

Plant Breeding Paradigms: Transition from Traditional Selection to AI-Enabled Systems

R. Shiva Shankar^{1*}, S. Sai Vamshi², K. Pravallika³

College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad- 500030.

Corresponding Author: ramishettyshivashankar@gmail.com

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Abstract

Plant breeding is a cornerstone of agriculture and global food security, enabling the transformation of wild plants into productive, resilient, and adaptable crops. Its evolution reflects progressive advances in biological understanding and technology. Early traditional breeding (Breeding 1.0) relied on farmer-based selection of visible traits, leading to crop domestication and the development of diverse landraces. The rediscovery of Mendelian genetics and the rise of quantitative genetics in the late nineteenth century initiated scientific breeding (Breeding 2.0), introducing controlled hybridization, statistical selection, and exploitation of heterosis to improve breeding efficiency. Advances in molecular biology and genomics subsequently gave rise to molecular breeding (Breeding 3.0), allowing genotype-based selection through molecular markers and genomic prediction. Today, plant breeding is entering a precision era (Breeding 4.0) that integrates genomics, high-throughput phenotyping, genome editing, big data, and artificial intelligence to enable predictive and targeted crop improvement. Emerging intelligent breeding systems (Breeding 5.0) promise AI-driven and partially autonomous strategies to address climate change, resource constraints, and long-term food security challenges.

Introduction

Plant breeding has been fundamental to human civilization, underpinning global agriculture and food security by transforming wild plants into high-yielding, adaptable, and resilient crops. Since its origin, plant breeding has evolved over centuries through farmer-led selection based on observable traits such as seed size, taste, and stress tolerance leading to the domestication of diverse landraces adapted to local environments. However, rapid population growth, agricultural intensification, and environmental degradation increasingly exposed the limitations of purely traditional methods, driving the need for more systematic and science-based breeding approaches.

A major transition occurred in the late nineteenth and early twentieth centuries with the rediscovery of Mendelian genetics and the development of quantitative genetic theory. These advances enabled breeders to understand inheritance, heritability, and genetic variation, leading to controlled hybridization, replicated field trials, and statistically informed selection. Later, advances in molecular biology and genomics shifted breeding from phenotype-based selection toward genotype-based decision-making, allowing precise identification of genes and quantitative trait loci controlling complex agronomic traits and significantly accelerating genetic gain.

Today, plant breeding is entering an era of precision and intelligence driven by genomics, high-throughput phenotyping, big data, and artificial intelligence. Genome editing technologies, combined with AI-based predictive models, enable targeted crop design tailored to specific environments and sustainability goals. As breeding systems increasingly integrate automation, machine learning, and intelligent data platforms,

understanding the evolution and major paradigms of plant breeding becomes essential for addressing future challenges related to climate change, resource constraints, and global food security.

Types of Plant Breeding and Their Evolution

Plant breeding is the science and art of improving plants to meet human needs such as higher yield, improved quality, stress tolerance, and sustainability. Over time, breeding methods have evolved in response to advances in biological knowledge and technology. These approaches are often grouped into successive generations, ranging from traditional selection to modern AI-driven systems.

1. Traditional Breeding (Breeding 1.0)

Traditional breeding represents the earliest form of crop improvement and dates back more than 10,000 years to the origin of agriculture. Early farmers selected plants with desirable visible traits—such as larger seeds, better taste, or improved survival—and saved their seeds for subsequent planting. This process relied entirely on phenotypic observation and experiential knowledge passed down through generations.

Without knowledge of genetics, crop improvement was slow and strongly influenced by environmental variations. Despite these limitations, traditional breeding successfully domesticated thousands of crop species and shaped the genetic diversity that underpins modern agriculture. Many landraces and indigenous varieties developed during this era remain critical reservoirs of stress tolerance, adaptability, and nutritional diversity.

2. Scientific Breeding (Breeding 2.0)

Breeding 2.0 began in the late nineteenth and early twentieth centuries with the rediscovery of Mendel's laws of inheritance and the development of quantitative genetics. This era marked a decisive transition from empirical breeding to science-based crop improvement. Breeders gained the ability to understand inheritance patterns, estimate heritability, and systematically manipulate genetic variation.

Key techniques included controlled hybridization, pedigree and bulk selection, replicated field trials, and statistical evaluation of traits such as yield, maturity, and disease resistance. The exploitation of heterosis, particularly in crops like maize, resulted in substantial yield gains and revolutionized commercial agriculture. Breeding programs became institutionalized, and professional plant breeders emerged as a specialized workforce. Although Breeding 2.0 greatly improved efficiency, it remained constrained by long breeding cycles and limited in dissecting complex traits controlled by many genes.

3. Molecular Breeding (Breeding 3.0)

Breeding 3.0 emerged with advances in molecular biology, biotechnology, and DNA sequencing, enabling direct analysis of genetic variation at the DNA level. The introduction of molecular markers, marker-assisted selection (MAS), linkage mapping, genome-wide association studies (GWAS), and genomic selection fundamentally transformed breeding strategies.

Rather than relying solely on phenotypic performance, breeders could identify specific genomic regions and markers associated with desirable traits. Genomic selection allowed the prediction of breeding values using genome-wide marker data, reducing breeding cycles and increasing selection accuracy. This stage marked the transition toward data-intensive breeding systems and laid the foundation for computational and machine-

learning–assisted breeding, although integration across multiple biological data layers remained limited. However, limited phenotyping capacity and incomplete integration of environmental data constrained the full realization of genotype-based selection.

4. Precision Breeding (Breeding 4.0)

Breeding 4.0 represents the current frontier of plant breeding and is defined by the convergence of biotechnology and information technology. It integrates large-scale genomic data, high-throughput phenotyping, multi-omics analyses (genomics, transcriptomics, proteomics, and metabolomics), and advanced artificial intelligence.

A defining feature of Breeding 4.0 is the application of genome editing technologies such as CRISPR/Cas systems, which enable precise modification of target genes without random genetic changes. High-throughput phenotyping platforms—using drones, sensors, imaging systems, and automation—generate accurate, large-scale trait data under real field conditions. AI and machine learning models analyze these datasets to predict genotype–phenotype–environment interactions, optimize selection decisions, and enhance genetic gain.

Despite its transformative potential, Breeding 4.0 faces challenges related to high costs, technical complexity, regulatory uncertainty, data integration, and ethical considerations, particularly in developing regions. Nevertheless, effective deployment of Breeding 4.0 depends on robust data infrastructure and interdisciplinary expertise.

Intelligent Breeding (Breeding 5.0)

Breeding 5.0 marks a transformative phase in plant breeding, where artificial intelligence, automation, and cross-disciplinary research converge to create hyper-intelligent, data-driven crop improvement systems. Powered by fifth-generation AI and generative foundation models, this paradigm integrates explainable AI (XAI) with domain expertise, making breeding strategies more transparent, controllable, and precise (Fang, 2024).

In this system, multidimensional datasets—including genomic, phenomic, environmental, and cross-disciplinary information—are analyzed in real time through deep learning, enabling breeders to optimize selection and design strategies dynamically (Zhu *et al.*, 2024). AI is transforming germplasm management transforming traditional static “gene banks” into intelligent, data-rich platforms capable of continuous learning and innovation (Farooq *et al.*, 2024; Khan *et al.*, 2022).

Standardized approaches such as simulated breeding design, accelerated breeding cycles, and robotic automation now allow unprecedented efficiency and precision. AI not only automates these operations but continuously refines breeding strategies, tailoring crop development to specific farm conditions, climate challenges, and consumer preferences (Sun *et al.*, 2024).

By combining precision-driven methodologies, AI-integrated decision-making, and sustainable agricultural practices, Breeding 5.0 ushers in a new era of crop improvement—one defined by speed, accuracy, and adaptability, with the potential to reshape global agriculture for a rapidly changing world.

Conclusion

The progression from traditional breeding to AI-driven intelligent breeding reflects a continuous increase in

biological understanding, data integration, and technological sophistication. Each breeding stage builds upon the previous one, transforming crop improvement from slow, empirical selection into a precise, predictive, and increasingly automated process. As global agriculture faces escalating pressures from climate change, population growth, and resource limitations, advanced breeding technologies—particularly those integrating artificial intelligence—will play a decisive role in ensuring sustainable and resilient food systems for the future.

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