

The Role of Plant Breeding in achieving global food security by 2050: Challenges and Opportunities

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Introduction:

Ensuring an adequate, safe, and nutritious food supply for a rapidly growing global population is one of the greatest challenges of the twenty-first century. The world's population is projected to reach approximately 9.7 billion by 2050, leading to a substantial increase in the demand for food, feed, fiber, and bio-based products. Meeting this growing demand is further complicated by shrinking arable land, climate change, declining soil fertility, water scarcity, the emergence of new pests and diseases, and increasing pressure on natural resources. These interconnected challenges threaten agricultural productivity and highlight the urgent need for sustainable approaches that can enhance crop production while conserving environmental resources (United Nations, 2022; FAO, 2023).

Plant breeding has long served as a cornerstone of agricultural development by improving the genetic potential of crop plants

to achieve higher yield, enhanced nutritional quality, resistance to biotic and abiotic stresses, and better adaptation to diverse agroecological conditions. Since the beginning of systematic crop improvement, plant breeders have contributed significantly to increasing global food production through the development of superior crop varieties. The remarkable achievements of the Green Revolution, driven by the introduction of high-yielding wheat and rice cultivars, demonstrated that genetic improvement of crops could substantially reduce hunger and improve food availability in many developing countries (Borlaug, 2007; Tester and Langridge, 2010).

The role of plant breeding has become even more critical in the era of climate change. Rising temperatures, erratic rainfall, frequent droughts, floods, salinity, and the spread of emerging pathogens are reducing crop

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productivity across many agricultural regions. Developing climate-resilient crop varieties capable of maintaining stable yields under changing environmental conditions has therefore become a global research priority. Modern breeding strategies now combine conventional selection with advanced technologies such as molecular markers, genomic selection, genome-wide association studies, speed breeding, and gene editing to accelerate the development of improved cultivars with greater precision and efficiency (Varshney et al., 2021; Hickey et al., 2019).

Beyond increasing crop productivity, plant breeding also plays a vital role in improving the nutritional quality of food crops, thereby addressing hidden hunger caused by deficiencies of essential vitamins and minerals. Biofortified varieties enriched with iron, zinc, provitamin A, and other micronutrients are increasingly being developed to improve human health, particularly in developing countries where micronutrient malnutrition remains widespread. Furthermore, breeding efforts focused on resource-use efficiency, disease resistance, and input-efficient cultivars contribute to environmentally sustainable agriculture by reducing dependence on fertilizers, pesticides, and irrigation water (Bouis and Saltzman, 2017; FAO, 2023).

Looking ahead to 2050, achieving global food security will require continuous

innovation in plant breeding supported by advances in genomics, biotechnology, artificial intelligence, digital phenotyping, and data-driven breeding approaches. Integrating these emerging technologies with conventional breeding methods will enable the development of resilient, high-yielding, and nutritionally superior crop varieties capable of meeting future food demands while promoting agricultural sustainability. Therefore, plant breeding remains one of the most effective scientific tools for ensuring food security, strengthening farmer livelihoods, and supporting resilient food systems in an increasingly uncertain global environment.

Why Food Security Matters in 2050?

Global food security has emerged as one of the defining challenges of the twenty-first century due to the combined effects of rapid population growth, climate change, urbanization, environmental degradation, and changing dietary preferences. According to the United Nations, the global population is expected to reach nearly 9.7 billion by 2050, with most of the increase occurring in developing countries where food demand is already rising rapidly (United Nations, 2022). Simultaneously, increasing incomes and urban lifestyles are driving greater consumption of cereals, fruits, vegetables, livestock products, and processed foods, thereby placing unprecedented pressure on agricultural

production systems (FAO, 2023). To meet these future demands, global agricultural production must increase substantially while ensuring that natural resources are used efficiently and sustainably (van Dijk et al., 2021).

The challenge extends beyond producing sufficient quantities of food to ensuring its accessibility, affordability, nutritional quality, and environmental sustainability. Despite remarkable advances in agricultural productivity, millions of people continue to experience hunger and malnutrition, while climate-related disasters, geopolitical conflicts, and disruptions in food supply chains have further intensified global food insecurity (FAO, 2023). At the same time, agriculture faces shrinking cultivable land, declining freshwater availability, soil degradation, and increasing frequency of droughts, floods, heat waves, and emerging pests and diseases, all of which threaten crop productivity (IPCC, 2023). Consequently, achieving global food security by 2050 will require innovative agricultural technologies capable of producing more food from limited resources while minimizing environmental impacts.

Ensuring food security is also fundamental to achieving the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), which aims to eliminate

hunger, improve nutrition, and promote sustainable agriculture by strengthening resilient food systems. Future agricultural development must therefore emphasize not only increased productivity but also resilience, nutritional security, environmental conservation, and economic sustainability. In this context, crop improvement through scientific plant breeding has become indispensable for ensuring stable food production under increasingly challenging environmental conditions (United Nations, 2015; Hickey et al., 2019).

The Contribution of Plant Breeding to Food Security

Plant breeding has consistently been one of the most effective scientific approaches for increasing agricultural productivity and ensuring global food security. By exploiting naturally occurring genetic variation and combining desirable traits through systematic selection, breeders have developed improved crop varieties with enhanced yield potential, superior quality, and greater resistance to environmental stresses. Historical evidence demonstrates that genetic improvement has contributed significantly to increases in crop productivity, with modern cultivars accounting for a substantial proportion of yield gains in major cereals over the past several decades (Duvick, 2005; Tester & Langridge, 2010).

The success of the Green Revolution clearly demonstrated the transformative role of plant breeding in combating hunger. The development of semi-dwarf, fertilizer-responsive wheat and rice varieties by scientists such as Norman E. Borlaug and subsequent breeding programs across Asia and Latin America dramatically increased cereal production, preventing widespread famine and improving food availability for millions of people (Borlaug, 2007). Today, plant breeding continues to address evolving agricultural challenges by developing varieties resistant to diseases, insects, drought, salinity, heat stress, and flooding, thereby reducing crop losses and stabilizing yields under adverse environmental conditions (Varshney et al., 2021).

Modern plant breeding has expanded beyond conventional selection to incorporate molecular breeding, genomic selection, high-throughput phenotyping, speed breeding, and genome editing technologies. These advanced approaches accelerate the identification and incorporation of beneficial genes, allowing breeders to develop improved cultivars more rapidly and accurately than traditional methods alone (Hickey et al., 2019). Additionally, breeding programs increasingly focus on improving nutritional quality through biofortification, enhancing the concentrations of essential micronutrients such as iron, zinc, and provitamin A in staple crops to combat

hidden hunger in vulnerable populations (Bouis & Saltzman, 2017).

Plant breeding also contributes to sustainable agriculture by developing varieties with improved nutrient-use efficiency, water-use efficiency, and resistance to biotic and abiotic stresses, thereby reducing dependence on fertilizers, pesticides, and irrigation. Such improvements not only increase farm productivity but also minimize environmental impacts and enhance the resilience of agricultural systems to climate change. Consequently, plant breeding represents a critical component of future strategies aimed at producing sufficient, nutritious, and climate-resilient food for a growing global population while conserving natural resources for future generations.

Major Challenges Facing Plant Breeders

Despite remarkable advances in crop improvement, plant breeders face numerous scientific, environmental, and socioeconomic challenges that complicate the development of improved crop varieties. Climate change has emerged as one of the most significant obstacles, with increasing temperatures, erratic rainfall patterns, prolonged droughts, floods, salinity, and extreme weather events adversely affecting crop growth and productivity worldwide (IPCC, 2023). These rapidly changing environmental conditions require breeders to develop climate-resilient cultivars

capable of maintaining stable yields across diverse and unpredictable environments, a task made more difficult by complex genotype $\times$ environment interactions (Hickey et al., 2019).

The continuous evolution of pathogens, insect pests, and weeds presents another major challenge. Many resistance genes incorporated into commercial cultivars gradually lose effectiveness due to the emergence of new pathogen races and pest biotypes. Consequently, breeders must continuously identify novel resistance sources from landraces, wild relatives, and germplasm collections while integrating durable resistance into elite breeding lines (McDonald & Linde, 2002). Simultaneously, the narrowing genetic base of many cultivated crops increases vulnerability to emerging diseases and environmental stresses, emphasizing the importance of conserving and utilizing plant genetic resources for future breeding efforts (FAO, 2019).

Plant breeders also face increasing pressure to simultaneously improve multiple complex traits, including yield, nutritional quality, stress tolerance, input-use efficiency, and consumer preferences. These traits are often controlled by numerous genes with strong environmental influences, making selection more challenging and time-consuming. Although advances in genomics, phenomics, artificial intelligence, and genome

editing have greatly enhanced breeding efficiency, their implementation remains constrained in many developing countries by limited financial resources, inadequate infrastructure, shortage of skilled personnel, and restrictive regulatory frameworks (Varshney et al., 2021).

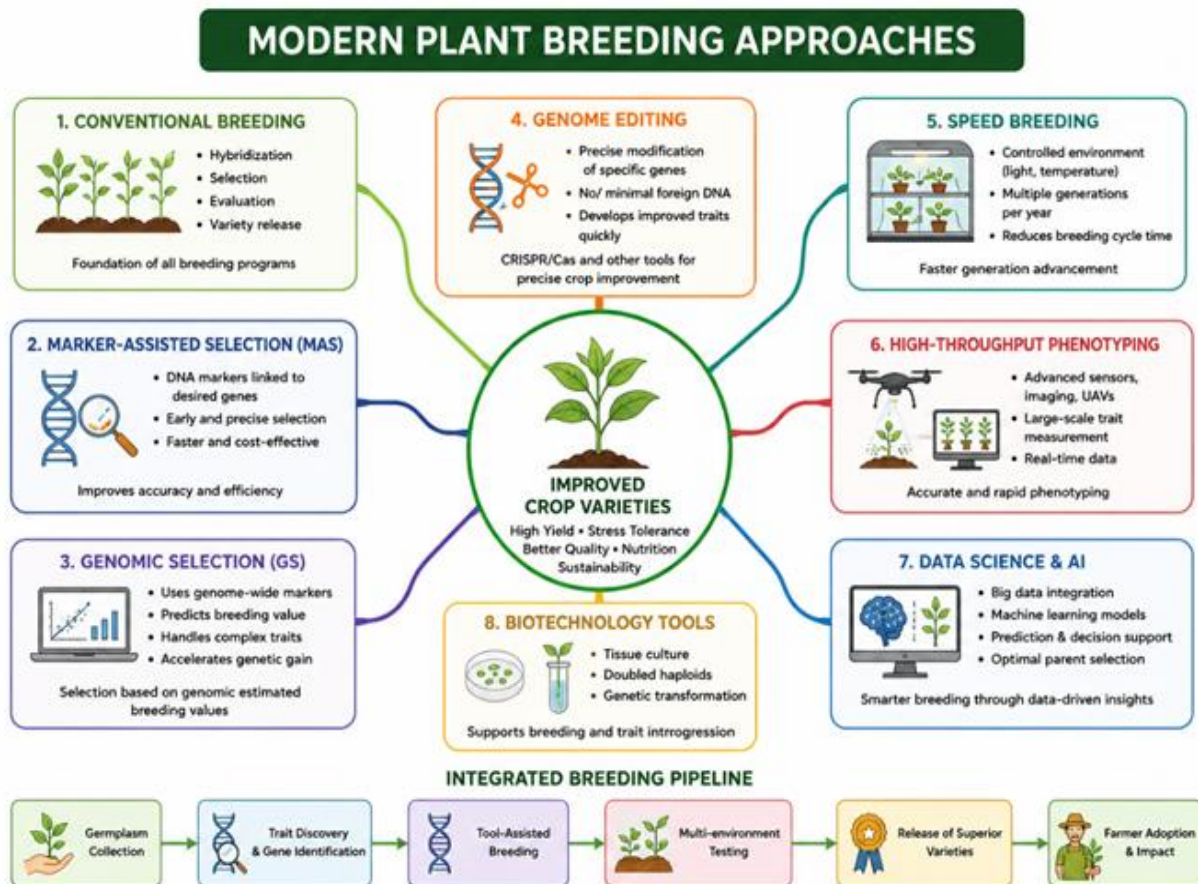
Furthermore, shortening the breeding cycle without compromising genetic gain has become a major priority. Conventional breeding typically requires several years to develop and release a new variety, whereas climate change and rapidly evolving agricultural challenges demand much faster genetic improvement. Integrating advanced technologies such as speed breeding, genomic selection, predictive breeding models, and artificial intelligence into conventional breeding pipelines offers promising solutions; however, widespread adoption requires substantial investment, international collaboration, effective germplasm exchange, and supportive public policies. Addressing these challenges will be essential for ensuring that plant breeding continues to meet future global food security needs.

Modern Plant Breeding Approaches

The increasing complexity of agricultural challenges has transformed plant breeding from a discipline primarily based on field selection to one that integrates genetics, genomics, biotechnology, computational

biology, and data science. While conventional breeding remains the foundation of crop improvement, modern breeding approaches have significantly accelerated the development of superior crop varieties by improving the precision and efficiency of selection. These innovations enable breeders to identify desirable genetic combinations earlier in the breeding cycle, shorten variety development time, and enhance genetic gain (Hickey et al., 2019).

other economically important traits. By using DNA markers closely linked to target genes, breeders can identify superior plants at the seedling stage without waiting for trait expression under field conditions, thereby reducing both time and cost (Collard & Mackill, 2008). The integration of high-density molecular markers, next-generation sequencing, and genomic selection has further enhanced breeding efficiency by allowing simultaneous prediction of multiple complex



Marker-assisted selection (MAS) has become an indispensable tool for transferring genes associated with disease resistance, abiotic stress tolerance, grain quality, and

traits controlled by numerous genes (Crosa et al., 2017).

Recent advances in genome editing technologies, particularly CRISPR-Cas

systems, have revolutionized crop improvement by enabling precise modification of specific genes without introducing foreign DNA in many applications. Genome editing has shown remarkable potential for developing crop varieties with enhanced yield, improved nutritional quality, resistance to diseases and insect pests, and tolerance to drought, salinity, and heat stress (Chen et al., 2019). Similarly, speed breeding techniques, which manipulate light and temperature conditions to accelerate plant growth, allow breeders to advance multiple generations within a single year, substantially reducing the time required for variety development (Watson et al., 2018).

Artificial intelligence (AI), machine learning, remote sensing, unmanned aerial vehicles (UAVs), and high-throughput phenotyping are emerging as powerful tools for data-driven plant breeding. These technologies enable rapid collection and analysis of large-scale phenotypic and environmental datasets, improving the prediction of breeding values and supporting more informed selection decisions. When combined with genomic information, digital agriculture technologies offer unprecedented opportunities to develop climate-resilient, resource-efficient, and high-yielding crop varieties capable of addressing future food security challenges (Varshney et al., 2021).

Opportunities for Sustainable Agriculture

Plant breeding offers tremendous opportunities to promote sustainable agriculture by developing crop varieties that produce higher yields while requiring fewer natural resources and agricultural inputs. Future crop improvement efforts are increasingly focused on enhancing resource-use efficiency, enabling plants to utilize water, nutrients, and sunlight more effectively. Varieties with improved nitrogen- and phosphorus-use efficiency can reduce fertilizer requirements, lower production costs, and minimize environmental pollution associated with excessive nutrient application (Lynch, 2019). Likewise, breeding for enhanced water-use efficiency has become essential for maintaining productivity under increasing water scarcity.

Climate-resilient crop varieties represent another significant opportunity for sustainable agricultural development. Breeding for tolerance to drought, heat, salinity, flooding, and other abiotic stresses can stabilize crop production despite increasing climatic variability. At the same time, incorporating durable resistance to major diseases and insect pests reduces dependence on chemical pesticides, thereby protecting biodiversity, improving ecosystem health, and promoting environmentally friendly farming systems (Tester & Langridge, 2010). Such genetic improvements contribute directly to

climate-smart agriculture by increasing resilience while reducing the environmental footprint of crop production.

Plant breeding also supports nutritional security through the development of biofortified crop varieties enriched with essential micronutrients such as iron, zinc, provitamin A, and quality proteins. These varieties provide an effective, sustainable, and economically viable approach to combating micronutrient deficiencies, particularly in developing countries where staple cereals constitute a major portion of the daily diet (Bouis & Saltzman, 2017). Furthermore, breeding programs aimed at improving shelf life, processing quality, and post-harvest characteristics can reduce food losses across the value chain, thereby increasing food availability without expanding cultivated land.

The integration of plant breeding with precision agriculture, digital technologies, and sustainable farming practices presents new opportunities for enhancing agricultural productivity while conserving natural resources. Collaborative efforts among breeders, agronomists, molecular biologists, policymakers, and farming communities will be essential to ensure that improved crop varieties effectively contribute to resilient, profitable, and environmentally sustainable agricultural systems capable of meeting future global food demands.

India's Role in Future Crop Improvement

India has emerged as one of the world's leading agricultural nations, possessing immense genetic diversity, a wide range of agroecological zones, and a well-established agricultural research system. Institutions such as the Indian Council of Agricultural Research (ICAR), the State Agricultural Universities (SAUs), and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have made significant contributions to crop improvement through the development of high-yielding, disease-resistant, and climate-resilient varieties of cereals, pulses, oilseeds, vegetables, and horticultural crops. These achievements have played a crucial role in strengthening national food security and improving farmers' livelihoods (ICAR, 2024).

India possesses one of the richest repositories of plant genetic resources in the world, providing breeders with valuable genetic variability for developing improved crop cultivars. The conservation and utilization of indigenous landraces, wild relatives, and traditional varieties offer enormous opportunities for breeding crops adapted to changing climatic conditions and emerging production constraints. Increasing emphasis is also being placed on orphan crops, millets, pulses, and underutilized species that possess superior nutritional quality and greater resilience to environmental stresses, thereby

contributing to diversified and sustainable food systems (FAO, 2019).

In recent years, Indian plant breeding programs have increasingly adopted advanced technologies such as marker-assisted breeding, genomic selection, genome sequencing, speed breeding, and genome editing. The integration of artificial intelligence, bioinformatics, phenomics, and precision agriculture into crop improvement programs is further enhancing breeding efficiency and accelerating the development of improved varieties. Public-private partnerships and international collaborations are also facilitating the exchange of germplasm, technologies, and expertise required to address future agricultural challenges (Varshney et al., 2021).

Looking toward 2050, India has the potential to become a global leader in climate-resilient and nutrition-sensitive crop improvement by combining conventional breeding expertise with modern genomic technologies. Continued investment in research infrastructure, human resource development, digital breeding platforms, and conservation of genetic resources will be essential to ensure that Indian agriculture remains productive, sustainable, and capable of contributing significantly to global food security.

Conclusion

Plant breeding has been one of the most influential scientific achievements in the history of agriculture, contributing substantially to increased food production, improved nutritional quality, and enhanced resilience of cropping systems. As the global population approaches 9.7 billion by 2050, the need for continuous genetic improvement of crops has become more urgent than ever. Conventional breeding, complemented by advances in molecular genetics, genomics, genome editing, artificial intelligence, and digital agriculture, provides powerful opportunities to develop crop varieties capable of meeting future food demands while adapting to climate change and conserving natural resources.

Nevertheless, realizing the full potential of plant breeding will require overcoming challenges related to climate variability, evolving pests and diseases, limited genetic diversity, resource constraints, and unequal access to improved technologies. Success will depend on sustained investment in agricultural research, conservation of plant genetic resources, international scientific collaboration, effective policy support, and active participation of farming communities. By integrating innovation with sustainability, plant breeding can continue to serve as a cornerstone of global food security and play a

decisive role in building resilient, productive, and environmentally sustainable agricultural systems for future generations.

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