

# Breeding to Feed Billions by 2050

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## ABSTRACT

By 2050, global agriculture must feed nearly 10 billion people under increasing constraints from climate change, land degradation, and resource scarcity. Conventional plant breeding, while historically successful, is no longer delivering yield gains at the pace required to meet future food demand. This article explores how modern plant breeding can rise to this challenge by integrating advances in genomics, pre-breeding, speed breeding, genome editing, phenomics, and artificial intelligence. Central to this transformation is the concept of genetic gain, achieved through improved selection accuracy, enhanced genetic diversity, intensified selection, and reduced breeding cycle time. Case studies in climate-resilient crops, biofortified varieties, and accelerated domestication illustrate the tangible impact of these innovations. The vision for breeding in 2050 emphasizes service-driven, data-enabled, and participatory breeding systems capable of delivering locally adapted, nutritionally rich, and climate-smart crops. Together, these strategies position plant breeding as a cornerstone of global food security in the coming decades.

## INTRODUCTION

**B**y 2050, the global population is projected to touch 10 billion, intensifying pressure on already strained food systems. While the Green Revolution of the twentieth century successfully boosted yields of staple crops, the

rate of yield gain in major cereals such as rice, wheat, and maize is now plateauing and remains insufficient to meet future demand (Hickey *et al.*, 2019). Compounding this challenge are climate change, shrinking arable land, water scarcity, and declining soil

fertility. Plant breeding, therefore, stands at a critical crossroads. The task is no longer limited to producing high-yielding varieties, but to develop crops that are climate-resilient, nutritionally enriched, resource-efficient, and locally adaptable. The question is not whether innovation is needed, but how fast and how inclusively breeding systems can evolve to feed billions sustainably.

### **Lessons from the Past: What Worked and What Didn't**

The late 1990s heralded great optimism for a genomic revolution in plant breeding. Advances such as molecular markers, genome sequencing, doubled haploids, and genetically modified crops were expected to transform breeding pipelines. While genome sequencing has indeed become routine, its direct impact on breeding outcomes has been uneven (Bassi *et al.*, 2023). Molecular marker technologies improved selection efficiency, yet their adoption has been slowed by high costs, regulatory barriers, and limited integration into public-sector breeding. In contrast, accelerated breeding cycles, improved statistical tools, and conservation agriculture practices such as zero tillage have had a more tangible impact on productivity. These mixed outcomes highlight a key lesson: technology alone is insufficient unless it is affordable, scalable, and well-integrated with breeding objectives.

### **Genetic Gain: The Central Currency of Breeding**

At the heart of modern plant breeding lies genetic gain, defined as the rate of improvement per year. Current estimates suggest annual gains of only 0.8–1.2%, whereas at least 2% gain is required to meet future food demands. Genetic gain is influenced by four key components: selection accuracy, selection intensity, genetic variance, and breeding cycle time. Improving phenotyping accuracy remains crucial, as

complex traits such as yield and stress tolerance are strongly influenced by genotype  $\times$  environment interactions. Emerging tools like high-throughput phenomics, near-infrared spectroscopy, and genomic selection are helping breeders make more accurate predictions earlier in the breeding cycle (Li *et al.*, 2018). Among these, genomic selection stands out as a disruptive technology, enabling the selection of superior lines before field testing, thereby dramatically reducing breeding cycle time.

### **Unlocking Diversity: Pre-Breeding and Wild Relatives**

One of the major constraints in modern breeding is the erosion of genetic diversity caused by domestication bottlenecks and repeated use of elite germplasm. Pre-breeding programs aim to reintroduce diversity by tapping into landraces and wild relatives that harbor valuable alleles for stress tolerance and adaptation. Successful pre-breeding initiatives, particularly in wheat, have demonstrated that introgressing exotic germplasm can enhance yield stability under heat and drought stress without compromising agronomic performance (Bassi *et al.*, 2023). Advances in genomics, skim sequencing, and haplotype-based breeding are transforming genebanks from passive repositories into active engines of genetic innovation. However, concerns over access and benefit-sharing regulations pose risks to the free exchange of germplasm, potentially limiting future breeding progress. Ensuring open yet equitable access to genetic resources remains a policy priority.

### **Speed Breeding and Genome Editing: Redefining Time**

Reducing the time required for a breeding cycle is one of the most effective ways to increase genetic gain. Speed breeding, which uses controlled environments, extended photoperiods, and optimized growth

conditions, allows multiple generations per year and has been successfully applied across crops (Hickey *et al.*, 2019). The integration of genome editing technologies, particularly CRISPR–Cas systems, further accelerates crop improvement. Express-editing approaches aim to bypass traditional tissue culture bottlenecks by directly applying editing reagents to plants, enabling rapid generation of improved lines without foreign DNA integration. This approach has already been demonstrated in accelerated domestication of wild tomato, where key domestication traits were engineered within a few generations (Li *et al.*, 2018). Such strategies blur the line between breeding and biotechnology, offering unprecedented speed while raising regulatory and ethical questions that societies must address.

#### **Climate-Resilient and Nutrient-Dense Crops**

Breeding for climate resilience has shifted from a long-term goal to an immediate necessity. Success stories such as Sub1 flood-tolerant rice and heat-tolerant maize hybrids from CIMMYT illustrate how targeted breeding can mitigate climate risks. Simultaneously, biofortification has emerged as a powerful tool to combat “hidden hunger.” Pearl millet variety *Dhanashakti*, enriched with iron and zinc, exemplifies how breeding can directly improve public health, benefiting tens of thousands of farmers and consumers (Rai *et al.*, 2012). Looking ahead, futuristic approaches such as enhancing photosynthetic efficiency in C3 crops, engineering C4 pathways in rice, and introducing biological nitrogen fixation into cereals hold transformative potential, albeit with significant scientific and regulatory challenges.

#### **Artificial Intelligence and the Breeding Systems of Tomorrow**

Artificial intelligence and machine learning are rapidly reshaping plant breeding by integrating

genomic, phenotypic, and environmental data into predictive models. These tools enable breeders to design optimal crosses, forecast performance under future climates, and allocate resources more efficiently. The vision for 2050 envisions a service-based breeding ecosystem, where specialized providers handle genomic analysis, phenotyping, accelerated generation advancement, and data analytics. Breeders of the future will increasingly act as system designers balancing accuracy, intensity, and speed while remaining grounded in field realities (Bassi *et al.*, 2023).

#### **CONCLUSION**

Feeding billions by 2050 will require more than incremental improvements—it demands a reimagining of plant breeding systems. By combining genetic diversity, accelerated breeding cycles, genome editing, climate resilience, and artificial intelligence, plant breeding can rise to the challenge. Yet, success will depend not only on technological innovation but also on supportive policies, equitable access to genetic resources, and strong links between science, farmers, and markets. If these elements align, plant breeding can once again deliver a quiet revolution one that sustains humanity in a changing world.

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