

Biofortification of Maize: A Sustainable Strategy for Global Nutritional Security

*Sunil Kumar Kumawat¹, P. K. Parmar² and M. K. Sharma³

¹Ph. D Scholar, Department of Genetics and Plant Breeding, Rajasthan Agricultural Research Institute (RARI), Durgapura, Jaipur, Rajasthan, India

²Associate Research Scientist, Main Maize Research Station (AAU), Godhra, India

³Assistant Professor, Department of Agricultural Statistics, SKNAU, Jobner, India

*Corresponding Author's email: sunilkumarb.sc2018@gmail.com

Maize (*Zea mays* L.), one of the world's most widely grown cereal crops, plays a critical role in global food and nutritional security. However, micronutrient malnutrition, particularly deficiencies of iron (Fe), zinc (Zn), and vitamin A, remains a major global health concern. Conventional fortification and supplementation strategies have limited reach in resource-poor regions, making biofortification the genetic enhancement of staple crops for higher nutrient content a cost-effective and sustainable alternative. In maize, the development of quality protein maize (QPM), pro-vitamin A-enriched lines, and Fe-Zn-dense germplasm has revolutionized nutritional breeding. This review synthesizes recent advances in maize biofortification, focusing on genetic, molecular, and biotechnological approaches that enhance nutritional quality while maintaining agronomic performance. It highlights India's contributions and discusses future perspectives for integrating biofortified maize into national food systems to combat hidden hunger.

Key Words: Biofortification, FAO, GFSI, SDG

Introduction

Micronutrient malnutrition, often referred to as “hidden hunger,” affects more than two billion people worldwide, predominantly in developing countries where cereal-based diets dominate daily food intake (FAO, 2023). Among staple crops, maize (*Zea mays* L.) holds a unique position as a source of calories, feed, and industrial raw material. Yet, conventional maize varieties are nutritionally imbalanced notably deficient in essential amino acids such as lysine and tryptophan, and lacking sufficient iron, zinc, and vitamin A precursors. These limitations exacerbate nutritional deficiencies, particularly among children and women in low-income populations. The Global Food Security Index (GFSI, 2022) and India's National Family Health Survey (NFHS-5) reveal that more than 50 % of women and children in India suffer from iron-deficiency anemia. Similarly, vitamin A deficiency contributes to preventable blindness and increased morbidity, while zinc deficiency impairs immune and reproductive health. In this context, biofortification—the process of enhancing the nutrient density of crops through breeding or biotechnology emerges as a sustainable, low-cost, and long-term solution to hidden hunger. India, being the fifth-largest producer of maize globally, offers tremendous potential for leveraging biofortified cultivars. Through strategic breeding and molecular tools, biofortified maize varieties can improve both human health and agricultural resilience, aligning with the United Nations Sustainable Development Goals (SDG 2 and SDG 3).

Global importance of maize: Maize is cultivated across more than 180 million ha globally with an annual production exceeding 1.2 billion tonnes (FAOStat, 2024). Known as the

“queen of cereals,” it contributes 36 % of total global grain production and serves as food (13 %), feed (56 %), and raw material for industry (FAOStat, 2021). In India, maize occupies about 9.8 million ha with a productivity of 3.1 t ha⁻¹ (DES, MoA&FW 2024). Despite steady production, the nutritional quality of commonly cultivated hybrids remains suboptimal, driving the need for nutritional breeding.

Concept of Biofortification

Biofortification refers to the genetic enhancement of crops for micronutrients such as iron, zinc, and provitamin A through plant breeding, transgenic, or gene-editing methods (Bouis & Saltzman, 2017). It is distinct from fortification, which adds nutrients during food processing, and from supplementation, which provides nutrients as tablets or syrups. Biofortified crops deliver nutrients directly through daily diets, particularly benefiting rural populations that rely on self-produced food. In maize, biofortification efforts primarily focus on:

1. **Quality Protein Maize (QPM):** enhanced lysine and tryptophan;
2. **Provitamin A-rich maize:** enhanced β -carotene content;
3. **Iron and Zinc-dense maize:** improved mineral bioavailability.

These initiatives integrate classical breeding, marker-assisted selection (MAS), QTL mapping, and genetic engineering to combine yield stability with enhanced nutritional value. Approaches and Advances in Maize Biofortification

Quality Protein Maize (QPM): A Breakthrough in Amino Acid Improvement: The development of Quality Protein Maize (QPM) represents one of the most successful examples of biofortification through conventional breeding. The discovery of the opaque-2 (o2) mutant by Mertz *et al.*, (1964) and its subsequent refinement into agronomically superior lines by Vasal and Villegas (1992) revolutionized nutritional maize breeding. The o2 gene, located on chromosome 7, encodes a basic leucine zipper (bZIP) transcription factor that regulates α -zein synthesis—proteins deficient in lysine and tryptophan. Mutation at this locus reduces zein synthesis, thus enriching non-zein fractions rich in essential amino acids (Gibbon & Larkins, 2005). However, early o2 mutants suffered from soft endosperm and poor kernel texture, which hindered adoption. Through recurrent selection and incorporation of endosperm modifier genes (γ -zein upregulation), breeders developed vitreous and high-yielding QPM genotypes. Modern QPM lines maintain 70–90 % of normal yield while doubling lysine and tryptophan concentrations compared to conventional maize. India’s ICAR-IARI, under the All India Coordinated Maize Improvement Project (AICMIP), released several QPM hybrids such as Pusa HQPM 5, HQPM 7, and Vivek QPM 9 Improved, each showing 2.6–2.8 % lysine and 0.7 % tryptophan (Muthusamy *et al.*, 2014). These varieties demonstrate how genetic enhancement can address protein-energy malnutrition without compromising productivity.

Provitamin A Enrichment: Combating Vitamin A Deficiency: Vitamin A deficiency remains one of the leading causes of preventable blindness globally (WHO, 2023). Maize, being a major dietary staple, offers a promising vehicle for provitamin A biofortification. The carotenoid biosynthetic pathway includes several critical genes *psy1*, *lcyE*, *crtRB1*, *zep1*, and *crtRB3* that regulate β -carotene accumulation. Among these, natural allelic variation in *crtRB1-3' TE* and *lcyE-Δ5' TE* significantly enhances kernel β -carotene content by redirecting carotenoid flux towards the β -branch (Harjes *et al.*, 2008). Marker-assisted selection for these favourable alleles has enabled the development of hybrids rich in provitamin A. At IARI and CIMMYT, the introgression of favourable *crtRB1* and *lcyE* alleles into elite inbreds resulted in Pusa Vivek QPM 9 Improved, the first high provitamin A hybrid in India (8.15 $\mu\text{g g}^{-1}$ kernel β -carotene). Transgenic approaches expressing *crtB* and *crtI* under γ -zein promoters further enhanced carotenoid accumulation up to 10-fold in white maize (Aluru *et al.*, 2008). These advancements highlight that molecular and transgenic interventions can effectively tackle vitamin A deficiency, complementing breeding-based gains.

Iron and Zinc Biofortification: Deficiency of Fe and Zn is widespread in South Asia and Sub-Saharan Africa, contributing to anemia and impaired immunity. In maize, both elements are primarily localized in the aleurone layer and embryo, while endosperm remains poor in

minerals. Genetic variation for grain Fe (12–54 $\mu\text{g g}^{-1}$) and Zn (18–52 $\mu\text{g g}^{-1}$) content has been reported across global germplasm. QTLs controlling Fe and Zn accumulation have been mapped to chromosomes 1, 6, 7, 9, and 10. Candidate genes such as ZmNAS3, ZmHMA2, and ZmZIP5 play roles in metal transport and homeostasis. Marker-assisted selection using these loci has yielded Fe-Zn-dense hybrids in India and Africa. In parallel, CIMMYT's HarvestPlus program has developed maize genotypes delivering 25 $\mu\text{g g}^{-1}$ Fe and 38 $\mu\text{g g}^{-1}$ Zn on average, sufficient to meet 50–60 % of daily requirements. Notably, epistatic interactions and $G \times E$ effects influence mineral accumulation; therefore, multi-environment testing is crucial for stable nutrient expression.

Integration of Conventional and Molecular Breeding: Modern maize biofortification integrates quantitative trait loci (QTL) mapping, marker-assisted backcrossing (MABC), genome-wide association studies (GWAS), and genomic selection (GS). MABC enables precise introgression of nutrient-enhancing alleles into elite backgrounds, while GS accelerates the selection cycle. Recent studies (Pandey *et al.*, 2023) emphasize combining additive and non-additive genetic effects for multi-nutrient improvement. CRISPR/Cas-based editing of *lcyE* and *crtRB1* genes has also demonstrated potential to enhance provitamin A content without linkage drag. The integration of molecular markers, omics technologies, and nutritional phenotyping is reshaping maize improvement from yield-centric to nutrition-centric breeding a paradigm essential for ensuring both productivity and public health outcomes.

Achievements in Maize Biofortification

India has made commendable progress in the biofortification of maize under the All India Coordinated Research Project on Maize (AICRP-Maize), led by ICAR-IIMR and collaborating research centres. Notable achievements include the development and release of nutritionally enriched hybrids and parental lines with enhanced amino acids, vitamins, and minerals. Among these, the Pusa Vivek QPM 9 Improved, developed at ICAR-IARI, New Delhi, remains a flagship success. It combines the *opaque-2* (*o2*) allele for lysine and tryptophan enrichment with the *crtRB1* favourable allele for provitamin A enhancement, achieving 8.15 $\mu\text{g g}^{-1}$ β -carotene, 2.67 % lysine, and 0.74 % tryptophan well above traditional hybrids (Muthusamy *et al.*, 2014). Other releases such as HQPM 5, HQPM 7, and Pusa HQPM 9 Improved have shown similar nutritional superiority while maintaining grain yield parity with commercial cultivars. In the Fe-Zn improvement domain, several Indian maize inbreds have been identified with kernel Fe (35–45 $\mu\text{g g}^{-1}$) and Zn (40–50 $\mu\text{g g}^{-1}$) content (ICAR-IIMR Annual Report, 2023). Marker-assisted selection targeting Zn transporter genes (ZmZIP5, ZmHMA2) has been integrated into mainstream breeding programs, leading to stable nutrient expression across environments. Furthermore, bioavailability studies at IIMR and BISA-Ludhiana have confirmed higher nutrient uptake from QPM and Fe-Zn-rich maize compared to standard hybrids, establishing their efficacy in human nutrition.

Socioeconomic and Nutritional Impacts: Empirical studies from Africa and South Asia indicate that replacing traditional maize with biofortified varieties can significantly improve dietary diversity scores and serum micronutrient levels. Farmer field data show that adoption of biofortified maize does not reduce yield or marketability, refuting earlier concerns about consumer acceptance. In India, QPM and provitamin A hybrids are now being utilized in mid-day meal schemes and supplementary nutrition programs, amplifying their nutritional reach. Thus, biofortification has transitioned from research innovation to a mainstream agricultural-nutrition strategy with measurable socioeconomic benefits.

Conclusion

Emerging trends in maize biofortification emphasize the integration of genomic innovations and systems biology to accelerate nutrient improvement. The use of multi-omics platforms genomics, transcriptomics, metabolomics, and ionomics has enabled precise identification of genes governing nutrient biosynthesis, storage, and bioavailability. Major loci such as

crtRB1, *lcyE*, and *psy1* (carotenoid metabolism), *ZmHMA2*, *ZmNAS3*, and *ZmZIP5* (metal transport), and *o2* and *o16* (protein quality) are now being exploited to enhance multiple nutrients simultaneously. Advanced approaches like gene stacking and CRISPR/Cas9 editing allow the combination or fine-tuning of favourable alleles to develop high-yielding, multi-nutrient maize capable of combating vitamin A, iron, and zinc deficiencies. Future programs must also ensure nutrient stability under climate stress, as heat and drought can alter kernel nutrient profiles. Hence, developing biofortified maize resilient to abiotic stress through multi-location and multi-year testing remains a priority at ICAR-IIMR, BISA, and CIMMYT. Moreover, strong policy and institutional support including FSSAI's endorsement, the Ministry of Agriculture's "Nutri-Cereals Mission," and initiatives by FAO and WHO along with public-private partnerships, farmer training, and supply-chain integration, are essential to scale adoption and embed biofortified maize within nutrition-sensitive agriculture programs such as PDS and school feeding schemes.

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