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Nutritional Quality improvement through Plant Genetics and Breeding: Biofortification Strategies

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Introduction:

Food security is no longer measured solely by the availability of sufficient calories but also by the nutritional quality of the food consumed. Although remarkable progress in agricultural production has substantially increased global food availability over the past few decades, micronutrient malnutrition continues to affect billions of people worldwide. Deficiencies of essential vitamins and minerals, particularly iron, zinc, vitamin A, iodine, and folate, impair physical growth, cognitive development, immune function, and overall human health. The challenge is expected to intensify with continued population growth, climate change, degradation of natural resources, and changing dietary patterns, making the production of nutrient-rich crops an important priority for global agriculture (FAO et al., 2024; WHO, 2024).

Plant genetics and breeding have emerged as powerful tools for addressing nutritional deficiencies through the development of crop varieties with enhanced concentrations of essential nutrients. Unlike conventional interventions such as dietary supplementation and industrial food fortification, genetic improvement enables crops to accumulate higher levels of micronutrients during plant growth, allowing these nutritional benefits to reach rural populations that often have limited access to healthcare services and commercially fortified foods. Advances in conventional breeding, molecular genetics, genomics, and genome editing have further accelerated the development of nutritionally improved crop varieties, providing sustainable and cost-effective solutions for combating micronutrient deficiencies (Bouis & Saltzman, 2017; Saltzman et al., 2013).

Biofortification has therefore become an integral component of global efforts to improve nutrition and public health. By

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combining genetic diversity with modern breeding technologies, scientists are developing staple crops that not only produce higher yields but also deliver greater nutritional value. This integrated approach contributes simultaneously to food security, nutritional security, and sustainable agricultural development, making plant breeding an essential strategy for achieving the Sustainable Development Goals, particularly the goal of ending hunger and all forms of malnutrition (WHO, 2024; Prasanna et al., 2020).

Global Burden of Hidden Hunger

Hidden hunger refers to a form of malnutrition caused by inadequate intake or poor absorption of essential vitamins and minerals despite the consumption of sufficient dietary calories. Unlike protein-energy malnutrition, hidden hunger often remains undetected because its symptoms develop gradually and may not be immediately visible. Nevertheless, micronutrient deficiencies have profound consequences for human health, reducing physical growth, weakening immunity, impairing cognitive development, lowering work productivity, and increasing the risk of illness and mortality, particularly among children, pregnant women, and other vulnerable populations (WHO, 2024).

Iron deficiency remains one of the leading causes of anemia worldwide, while zinc deficiency compromises immune function and child development. Vitamin A deficiency is a major cause of preventable childhood blindness and significantly increases susceptibility to infectious diseases. Deficiencies of iodine, folate, and other micronutrients similarly contribute to developmental disorders and adverse pregnancy outcomes. According to recent global assessments, billions of people continue to consume diets that fail to provide adequate amounts of one or more essential micronutrients, especially in low- and middle-income countries where staple cereals constitute a major proportion of daily food intake (FAO et al., 2024).

The persistence of hidden hunger reflects not only insufficient food availability but also limited dietary diversity, poverty, unequal access to nutrient-rich foods, declining soil fertility, and the impacts of climate change on crop nutritional quality. Increasing atmospheric carbon dioxide concentrations have also been reported to reduce the concentration of important minerals such as zinc and iron in several staple crops, thereby posing additional challenges to global nutritional security (Myers et al., 2014). Addressing hidden hunger therefore requires integrated strategies that improve both agricultural productivity and the nutritional composition of staple food crops.

What is Biofortification?

Biofortification is the process of increasing the concentration and bioavailability of essential vitamins and minerals in food crops through plant breeding, genetic improvement, agronomic practices, or modern biotechnological approaches. Unlike post-harvest food fortification, where nutrients are added during food processing, biofortification enhances the nutritional value of crops while they are growing in the field. As a result, farmers cultivate nutrient-enriched varieties using standard agricultural practices, and consumers receive enhanced nutrition through their regular diets without requiring major changes in food habits (Bouis & Saltzman, 2017). Plant breeding remains the most widely adopted and sustainable approach to biofortification. Breeders identify naturally occurring genetic variation for target nutrients within crop germplasm and incorporate these desirable traits into high-yielding cultivars through repeated crossing and selection. More recently, molecular markers, genomic selection, and genome editing technologies have accelerated the development of biofortified varieties with improved concentrations of iron, zinc, provitamin A, quality protein, and other essential nutrients while simultaneously maintaining desirable agronomic performance (Pfeiffer & McClafferty, 2007; Garg et al., 2018).

Several biofortified crop varieties have already demonstrated significant success in improving nutritional outcomes across different regions of the world. Zinc-enriched wheat and rice, iron-rich pearl millet and beans, provitamin A maize, orange-fleshed sweet potato, and Golden Rice represent important milestones in nutritional crop improvement. These crops provide sustainable and cost-effective solutions for combating hidden hunger because the nutritional benefits continue from one generation of seed to the next without requiring repeated external interventions. Consequently, biofortification has become a key strategy for integrating agriculture, nutrition, and public health to improve the well-being of millions of people while strengthening sustainable food systems (Saltzman et al., 2013; Prasanna et al., 2020).

Role of Plant Genetics in Nutritional Quality Improvement

Genetic variation is the foundation of crop improvement and plays a decisive role in enhancing the nutritional quality of food crops. Naturally occurring allelic variation present in landraces, wild relatives, traditional cultivars, and germplasm collections provides valuable genetic resources for increasing the concentration of essential micronutrients such as iron, zinc, calcium, selenium, provitamin A, and quality proteins in staple crops. Plant breeders utilize this genetic diversity to identify donor parents possessing superior nutritional traits and incorporate these traits into high-yielding cultivars through systematic breeding programmes (Pfeiffer & McClafferty, 2007).

The nutritional composition of crops is generally governed by multiple genes controlling nutrient uptake, transport, accumulation, metabolism, and storage within plant tissues. Understanding the genetic architecture of these complex traits has enabled breeders to develop nutrient-dense varieties without compromising yield, adaptability, or consumer acceptance. Advances in plant genomics, quantitative genetics, and molecular biology have facilitated the identification of quantitative trait loci (QTLs) and candidate genes associated with micronutrient accumulation, thereby improving breeding efficiency and accelerating varietal development (Bouis & Saltzman, 2017).

Plant genetics also contributes to improving the bioavailability of nutrients rather than merely increasing their concentration. Breeding efforts increasingly focus on reducing anti-nutritional compounds such as phytic acid, which limits the absorption of iron and zinc in the human digestive system. Simultaneously, increasing promoters of nutrient absorption, including provitamin A carotenoids and quality proteins, enhances the nutritional effectiveness of biofortified crops. Consequently, genetic improvement has become one of the most sustainable approaches for simultaneously addressing food security, nutritional security, and public health challenges (Garg et al., 2018).

Conventional Plant Breeding for Biofortification

Conventional plant breeding remains the most widely adopted and economically sustainable approach for developing biofortified crop varieties. This strategy exploits naturally existing genetic variability within crop species by crossing nutritionally superior donor parents with elite, high-yielding cultivars followed by repeated selection over successive generations. Unlike transgenic approaches, conventional breeding does not involve the introduction of foreign DNA, making biofortified varieties more readily accepted by farmers, consumers, and regulatory agencies (Pfeiffer & McClafferty, 2007).

The success of conventional biofortification depends on the availability of sufficient genetic diversity for target nutrients. Large germplasm collections maintained by national and international gene banks provide breeders with valuable sources of micronutrient-rich genetic material. Through pedigree selection, backcross breeding, recurrent selection, and population improvement, breeders combine superior nutritional quality with desirable agronomic traits such as high yield, disease resistance, stress tolerance, and grain quality. Multi-location testing is subsequently conducted to ensure that nutrient accumulation remains stable across diverse environmental conditions (Saltzman et al., 2013).

Conventional breeding has already resulted in the successful development and release of several biofortified crop varieties worldwide. Zinc-rich wheat and rice, iron-rich pearl millet and beans, provitamin A maize, orange-fleshed sweet potato, and quality protein maize are notable examples that have significantly improved the nutritional status of millions of people in developing countries. These varieties require no change in farmers' cultivation practices while continuously delivering enhanced nutritional benefits through each harvest, making conventional breeding one of the most cost-effective interventions against hidden hunger (Prasanna et al., 2020).

Molecular Breeding and Genomic Approaches

The emergence of molecular genetics has transformed plant breeding by enabling the precise identification and selection of genes controlling nutritional traits. Molecular breeding integrates DNA marker technologies with conventional breeding, allowing breeders to select superior plants based on their genetic makeup rather than relying solely on field observations. Marker-assisted selection (MAS) has become particularly valuable for transferring genes associated with enhanced

Table 1. Examples of conventionally developed biofortified crops

Crop	Target nutrient	Breeding objective	Major benefit
Wheat	Zinc, Iron	Increase grain micronutrient concentration	Reduces zinc and iron deficiency
Rice	Zinc	Improve grain zinc content	Supports child growth and immunity
Pearl millet	Iron, Zinc	Enhance mineral density	Reduces anemia in vulnerable populations
Maize	Provitamin A	Increase β-carotene content	Helps prevent vitamin A deficiency
Sweet potato	Provitamin A	Improve carotenoid concentration	Improves eye health and immunity
Common bean	Iron	Increase seed iron concentration	Supports healthy blood formation

iron, zinc, provitamin A, and protein content while minimizing the time required for variety development (Collard & Mackill, 2008).

The availability of complete crop genome sequences, high-density single nucleotide polymorphism (SNP) markers, and next-generation sequencing technologies has greatly accelerated nutritional crop improvement. Quantitative trait loci (QTL) mapping and genome-wide association studies (GWAS) have identified numerous genomic regions controlling micronutrient accumulation in cereals, legumes, and horticultural crops. These discoveries allow breeders to combine multiple favourable alleles simultaneously through marker-assisted pyramiding, thereby increasing breeding precision and efficiency (Crossa et al., 2017).

Genomic selection represents another major advancement in nutritional breeding. Instead of selecting individual genes, genomic selection uses genome-wide marker information to predict the breeding value of plants for complex traits controlled by numerous genes. This approach enables early selection of promising breeding lines, shortens breeding cycles, and increases genetic gain for nutritional quality traits. The integration of high-throughput phenotyping, bioinformatics, artificial intelligence, and predictive modelling further enhances breeders' ability to develop nutrient-rich crop varieties adapted to diverse environments (Varshney et al., 2021).

Genome Editing and Biotechnology in Biofortification

Genome editing has opened a new era in nutritional crop improvement by enabling precise modification of genes responsible for nutrient synthesis, transport, and storage. Among the available genome editing technologies, the CRISPR-Cas system has

Table 2. Molecular tools used in nutritional crop improvement

Technology	Primary purpose	Application in biofortification
Marker-assisted selection (MAS)	Selection using DNA markers	Transfer of iron, zinc and provitamin A genes
QTL mapping	Identification of genomic regions	Detection of nutrient-related loci
GWAS	Genome-wide gene discovery	Identification of favourable alleles
SNP genotyping	High-resolution genetic analysis	Parent selection and trait tracking
Genomic selection	Prediction of breeding value	Improvement of complex nutritional traits
High-throughput phenotyping	Rapid trait evaluation	Accurate screening of breeding populations

become the most widely adopted because of its simplicity, efficiency, accuracy, and versatility. Unlike conventional genetic engineering, genome editing can precisely alter native genes without necessarily introducing foreign DNA, thereby offering opportunities to rapidly improve crop nutritional quality while maintaining desirable agronomic characteristics (Chen et al., 2019).

Researchers have successfully employed genome editing to increase the accumulation of provitamin A, iron, zinc, folate, and essential amino acids in several crop species. In addition to enhancing nutrient concentration, genome editing is also being used to reduce anti-nutritional compounds such as phytic acid, thereby improving the bioavailability of minerals consumed by humans. Such targeted modifications allow breeders to address multiple nutritional objectives simultaneously while minimizing undesirable effects on plant growth and productivity (Li et al., 2021).

Biotechnological approaches complement genome editing by providing additional tools such as transgenic technology, RNA interference (RNAi), tissue culture, doubled haploid production, and genetic transformation. These technologies facilitate rapid incorporation of beneficial genes from diverse genetic sources and accelerate breeding programmes. A well-known example is **Golden Rice**, developed through genetic engineering to produce β-carotene in rice endosperm, demonstrating the enormous potential of biotechnology to address vitamin A deficiency in rice-dependent populations (Ye et al., 2000).

Although regulatory frameworks, biosafety evaluation, and public acceptance remain important considerations, advances in genome editing and biotechnology are

Table 3. Biotechnology-based approaches for nutritional enhancement

Technology	Principle	Major nutritional application
CRISPR-Cas genome editing	Precise gene modification	Increase iron, zinc, provitamin A and folate
Genetic transformation	Introduction of beneficial genes	Development of Golden Rice and other nutrient-rich crops
RNA interference (RNAi)	Gene silencing	Reduction of anti-nutritional compounds
Tissue culture	Rapid propagation	Multiplication of elite biofortified lines
Doubled haploid technology	Rapid production of homozygous lines	Accelerated breeding of nutrient-rich cultivars
Bioinformatics & AI	Data-driven gene discovery	Identification of candidate genes and breeding targets

expected to play an increasingly important role in future biofortification programmes. When integrated with conventional breeding and genomics-assisted selection, these technologies provide powerful opportunities to develop nutritionally superior crop varieties capable of contributing significantly to global food and nutritional security under changing climatic conditions.

Success Stories of Biofortified Crops

Biofortification has evolved from a research concept into a practical strategy that has improved the nutritional status of millions of people across the globe. Collaborative efforts among plant breeders, nutritionists, governments, and international organizations have led to the development and widespread adoption of several biofortified crop varieties. These success stories demonstrate that plant breeding can effectively address micronutrient deficiencies while maintaining high yield and farmer acceptance (Bouis & Saltzman, 2017).

One of the earliest and most recognized examples is **Golden Rice**, which was developed through genetic engineering to accumulate β-carotene in the rice endosperm, providing a potential dietary source of vitamin A for populations that rely heavily on rice as their staple food (Ye et al., 2000). Similarly, **orange-fleshed sweet potato** enriched with provitamin A has been successfully introduced in several African countries, significantly improving vitamin A intake among children and women (Saltzman et al., 2013).

Conventional breeding has also produced remarkable achievements. **Iron-rich pearl millet (Dhanashakti)**, developed through conventional breeding, has shown significant improvements in iron intake and has contributed to reducing iron deficiency in

Table 4. Major biofortified crops and their nutritional benefits

Crop	Nutrient enhanced	Method	Major benefit
Golden Rice	Provitamin A	Genetic engineering	Reduces vitamin A deficiency
Wheat	Zinc	Conventional breeding	Improves immune function and growth
Rice	Zinc	Conventional breeding	Enhances dietary zinc intake
Pearl millet (Dhanashakti)	Iron	Conventional breeding	Helps reduce iron-deficiency anemia
Maize (QPM)	Lysine & Tryptophan	Conventional breeding	Improves protein quality
Orange-fleshed sweet potato	β-carotene	Conventional breeding	Supports eye health and immunity
Common bean	Iron	Conventional breeding	Improves iron nutrition

India (Finkelstein et al., 2015). Zinc-enriched wheat and rice varieties released in South Asia have demonstrated higher grain zinc concentrations without compromising yield, thereby supporting nutritional security in cereal-based diets. Likewise, **quality protein maize (QPM)**, enriched with lysine and tryptophan, has enhanced protein quality and improved child nutrition in many developing countries (Prasanna et al., 2020).

These examples clearly illustrate that biofortification is not merely an experimental technology but a practical, sustainable, and cost-effective intervention capable of reaching rural communities where conventional nutrition programmes often have limited impact. As more nutrient-rich crop varieties become available, biofortification is expected to play an increasingly important role in combating hidden hunger worldwide.

Challenges and Future Prospects

Despite remarkable progress, several scientific and practical challenges continue to limit the large-scale adoption of biofortified crops. Many nutritional traits are quantitatively inherited and strongly influenced by environmental conditions, making their improvement more complex than simple yield traits. Maintaining high nutrient concentrations while simultaneously improving yield, disease resistance, climate resilience, and consumer-preferred characteristics remains a major breeding challenge (Bouis & Saltzman, 2017).

Another important limitation is the relatively low awareness among farmers and consumers regarding the health benefits of biofortified crops. Limited seed availability, weak dissemination systems, inadequate policy support, and market incentives often slow the adoption of newly released varieties. In addition, regulatory frameworks and public perception continue to influence the acceptance of genetically engineered and genome-edited biofortified crops in many countries (Garg et al., 2018).

India's Contribution to Biofortification

India has emerged as a global leader in biofortification research and the development of nutrient-rich crop varieties. The **Indian Council of Agricultural Research (ICAR)**, together with State Agricultural Universities, the **Indian Institute of Millets Research (IIMR)**, the **Indian Institute of Wheat and Barley Research (IIWBR)**, and international partners such as **HarvestPlus**, has played a pivotal role in developing biofortified varieties of wheat, rice, pearl millet, maize, lentil, mustard, and several other crops.

One of India's notable achievements is the development of **Dhanashakti**, the world's first commercially released iron-rich pearl millet variety developed through conventional breeding. Similarly, several zinc-enriched wheat and rice varieties have been released for cultivation in different agro-climatic regions, providing farmers with nutrient-rich alternatives that maintain competitive yield performance. Biofortified maize and lentil varieties with enhanced micronutrient content have also been developed to improve dietary diversity and nutritional outcomes.

Recognizing the importance of nutritional security, the Government of India has incorporated biofortification into national agricultural and nutrition programmes. The promotion of biofortified crops through seed distribution, public procurement, school feeding programmes, and awareness campaigns reflects India's commitment to addressing hidden hunger through science-based agricultural innovation. Continued investment in genomics, molecular breeding, genome editing, and digital breeding technologies will further strengthen India's leadership in developing climate-resilient and nutrient-dense crop varieties for both domestic and global food systems.

Conclusion

Biofortification represents one of the most sustainable and scientifically proven strategies for improving the nutritional quality of staple food crops and addressing the widespread problem of hidden hunger. By harnessing the power of plant genetics, conventional breeding, molecular tools, and modern biotechnological approaches, breeders have successfully developed crop varieties enriched with essential vitamins, minerals, and quality proteins without compromising agronomic performance. These nutrient-rich varieties offer a long-term, cost-effective solution that complements dietary diversification, food fortification, and nutritional supplementation programmes.

The successful adoption of biofortified crops across several countries demonstrates the enormous potential of plant breeding to improve public health while strengthening food and nutritional security. Nevertheless, maximizing the impact of biofortification will require continued research, greater investment in breeding programmes, supportive government policies, efficient seed delivery systems, and increased awareness among farmers and consumers. Looking ahead, the integration of genomics, artificial intelligence, genome editing, and precision breeding technologies is expected to further accelerate the development of climate-resilient, high-yielding, and nutritionally superior crop varieties. Through sustained scientific innovation and collaborative efforts, biofortification will remain a cornerstone of sustainable agriculture and a vital pathway toward achieving global nutritional security in the coming decades.

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