



POPULAR ARTICLE

Evolution of plant breeding: From traditional methods to predictive breeding

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Introduction

Agriculture has always been the backbone of human civilization, providing food, fibre, and raw materials for a growing global population. However, agriculture today faces unprecedented challenges, including climate change, shrinking cultivable land, emerging pests and diseases, and increasing demand for nutritious food. Meeting these challenges requires the development of crop varieties that are more productive, resilient, and adaptable. Plant breeding has played a vital role in achieving this goal and continues to evolve with advances in science and technology. Plant breeding is the process of developing improved crop varieties with desirable characteristics such as high yield, better quality, resistance to diseases and insect pests, tolerance to drought, heat, salinity, and other environmental stresses. For centuries, breeders relied on careful observation and selection of superior plants to improve crops. Over time, scientific discoveries and modern technologies have transformed plant breeding into a faster, more precise, and data-driven discipline.

The foundation: Classical plant breeding

Classical plant breeding laid the foundation for modern crop improvement. It involves techniques such as introduction, selection, hybridization, mutation breeding, and polyploidy breeding. Among these, hybridization has been the most widely used method, allowing breeders to combine desirable traits from different parents into a single variety. After crossing selected parents, breeders evaluate thousands of offspring over several generations to identify superior plants. Although this approach has successfully produced many high-yielding crop varieties, it is time-consuming, labour-intensive, and often takes 10–15 years to develop and release a new variety. Moreover, selecting complex traits such as yield, quality, and stress tolerance remains challenging because these traits are influenced by many genes as well as environmental conditions.

The rise of modern plant breeding

Rapid advances in molecular biology, genomics, and computational sciences have revolutionized plant breeding. Modern breeding integrates molecular markers, genomics, high-throughput phenotyping



artificial intelligence (AI), machine learning (ML), and predictive analytics to improve the efficiency of crop improvement. These technologies enable breeders to identify promising plants at an early stage, reduce the number of field trials, shorten breeding cycles, and increase the chances of developing superior crop varieties. As a result, breeders can respond more quickly to the challenges posed by climate change and the increasing demand for food.

Marker-assisted breeding: A step forward

One of the major breakthroughs in modern breeding is marker-assisted breeding (MAB). Instead of relying solely on visible plant characteristics, this approach uses DNA markers that are linked to desirable genes. By analysing a small leaf sample from young seedlings, breeders can determine whether a plant carries the required genes without waiting for the crop to mature. Marker-assisted breeding saves time, reduces the cost of field evaluation, and improves selection accuracy. It has become an important tool for developing crop varieties with improved disease resistance, pest resistance, and other simply inherited traits. However, its effectiveness is limited when dealing with complex traits such

Key technologies driving predictive breeding

Predictive breeding is supported by several advanced technologies that work together to improve prediction accuracy.

Genomic selection (GS): This approach uses thousands of DNA markers distributed across the entire genome to estimate the breeding value of individual plants. Instead of evaluating every plant in the field, breeders can identify superior genotypes at an early stage, saving both time and resources.

as grain yield or drought tolerance, which are controlled by many genes acting together.

Predictive breeding: The future of crop improvement

The latest advancement in plant breeding is predictive breeding, an innovative approach that combines genomics, artificial intelligence (AI), machine learning (ML), quantitative genetics, and environmental information to predict the performance of breeding materials even before extensive field testing. Instead of relying only on past observations, predictive breeding uses large volumes of biological and environmental data to identify the most promising parental combinations and offspring. Unlike marker-assisted breeding, which focuses mainly on a few genes associated with specific traits, predictive breeding considers the combined effects of thousands of genes along with environmental factors. This makes it particularly effective for improving complex traits such as grain yield, drought tolerance, heat tolerance, disease resistance, and quality. As a result, breeders can reduce the number of unnecessary crosses, shorten breeding cycles, and achieve greater genetic gain in less time.

High-throughput phenotyping (HTP):

Modern sensors, drones, digital imaging systems, and remote sensing technologies allow breeders to measure plant growth, canopy temperature, biomass, and other traits quickly and accurately across large breeding populations.

Enviromics: Environmental conditions such as rainfall, temperature, soil properties, and humidity strongly influence crop performance. Enviromics integrates these environmental data into prediction models, helping breeders identify varieties that perform consistently under different climatic conditions.



Multi-omics: Plant performance is influenced not only by genes but also by gene expression, proteins, metabolites, and observable characteristics. Multi-omics integrates genomics, transcriptomics, proteomics, metabolomics, phenomics, and enviromics to provide a comprehensive understanding of plant performance and improve prediction accuracy.

Artificial intelligence and machine learning: AI and ML analyse massive datasets that would be difficult to interpret using conventional statistical methods. These technologies recognize complex relationships among genes, traits, and environments, enabling more accurate prediction of breeding outcomes and accelerating decision-making.

Marker-assisted breeding and predictive breeding: Working together

Marker-assisted breeding and predictive breeding are not competing technologies; rather, they complement each other. Marker-assisted breeding is highly effective for selecting traits controlled by one or a few major genes, such as resistance to specific diseases. Predictive breeding, on the other hand, excels in improving complex traits controlled by many genes and influenced by the environment. When used together, these approaches enable breeders to identify

superior plants more efficiently, reduce breeding costs, minimize field testing, and develop improved crop varieties within a shorter period.

A promising future

As climate change continues to challenge global agriculture, the demand for resilient, high-yielding, and resource-efficient crop varieties is increasing. Predictive breeding offers an opportunity to accelerate crop improvement while reducing the time and cost involved in variety development. By integrating genomics, artificial intelligence, high-throughput phenotyping, and environmental data, breeders can make more informed decisions and deliver superior varieties to farmers faster than ever before. The evolution of plant breeding—from traditional selection to marker-assisted breeding and now predictive breeding demonstrates how science continues to transform agriculture. Although conventional breeding will remain an essential foundation, predictive breeding represents the next frontier in crop improvement. By combining biological knowledge with advanced data analytics, it promises to enhance agricultural productivity, strengthen climate resilience, and contribute significantly to global food and nutritional security for future generations.

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