



Biofortification in Sorghum: Improving Micronutrients for Public Health

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Micronutrient malnutrition, commonly known as “hidden hunger,” remains a major public-health concern, particularly among populations dependent on cereal-based diets. Deficiencies of iron (Fe), zinc (Zn) and vitamin A can adversely affect growth, immunity and overall well-being. Sorghum (*Sorghum bicolor* (L.) Moench) is an important cereal in semi-arid and drought-prone regions because of its adaptability and ability to produce grain under challenging environmental conditions. Biofortification offers an agricultural strategy for improving the nutritional quality of staple crops through genetic, agronomic and biotechnological approaches. In sorghum, major efforts have focused on increasing provitamin A carotenoids and enhancing grain iron and zinc concentrations while improving their bioavailability (Kumar *et al.*, 2013; Obukosia, 2014). Conventional breeding and allele mining exploit naturally occurring variation, whereas molecular markers and genomic approaches can accelerate the selection of nutrient-rich genotypes (Cruet-Burgos *et al.*, 2026). Agronomic biofortification through micronutrient fertilization can further enhance grain mineral accumulation (Kumar *et al.*, 2011). Biotechnology provides opportunities to modify carotenoid pathways, mineral accumulation and antinutritional factors such as phytate (Zhao *et al.*, 2019; Dzakovich *et al.*, 2022). Recent research emphasizes that nutrient concentration alone does not determine nutritional value; storage, processing and bioaccessibility also influence the potential nutritional benefit of biofortified grain (Debelo *et al.*, 2020; Dzakovich *et al.*, 2022). Integrating crop breeding, genomics, agronomy, biotechnology and food science can therefore support the development of nutritionally improved and climate-resilient sorghum.

Keywords: Sorghum; Biofortification; Hidden hunger; Iron; Zinc; Provitamin A; Carotenoids; Bioavailability; Crop improvement

Introduction

Micronutrient deficiencies are a widespread nutritional challenge, particularly in populations where diets are dominated by staple cereals. The term “hidden hunger” describes inadequate intake of essential vitamins and minerals despite sufficient consumption of calories. Deficiencies of iron, zinc and vitamin A are particularly important because they can affect growth, immunity, metabolism and normal physiological development (Kumar *et al.*, 2013; Obukosia, 2014). Supplementation and industrial food fortification can improve micronutrient intake, but their effectiveness may be limited by cost, accessibility and distribution systems. Biofortification provides a complementary approach by improving the nutritional quality of food crops through breeding and crop management. Once an improved variety is developed and adopted, its nutritional characteristics can be delivered through repeated cultivation and consumption (Kumar *et al.*, 2012; Obukosia, 2014).

Sorghum is particularly suitable for biofortification because it is adapted to hot and relatively dry environments. It is an important staple crop in parts of Africa and Asia, especially where drought and limited water availability restrict the productivity of other cereals

(Obukosia, 2014; Zhao *et al.*, 2019). Improving its nutritional quality could therefore contribute to both food and nutritional security. Current sorghum biofortification research focuses mainly on provitamin A carotenoids, iron and zinc. However, improving nutrient concentration alone is insufficient because antinutritional compounds, storage and food processing can influence nutrient bioavailability (Debelo *et al.*, 2020; Dzakovich *et al.*, 2022).

Major Nutritional Targets in Sorghum

Provitamin A Carotenoids

Provitamin A carotenoids, particularly β -carotene, are important targets because they can be converted into vitamin A in the human body. Vitamin A is essential for vision, immune function and normal growth (Zhao *et al.*, 2019). Natural variation in sorghum provides opportunities for increasing grain carotenoid concentration through breeding. Recent research has emphasized allele mining and marker development to identify genetic factors controlling provitamin A accumulation (Cruet-Burgos *et al.*, 2026). Molecular markers associated with favorable alleles can help breeders select promising plants more efficiently than relying entirely on biochemical screening.

Iron and Zinc

Iron and zinc are essential micronutrients with important roles in oxygen transport, enzyme activity, growth and immune function. Sorghum germplasm contains substantial genetic variation for grain Fe and Zn concentration, providing opportunities for genetic improvement (Kumar *et al.*, 2011; Kumar *et al.*, 2013). Kumar *et al.* (2012) emphasized the importance of systematic databases for grain Fe and Zn in sorghum to support the identification and utilization of nutritionally superior germplasm. However, mineral concentration does not necessarily correspond directly to nutritional benefit because phytate and other compounds can reduce mineral bioavailability (Dzakovich *et al.*, 2022).

Approaches to Sorghum Biofortification

Conventional Breeding

Conventional breeding remains a fundamental method for sorghum biofortification. Genotypes with high concentrations of Fe, Zn or carotenoids can be identified and crossed with high-yielding, locally adapted materials (Kumar *et al.*, 2013; Cruet-Burgos *et al.*, 2026). An important advantage is that nutritional traits can be combined with agronomic characteristics such as yield, drought tolerance and adaptation. However, nutrient concentration may be influenced by environmental conditions and genotype $\times$ environment interactions. Therefore, promising materials require evaluation across environments before release.

Molecular Breeding and Genomics

Molecular breeding can accelerate nutritional improvement by identifying favorable alleles and genomic regions. For provitamin A biofortification, allele mining and marker development have provided opportunities to identify useful genetic variation and support marker-assisted selection (Cruet-Burgos *et al.*, 2026). Genomic resources can also help identify genes and biological pathways associated with mineral accumulation. Pathway-based investigations have provided insights into the mechanisms controlling iron and zinc accumulation in sorghum (Shobhana *et al.*, 2026). Integrating genomic information with nutritional phenotyping can therefore improve the efficiency of breeding programs.

Agronomic Biofortification

Agronomic biofortification involves increasing grain nutrient concentration through crop management, particularly micronutrient fertilization. Application of zinc- or iron-containing fertilizers can enhance grain mineral accumulation under suitable soil and environmental conditions (Kumar *et al.*, 2011). The effectiveness of this approach depends on soil properties, fertilizer source and application method, genotype and environmental conditions. Agronomic biofortification can therefore complement genetic improvement, particularly in areas where soil micronutrient deficiency limits crop nutritional quality.

Biotechnology

Biotechnology provides opportunities to modify nutritional pathways more directly. Genetic engineering approaches have been investigated for increasing provitamin A carotenoids, improving mineral accumulation and modifying factors that restrict nutrient availability (Zhao *et al.*, 2019). The Africa Biofortified Sorghum initiative represents an important example of biotechnology-oriented nutritional improvement. Such approaches have targeted enhanced nutritional quality while maintaining the importance of sorghum as a crop adapted to African production environments (Obukosia, 2014; Zhao *et al.*, 2019).

Improving Nutrient Bioavailability

Modern biofortification research increasingly recognizes that nutrient concentration alone is not sufficient. Nutrients must be released from the food matrix and become accessible during digestion before they can potentially be absorbed. Phytate is an important antinutritional compound in cereals because it can bind minerals such as iron and zinc and reduce their bioaccessibility (Dzakovich *et al.*, 2022). Therefore, increasing mineral concentration without addressing mineral bioavailability may not provide the expected nutritional benefit. Trait stacking provides an approach for addressing several nutritional constraints simultaneously. Dzakovich *et al.* (2022) demonstrated the potential of combining enhanced provitamin A carotenoids with improved mineral bioaccessibility. This approach represents a shift from focusing solely on nutrient concentration toward considering the complete pathway from grain composition to potential nutritional benefit.

Effect of Storage and Processing

Nutritional quality can change after harvest. Storage and food processing may affect carotenoid stability and nutrient availability. Carotenoids can be susceptible to degradation during storage, making stability an important consideration when evaluating biofortified materials (Debelo *et al.*, 2020). Food preparation can also influence nutrient retention and bioaccessibility. Therefore, promising biofortified genotypes should ideally be evaluated not only as raw grain but also after processing methods commonly used for food preparation (Debelo *et al.*, 2020; Dzakovich *et al.*, 2022). This highlights the importance of collaboration between crop breeders, nutritionists and food scientists. A nutritionally superior genotype should retain useful nutritional characteristics throughout storage and processing.

Trait Stacking and Data-Driven Breeding

Micronutrient malnutrition is complex, and improving one nutrient may not address all nutritional requirements. Trait stacking can combine multiple nutritional characteristics, including increased provitamin A, enhanced Fe and Zn, improved mineral bioaccessibility and reduced effects of antinutritional compounds (Dzakovich *et al.*, 2022; Zhao *et al.*, 2019). Genomics can support this process by enabling the identification of favorable alleles and genomic regions. Databases containing grain Fe and Zn information provide useful resources for selecting nutritionally promising germplasm (Kumar *et al.*, 2012). Pathway-mining approaches can further identify biological mechanisms associated with nutrient accumulation (Shobhana *et al.*, 2026). The integration of genomics, high-throughput phenotyping, nutritional analysis and molecular breeding can improve the efficiency of developing nutritionally enhanced sorghum.

Challenges in Sorghum Biofortification

Several challenges must be addressed to achieve effective sorghum biofortification. Nutritional traits can vary with environment, soil fertility and genotype $\times$ environment interactions, making multi-location evaluation important (Kumar *et al.*, 2011). Biofortified varieties must also maintain acceptable yield, stress tolerance, grain quality and adaptation. High nutrient concentration should not compromise agronomic performance. Furthermore, nutrient concentration does not necessarily indicate bioavailability because phytate and other antinutritional factors can restrict absorption (Dzakovich *et al.*, 2022).

Post-harvest stability is another consideration. Nutrients such as carotenoids can be affected by storage and processing, requiring evaluation beyond the field stage (Debelo *et al.*, 2020). Consumer acceptance is equally important because taste, texture, appearance and traditional processing characteristics can influence adoption. Finally, genetic improvement must be supported by effective seed systems, extension services and dissemination strategies. Without adoption by farmers and consumers, genetic gains cannot translate into population-level nutritional benefits (Obukosia, 2014).

Future Prospects

Future sorghum biofortification will increasingly combine conventional breeding with genomics, molecular breeding, biotechnology and nutritional evaluation. Natural genetic variation can provide useful alleles, while molecular markers and genomic tools can accelerate their identification and deployment (Cruet-Burgos *et al.*, 2026). Trait stacking may allow simultaneous improvement of provitamin A, iron and zinc while addressing antinutritional factors and bioavailability (Dzakovich *et al.*, 2022). Importantly, nutritional improvement should be combined with climate resilience. Sorghum's inherent adaptation to drought and heat provides a useful foundation for developing varieties that combine nutritional quality with stable productivity under environmental stress (Obukosia, 2014; Zhao *et al.*, 2019). Future studies should therefore evaluate nutrient concentration, bioavailability, stability during storage, processing effects and agronomic performance together rather than as independent traits.

Conclusion

Sorghum provides an important opportunity to integrate nutritional improvement with climate-resilient crop production. Its adaptation to drought-prone environments and importance as a staple food make it a valuable crop for biofortification programs (Obukosia, 2014; Zhao *et al.*, 2019). Research has demonstrated opportunities to improve provitamin A carotenoids, iron and zinc through conventional breeding, molecular approaches, agronomic management and biotechnology (Kumar *et al.*, 2011; Kumar *et al.*, 2013; Cruet-Burgos *et al.*, 2026). However, effective biofortification requires consideration of nutrient bioavailability, phytate, storage stability and food processing in addition to nutrient concentration (Debelo *et al.*, 2020; Dzakovich *et al.*, 2022). The integration of genetic diversity, genomics, molecular breeding, biotechnology, agronomy and food science can accelerate the development of nutritionally enhanced sorghum. Combining nutritional improvement with yield, adaptation and climate resilience can strengthen the contribution of sorghum to food security and strategies for reducing hidden hunger.

References

1. Cruet-Burgos, C., Banda, L., Faye, J., Diatta, C., & Zapata, D. (2026). *Advancing provitamin A biofortification in sorghum: From allele mining and marker development to prebreeding and breeding*. Theoretical and Applied Genetics.
2. Debelo, H., Albertsen, M., Simon, M. K., Che, P., & Ferruzzi, M. (2020). Identification and characterization of carotenoids, vitamin E and minerals of biofortified sorghum. *Current Developments in Nutrition*.
3. Dzakovich, M., Debelo, H., Albertsen, M., Che, P., & Jones, T. (2022). Trait stacking simultaneously enhances mineral and provitamin A carotenoid bioaccessibility in biofortified *Sorghum bicolor*. *Current Developments in Nutrition*.
4. Kumar, A., Anuradha, K., & Ramaiah, B. (2013). Increasing grain Fe and Zn concentration in sorghum: Progress and way forward.
5. Kumar, A., Pfeiffer, W., Ramaiah, B., Reddy, B., & Sahrawat, K. (2011). Options for enhancing grain iron and zinc concentrations in sorghum.
6. Kumar, A., Reddy, B., & Ramaiah, B. (2012). Database for grain Fe and Zn in sorghum – A proposal.

7. Obukosia, S. (2014). Biotechnology of nutritionally enhanced food crops targeting malnutrition in rural agricultural populations: The case study of Africa biofortified sorghum.
8. Shobhana, V. R., Selvi, N. R., Nivetha, D., Kumar, G., & Muthuvijayaragavan, R. (2026). Pathway mining reveals novel insights into iron and zinc accumulation in sorghum. *Agrica*.
9. Zhao, Z.-Y., Che, P., Glassman, K., & Albertsen, M. (2019). Nutritionally enhanced sorghum for the arid and semiarid tropical areas of Africa. *Methods in Molecular Biology*.