled by numerous genes and are strongly influenced by the environment. Quantitative genetics provided breeders with tools such as heritability, genetic advance, combining ability and genotype-by-environment analysis. These concepts helped breeders decide how much



progress could realistically be achieved through selection. Hybrid breeding added another major dimension. The exploitation of heterosis made it possible to combine complementary parental traits and achieve high performance in crops such as maize, rice, sunflower, sorghum and many vegetables. Breeding became increasingly organized around large populations, repeated testing and efficient selection. However, conventional selection can be slow when traits are expressed late, require destructive measurement or show low heritability. This created the need for tools that could see useful genetic variation before the final phenotype was fully expressed.

Generation 3: Molecular markers enter the breeding pipeline

DNA markers changed the breeder's ability to follow inheritance. Instead of selecting only by appearance, breeders could identify genomic regions associated with traits. Techniques evolved from early marker systems such as RFLP, RAPD and AFLP to SSRs, SNP arrays and sequencing-based markers. Marker-assisted selection became particularly useful for traits controlled by major genes or well-characterized genomic regions. Disease resistance genes, quality traits and specific resistance loci could be tracked in breeding populations even when the phenotype was difficult to measure. This was an important shift: selection moved closer to the genetic source of variation. Yet complex traits such as yield, drought tolerance and nutrient-use efficiency often involve many small-effect loci. For these traits, marker-by-marker selection has limitations.

Generation 4: Genomics, phenomics and big data

The sequencing revolution dramatically increased the amount of information available

to breeders. Whole-genome sequences, dense SNP datasets, genotyping-by-sequencing and pangenomes have made it possible to characterize diversity at unprecedented resolution. At the same time, phenotyping is becoming more automated. Drones, cameras, multispectral sensors, thermal imaging and ground platforms can collect measurements from thousands of plants. Traits such as canopy temperature, vegetation indices, plant height, biomass and disease symptoms can be measured repeatedly without harvesting every plant. This combination of genomics and phenomics is powerful because breeding depends on both sides of the equation. Genomics tells us about the genetic potential of a plant; phenotyping tells us how that potential is expressed in a particular environment.

Generation 5: AI-driven crop improvement

The newest phase is not simply about collecting more data. It is about connecting the data. A modern breeding programme can generate genomic markers, pedigree information, multi-location phenotypes, weather records, soil measurements, images and laboratory data. Artificial intelligence and machine learning can help detect patterns within these large datasets. Genomic selection is an important example. Instead of waiting for every breeding line to complete expensive multi-environment testing, models can use genome-wide marker information and training populations to predict breeding values. Lines with high predicted performance can then be advanced, while less promising material can be discarded earlier. Machine-learning models can also help interpret images and sensor data. Computer vision can identify disease symptoms or estimate plant traits from photographs. Predictive models can combine environmental variables with genotype information to estimate which are likely to the



biggest conceptual change in AI-assisted breeding is the movement from selection after observation to prediction before complete observation. Traditional breeding asks: 'Which plants performed best?' Data-driven breeding increasingly asks: 'Based on everything we know about this plant and its environment, which plants are most likely to perform best?' This can shorten breeding cycles and reduce the cost of evaluating very large populations. It can also improve the use of limited field space. Instead of testing every line equally, breeders can prioritize materials with the strongest predicted potential. Prediction does not eliminate field testing. Models can make mistakes when they encounter new genetic backgrounds, unusual environments or data outside the range used for training. Therefore, prediction and field validation must work as a continuous cycle: predict, test, update the model and predict again.

The role of digital breeding platforms

The future breeding programme may look very different from a conventional field notebook. A breeder could view a digital dashboard containing pedigrees, genomic relationships, phenotype histories, environmental data and model predictions. Field observations could be uploaded directly from mobile devices. Drone images could be processed automatically. Trial designs could be optimized using statistical algorithms. Such systems can also support faster decision-making across locations. If a genotype performs well under drought in one environment but poorly under high humidity in another, the breeder can examine the interaction between genotype and environment rather than relying on a single overall mean. For developing breeding programmes, this does not necessarily mean buying every expensive technology at once. Even basic digital data management, standardized phenotyping and R-based statistical analysis

can substantially improve the quality and reproducibility of breeding decisions.

Speed breeding: making every generation count

The 5G concept becomes even more powerful when combined with speed breeding. Controlled environments can accelerate plant growth and generation turnover in several crops. When rapid generation advancement is combined with genomic selection, marker-assisted selection or gene editing, breeders can move desirable material through generations much faster. For example, a breeder may identify promising parents using genomic information, create crosses, accelerate generation advancement under controlled conditions, genotype young plants and select the best individuals before field evaluation. The field is then used more strategically for confirmation and adaptation testing. The result is not merely faster breeding. It is more efficient breeding, because time, field area, labour and laboratory resources can be concentrated on the most promising materials.

Challenges behind the revolution

Technology alone cannot guarantee breeding progress. High-quality data are essential. Incorrect trait measurements, missing records, unbalanced trials or poorly designed training populations can produce misleading predictions. Models may also perform well in one population but poorly in another. Breeders therefore need strong foundations in experimental design, statistics and biological interpretation. Data science should strengthen breeding knowledge, not replace it. A model may identify a correlation, but breeders still need to determine whether it makes biological and agronomic sense. There are also challenges related to infrastructure, computing capacity, data standards, skilled personnel.



What will the breeder of tomorrow do?

The breeder of tomorrow is unlikely to be only a field scientist or only a molecular biologist. Knowledge of genetics and breeding will need to be combined with statistics, programming, bioinformatics, remote sensing and data interpretation. A breeder may use R to analyse trials, genomic software to examine marker data, image-analysis tools to measure plant traits and machine-learning models to predict performance. Yet the final decisions will still require an understanding of crops, environments and farmers' needs. This is why the 5G revolution should be understood as an evolution of breeding rather than a replacement of breeders. Every new technology adds another layer to the selection process. The strongest programmes will combine those layers intelligently.

Towards faster variety evolution

The ultimate goal of modern breeding is not technology for its own sake. It is to deliver improved varieties faster and more reliably.

Farmers need crops that can produce stable yields, tolerate stresses, use resources efficiently and meet changing quality requirements. The journey from visual field selection to AI-driven crop improvement shows how breeding has progressively moved from observation to measurement, from measurement to molecular information and from molecular information to prediction. The next step is integration. In the coming years, the most successful breeding pipelines may combine genomic selection, pangenomes, speed breeding, gene editing, high-throughput phenotyping, multi-environment testing and AI. The breeder's field will remain essential, but it will increasingly be connected to a digital ecosystem that can process information at a scale no human team could manage alone. The real 5G revolution, therefore, is not simply faster technology. It is faster learning: each breeding cycle generates data, each dataset improves prediction, and each prediction helps breeders make better choices in the next cycle. That continuous loop could shorten the journey from genetic diversity to farmer-ready varieties.

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