



Biofortification: A Sustainable Solution to Hidden Hunger

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Biofortification is a process of improving the nutritional quality of food crops by increasing their essential vitamins and minerals content like iron, zinc and vitamin A. This strategy is important especially for the people in developing countries who rely heavily on staple foods and often suffer from hidden hunger *i.e.*, malnutrition caused by lack of micronutrients. Biofortified crops can be developed through traditional breeding, better agronomic practices, or modern genetic engineering. Several nutrient-rich varieties of rice, wheat, maize, sweet potato and other crops have been released in countries like India, Nigeria, Bangladesh etc. These crops offer long-term and cost-effective way to improve people's health. However, issues such as taste, awareness, bioavailability of nutrients and market acceptance still need to be addressed. Future efforts should focus on combining multiple nutrients, using advanced breeding tools like CRISPR and promoting biofortified crops through national programs and public education. Overall, biofortification has great potential to make diets healthier and farming more sustainable.

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1. INTRODUCTION

Micronutrient deficiencies, often called as "hidden hunger," continue to affect large segment of the global population, especially in low-income and rural regions (Zulfiqar *et al.*, 2024). Deficiencies in such as iron, zinc and vitamin A contribute significantly to impaired physical and cognitive development, weakened immunity and increased vulnerability to various diseases. Despite efforts through supplementation and industrial fortification, the interventions often fail to reach the populations due to logistical, economic and infrastructural constraints (Ofori *et al.*, 2022). Biofortification has emerged as an important and promising agricultural approach aimed at improving the nutritional quality of food crops by increasing their micronutrient content during growth (Dhiman *et al.*, 2023). Unlike traditional food fortification that occurs during food processing, biofortification integrates nutrition directly into the crop through plant breeding or modern genetic engineering techniques. This strategy ensures nutrient-rich foods available to communities who primarily depend on crops such as rice, wheat, maize, millet and cassava for their daily dietary needs (Mishra *et al.*, 2022).

In addition to enhancing nutritional value, many biofortified crops are bred for improved tolerance to biotic and abiotic stresses, making them more resilient under changing climatic conditions (Lewis, 2021). Dual benefit like this supports both food and nutrition security in sustainable manner (Kellogg *et al.*, 2022). Over the past decade, biofortification efforts have gained the global traction, supported by various organizations like HarvestPlus, national research programs and various policy initiatives (Jaiswal *et al.*, 2022). The present review aims to provide a detailed examination of the progress in biofortification, including the scientific approaches used, key crop varieties released and their impact on nutrition and agriculture. It also explores ongoing challenges and future directions to integrate biofortification more effectively into global food systems.

2. WHAT IS BIOFORTIFICATION?

Biofortification is the process of increasing the bioavailable micronutrient content in the edible portions of crops. It involves enhancing nutrient

content of food crops through methods like breeding, offering a sustainable, affordable and long-lasting strategy to increase the micronutrient intake (Srivastav *et al.*, 2022). This method not only reduces reliance on the therapeutic interventions for severe malnutrition, but also supports the continued improvement in nutritional health of the individual. This can be achieved through conventional plant breeding, agronomic practices or transgenic (genetic engineering) approaches.

3. METHODS OF BIOFORTIFICATION

3.1 Conventional Plant Breeding Method

Conventional breeding involves crossing of high-yielding crop varieties and those with naturally rich nutrients like iron, zinc, or provitamin A to develop nutritionally enhanced cultivars, like vitamin A-rich maize and iron-rich pearl millet (Lakshmi *et al.*, 2022; Gangashetty *et al.*, 2021). Agronomic biofortification enhances nutrient content by applying micronutrient-rich fertilizers (like zinc or selenium) to soil or foliage, helping the plants to absorb and store these nutrients in the edible parts; however, this requires seasonal application and is also soil-dependent (Marques *et al.*, 2021). Transgenic approaches involving inserting specific genes into crops to enable them to produce or accumulate essential nutrients not naturally present in sufficient amount, as seen in the Golden Rice, which is engineered to produce beta-carotene (Medina-Lozano & Diaz, 2022). Each method has its advantages and limitations, but together offer complementary pathways to combat the micronutrient deficiencies through agriculture.

3.2 Agronomic Practices

Agronomic biofortification means improving the nutrient content of crops by adding special fertilizers to the soil or spraying them on plants. These fertilizers contain important minerals like zinc and selenium, which help plants to absorb and store more nutrients in the parts we consume, such as grains or tubers. For example, farmers use ZnSO₄ in wheat and rice fields to boost zinc levels in grains, or selenium-rich fertilizers in countries like Finland to improve people's selenium intake through food (Lagoriya *et al.*, 2023). This method is easy to apply and also gives quick results. It fits well with current

Table 1. Major Target Nutrients and Crops

Nutrient	Major Crops	Health Benefits
Iron	Pearl millet, rice, beans	Prevents anaemia, improves cognition
Zinc	Wheat, rice, maize	Supports immune function, growth
Vitamin A	Sweet potato, maize, rice	Prevents blindness, boosts immunity
Protein	Quality Protein Maize (QPM)	Growth and repair of body tissues

farming practices and works well in the areas where, developing of new crop varieties is difficult. However, the nutrients need to be added every season and how well it works depends on the type of soil and how easily plants can absorb nutrients (Baum *et al.*, 2024).

3.3 Transgenic (Genetic Engineering) Approaches

The transgenic approach in biofortification involves altering the plant's genetic structure by introducing specific genes which enable the production or accumulation of essential micronutrients which the crop either deficit or produces in insufficient amounts. Scientists identify genes responsible for nutrient biosynthesis, such as those involved in the beta-carotene pathway and incorporate them into staple crops using advanced genetic engineering techniques (Nawaz *et al.*, 2025). A well-known example is Golden Rice, engineered with genes from maize and bacteria to synthesize provitamin A, while recent innovations have led to iron and zinc enriched rice through gene editing. This method allows introduction of traits beyond the scope of traditional breeding, offering much greater precision and faster results. However, adoption of this faces significant challenges, including public skepticism toward GMOs, strict regulatory frameworks and high research and development costs (Meena *et al.*, 2022).

4. MAJOR TARGET NUTRIENTS AND CROPS

Biofortified crops are developed to address nutrient deficiencies by increasing the levels of essential vitamins and minerals. For example, iron-rich crops like pearl millet, rice and beans help prevent anaemia and support brain function (Shohael *et al.*, 2025). Zinc-enriched wheat, rice and maize strengthen the immune system and promote healthy growth. Vitamin A is boosted in sweet potato, maize and rice, helping to prevent vision problems and improve immunity. Quality Protein Maize (QPM) provides better protein, which is crucial for growth and tissue repair,

especially in children. These nutrient-rich crops offer a sustainable way to improve public health through daily diets (Table 1).

5. GLOBAL ADOPTION OF BIOFORTIFIED CROPS FOR BETTER NUTRITION

Over the past two decades, various countries have introduced biofortified crops enriched with essential nutrients like iron, zinc and provitamin A to combat hidden hunger. These crops are bred not only for improved nutrition but also for resilience against pests, diseases and harsh climate conditions. For example, sweet potato enriched with provitamin A was first released in Uganda and Mozambique in 2007 with added drought resistance, while iron- and zinc-rich beans were introduced in Rwanda and DR Congo in 2012 with improved heat and virus tolerance. Countries like India and Bangladesh have released zinc and iron-fortified rice and wheat varieties with pest resistance and climate adaptability. Golden Rice, genetically modified to contain provitamin A, was officially released in the Philippines in 2021. These innovations represent a significant step toward improving public health through agriculture (Indian Council of Agricultural Research, 2017) (Table 2).

6. BIOFORTIFIED CROPS: NUTRIENTS, TRAITS AND GLOBAL RELEASE

Sweet potato varieties enhanced with provitamin A were first made available in 2007 in Uganda and Mozambique, developed to withstand diseases and prolonged dry spells. A more recent variant, the orange-fleshed sweet potato, reached farmers in Kenya, Rwanda, and Malawi in 2020, offering resilience against weevil damage and drought (Nkhata *et al.*, 2020). In 2012, iron and zinc rich bean varieties were introduced in Rwanda and the Democratic Republic of Congo, carrying traits for virus resistance and tolerance to both heat and water scarcity (Mulambu *et al.*, 2017). India released pearl millet high in iron and zinc in 2013, notable for its mildew resistance and ability to thrive

under drought conditions (Rai, 2017). Cassava biofortified with provitamin A appeared in Nigeria and DR Congo in 2011, providing stronger protection against common diseases (Afolami *et al.*, 2021). Maize enriched with provitamin A was introduced in Zambia and Nigeria in 2012 with both drought and disease resistance, followed by the 2016 release of orange maize in Zimbabwe and Ghana, which combined the same nutritional improvement with enhanced drought and disease resilience (Nkhata *et al.*, 2020).

Rice containing higher levels of zinc and iron was launched in Bangladesh and India in 2013, bred to resist pests and diseases while enduring cold temperatures and submergence (De Moura *et al.*, 2024). In 2017, India released zinc-enriched rice under the DRR Dhan series, which also resists bacterial blight and survives underwater conditions. The Philippines brought forward Golden Rice, a genetically modified provitamin A variety, in 2021, designed with pest resistance (The Agro Tech Daily, 2021). Wheat fortified with zinc and iron reached farmers in India and Pakistan in 2013, valued for its disease resistance and lodging tolerance, while in 2017, India introduced zinc-rich wheat cultivars BHU-25 and WB-02, offering high yield and better resilience against lodging and disease (Mishra *et al.*, 2025). Uganda began trials in 2014 on provitamin A-fortified bananas, a genetically modified and nutrient-dense type. Sorghum high in iron and zinc was rolled out in Nigeria in 2015 for drought-prone regions. In 2017, Ethiopia

introduced biofortified barley with iron and zinc, recognized for early maturation and tolerance to environmental stress.

7. IMPORTANT NUTRIENT-ENRICHED CROP VARIETIES RELEASED IN INDIA

India has made significant strides in promoting nutrition-sensitive agriculture through the release of biofortified crop varieties (Table 2). In the cereals category, rice varieties *viz.*, CR Dhan 310, enriched with protein and DRR Dhan 45, fortified with zinc, were both released in 2016. In wheat, WB 02 and HPBW 01, both rich in zinc and iron, were introduced in 2017. Biofortified maize saw a major push with the release of hybrids like Pusa Vivek QPM9 Improved, which is rich in provitamin A, lysine and tryptophan, along with Pusa HM4, HM8 and HM9 Improved, each enriched with lysine and tryptophan. Bajra hybrids HHB 299 and AHB 1200, known for their high iron and zinc content, were also made available the same year. In pulses, Pusa Ageti Masoor, which is an iron-rich lentil variety, was released in 2017. Among oilseeds, Pusa Mustard 30, low in erucic acid, was released in 2013, followed by Pusa Double Zero Mustard 31 in 2016, which has both low erucic acid and low glucosinolate content. In horticulture, Pusa Beta Kesari 1, a β -carotene-rich cauliflower, was released in 2015. In root crops, 2017 saw the introduction of sweet potato varieties Bhu Sona (β -carotene rich) and Bhu Krishna (rich in anthocyanin) (Paul *et al.*, 2024). Additionally, the

Table 2. Few important crop-wise nutritional improvements in India*

Crop	Variety	Trait
Rice	CR Dhan 310	Protein rich
	DRR Dhan 45	Zinc rich
Wheat	WB 02	Zinc & iron rich
	HPBW 01	Iron & zinc rich
Maize	Pusa Vivek QPM9 Improved	Provitamin-A, lysine & tryptophan rich hybrid
	Pusa HM4 Improved	Lysine & tryptophan rich hybrid
	Pusa HM8 Improved	Lysine & tryptophan rich hybrid
	Pusa HM9 Improved	Lysine & tryptophan rich hybrid
Pearl Millet	HHB 299	Iron & zinc rich hybrid
	AHB 1200	Iron rich hybrid
Lentil	Pusa Ageti Masoor	Iron rich
Mustard	Pusa Mustard 30	Low erucic acid
	Pusa Double Zero Mustard 31	Low erucic acid & low glucosinolate
Cauliflower	Pusa Beta Kesari 1	β -carotene rich
Sweet Potato	Bhu Sona	β -carotene rich
	Bhu Krishna	Anthocyanin rich
Pomegranate	Solapur Lal	Iron, zinc & vitamin-C rich

(*Source: https://icar.org.in/sites/default/files/Circulars/Biofortified-Varieties-English_for_0%20%281%29.pdf)

pomegranate variety Solapur Lal, enriched with iron, zinc and vitamin C, was also released in 2017. These varieties highlight India's commitment to addressing micronutrient malnutrition through biofortified agriculture (Indian Council of Agricultural Research, 2022) (Table 2).

8. PRIME MINISTER UNVEILS 109 CLIMATE-RESILIENT AND NUTRIENT-RICH CROP VARIETIES

During an event at the IARI, New Delhi, Prime Minister of India launched 109 newly developed crop varieties known for high yield, climate resilience and enhanced nutritional content. While interacting with farmers and scientists, he emphasized the need for value addition in agriculture to ensure better returns for farmers. Farmers expressed optimism that these varieties would lower the production costs and contribute positively to the environment. The Prime Minister also highlighted the rising demand for nutritious foods like millets and stressed the importance of natural and organic farming, which is gaining popularity among consumers (Birol & Bouis, 2023). Acknowledging the efforts of agricultural scientists, he noted their work in promoting underutilized crops. The 109 released varieties span 61 crops, including 34 field crops such as cereals, pulses, oilseeds and fibre crops and 27 horticultural crops like fruits, vegetables, spices and medicinal plants marking a significant step towards sustainable and nutrition focused farming (Ministry of Agriculture & Farmers Welfare 2024).

9. BENEFITS OF BIOFORTIFICATION

Biofortification brings a range of benefits making it a sustainable and impactful strategy for improving public health (Labuschagne, 2023). One of its key advantages is sustainability once nutrient-rich seeds are developed and distributed, they continue to deliver health benefits year after year without any recurring costs (Rawal *et al.*, 2024). This approach effectively reaches rural and underserved communities who depend heavily on staple crops for their daily caloric intake. Unlike supplementation/food fortification, which require ongoing investment and infrastructure, biofortification provides a cost-effective and long-term nutritional solution (Shohael *et al.*, 2025; Glatzel *et al.*, 2025). Moreover, it also supports broader goals of food system resilience and aligns well with the climate-smart agricultural practices (Bhardwaj *et al.*, 2022), making it a

promising tool in addressing both malnutrition and environmental challenges simultaneously.

10. CHALLENGES AND LIMITATIONS

Despite its potential, biofortification faces several challenges that limit its widespread adoption and impact. One major concern is acceptability, as biofortified crops may differ in taste, texture, or cooking quality, which can affect consumer preferences and cultural acceptance (Marques *et al.*, 2021). Another limitation is the issue of bioavailability—although the crops are enriched with nutrients, the presence of anti-nutritional factors such as phytates can inhibit the body's ability to absorb them effectively (Kumari *et al.*, 2022). Additionally, there is a significant gap in awareness among farmers, consumers and even policymakers, which hampers large-scale implementation (Mishra *et al.*, 2022). Furthermore, inadequate market linkages make it difficult to differentiate biofortified produce from conventional varieties, posing challenges in branding, marketing and ensuring fair returns to farmers. Addressing these issues is essential to fully realize the potential of biofortification in combating hidden hunger (Ginkel *et al.*, 2023).

11. ECONOMIC IMPLICATION OF BIOFORTIFIED CROPS

Biofortified crops generate economic benefits by simultaneously improving nutrition and enhancing agricultural productivity. For farmers, these varieties often deliver competitive or higher yields, greater resilience to environmental stresses, and potential market premiums, thereby stabilizing and increasing income. Consumers benefit through reduced healthcare expenses and improved well-being, as enhanced micronutrient intake lowers the prevalence of deficiencies that impair growth, learning, and productivity. At the national level, biofortification can lessen the financial burden on public health systems, strengthen the labour force, and create export opportunities for nutritionally enriched staples. Economic analyses consistently indicate that the return on investment in biofortification is high, as the initial breeding and dissemination costs are modest compared to the sustained health and productivity gains, they produce (Choudhary *et al.*, 2022; Jangra & Tiwari, 2025).

12. CONCLUSION

Biofortification is a smart and sustainable way to make our everyday food—like rice, wheat and maize—healthier by increasing the amount of

vitamins and minerals in them. This helps fight hidden hunger, which is when people eat enough food but don't get enough nutrients. Scientists are using new farming methods, fertilizers and even gene technologies to develop these special crops. Many such varieties are already being grown in countries like India, helping especially poor and rural families who depend on staple foods. However, some challenges still exist—people may not know about these crops, or may prefer the taste of regular ones and farmers may not get good prices in the market. In the future, more awareness, better technology and support from governments can make biofortified crops a normal part of our food system. This way, we can build a healthier and stronger society, one meal at a time.

13. FUTURE DIRECTIONS

The future of biofortification lies in harnessing advanced technologies and integrating nutrition goals with broader agricultural strategies. Genomic tools such as CRISPR and marker-assisted breeding are opening new avenues for faster and more precise development of nutrient-rich crop varieties (Sheoran et al., 2022). There is a growing focus on developing multi-nutrient crops that combine essential micronutrients like iron, zinc and vitamin A within a single variety to maximize health benefits. In the context of climate change, breeding biofortified crops that are also resilient to drought, pests and diseases is becoming increasingly important (Panwar et al., 2024). A critical step forward is the mainstreaming of biofortified varieties into national agricultural programs, including their incorporation into public procurement systems and food safety net schemes. Additionally, improving consumer education through branding, certification and awareness campaigns can enhance acceptance and demand, helping to scale up adoption and impact.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) here by declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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