



REVIEW ARTICLE

# Biofortification frontiers: Current advances, challenges and future opportunities in combating global nutrition and food security goals

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## Abstract

Malnutrition or hidden hunger due to micronutrient deficiencies (iron, zinc, vitamin A, iodine) affects over 2 billion people worldwide, with the greatest burden in developing countries. Biofortification, the practice of breeding staple food crops that are rich in specific micronutrients through agronomic, conventional or modern genetic approaches, is a cost-effective and sustainable approach to combat malnutrition at a population scale. This review paper covers recent developments in biofortification with special focus on developing nutrient-dense varieties using genomic tools, marker-assisted selection (MAS) and omics technologies, as well as microbial-assisted biofortification using plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi (MF). Additionally, the paper identifies future research trajectories, including the potential biofortification of other underutilized crops such as millets and pulses (many of which are already naturally high in key micronutrients and adapted to harsh climates), digital agriculture, artificial intelligence and climate-resilient practices for greater efficiency and scale. Biofortification is a science-based strategy that holds great promise for achieving nutrition goals globally, but its success will rely on interdisciplinary collaboration, policy support and stakeholder engagement within the agriculture, health and education sectors. Prospective directions for further research include exploring multi-nutrient biofortification, integrating biofortification with sustainable soil–plant–microbe interactions and leveraging systems biology to optimize nutrient uptake and stability. Future challenges involve ensuring consumer acceptance, addressing bioavailability issues, minimizing trade-offs with yield and quality and strengthening policy frameworks to enable large-scale adoption and equitable access.

**Keywords:** golden rice; malnutrition; marker-assisted selection; mycorrhizal fungi; QTL mapping; rhizobacteria

## Introduction

Biofortification is the process of enhancing plant nutrient content to alleviate hidden hunger in the overall population (1). The main aim of biofortification is to help malnourished populations obtain higher levels of essential nutrients through commonly consumed staple foods such as rice, wheat and maize. Biofortification plays an important role in addressing hidden hunger through sustainable agricultural practices. Enhancing staple crops such as wheat, maize, rice and sweet potatoes with essential nutrients like iron (Fe), Zinc (Zn) and Vitamin A offers a promising solution (2). This approach not only decreases reliance on fortified foods and external supplements

but also empowers farmers in low-income areas to cultivate and consume more nutrient-dense foods, aligning with their traditional farming and dietary practices. Hidden hunger refers to the deficiency of essential minerals and vitamins in one's diet. Even when individuals consume sufficient calories, they may not feel hungry; however, they suffer from nutrient deficiencies such as Zn, iodine (I) and Vitamin A. Alarmingly, about 2 billion people, one in three, are affected by nutrient deficiencies, particularly in developing nations like India (3). Iron deficiency can lead to fatigue, diminished work capacity and hindered learning. Pregnant and lactating women are particularly vulnerable, facing increased risks of complications, mental health challenges and unfavourable birth outcomes due to

Fe deficiency. Currently, 30 % of the global population is impacted, children and women being the most severely affected. Furthermore, around 190 million pre-school children are impacted by Vitamin A deficiency, which can result in preventable blindness, as well as susceptibility to infections and mortality (4). Deficiencies in Zn and I were also present, which were a critical concern. Zn plays a crucial role in immune function and growth, while a lack of I can lead to mental disabilities in newborns and the development of goitre. The implications of these nutrient deficiencies extend beyond individual health, impacting economies by diminishing productivity and learning capacities (5). This hidden hunger accounts for a significant economic cost, potentially reducing a country's GDP by up to 5 % due to adverse health effects and decreased work output. Several factors contribute to hidden hunger, including diets that lack variety (often consisting mainly of staples like rice or maize), poverty and food insecurity, insufficient awareness about nutrition and inadequacies in healthcare and sanitation.

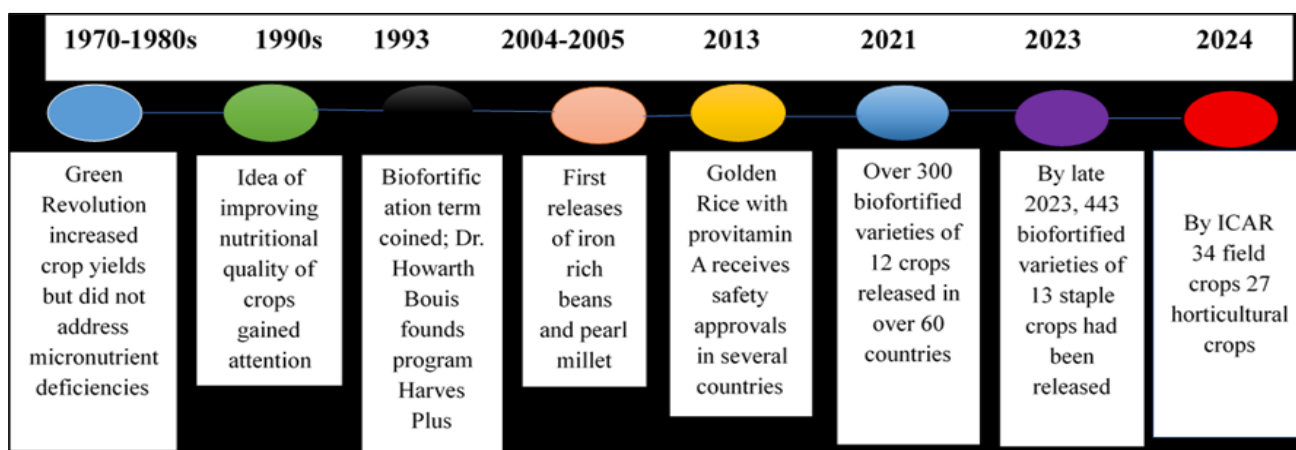
To address the critical issue of hidden hunger, micronutrients play a vital role in implementing strategies like biofortification of crops, enhancing everyday foods such as salt, flour and oil with essential nutrients, promoting supplements for key vitamins and minerals such as Fe and vitamin A (6). Additionally, initiatives aimed at encouraging dietary diversity and raising nutritional awareness are crucial. This silent crisis continues to impact communities around the globe (7). While supplement pills can provide immediate relief from nutrient deficiencies, they are only a temporary fix. In contrast, opting for food-based solutions can lead to meaningful, long-term changes by improving daily diet. Developing nutrient-rich crops, such as biofortified varieties, proves to be a cost-effective approach, as these crops can be repeatedly cultivated by farmers without ongoing expenses. Many individuals affected by hidden hunger reside in remote areas, making food-based strategies, such as the cultivation of biofortified crops, particularly effective in directly reaching these communities (8). Examples of biofortified crops include Fe-rich pearl millet, which is effective in combating anaemia among women and children as well as orange-fleshed sweet potatoes (OFSPs), a natural source of  $\beta$ -carotene (a precursor of Vitamin A). Additionally, Zn-enriched wheat and rice contribute to enhanced immunity and support child development. Golden rice, which is biofortified with vitamin A, aims to reduce childhood blindness (9). The challenge of hidden hunger requires long-term, sustainable solutions that are adapted to local contexts (10). Biofortification stands out as a powerful food-based intervention that functions effectively from farm to table, particularly when paired with nutrition education initiatives. Promoting crop diversity is essential to fight against

hidden hunger, making biofortification a key strategy for improving nutritional outcomes.

By addressing hidden hunger, biofortification plays a crucial role in minimizing micronutrient deficiencies, particularly in rural communities that depend heavily on these staple crops. It contributes to improved public health by reducing the incidence of diseases caused by nutrient deficiencies such as anaemia, blindness and weak immune systems, without necessitating changes in dietary habits (11). This method not only provides a cost-effective, long-term solution through the initial enrichment of crops during development, allowing for ongoing benefits in future harvests, but it also helps agricultural systems by fostering the development of nutrient-rich and climate-resilient crop varieties (12). The urgency of advancing biofortification lies not only in addressing global malnutrition but also in its pivotal role within the environmental economic nexus. As climate variability threatens crop productivity and micronutrient density, sustainable biofortification strategies offer a cost-effective solution that minimizes dependence on external inputs and reduces environmental footprints. Integrating nutritional enhancement with climate-resilient agriculture can thus deliver dual dividends improving human health while strengthening the economic sustainability of agri-food systems. To implement biofortification, three methods were used. The first method is a breeding approach in which plants that naturally contain higher nutrient levels are selected and cultivated. Second method is genetic engineering introducing genes to enhance nutrient composition in plants and the third method is adding nutrients to soil or through fertilizers to plants so that plant absorbs more nutrients during crop growth period.

### Historical milestones of biofortification

The journey of biofortification as a targeted strategy to combat hidden hunger has evolved significantly over the past 5 decades. As depicted in Fig. 1, the Green Revolution during the 1970s and 1980s primarily focused on increasing crop yields yet failed to address widespread micronutrient deficiencies. This limitation sparked discussions in the 1990s around improving the nutritional quality of crops. In 1993, the term "biofortification" was formally introduced, coinciding with the establishment of the HarvestPlus program by Dr. Howarth Bouis, marking a critical turning point in the field. The first significant success came in 2004–2005 with the release of Fe-rich beans and pearl millet. A major milestone was achieved in 2013 when Golden Rice, biofortified with provitamin A, received safety approvals in several countries. By 2021, over 300 biofortified varieties of 12 crops released in over 60 countries. By late 2023, 443 biofortified varieties of 13 staple crops had been released. By 2024, ICAR released 34 field crops and 27 horticultural crops.



**Fig. 1.** Timeline illustrating key milestones in the development and adoption of biofortification.

further expanded by late 2023, with 443 varieties of 13 staple crops available. In 2024, Indian Council of Agricultural Research (ICAR) reported the development of 34 biofortified field crop varieties and 27 horticultural crop varieties, underscoring national-level commitment to nutrition-sensitive agriculture (14). This timeline reflects the progressive integration of biofortification into global food systems, highlighting its increasing relevance in addressing micronutrient malnutrition.

Government initiatives like the National Biofortification Program under the ICAR and inclusion of biofortified varieties in national seed chains accelerated mainstreaming. Integration with existing schemes such as Poshan Abhiyaan (National Nutrition Mission) and Mid-Day Meal program created direct pathways for nutritional impact. The presence of a robust agricultural research infrastructure, including state agricultural universities and organizations like HarvestPlus, further facilitated fast-track development, testing and release of biofortified cultivars. By contrast, slower adoption in some regions reflects limited policy prioritisation, weak seed dissemination systems and insufficient cross-sectoral coordination between agriculture and health ministries.

## Mechanisms of biofortification

### Agronomic biofortification

Combining foliar and soil applications of micronutrients with beneficial microbes enhances plant nutrition. Foliar sprays and soil amendments provide immediate nutrient supply, while microbes like arbuscular mycorrhizal fungi (AMF) and rhizobacteria improve nutrient uptake through solubilization, increased root surface area and enhanced transporter activity, leading to better micronutrient availability in edible tissues (Fig. 2).

### Conventional breeding

Conventional biofortification leverages natural genetic variation by crossing nutrient-dense donor lines with high-yielding elite cultivars, followed by meticulous selection and pyramiding of progeny that exhibit both enhanced micronutrient content and strong agronomic performance across diverse environments. Conventional breeding remains the most scalable and cost-effective strategy in low-resource rural settings, as it requires no specialized infrastructure and can be integrated into existing seed systems. Agronomic biofortification, involving fertilizer-based nutrient enrichment, delivers rapid results but is limited by farmers' access to inputs and

extension support. In contrast, transgenic and genome-editing approaches enable the precise enhancement of multiple micronutrients simultaneously and are particularly valuable where genetic variation for target traits is limited; however, they require regulatory approval, specialized expertise and higher initial investment. Therefore, the choice of method depends on the balance between technical feasibility, cost, regulatory context and the long-term sustainability of nutrient delivery in the target population. Wild relatives such as those carrying the *Gpc-B1* locus in wheat are introgressed to boost Fe and Zn levels while maintaining yield potential (15). Advances like speed breeding and rapid cycling techniques have significantly shortened the breeding cycle, reducing the typical 6–10 yr timeframe to approximately 2–4 yr, thereby accelerating the delivery of biofortified varieties.

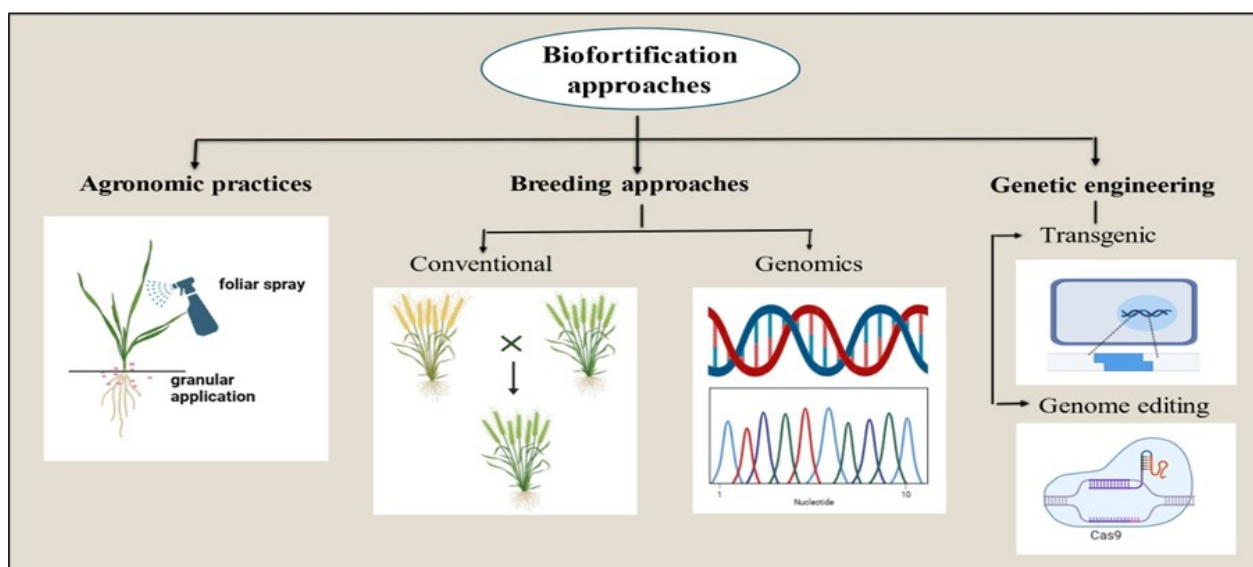
### Genetic / molecular approaches: Quantitative Trait Locus (QTL) mapping

Genetic engineering (GM): Transgenic addition/overexpression of nutrient-related genes (e.g., *NAS*, *CrtB*) to boost micronutrient synthesis or to reduce anti-nutrient contents (16).

Genome editing (e.g., CRISPR-Cas): targeted gene knockouts (e.g., reducing phytates) or regulatory modifications without introducing foreign DNA.

Several studies have been undertaken to map QTLs associated with grain iron and zinc concentrations in wheat. In 1997, the first QTL for Fe and Zn concentration in wheat was mapped on chromosome 6BS in a recombinant inbred line (RIL) population developed from a hybrid between durum wheat and wild emmer (*Triticum turgidum*) (17). The QTL, *Gpc-B1* showed an increase in Fe concentration by 18 % and Zn concentration by 12 %. Many QTL studies have been undertaken to investigate the genomic areas for Fe and Zn contents in wheat.

Several biparental mapping populations have been used to map the Fe and Zn concentration in wheat grains. Biparental mapping populations were mostly created with bread wheat cultivars as parents, but other hexaploid species such as *Triticum spelta*, stabilised synthetic hexaploid wheat (SHW) lines and tetraploid parents were also used. Many research use (multi-environment trial) data to identify stable QTL's for grain Fe and Zn content (18). Several QTLs for grain Fe and Zn content in wheat have been reported and can be used further for biofortification in wheat.



**Fig. 2.** Different approaches for biofortification.

In the study above, each QTL were frequently distinct from one another because of the variations in populations, environments and marker sets, all of which had a significant impact on the precise position and identification accuracy of the QTLs. By projecting the markers onto the genome sequence, it should now be easier to compare the actual location of QTLs found in various investigations, using the new reference sequence as a benchmark. This could make it possible to identify the QTLs that consistently produce higher levels of Fe and Zn concentration. However, due to practical limitations on the number of markers that can be used simultaneously, marker-assisted selection (MAS) for multiple QTLs can be challenging in large breeding populations. Alternatively, MAS can be used to stack small-effect QTLs within the same genomic region to create a favorable haplotype comprising multiple advantageous QTLs. A haplotype refers to a set of DNA variants located on a single chromosome that tend to be inherited together. By using MAS, this haplotype might then be chosen as a single unit, lowering the number of markers needed for further selection stages. Using this approach can also increase the value of marker usage by combining QTLs for higher iron and zinc content with QTLs for other advantageous traits, such as yield or disease resistance, which are more likely to already be under MAS (19).

For instance, studies at International Maize and Wheat Improvement Center (CIMMYT) and ICAR have shown that introgression of the *Gpc-B1* locus for Fe and Zn enrichment in wheat did not significantly reduce yield or kernel weight when combined with high-yield QTLs and disease resistance genes under multi-environment trials. Similarly, biofortified rice lines pyramided with both *OsNAS2* (nicotianamine synthase) and *OsFER2* (ferritin) genes maintained grain yield and plant vigor comparable to their recurrent parents. However, some trade-offs can emerge under nutrient-deficient or stress-prone conditions, emphasizing the need for genomic selection models that incorporate pleiotropic effects and genotype  $\times$  environment interactions.

Several QTL studies have been undertaken to investigate the genomic areas for Fe and Zn concentration in wheat. A double haploid population crossing Berkut and Krichauff was developed. Zn and Fe concentrations in grains were measured using X-ray fluorescence. Three QTLs were found using composite interval mapping: one for protein (1A), two for Zn with a QTL being co-located for Fe (20). The QTLs that were found throughout several seasons seemed to be reliable and beneficial for MAS. In current investigation at CIMMYT in Mexico, a high grain Zn content line of Chinese provenance was crossed with a Mexican bread wheat cultivar, Roelfs F2007 to create a RIL mapping population for QTL identification. Using the annotated wheat genome sequence, they have also discovered 55 potential genes responsible for the Zn and Fe content of the grain. Also, 4 QTLs were discovered for grain Zn and Fe concentration in a RIL population generated from the cross of Indian variety 'WH 542' and the SHW line (21) (Table 1).

#### Biochemical uptake & transport mechanisms

Fe uptake strategies reduction: In non-grasses, Fe<sup>3+</sup> reduced to Fe<sup>2+</sup> and absorbed via transporters like IRT1. Strategy II chelation: In grasses, plants release chelators (e.g., mugineic acid and nicotianamine) to mobilise Fe<sup>3+</sup>. Conventional breeding approaches harness genetic diversity and QTL mapping to develop biofortified crops. First, breeders screen diverse germplasm including landraces and wild relatives for natural variation in key nutrients like Fe and Zn. They then cross high-nutrient donor lines with elite, high-yield

cultivars and use QTL mapping to pinpoint genomic regions linked to nutrient traits. With markers identified, MAS enables breeders to efficiently pyramid these beneficial regions into new varieties. Biofortified crops that combine enhanced micronutrient levels with robust yield and agronomic performance.

#### Conventional breeding approaches

As shown in Fig. 3, conventional breeding for biofortification relies on exploiting natural genetic diversity by identifying donor lines rich in essential nutrients like Fe and Zn. Through crossing and selection, these traits are introduced into elite cultivars. QTL mapping plays a key role by pinpointing genomic regions associated with nutrient traits, enabling MAS to accelerate the development of nutrient-dense crop varieties. Genetic diversity is an essential prerequisite for conventional breeding in biofortification efforts, as it underpins the exploitation of natural variation in nutrient content, such as Fe, Zn and provitamin A (32). By screening diverse germplasm collections, researchers can identify and select beneficial traits and develop new varieties like land races, wild relatives and traditional varieties. Breeders identified high-nutrient donor lines and the developed lines are used in crossing programs to develop beneficial traits and to increase high-yielding varieties (33).

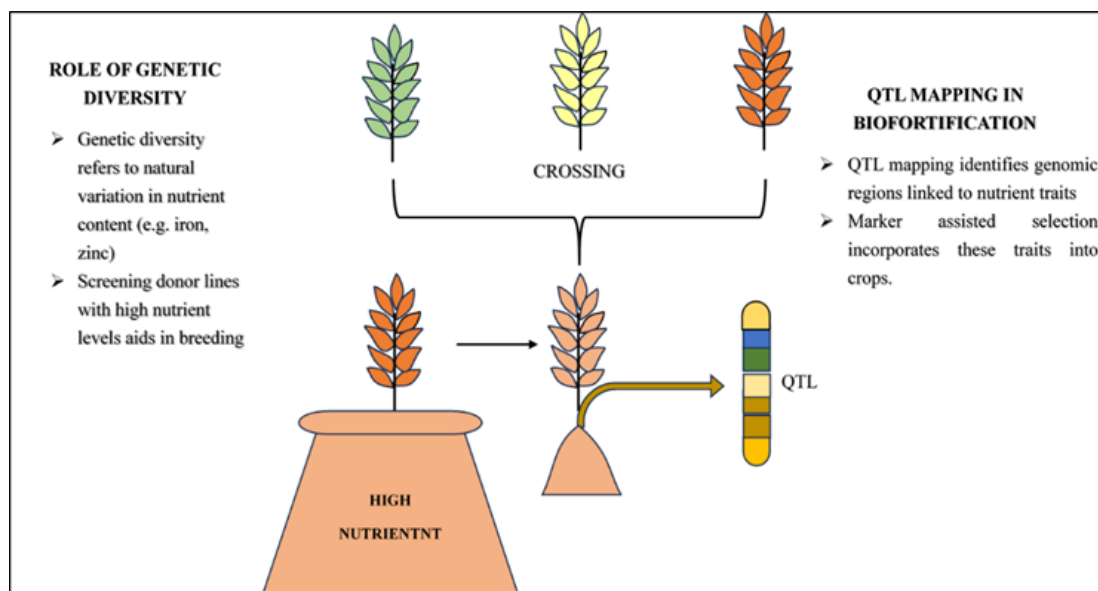
Genetic diversity plays a crucial role in enhancing the nutritional quality of crops through conventional breeding. Broad genetic variations in crop species and their wild relatives, including naturally occurring alleles, play a crucial role in influencing essential nutrient concentrations. Germplasm collections, encompassing wild relatives and landraces, allow breeders to discover superior alleles responsible for nutrient levels, a key aspect of biofortification (34). With the help of nutrient-dense genotypes, we can incorporate them into breeding methods to develop improved cultivars that can meet our nutritional goals (35).

The success of biofortification programs is reflected in the development and release of several high-impact nutrient-rich crop varieties across the globe. As detailed in Table 2, collaborative efforts by institutions such as HarvestPlus, International Potato Center (CIP), International Institute of Tropical Agriculture (IITA), International Center for Tropical Agriculture (CIAT), CIMMYT, International Rice Research Institute (IRRI) and National Agricultural Research Systems (NARS) have led to the release of biofortified staples like OFSP, yellow cassava, Fe-rich pearl millet and common beans and Zn-biofortified rice and wheat. OFSP, developed through accelerated conventional breeding, exhibited a 2–3 times increase in  $\beta$ -carotene content compared to the white-fleshed types (36). Yellow cassava, bred for high  $\beta$ -carotene content, achieved a dramatic improvement from nearly 0 to  $\sim 15 \mu\text{g/g}$  (37). Iron biofortification in pearl millet and common bean showed 1.9 times and 2.1 times increase respectively, using QTL mapping and backcrossing strategies (38, 39). Meanwhile, Zn content in rice and wheat increased by  $\sim 7.5$  times and 2 times respectively, with additional co-segregated gains in Fe levels (40, 41). These examples demonstrate the potential of conventional breeding, when enhanced with genomic tools and trait-specific selection, to substantially improve the micronutrient profile of staple crops and combat hidden hunger at scale.

Empirical studies indicate that Fe and Zn retention in biofortified wheat and rice typically ranges between 70–90 % after milling and cooking, provided polishing or excessive washing is minimised. In contrast, vitamin A precursors such as  $\beta$ -carotene in

**Table 1.** Various QTL's for iron and zinc in mapping population of wheat

Mapping population	Trait	Ch. No.	QTL	Flanking markers	Source
RILs (PBW343 × Kenya Swara)	Zn	2B	QGzncpk.cimmyt-2Bc	wPt-6174	(22)
		1BS	QGzncpk.cimmyt-1BS	wPt-3103	
		3AL	QGzncpk.cimmyt-3AL	wPt-0286	
RILs (SHW-L1 × Chuan mai 32)	Zn	2D	QZn-2D	wPt-730,057-wPt-671,700	(23)
	Fe	2B	QFe-2B	wPt-7004-wPt-4210	
	Zn	4A 1A	QZn-4 A Zn-1 A	Xgwm4026-Xgwm1081 Xgwm3094-Xgwm164	
RILs (Tabassi × Taifun)	Fe	7B	QFe-7B	Xgwm767-Xgwm3036	(24)
		4D	QFe-4D	Xgwm4670-Xgwm194	
		3D	QFe-3D	Xgwm1047-Xgwm383	
DH (Berkut × Krichauff)	Zn	2B 1B	QZn.bhu-2B QZn.bhu-1B	gwm120-wpt2430 wmc036c-cfa2129	(20)
	Fe	2B	Fe.bhu-2B	gwm120-wpt2430	
	Zn	4BS 4BS 4BS	QZn.Y13-14_4BS QZn.Y12-13_4BS QZn.Across_4BS	TP91631-TP81797 TP73864-TP71929 TP91631-TP81797	
RILs (Seri M82 × SHW CWI76364)	Fe	4BS	QFe.Across_4BS	TP91631-TP81797	(25)
		5BS	QFe.Y13-14_5BS	TP91631-TP81797	
		7DS	QFe.Across_7DS	TP43715-TP37547	
RILs (WH542 × SHW line)	Zn	2A 2A	QGZn.iari-2A QGZn.iari-2A	Xgwm359-Xgwm249 Xgwm359-Xwmc407	(26)
	Fe	7B 2A	QGFe.iari-7B QGFe.iari-2 A	Xgwm577-Xbarc264 gwm359-Xgwm249	
	Zn	7B 6B 7A 1D 1B 3A	QGZn.ada-7B QGZn.ada-6B QGZn.ada-7A QGZn.ada-1D QGZn.ada-1B QGZn.ada-3A	wPt-733,112 wPt-667,798-wPt-7065 wPt-2083-wPt-6083 wPt-6979-wPt-730,718 rPt-6561 wPt-2698-wPt-0398	
RILs (Adana99 × 70,711) Hexaploid population	Fe	2B	QGFe.ada-2B	wPt-1394-wPt-7864	(21)
		6B	QGFe.ada-6B	wPt-667,798-wPt-7065	
		2B	QGFe.ada-2B	wPt-9812	
		7B	QGFe.ada-7B	wPt-5922	
		Zn	1B 6B	QGZn.sar-1B QGZn.sar-6B	
RILs (Saricanak98 × MM5/4) Tetraploid population	Fe	5B	QGFe.sar-5BTKM	wPt-81.25 wPt-9504	(27)
		3A/3B	QGFe.sar-3 A/3B	wPt-0784- wPt-8875	
		5B	QGFe.sar-5BMCO	wPt-7400 wPt-8449	
RILs (Bubo × Turtur)	Zn	7B 1B	QGZn.cimmyt-7B_1P1 QGZn.cimmyt 1B_P1	3,945,822; 1132640F0-5CG 3,934,172; 3,934,936	(28)
	Fe	3A	QGFe.cimmyt-3A_1P1	1,234,521; 3034169F0-11AG	
	Zn	1B 7B	QGZn.cimmyt-1B_1P2 QGZn.cimmyt-7B_1P2	4,991,478; 3,937,490 1,079,651; 1,262,636	
RILs (Louries × Batelur)	Fe	2A	QGFe.cimmyt-2A_P2	4,262,668; 1,226,245	(29)
		4D	QGFe.cimmyt-4D_P2	2,363,822; 3,961,236	
		4A	QGFe.cimmyt-4A_P2	338,535; 1,211,533	
RILs (Roelfs F2007 × Chinese parental line)	Zn	7A 5B	QGZn.co-7 A QGZn.co-5 A	5,356,706 5,325,178 F 0 1,244,217 1,272,027 F 0	(30)
	Fe	5A 3B	QGFe.co-5 A. 2 e QGFe.co-3B.1	1,102,433 988,523 1,089,107 1,127,875 F 0	
	Zn	1B 6A	QGZn_Y17_1b QGZn_Y17_6a	13,142,877; 3,954,275 1,092,057; 1,082,014	
RILs (Kachu × Zinc shakti)	Fe	4A	QGFe_Y17_4a	1,099,697; 5,324,893	(31)
		6B	QGFe_Y17_6b	1,864,870; 2,278,502	



**Fig. 3.** Conventional breeding approaches, role of genetic diversity and QTL mapping.

**Table 2.** Major biofortified crops, their developers and nutritional gains achieved through conventional breeding

Crop & variety	Developer(s)	Year released	Breeding method & process	Target micronutrient	Increase achieved	References
OFSP	CIP, Robert Mwangi, HarvestPlus	2015–2020	Accelerated conventional breeding using local/introduced germplasm; 4-year cycle; selection for $\beta$ -carotene, drought & virus resistance	Beta-carotene (provitamin A)	2–3 $\times$ increase vs. white sweet potato (from <math><2 \mu\text{g/g}</math> to $\sim 6 \mu\text{g/g}</math>)$	(36)
Yellow cassava (UMUCASS 36/37/38)	IITA, NRCRI, HarvestPlus	$\sim 2015$	Conventional breeding: cross yellow-fleshed lines; selection for $\beta$ -carotene, yield, pest resistance	Beta-carotene	Up to $\sim 15 \mu\text{g/g}$ vs. $\sim 0 \mu\text{g/g}$ (infinite fold)	(37)
Iron-biofortified pearl millet	HarvestPlus, India NARS (ICRISAT)	2015–2020	Conventional breeding: QTL mapping, selection from high-Fe lines, trait introgression	Fe	1.9 $\times$ increase ( $\sim 88 \mu\text{g/g}$ vs. $\sim 47 \mu\text{g/g}$ )	(38, 39)
Iron-biofortified common bean	CIAT, HarvestPlus, National Agricultural Research Systems	2015–2025	Conventional breeding: backcrossing high-Fe genes into farmer-preferred varieties	Fe	2.1 $\times$ increase ( $\sim 107 \mu\text{g/g}$ vs. $\sim 50 \mu\text{g/g}$ )	(40)
Zinc-biofortified wheat & rice	HarvestPlus, CIMMYT, IRRI, NARS	2015–2025	Conventional breeding: screen high-Zn germplasm; select agronomically favourable high-Zn lines	Zn	Rice: $\sim 7.5\times$ ( $2 \rightarrow 15 \mu\text{g/g}$ ), Wheat: $\sim 2\times$ ( $30 \rightarrow 59 \mu\text{g/g}$ ); also improved Fe via co-segregation	(41)

biofortified cassava and OFSP show higher sensitivity to heat and light, with losses of 30–50 % depending on cooking duration and storage conditions. Nonetheless, even after these reductions, biofortified staples generally deliver higher bioavailable micronutrient levels than conventional varieties. Techniques such as parboiling in rice, low-temperature storage for cassava and fortification of composite flours can further enhance nutrient retention.

### Transgenic and genome editing techniques

Molecular biology opened new techniques for biofortification through genome editing tools and transgenic approaches, both methods offer speed in increasing nutrient content, especially for traits that are difficult to improve with the help of conventional breeding methods.

#### Genetically modified (GM) crops

The transgenic method, in this insertion of genes from one species to another crop genome, is possible to increase the nutrient traits. An example of this approach is Golden Rice, which produces  $\beta$ -carotene (a precursor of vitamin A) in the endosperm through the incorporation of genes from bacteria and daffodil (42). Same as GM crops like Zn-enriched wheat and Fe-fortified rice, it was developed using the transgenic method, which involves manipulating genes for micronutrient uptake, storage and transport (43). Golden Rice is a GM crop. It is a rice variety developed to accumulate  $\beta$ -carotene, a precursor of vitamin A, in its edible parts. The main concept of biofortification is to combat vitamin A deficiency in rural areas where

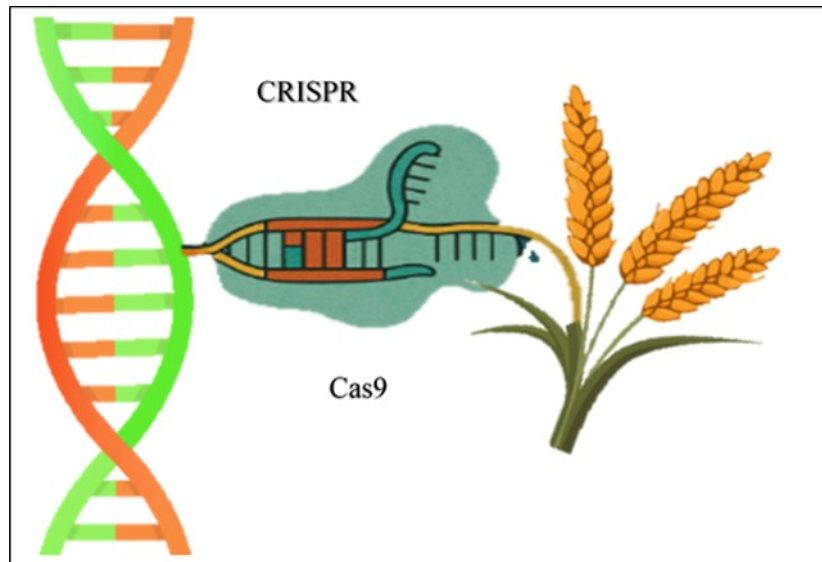
rice is the staple crop. In the year 2021, the Philippines was the first country to approve the Golden Rice for commercial propagation. In 2024, the Philippines' Court of Appeals issued a cease-and-desist order for cultivation (44). Despite approvals from organizations like Health Canada and the Food and Drug Administration (FDA), Golden Rice was rejected by environmental groups, such as Greenpeace, which opposed genetically modified organisms (GMOs) (45).

#### RNA interference (RNAi)

RNAi is a post-transcriptional gene silencing tool used to downregulate antinutritional factors, thereby increasing nutrient bioavailability. A notable example is the suppression of inositol pentakisphosphate 2-kinase (IPK1) in rice through RNAi technology, which significantly reduces phytate (phytic acid) levels in the grain. Since phytate chelates essential minerals like Fe and Zn, its reduction enhances mineral absorption and nutritional value in human diets (46).

#### CRISPR/Cas9 genome editing tool

As illustrated in Fig. 4, CRISPR-Cas9 technology enables precise genome editing for crop biofortification by targeting specific genes associated with nutrient biosynthesis and regulation. This modern tool offers a rapid and efficient approach to enhance micronutrient content in crops without introducing foreign DNA, thereby contributing to the development of nutritionally improved, non-transgenic varieties. CRISPR/Cas9 emerged as a powerful gene editing tool with versatility, efficiency and precision. CRISPR, enables



**Fig. 4.** Application of CRISPR-Cas9 genome editing in nutritional enhancement of crops.

targeted edits within the native genome without introducing foreign DNA, making it acceptable under certain regulatory frameworks. To reduce antinutrient content and favour nutrient accumulation, negative regulators of nutrient uptake have been knocked out to enhance carotenoid biosynthesis in tomato and rice (47). Genome editing and transgenic technologies hold significant promise for the next generation of biofortified crops. They can modify traits at the molecular level, complementing traditional breeding approaches, offering more targeted solutions to combat micronutrient deficiencies.

Cutting-edge molecular tools such as transgenic technologies and CRISPR/Cas genome editing are revolutionizing biofortification by enabling precise manipulation of nutritional traits. As summarised in Table 3, Golden Rice 2, a landmark transgenic variety, demonstrated an approximately 23-fold increase in  $\beta$ -carotene content ( $\sim 37 \mu\text{g/g}$ ) by incorporating a biosynthetic cassette carrying maize *psy* and bacterial *cr1* genes under an endosperm-specific promoter via *Agrobacterium*-mediated transformation (48). More recently, CRISPR/Cas9-based editing has emerged as a transgene-free alternative for enhancing  $\beta$ -carotene in rice, as seen in CRISPR-edited Kitaake rice, which achieved approximately  $7.9 \mu\text{g/g}$  dry weight using homology-directed repair (HDR) to insert a carotenogenesis cassette (49).

CRISPR approaches have also been applied to tomato for nutritional and flavour improvements modulating genes to increase GABA ( $\gamma$ -aminobutyric acid), anthocyanins and other desirable traits by knocking out repressors or activating biosynthetic pathways (50). In cereal crops, genome editing has been employed to enhance starch, protein, gluten and secondary metabolites, often yielding 30–50 %

improvements depending on the trait (51). Notably, CRISPR strategies targeting endogenous gene regulation offer similar  $\beta$ -carotene enrichment as transgenic Golden Rice, but with regulatory and consumer acceptance advantages. These molecular innovations highlight the transformative role of precise genome editing in accelerating crop nutritional enhancement beyond the limitations of conventional breeding.

#### Agronomic biofortification via micronutrient fertilizers and foliar sprays

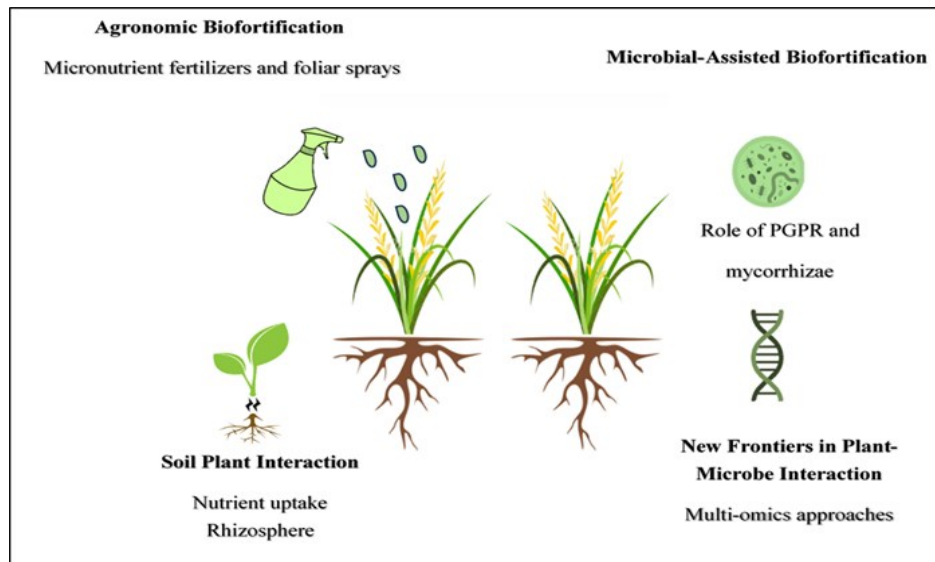
As shown in Fig. 5, biofortification can be achieved through both agronomic and microbial-assisted strategies. Agronomic biofortification involves the application of micronutrient fertilizers and foliar sprays to enhance nutrient uptake via soil-plant interactions. In parallel, microbial-assisted biofortification leverages beneficial microbes such as PGPR and mycorrhizae to improve nutrient assimilation. Emerging multi-omics approaches are expanding our understanding of plant-microbe interactions, opening new avenues for enhancing crop nutritional quality in a sustainable manner.

#### Agronomic biofortification

Agronomic biofortification means the application of micronutrient fertilizers to increase the nutritional content in crops. This process will help to solve the hidden hunger caused by deficiencies of micronutrients like Zn, Fe, Selenium (Se) and I. There are so many methods available, but the foliar application method is very useful and the best method to increase the Zn content in soil where nutrient content is limited (52). Foliar spraying is used for the direct absorption of nutrients through leaf surfaces, bypassing soil-related

**Table 3.** Genome editing and transgenic approaches in crop biofortification

Crop & variety	Method	Target nutrient	Increase vs previous variety	Process overview	References
<b>Golden Rice 2</b>	Transgenic	$\beta$ -carotene (vitamin A precursor)	$\sim 23\times$ more carotenoids (up to $\sim 37 \mu\text{g/g}$ vs $\sim 1.6 \mu\text{g/g}$ in original sentinel)	Cassette with maize <i>psy</i> + bacterial <i>cr1</i> genes inserted under endosperm-specific promoter via <i>Agrobacterium</i> -mediated transformation	(48)
<b>CRISPR-edited Golden Rice (Kitaake)</b>	Genome editing	$\beta$ -carotene	$7.9 \mu\text{g/g}$ DW (biofortified)	HDR used to insert 5.2 kb carotenogenesis cassette ( <i>Crt1</i> + <i>PSY</i> ) into genome	(49)
<b>CRISPR-edited tomato</b>	Genome editing	GABA, anthocyanins, oleic acid, starch, proteins, flavour	Partial increases (e.g., 2–5 $\times$ GABA)	CRISPR used to knock out repressors/ upregulate biosynthetic genes	(50)
<b>CRISPR Golden Rice via CRISPR-Cas</b>	Genome editing	Provitamin A	Similar high $\beta$ -carotene as transgenic lines ( $\sim$ few $\mu\text{g/g}$ )	CRISPR fine-tuning endogenous pathway genes, transgene-free	(49, 50)
<b>CRISPR-edited cereal crops</b>	Genome editing	Starch, protein, anthocyanin, GABA, gluten	30–50 % increases (trait-dependent)	CRISPR/Cas used for knock-ins, gene edits, QTL modifications	(50, 51)



**Fig. 5.** Integrated role of agronomic and microbial-assisted approaches in crop biofortification.

issues such as nutrient fixation in calcareous and alkaline soils (53). This process is particularly effective in soils deficient in micronutrients with low nutrient-holding capacity and during critical crop growth stages. In 2024, wheat varieties with enhanced Zn and Fe content were developed through foliar application of Zn and Fe, which increased grain micronutrient concentration and protein content (54). Multi-micronutrient biofortification studies have shown that the simultaneous foliar application of Zn, Fe and Cu (copper) is effective in crops such as mosambi, resulting in improved yield and fruit quality. In addition, innovations in nano-fertilizers have helped increase micronutrient content by enhancing plant nutrient uptake while reducing environmental impact. Foliar application timing is a crucial factor for improving Fe and Zn content, with the flowering and early grain-filling stages representing periods of peak nutrient demand. Next, the formulation of micronutrients in chemical chelated forms, such as Zinc ethylenediaminetetraacetic acid (Zn-EDTA) and Iron ethylenediamine-N,N'-bis(2-hydroxyphenylacetic acid) (Fe-EDDHA), has shown higher efficacy in foliar application due to improved plant absorption. In combination with soil application, foliar spraying of these fertilizers can increase nutrient availability in the soil, leading to improved crop yield (55). The interaction between the soil proportion and plant physiology is the basic step to nutrient uptake. It affects the plant crop productivity and sustainability. Researchers have recently elucidated the mechanisms underlying these interactions, highlighting the roles of root architecture, soil management and microbial associations in optimizing nutrient acquisition (56).

Adaptive characteristics of plant roots, such as altered branching patterns and increased root hair density, enhance nutrient foraging in heterogeneous soils. These morphological changes respond to nutrient gradients and are mediated by specific signalling pathways. The rhizosphere, the narrow zone of soil influenced by root secretions, plays an important role in nutrient mobilization. Root exudates, including organic acids and enzymes, modify the chemical environment and increase the availability of nutrients such as Fe and phosphorus (P). These exudates also shape the microbial community by fostering beneficial microorganisms, which further contribute to improved nutrient acquisition (57). The symbiotic relationship between soil microorganisms and plants, especially phosphate-solubilizing microorganisms (PSMs) and AMF is instrumental in nutrient intake. AMF will extend the root absorption capability by accessing phosphorus beyond the

depletion zone. On the other side, PSMs convert insoluble phosphorus compounds into accessible plants' secretion of organic acids and enzymes. Microbial partnership not only increases the nutrient content availability but also improves the resistance of plants to abiotic stress (58). Agronomic practices influence plant-soil interactions. Long-term studies have demonstrated that reduced tillage combined with integrated nutrient management, involving the use of both inorganic and organic fertilizers, increases water infiltration, soil organic carbon content and nutrient availability. Such practices improve nutrient uptake and enhance crop yield in wheat and maize (59). Intercropping, defined as the cultivation of multiple crops on the same bed, has also been shown to favourably modify rhizosphere dynamics. An example of a maize-soybean intercropping system is practiced to increase the nutrient uptake and crop yields compared to monocultures. The improvement is attributed to alterations in soil enzymatic activities and physicochemical properties by diverse root exudates and microbial interactions (60).

To maintain nutrient-enhancing effects of agronomic and microbial-assisted biofortification under variable field conditions (drought, degraded soils, heavy rainfall), integrated, context-specific strategies are essential. Combining foliar micronutrient sprays, timed at flowering and grain-filling stages, with modest soil applications helps buffer against micronutrient fixation in calcareous soils and enhances Zn and Fe accumulation in grains. Integrated foliar + soil application often outperforms either method alone under adverse soil conditions. Increasing soil organic matter through the application of compost, manure or biochar, together with the adoption of mulching or no-till practices, improves water retention, reduces nutrient leaching during heavy rainfall and stabilizes the root-zone microclimate. The use of stress-tolerant PGPR and AMF, preferably as locally adapted isolates or consortia selected for drought and salinity tolerance, applied as seed coatings or granular inoculants, helps protect nutrient uptake under transient stress conditions. These management practices should be matched with stress-resilient crop varieties and monitored using simple diagnostic tools, such as soil tests, leaf-tissue or foliar analyses and mobile- or remote-sensing-based assessments of crop stress, to enable timely targeted sprays or re-inoculation. Finally, integrated management packages should be validated through multi-environment, on-farm trials and participatory monitoring to ensure robustness across seasons and soil types.

### Microbial-assisted biofortification (MAB)

The MAB is beneficial for soil microorganisms for plant growth-promoting AMF and rhizobacteria to increase the nutrient content of crops (61). These symbiotic relationships will improve nutrient uptake, plant growth and resistance to environmental stresses for a sustainable approach to address micronutrient deficiencies in human health.

Plant growth-promoting rhizobacteria (PGPR) are beneficial bacteria that colonize plant roots and stimulate growth through several mechanisms, including the solubilization of nutrients such as Fe, Zn and P, thereby increasing their availability and accumulation in plants (62). For example, *Bacillus* and *Paenibacillus* species have been seen to increase Zn and Fe uptake in maize to increase yield and growth. Another important mechanism is phytohormone production, whereby PGPR synthesize hormones such as indole-3-acetic acid, cytokinins and gibberellins. These hormones enhance nutrient acquisition and promote root elongation and branching. In addition, PGPR contribute to stress alleviation by mitigating abiotic stresses, such as salinity and drought, through the production of enzymes like 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which lowers ethylene levels in plants-an important hormone associated with stress responses (63). AMF form a symbiotic association between plant roots and extensive hyphal networks in the soil, which enhance nutrient uptake by increasing the effective surface area for water and nutrient absorption, particularly phosphorus and micronutrients. AMF also improve soil structure by contributing to soil aggregation through hyphal growth, thereby increasing soil stability and aeration (64). In addition, AMF enhance plant resilience by improving tolerance to abiotic stresses, including soil salinity and drought. The combined application of PGPR and AMF enhances crop performance in rice through synergistic inoculation, resulting in improved plant height, spike length and grain yield. This integrated approach also improves soil fertility by increasing soil nutrient availability and microbial activity, thereby contributing to sustainable soil health. Plant-microbe interactions will play a crucial role in plant health, development and productivity. New scientific discoveries about how different organisms interact with each other in ecosystems are providing exciting possibilities for developing sustainable farming practices and managing ecosystems in a more environmentally responsible manner (65). Multi-omics approaches in the integration of genomics, proteomics, transcriptomics and metabolomics have developed. Understanding plant-microbe dynamics, these technologies facilitate the identification of proteins, metabolites and genes involved in symbiotic relationships, nutrient acquisition and pathogen defense. This type of analysis is used in the development of precision agriculture strategies to enhance plant health and productivity (66).

### Advances in omics and bioinformatics

By integrating genomics, proteomics, metabolomics and transcriptomics, this approach has revolutionized our understanding of plant nutrient pathways. These approaches enable the identification of key genes, proteins and metabolites involved in nutrient uptake, storage and transport (67). Plant metabolomics has been instrumental in identifying metabolic markers linked with stress tolerance for crop improvement strategies. MAS is used for molecular markers linked with desirable traits, developing nutrient-rich varieties. With the help of genomics, it is a prediction model. On the other hand, it helps to increase breeding values of plants by

analysing genome-wide markers and increasing the efficiency of breeding programs. The application of bioinformatics has led to the development of numerous tools to support biofortification research. This research, like the HarvestPlus biofortification Hub, provides stakeholders with many access tools and case studies regarding biofortified crops. Databases such as BRENDA, which provide comprehensive enzyme information, are crucial for understanding metabolic pathways (68).

### Biosafety and ecological considerations

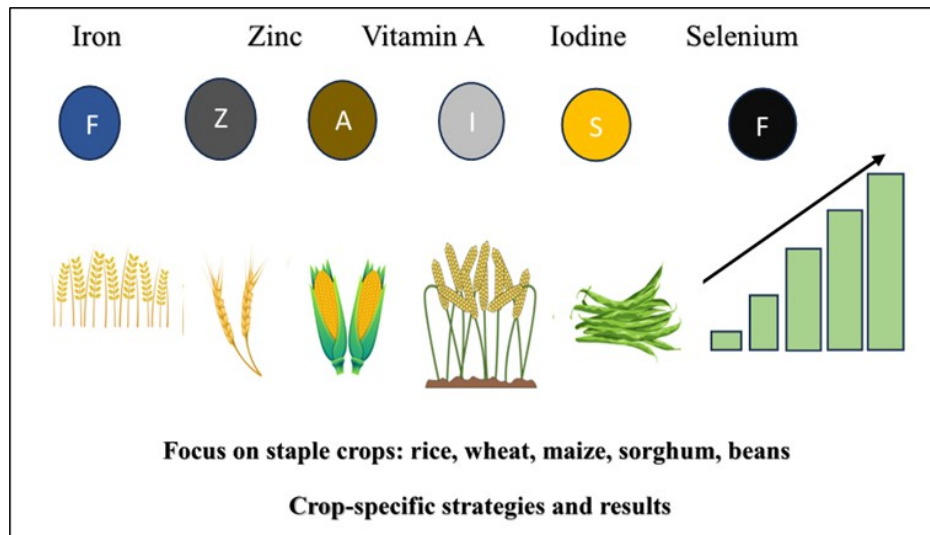
While CRISPR/Cas and transgenic biofortification strategies have achieved significant nutrient enhancement, potential off-target edits, metabolic alterations and ecological effects remain critical areas of monitoring. Continuous improvements in high-fidelity CRISPR variants and whole-genome sequencing are now being employed to minimize and detect off-target mutations with greater precision. Long-term field studies and multi-generational assessments are being conducted to evaluate unintended changes in plant metabolism, nutrient composition and interaction with soil microbiota. Environmental risk assessments mandated by regulatory bodies such as EFSA (European Food Safety Authority) and USDA-APHIS (U S Department of Agriculture-Animal and Plant Health Inspection Service) include gene flow analysis, allergenicity testing and ecological stability evaluations. Integrating omics-based profiling metabolomics, proteomics and transcriptomics further aids in detecting subtle biochemical perturbations, ensuring that genome-edited and transgenic crops maintain nutritional safety and environmental integrity. Thus, scientific oversight and regulatory frameworks are evolving in tandem with molecular innovation to promote responsible deployment of biofortified crops.

### Major target nutrients and their crops

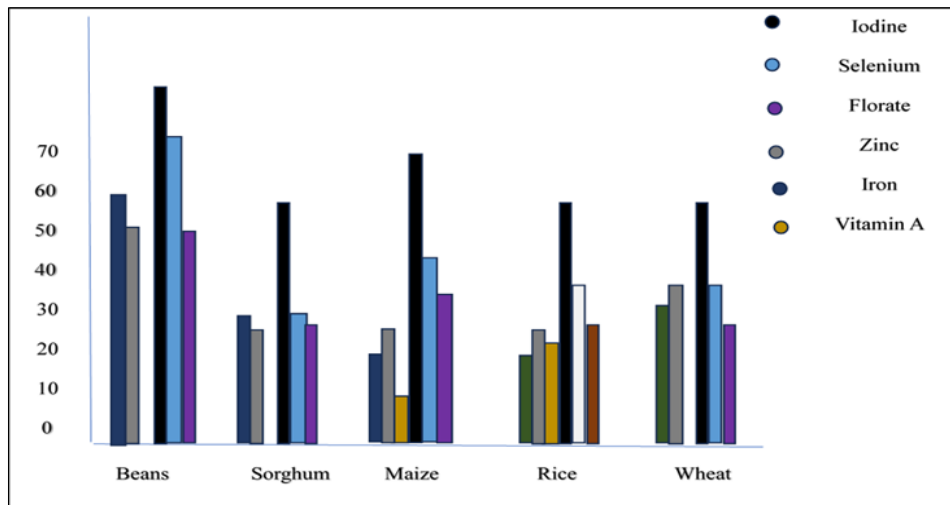
As illustrated in Fig. 6, the bar graph compares the concentrations of key micronutrients-I, Se, Zn, Fe and vitamin A-across five major biofortified staple crops: beans, sorghum, maize, rice and wheat. The data highlight significant crop-specific variation in nutrient accumulation, with beans and maize showing the highest I and Se enhancements, while rice and wheat exhibit balanced increases across several nutrients. This underscores the effectiveness of tailored biofortification strategies for meeting diverse nutritional requirements. Below is the real bar graph (Fig. 7) which represent the levels of biofortification for key nutrients, including Fe, Se, folate, Zn, vitamin A and I, across major staple crops such as beans, maize, wheat, sorghum and rice. The data illustrate that nutrient content varies among crops, highlighting the need for crop-specific biofortification strategies.

### Success stories in biofortification: iron-rich pearl millet and provitamin ‘A’ maize

As illustrated in Fig. 7, biofortification efforts are strategically targeted toward key micronutrients such as Fe, Zn, vitamin A, I and Se, focusing primarily on staple crops like rice, wheat, maize, sorghum and beans. Each crop requires tailored biofortification strategies based on its nutrient uptake potential, genetic background and consumption pattern. The figure highlights not only the diversity of micronutrient targets but also the positive trajectory in nutritional outcomes achieved through crop-specific interventions. Biofortification has evolved from a conceptual breeding goal to a field-validated strategy for addressing micronutrient deficiencies in rural areas (69). Several biofortified crops have succeeded in research, adoption levels. Among them, provitamin A in maize and Fe-rich pearl millets are examples.



**Fig. 6.** Micronutrient targets and crop-specific strategies in staple food biofortification.



**Fig. 7.** Comparative micronutrient enhancement in biofortified staple crops.

#### Iron-rich pearl millet

Iron (Fe) deficiency contributes significantly to the prevalence of anaemia in many countries, particularly in arid and semi-arid regions where pearl millet serves as a staple food. The International Crop Research Institute for Arid Tropics (ICRISAT) and some partners developed the Fe-rich varieties of pearl millet with the help of the conventional breeding program. Dhanashakti is the first biofortified pearl millet cultivar released in India (70). The developed cultivar Dhanashakti contains 71 mg/kg of Fe, which is higher than the traditional varieties (~30–40 mg/kg). It combines drought tolerance with high yield potential, thereby fostering strong farmer acceptance (71). Field trials have shown that regular consumption of Fe-rich pearl millet improves Fe content in adolescent girls and children. The success of Dhanashakti prompted inclusion in meal programs in schools and it was adopted in many states in India.

#### Provitamin A maize

In the overall population, Vitamin A deficiency is the major issue in Africa and parts of Asia, as it affects weakened immunity, impaired vision and mortality in children. In response, the NARS collaborated with the HarvestPlus program to develop maize varieties with enhanced provitamin A content, primarily  $\beta$ -carotene. In Zambia and Nigeria, provitamin A-enriched maize hybrids have been released as staple dietary crops. These hybrids contain up to 10–12  $\mu\text{g/g}$  provitamin A, compared with less than 2  $\mu\text{g/g}$  in traditional maize cultivars. Bioavailability studies show that provitamin A is

converted into vitamin A in human bodies. These studies also confirmed that yellow-to-orange grain colour was culturally acceptable (72).

#### Challenges and limitations

##### Genetic bottlenecks and trait trade-offs

Genetic improvement of crops helps to increase the nutrient content. Nowadays, it faces very critical challenges due to trait trade-offs and genetic bottlenecks (40). As we know, the genetic bottleneck issue arises from historical domestication and some other breeding events that narrowed the genetic base of many crops, such as staples. In this way, diversity limits the natural variation available for micronutrient traits such as provitamin A, Fe and Zn, particularly in breeding lines (73). The major trade-off is between nutrient content and yield. For example, increasing micronutrient density in grains, such as Zn and Fe, often correlates negatively with yield due to allocation conflicts within plants (74). So, breeders will balance productivity with nutrient goals. There is an important task given to the genetic nature of both nutrient traits and yield. To solve these challenges, the researchers are using genomic selection and multi-parent advanced generation intercross (MAGIC) population and CRISPR/Cas9 genome editing to introduce variation and to reduce the negative effects of such trade-offs. In the crops with limited variation for specific nutrients, land races and wild relatives are also explored as novel alleles for improvement (75).

### Environmental and soil constraints

Micronutrient bioavailability is a critical factor determining the success of biofortification, particularly for elements such as Zn, Fe and Se. Although total micronutrient content may be sufficient in many soils, their availability to plants is strongly influenced by soil pH, redox conditions, organic matter content and interactions among elements, such as phosphorus-induced inhibition of Zn uptake. Calcareous and alkaline soils, which are widespread in semi-arid and arid regions, typically exhibit low bioavailability of Zn and Fe due to nutrient fixation (76). In addition, climate change compounds these challenges by altering rainfall patterns and increasing the frequency and intensity of droughts and floods. Such environmental shifts can disrupt soil microbial communities, root functioning and nutrient cycling, thereby limiting plant access to micronutrients. Drought stress reduces root biomass and restricts nutrient uptake, while excessive rainfall and waterlogging disturb nutrient balance and availability. For this, we have adaptation strategies that include agronomic biofortification development for varieties suited for soils and microbial inoculants to mobilise nutrients under stress-prone conditions.

### Regulatory and public acceptance issues

The development of biofortified crops, mainly those developed using genetic modification or genomic editing, faces regulatory hurdles and public resistance. The primary concern revolves around biosafety, which includes the potential for unintended ecological effects and gene flow to wild relatives. The release of GM biofortified crops is subject to stringent regulatory frameworks in many countries, often resulting in delays and increased costs during the approval process (77). Another significant barrier is public acceptance due to misinformation and a lack of awareness about safety and advantages of GM biofortified crops, which fuels scepticism. Despite the scientific consensus supporting the safety of GMOs, consumers in some regions continue to associate GM foods with environmental harm and health risks, with perceptions shaped by cultural beliefs, media narratives and levels of trust in regulatory institutions (78). To address these challenges, effective communication, public engagement and education are essential. In parallel, regulatory frameworks are evolving to distinguish genome-edited crops from transgenic GMOs, thereby easing approval pathways for CRISPR-based biofortification.

### Policy, economics and distribution challenges

Biofortification has proven effective in combating micronutrient deficiencies; however, scaling up biofortified staple crop varieties continues to face major challenges. The main barriers include limited integration into national agricultural policies, with a lack of infrastructure for seed multiplication and insufficient awareness among consumers and farmers. This policy alignment across sectors such as nutrition, agriculture and trade is essential for mainstreaming biofortification (78). Cost-effectiveness studies indicate that biofortified crops, such as provitamin A maize and Fe-rich beans, offer substantial long-term health benefits at relatively low initial investment costs. However, adoption by farmers can be hindered by factors such as yield constraints, limited access to quality seed, weak extension services and insufficient market incentives, as biofortified crops often lack premium pricing. Hidden hunger persists globally due to a complex interplay of socioeconomic, environmental and cultural factors. Limited access to diverse diets, reliance on staple grains with low micronutrient content and region-specific food preferences rooted in tradition can exacerbate micronutrient deficiencies. Addressing these challenges requires context-sensitive interventions that respect

cultural practices while promoting nutrition education and biofortified crop adoption. Non-governmental organisations (NGOs) and governments, along with private seed companies, must collaborate to subsidise early adoption, raise awareness and develop supportive regulatory frameworks. Public-private partnerships and the inclusion of biofortified crops in food procurement programs can further accelerate adoption and distribution.

### Future prospects and research directions

Future biofortification is shifting towards broader crop diversity, sustainable intensification and technological integration. A key frontier in biofortification research is the underutilization of biofortification efforts in crops such as millets, leafy vegetables and pulses. These crops are not only nutrient-dense but also climatically resistant, making them ideal candidates for the diversification of diets and cropping systems in marginal environments (79). Advanced digital agriculture is revolutionizing biofortification research, mainly through machine learning models, high-throughput phenotyping and genomic prediction can accelerate the identification of micronutrient-associated traits. Integration of digital tools can also help with tracking nutrient content, adoption in real time and seed distribution. For sustainable agriculture and climate resilience, it is the heart of future biofortification strategies. Biofortified crops will play an important role in mitigating climate risk by offering a more resistant food system, enhancing soil health with microbial partnership and reducing dependency on chemical inputs (80). A major focus is the expansion from single-nutrient to multi-nutrient biofortification strategies. It will address coexisting defects by pyramiding technologies and combining targets. These innovations hold promise for achieving global nutrition goals more holistically.

### Bridging the resource gap in technological integration

While digital and omics-driven technologies such as high-throughput phenotyping, machine learning and genomic prediction are transforming biofortification research, their large-scale deployment in low- and middle-income countries (LMICs) remains constrained by limited infrastructure, high equipment costs and technical capacity gaps. To ensure equitable access, international collaborations and capacity-building initiatives must prioritize open-access platforms, shared data repositories and low-cost phenotyping solutions. Cloud-based analytic pipelines and portable field phenotyping tools such as smartphone-based imaging and handheld spectrometers can democratize access to precision technologies without requiring high-end facilities. Establishing regional genomics and phenomics hubs under public-private partnerships can provide shared resources, training and technical support for national breeding programs. Additionally, integrating open-source AI models trained on global datasets can help local researchers leverage predictive insights for nutrient trait selection without prohibitive investment. Ultimately, the success of technological integration in biofortification depends not only on innovation but also on inclusive models that enable LMICs to co-develop, adapt and scale these tools for locally relevant nutrition challenges.

### Conclusion

Omics-driven insights including genomics, transcriptomics and metabolomics are further refining trait selection and enhancing breeding efficiency. Equally notable is the growing role of microbial-assisted biofortification, involving PGPR and MF, which improve nutrient uptake and soil health. The adoption of digital agriculture

tools and AI-based platforms is also expanding precision in nutrient monitoring and crop improvement. However, scientific progress alone is not enough. Large-scale adoption of biofortified crops has already demonstrated measurable nutritional benefits. For example, Fe-biofortified pearl millet (“Dhanashakti”) improved haemoglobin levels in Indian women and children by 10–12 % after daily consumption, while Vitamin A-enriched OFSP reduced Vitamin A deficiency by up to 42 % among African children in pilot programs. As of 2024, more than 80 countries have released over 440 biofortified crop varieties developed through HarvestPlus and national partners, benefiting an estimated 100 million people globally. These real-world outcomes affirm that biofortification is not merely a research innovation but a proven, scalable strategy for improving nutrition and public health. When supported by strong policy frameworks, community awareness and public-private partnerships, biofortification can serve as a cornerstone for achieving global food and nutrition security goals.

### Authors' contributions

S, GP and GN approved the final manuscript. SH, ALK, HB, SCM, PD, DP, AT, RK<sup>1</sup> contributed by imposing the experiment and helped edit, summarise and revise the manuscript. GN and RK<sup>2</sup> helped summarise and revise the manuscript. All authors read and approved the final manuscript. [RK<sup>1</sup> stands for Rohit Kumar & RK<sup>2</sup> stands for Rajneesh Kumar]

### Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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