
POPULAR ARTICLE

Where plant breeding is moving forward?

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Plant breeding looks forward by integrating cutting-edge technologies like genomics, gene editing (CRISPR-Cas9), and data analytics with traditional methods to develop crops that are high-yielding, resilient to climate change, and nutritionally enhanced.

Key future in plant breeding and directions are given here. Precision and speed with genomics and gene editing are components. The future of plant breeding is focused on precision and efficiency. Genomic tools, such as genome-wide association studies (GWAS) and molecular markers, enable breeders to identify and track genes for desirable traits at the DNA level, rather than waiting for the plant to mature to observe the physical trait (phenotyping). This dramatically shortens the development cycle for new varieties from over a decade to just a few years in some cases. Gene editing technologies like CRISPR-Cas9 provide an unprecedented ability to make targeted, small changes to a plant's existing DNA, allowing for the removal of unwanted traits or the addition of positive ones with high accuracy.

Climate Change Adaptation

A primary focus is developing crops that can withstand environmental pressures such as drought, extreme temperatures, and salinity, which are becoming more frequent due to climate change. Which involves breeding for resilience to a range of abiotic stresses by

using both conventional and modern techniques to identify and incorporate relevant genetic variations, including those found in crop wild relatives. Utilizing "speed breeding" techniques (manipulating light and temperature conditions) to achieve multiple generations per year, accelerating the selection process for climate-adapted traits. Data-driven decisions and AI is new area. The vast amount of data generated from genomics and high-throughput phenotyping (automated data collection on plant traits using sensors, drones, and satellites) is managed and interpreted using big data analytics, artificial intelligence (AI), and machine learning.

These tools help breeders to

Predict performance of new lines and crosses more accurately. Optimize breeding programs and make better-informed decisions. Sustainability and Nutrition: Future breeding efforts aim to reduce agriculture's environmental impact by focusing on increasing nutrient and water use efficiency in crops, reducing the need for chemical fertilizers and irrigation. Enhancing nutritional content (biofortification) to help address global malnutrition. Moving towards integrated systems approaches that consider not just the plant, but also its associated microbiome and the overall farming system for better resilience and productivity.

In essence, plant breeding is moving beyond traditional field-based selection to a more predictive, data-intensive, and molecular-level science, with the ultimate goal of ensuring global food security and sustainable agricultural practices in a changing world. Future directions in plant breeding include accelerating the process with new technologies like speed breeding and genomic selection, and using gene editing technologies such as CRISPR for precise genetic modifications. There is also a strong emphasis on a systems biology approach and the use of data science, including AI and machine learning, to manage vast amounts of genomic and phenotyping data. The ultimate goals are to create crops that are more productive, nutritious, and resilient to climate stress, and to address food security challenges for a growing global population.

Key technologies and approaches

Genomic-assisted breeding: This revolutionizes breeding by leveraging genomic information from parent selection to commercialization, leading to higher and more precise genetic gains.

Speed breeding: This technique rapidly cycles through generations of plants, significantly shortening the time needed to develop new lines.

Gene editing: Technologies like CRISPR allow for targeted and precise changes to a plant's DNA, enabling more efficient crop improvement.

Data science and AI: Artificial intelligence, machine learning, and data analytics are becoming essential for analyzing large datasets from genomics and phenotyping, improving the accuracy and efficiency of prediction models.

Systems biology: This approach provides a holistic view of a plant's genetic and biological pathways, enabling the targeted design of genomes for desired traits.

High-throughput phenotyping: Drones and robotics with sensors will be used to collect detailed data on thousands of plants, even measuring physiological traits that are difficult to assess manually.

Goals and applications

1. **Climate resilience:** Developing crops that can tolerate predicted future environmental conditions and extreme stresses.
2. **Increased yield and nutrition:** Creating high-performing, resource-efficient crops to help feed a growing global population.
3. **Disease and pest resistance:** Breeding crops that are inherently more resistant to diseases and pests.
4. **Diverse approaches:** Combining conventional breeding with newer methods like mutation breeding, cisgenesis, gene editing, and genetically modified crops to achieve different goals.

Upcoming technologies in plant breeding are primarily characterized by the integration of data science and advanced biotechnology, such as artificial intelligence (AI) and cutting-edge genome editing tools like CRISPR-Cas systems. These innovations aim to make crop improvement faster, more precise, and better adapted to modern challenges like climate change and global food demand.

Following are the key upcoming technologies and trends included in following discussions.

Precision breeding and molecular tools

Genome Editing (CRISPR-Cas9, Base/Prime Editing): This technology allows scientists to make targeted, specific changes to a plant's DNA sequence with unprecedented accuracy. This targeted approach can speed up the development of desirable traits, such as disease resistance, drought tolerance, and enhanced nutritional content, without introducing foreign DNA from unrelated species (which can avoid some GMO regulations).

Genomic Selection (GS): This method uses genome-wide DNA markers and advanced statistical models to predict the genetic performance of plants for complex traits like yield. It enables breeders to select superior individuals earlier in the breeding cycle, saving significant time and resources compared to traditional methods that rely solely on physical observation.

Marker-assisted selection (MAS): While already established, MAS continues to be refined with the discovery of more extensive DNA markers and is used for tracking specific genes or quantitative trait loci (QTLs) to improve traits.

Multi-omics integration: The convergence of data from genomics (DNA sequences), transcriptomics (gene expression), proteomics (proteins), and metabolomics (metabolites) provides a holistic understanding of plant biology and accelerates trait discovery and development.

Data-Driven and Automated Approaches

Artificial intelligence (AI) and machine learning (ML): AI is transforming plant breeding by analyzing vast datasets (genomic, phenotypic, and environmental) to optimize breeding strategies, predict crop performance in various environments, and identify ideal parent combinations.

High-throughput phenotyping (HTP) and phenomics: Phenotyping (measuring physical

characteristics) has traditionally been a bottleneck. HTP uses automated systems, such as drones, sensors, and computer vision, to quickly and non-destructively collect large amounts of data on plant growth, health, and stress responses, even in field conditions.

Big data analytics and bioinformatics: The immense amount of data generated by sequencing and phenotyping requires sophisticated bioinformatics and big data management systems for analysis and predictive modeling, enabling a data-driven "intelligent" breeding approach.

Accelerated growth techniques: Speed Breeding: This technique uses controlled environments (e.g., extended photoperiods, optimized temperature, and light quality with LEDs) to accelerate plant growth and achieve up to six generations per year for certain crops like wheat, barley, and canola, significantly shortening the development time for new varieties.

Haploid induction: This method rapidly produces completely homozygous lines, which can significantly speed up the breeding process compared to repeated self-pollination.

The future of plant breeding lies in the deep integration of these technologies to develop new crop varieties that are high-yielding, nutritious, and resilient to a changing climate.

References

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