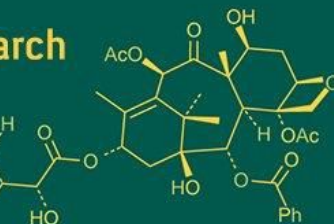


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Chhavi Tiwari
Associate Professor,
Shri Vaishnav Institute of
Agriculture, Shri Vaishnav
Vidyapeeth Vishwavidyalaya,
Indore, Madhya Pradesh,
India

Importance of biofortification in crops

Chhavi Tiwari

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Abstract

Micronutrient malnutrition, commonly referred to as hidden hunger, affects billions of people worldwide, particularly in developing countries where diets are dominated by micronutrient-poor staple crops. Biofortification has emerged as a sustainable, agriculture-based strategy to enhance the nutritional quality of food crops by increasing the concentration and bioavailability of essential micronutrients during plant growth. This review synthesizes current knowledge on the concept, approaches and importance of biofortification, with emphasis on targeted nutrients such as iron, zinc and vitamin A and their role in improving human health. The agronomic and environmental benefits of biofortification, including improved crop productivity, nutrient use efficiency and climate resilience, are discussed. The review also highlights challenges related to nutrient bioavailability, adoption and policy integration, along with future research needs. Particular attention is given to the relevance of biofortification in the Indian context and its role in addressing nutritional security under climate change. Biofortification represents a cost-effective and scalable intervention that bridges agriculture and nutrition, offering long-term solutions to micronutrient deficiencies and contributing to sustainable food systems.

Keywords: Bio-fortification, hidden hunger, micronutrient malnutrition, iron, zinc, vitamin A, nutritional security, climate change, sustainable agriculture

1. Introduction

Micronutrient malnutrition, often described as *hidden hunger*, remains a major global public health concern affecting more than two billion people worldwide, with the highest prevalence observed in developing and underdeveloped regions where diets are predominantly cereal based and lack dietary diversity (FAO *et al.*, 2023; Ritchie & Roser, 2021) [7, 17]. Unlike energy deficiencies, micronutrient malnutrition frequently goes unnoticed in its early stages but leads to profound and long-term consequences for human health, cognitive development and economic productivity.

Deficiencies of iron, zinc and vitamin A are among the most widespread and nutritionally critical forms of hidden hunger. Iron deficiency is the leading cause of anemia globally, particularly among women, adolescent girls and young children, resulting in impaired cognitive performance, reduced physical work capacity and increased risk of maternal and child mortality (WHO, 2020; Hurrell & Egli, 2010) [22, 10]. Zinc deficiency compromises immune competence, increases susceptibility to infectious diseases and negatively affects growth and reproductive health, while vitamin A deficiency remains a leading cause of preventable blindness and heightened childhood morbidity and mortality in low-income populations.

Traditional interventions aimed at addressing micronutrient deficiencies, such as dietary supplementation and industrial food fortification, have shown positive outcomes in controlled and urban settings. However, their effectiveness at scale is often constrained by high recurring financial costs, dependence on centralized processing facilities, logistical challenges and limited penetration in rural and marginal communities (Allen *et al.*, 2006; Bhutta *et al.*, 2013) [1, 3]. Moreover, these interventions require sustained policy support and consumer compliance, which may be difficult to maintain over extended periods.

Against this backdrop, biofortification has emerged as a sustainable, cost-effective and agriculture-based strategy to improve the micronutrient density of staple crops that form the dietary backbone of vulnerable populations. Biofortification enhances the concentration and bioavailability of essential micronutrients in crops during plant growth through conventional

Corresponding Author:
Chhavi Tiwari
Associate Professor,
Shri Vaishnav Institute of
Agriculture, Shri Vaishnav
Vidyapeeth Vishwavidyalaya,
Indore, Madhya Pradesh,
India

breeding, agronomic interventions or modern biotechnological approaches (Bouis *et al.*, 2011; White & Broadley, 2009) ^[4, 21]. By delivering nutrients through regularly consumed foods, biofortification reduces reliance on external supplementation programs and ensures long-term nutritional benefits with minimal recurring costs. Empirical evidence from global initiatives has demonstrated that consumption of biofortified crops significantly improves micronutrient intake and nutritional status among target populations, thereby offering a robust and scalable solution to hidden hunger and contributing to sustainable food and nutritional security (Bouis & Saltzman, 2017; Saltzman *et al.*, 2013) ^[5, 18].

2. Concept of Biofortification

Biofortification is defined as the process of increasing the concentration, bioavailability and retention of essential micronutrients in the edible parts of food crops during plant growth, rather than through post-harvest food processing or fortification (Bouis *et al.*, 2011; Saltzman *et al.*, 2013) ^[4, 18]. The central objective of biofortification is to improve the nutritional quality of staple foods that are regularly consumed by large segments of the population, particularly in regions where dietary diversity is limited and access to fortified foods or supplements is inadequate.

Unlike conventional food fortification, which relies on centralized industrial infrastructure and continuous external inputs, biofortification operates at the agricultural production level. Once nutrient-dense crop varieties are developed and adopted, the enhanced nutritional trait is retained in successive harvests, making biofortification a self-sustaining and cost-effective intervention (Bouis & Saltzman, 2017) ^[5]. This approach ensures that essential micronutrients reach rural and economically marginalized communities through their daily diets without requiring changes in food preferences or consumption patterns.

Biofortification can be achieved through several complementary approaches. Conventional plant breeding involves identifying genetic variability for micronutrient content within crop germplasm and incorporating desirable traits into high-yielding varieties through selective breeding. This method has been widely used for enhancing iron and zinc content in cereals and legumes and is generally well accepted due to its non-transgenic nature (White & Broadley, 2009; Rai *et al.*, 2016) ^[21, 16].

Agronomic biofortification refers to the application of mineral fertilizers, either to the soil or as foliar sprays, to increase micronutrient concentrations in crop tissues. This approach is particularly effective for nutrients such as zinc, selenium and iodine and offers the additional advantage of improving crop productivity and nutrient use efficiency, especially in micronutrient-deficient soils (Cakmak, 2008; Joy *et al.*, 2015) ^[6, 12].

Transgenic biofortification employs modern biotechnological tools to introduce or modify genes involved in nutrient biosynthesis, transport or storage pathways. This approach has enabled the development of crops with significantly enhanced levels of nutrients that are otherwise difficult to improve through conventional breeding, such as provitamin A-enriched rice and cassava (Zhu *et al.*, 2013) ^[23]. Although transgenic biofortification offers high potential, its adoption is influenced by regulatory frameworks and public acceptance.

Microbial-assisted biofortification has gained attention as an eco-friendly approach wherein plant growth-promoting rhizobacteria, mycorrhizal fungi and other beneficial microorganisms enhance nutrient solubilization, uptake and translocation in plants. This strategy aligns well with sustainable and organic farming systems and complements both genetic and agronomic biofortification methods (Singh *et al.*, 2021; Kumar *et al.*, 2023) ^[19, 13].

The concept of biofortification represents an integrated framework linking agriculture, nutrition and public health. By embedding enhanced nutritional traits within staple crops, biofortification addresses micronutrient deficiencies at their source and contributes to long-term food and nutritional security, particularly in resource-constrained regions.

“The overall concept and pathways through which biofortification enhances micronutrient availability and contributes to nutritional security are illustrated in Figure 1.”

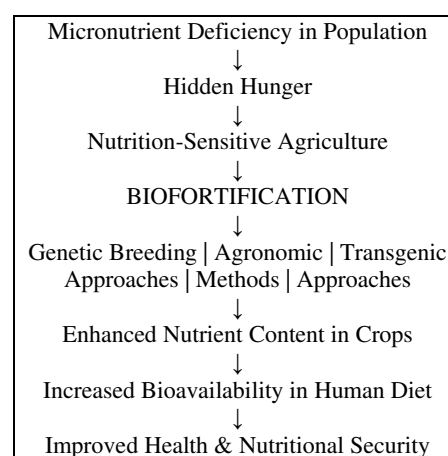


Fig 1: Contributes to nutritional security are illustrated

3. Target Nutrients and Biofortified Crops

Biofortification primarily targets micronutrients that are widely deficient in human diets and have well-established public health significance. The selection of target nutrients and crops is guided by the prevalence of deficiencies, dietary consumption patterns, genetic feasibility and potential health impact. Globally, iron, zinc and vitamin A have received the greatest attention, followed by selenium, iodine and folate, due to their critical roles in human growth, immunity and metabolic regulation (Bouis *et al.*, 2011; Saltzman *et al.*, 2013) ^[4, 18].

Iron (Fe) is the most extensively targeted micronutrient in biofortification programs owing to the high global burden of iron-deficiency anemia. Cereals such as rice and wheat, as well as legumes like beans and lentils, are major vehicles for iron biofortification because they constitute staple foods for large populations. Breeding efforts have successfully developed iron-rich pearl millet and common bean varieties, which have demonstrated improved iron intake and bioavailability among consumers (Rai *et al.*, 2016; Bouis & Saltzman, 2017) ^[16, 5].

Zinc (Zn) deficiency is closely associated with impaired immune response, growth retardation and increased susceptibility to infections. Zinc biofortification has been widely implemented in cereals including wheat, rice and maize, as well as in pulses. Both genetic and agronomic biofortification strategies have proven effective in enhancing grain zinc concentration, particularly in zinc-

deficient soils, while also improving crop yields (Cakmak, 2008; Joy *et al.*, 2015) ^[6, 12].

Vitamin A, delivered mainly in the form of provitamin A carotenoids (β -carotene), is another key target of biofortification initiatives. Crops such as sweet potato, maize, cassava and rice have been successfully biofortified to address vitamin A deficiency, especially among children and pregnant women. Orange-fleshed sweet potato has been widely adopted in several countries and has shown significant improvements in vitamin A status, while transgenic approaches have enabled the development of provitamin A-enriched rice (Saltzman *et al.*, 2013) ^[18].

Selenium (Se) biofortification has gained importance due to its role in antioxidant defense, thyroid hormone metabolism and immune function. Selenium enrichment of cereals through agronomic practices has been particularly successful in regions with selenium-deficient soils (White & Broadley, 2009) ^[21]. Iodine (I) and folate biofortification efforts are also emerging, though they pose greater technical

challenges due to nutrient instability and complex plant metabolic pathways (Zhu *et al.*, 2013) ^[23].

The choice of crops for biofortification is equally critical. Staple crops such as rice, wheat, maize, pearl millet, sorghum, cassava and legumes are prioritized because of their widespread consumption among nutritionally vulnerable populations. These crops serve as effective delivery vehicles for micronutrients and ensure maximum population-level impact without altering dietary habits (Bouis *et al.*, 2011; Kumar *et al.*, 2023) ^[4, 13].

Targeting specific micronutrients through biofortified staple crops represents a strategic and evidence-based approach to reducing hidden hunger. By aligning crop improvement efforts with nutritional priorities, biofortification bridges the gap between agricultural productivity and human health, thereby strengthening global food and nutritional security.

The major target micronutrients, commonly biofortified crops and their associated health benefits are summarized in Table 1.

Table 1: Target Nutrients, Biofortified Crops and Health Benefits

Target nutrient	Major biofortified crops	Key health benefits	Major target population
Iron (Fe)	Rice, wheat, pearl millet, beans	Prevention of anemia, improved cognitive function	Women, children
Zinc (Zn)	Wheat, rice, maize, pulses	Improved immunity, growth and reproduction	Children, adolescents
Vitamin A (β -carotene)	Sweet potato, maize, cassava, rice	Prevention of night blindness, reduced child mortality	Children, pregnant women
Selenium (Se)	Wheat, rice	Antioxidant defense, thyroid function	General population
Folate	Rice, legumes	Neural development, reduced birth defects	Pregnant women

4. Importance of Biofortification

Biofortification has emerged as a transformative strategy at the interface of agriculture, nutrition and public health. Its importance lies in its ability to address micronutrient deficiencies in a sustainable, cost-effective and socially acceptable manner, particularly among populations that rely heavily on staple crops for their daily dietary intake. By

improving the nutritional quality of crops at the production level, biofortification contributes significantly to long-term food and nutritional security.

A comparative assessment of biofortification with conventional approaches such as food fortification and supplementation highlights its long-term sustainability and cost-effectiveness (Table 2).

Table 2: Comparison of Biofortification with Other Nutrition Interventions

Parameter	Biofortification	Food fortification	Supplementation
Point of intervention	Farm level	Processing level	Health system
Sustainability	High	Moderate	Low
Recurring cost	Low	Medium	High
Infrastructure requirement	Minimal	High	High
Reach to rural population	High	Limited	Limited
Change in food habits	Not required	Not required	Required

4.1 Addressing Hidden Hunger and Nutritional Security

One of the foremost benefits of biofortification is its effectiveness in combating hidden hunger. Staple foods such as rice, wheat and maize provide a major proportion of daily caloric intake in many developing countries but are inherently poor sources of essential micronutrients. Biofortification enhances the micronutrient density of these staples, thereby improving dietary quality without requiring changes in food habits or consumption patterns (Bouis *et al.*, 2011; Saltzman *et al.*, 2013) ^[4, 18]. Empirical evidence from intervention studies has demonstrated that regular consumption of biofortified crops leads to measurable improvements in iron, zinc and vitamin A status among vulnerable groups, including women and children (Bouis & Saltzman, 2017) ^[5].

4.2 Sustainability and Cost-Effectiveness

Biofortification is widely recognized as one of the most cost-effective interventions for addressing micronutrient

malnutrition. Unlike supplementation and industrial fortification programs, which require continuous financial and logistical inputs, biofortified crops deliver nutritional benefits year after year once adopted by farmers. The initial investment in research and breeding is offset by long-term health and economic gains, resulting in a high benefit-cost ratio (Bouis *et al.*, 2011; Bhutta *et al.*, 2013) ^[4, 3]. This sustainability makes biofortification particularly suitable for resource-poor and rural settings where conventional nutrition interventions face operational constraints.

4.3 Accessibility and Equity

A key strength of biofortification is its ability to reach populations that are often excluded from formal food distribution and health systems. Rural households that depend on subsistence or semi-subsistence agriculture benefit directly from growing and consuming biofortified crops. This inherent accessibility ensures equitable nutrient delivery, especially among marginalized communities with

limited access to fortified foods or dietary supplements (Ritchie & Roser, 2021; FAO *et al.*, 2023)^[17, 7].

4.4 Synergy with Agricultural Productivity and Soil Health

Biofortification, particularly agronomic biofortification, often results in improved crop productivity alongside enhanced nutritional quality. Application of micronutrient fertilizers such as zinc not only increases grain micronutrient concentration but also improves yield, stress tolerance and nutrient use efficiency in crops grown on deficient soils (Cakmak, 2008; Joy *et al.*, 2015)^[6, 12]. This dual advantage strengthens farmer adoption and contributes to sustainable agricultural intensification.

4.5 Role in Climate-Resilient Food Systems

Climate change poses a growing threat to global nutrition by reducing the concentration of essential minerals in crops under elevated atmospheric CO₂ conditions. Biofortification offers a viable strategy to counteract this nutrient dilution effect and maintain the nutritional quality of staple foods in the face of changing climatic conditions (Myers *et al.*, 2014; Smith & Myers, 2018)^[14, 20]. Thus, biofortification supports the development of resilient food systems capable of sustaining both yield and nutritional value.

4.6 Policy and Developmental Significance

Biofortification aligns closely with global and national nutrition and development goals, including the Sustainable Development Goals related to zero hunger, good health and well-being and poverty reduction. Several countries, including India, have incorporated biofortified crops into national agricultural and nutrition policies to address micronutrient deficiencies at scale (ICAR, 2021; NITI Aayog, 2021)^[11, 15]. This policy integration underscores the strategic importance of biofortification as a long-term public health intervention.

The importance of biofortification extends beyond improving crop nutrient content. It represents a holistic approach that integrates agricultural innovation with nutritional outcomes, enhances resilience of food systems and promotes equitable access to essential micronutrients. As such, biofortification stands out as a cornerstone strategy for achieving sustainable food and nutritional security in the twenty-first century.

5. Agronomic and Environmental Benefits of Biofortification

Beyond its nutritional advantages, biofortification offers several agronomic and environmental benefits that contribute to sustainable crop production systems. By improving micronutrient availability and utilization within plants, biofortification enhances crop performance, soil health and resource-use efficiency, thereby supporting both agricultural productivity and environmental sustainability.

5.1 Improvement in Crop Growth and Yield

Micronutrients such as iron, zinc and selenium play essential roles in plant physiological processes including enzyme activation, photosynthesis, chlorophyll synthesis and hormone regulation. Deficiencies of these micronutrients in soils often lead to poor crop growth and reduced yields. Agronomic biofortification through soil or foliar application of micronutrient fertilizers has been shown

to improve plant vigor, biomass accumulation and grain yield, particularly in micronutrient-deficient soils (Cakmak, 2008; Alloway, 2009)^[6, 2]. Zinc fertilization, for instance, enhances root development and stress tolerance, leading to improved productivity in cereals such as wheat and rice (Joy *et al.*, 2015)^[4, 12].

5.2 Enhanced Nutrient Use Efficiency

Biofortification improves the efficiency with which plants absorb, translocate and store micronutrients. This increased nutrient use efficiency reduces losses of applied fertilizers through leaching, volatilization or fixation in soil, thereby optimizing input use and lowering production costs for farmers (White & Broadley, 2009)^[21]. Improved nutrient uptake also minimizes the need for repeated fertilizer applications, contributing to environmentally responsible nutrient management.

5.3 Soil Health and Sustainability

Micronutrient-enriched cropping systems can positively influence soil health by promoting balanced nutrient cycling and enhancing microbial activity in the rhizosphere. The use of microbial-assisted biofortification, involving plant growth-promoting rhizobacteria and mycorrhizal fungi, improves soil biological properties, nutrient solubilization and root-soil interactions (Singh *et al.*, 2021)^[19]. These processes contribute to improved soil structure, fertility and long-term sustainability of agricultural soils.

5.4 Reduced Environmental Footprint

By increasing nutrient density in crops at the source, biofortification reduces reliance on external nutritional interventions such as supplementation and industrial fortification, which often require energy-intensive processing, packaging and transportation. Additionally, improved nutrient use efficiency in biofortified cropping systems can reduce excessive fertilizer use, thereby lowering greenhouse gas emissions and minimizing soil and water contamination (Smith & Myers, 2018; FAO *et al.*, 2023)^[20, 7].

5.5 Integration with Sustainable and Climate-Smart Agriculture

Biofortification aligns closely with the principles of sustainable and climate-smart agriculture. Biofortified crops often exhibit improved tolerance to abiotic stresses such as drought and heat, partly due to enhanced micronutrient-mediated physiological resilience. This contributes to yield stability under variable climatic conditions and supports adaptive strategies for climate change mitigation (Myers *et al.*, 2014; Kumar *et al.*, 2023)^[14, 13].

The agronomic and environmental benefits of biofortification extend its value beyond nutrition alone. By improving crop productivity, enhancing nutrient efficiency, strengthening soil health and reducing environmental impacts, biofortification serves as a multifunctional approach that supports sustainable agricultural development while simultaneously addressing global nutritional challenges.

5.6 Biofortification under Climate Change

Climate change poses a significant and growing threat to global food and nutritional security by affecting crop productivity as well as the nutritional quality of food crops.

Rising atmospheric carbon dioxide (CO₂) concentrations, increasing temperatures and altered rainfall patterns have been shown to influence plant metabolism, often leading to a reduction in the concentration of essential micronutrients such as iron, zinc and protein in cereal grains. This phenomenon, commonly referred to as the “nutrient dilution effect,” exacerbates the risk of micronutrient deficiencies, particularly among populations that depend heavily on staple crops for their daily diets (Myers *et al.*, 2014) ^[14].

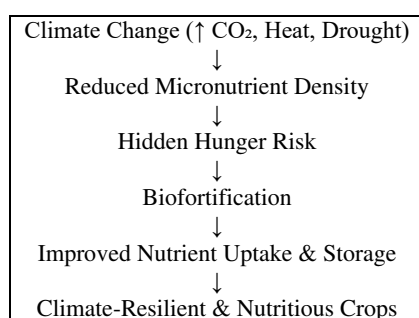
Elevated CO₂ levels can increase carbohydrate accumulation in plants while simultaneously reducing mineral uptake and translocation, resulting in lower micronutrient density in edible plant parts. Studies have demonstrated that future climate scenarios may significantly decrease iron and zinc content in major staples such as rice and wheat, thereby intensifying hidden hunger at a global scale (Smith & Myers, 2018) ^[20]. In addition, climate-induced stresses such as drought and heat can impair root growth and soil nutrient availability, further limiting micronutrient acquisition by crops.

Biofortification offers a promising adaptation strategy to safeguard nutritional quality under changing climatic conditions. Biofortified crop varieties with enhanced micronutrient uptake, transport and storage efficiency can help counteract climate-related nutrient losses. Moreover, agronomic biofortification practices, including targeted micronutrient fertilization, can improve crop resilience and maintain grain nutrient concentration even under adverse environmental conditions (Cakmak, 2008; Joy *et al.*, 2015) ^[6, 12].

Biofortification also aligns with climate-resilient and climate-smart agriculture by promoting efficient resource use, yield stability and improved nutritional outcomes simultaneously. When combined with soil health management and sustainable farming practices, biofortification can strengthen the capacity of food systems to adapt to climate variability while ensuring adequate micronutrient supply.

Integrating biofortification into climate change adaptation strategies is essential for maintaining both food quantity and food quality. By addressing the nutritional impacts of climate change, biofortification contributes to resilient food systems capable of supporting human health in an era of increasing environmental uncertainty.

The role of biofortification in mitigating climate-induced nutrient dilution and strengthening climate-resilient food systems is illustrated in Figure 2.



6. Challenges and Limitations of Biofortification

Despite its considerable potential and demonstrated benefits, biofortification faces several scientific, agronomic, socio-economic and policy-related challenges that may influence its large-scale adoption and long-term effectiveness.

Understanding these limitations is essential for refining biofortification strategies and ensuring their successful integration into food and nutrition systems.

6.1 Nutrient Bioavailability and Retention

A major challenge in biofortification is ensuring that increased micronutrient concentrations in crops translate into improved nutritional status in humans. The bioavailability of minerals such as iron and zinc is often reduced by the presence of anti-nutritional factors, particularly phytates and polyphenols, which inhibit mineral absorption in the human gut (Hurrell & Egli, 2010; Gibson & Ferguson, 2008) ^[10, 9]. Additionally, nutrient losses during post-harvest processing, storage and cooking can reduce the effective micronutrient intake from biofortified foods, necessitating strategies to enhance nutrient retention and absorption.

6.2 Genetic and Breeding Constraints

The success of genetic biofortification depends on the availability of sufficient genetic variability for targeted micronutrients within crop germplasm. In some staple crops, natural variation for certain nutrients is limited, making breeding efforts time-consuming and technically challenging. Moreover, the simultaneous improvement of yield, micronutrient concentration and bioavailability can be constrained by potential trade-offs between agronomic performance and nutritional traits (White & Broadley, 2009; Bouis *et al.*, 2011) ^[21, 4].

6.3 Agronomic and Environmental Variability

The effectiveness of agronomic biofortification is influenced by soil properties, climate, cropping systems and fertilizer management practices. Variability in soil pH, organic matter content and micronutrient availability can lead to inconsistent nutrient accumulation in crops across different agro-ecological zones (Alloway, 2009) ^[2]. This variability poses challenges for standardizing agronomic recommendations and achieving uniform nutritional outcomes at scale.

6.4 Acceptance and Adoption by Farmers and Consumers

Farmer adoption of biofortified varieties may be constrained by factors such as limited seed availability, lack of awareness and perceptions regarding yield performance or market demand. Similarly, consumer acceptance can be influenced by changes in sensory attributes such as color, taste or texture, particularly in the case of provitamin A-rich crops with altered pigmentation (Saltzman *et al.*, 2013) ^[18]. Addressing these challenges requires effective extension services, awareness campaigns and market integration strategies.

6.5 Regulatory and Policy Challenges

Transgenic biofortification, while scientifically promising, faces regulatory hurdles and public skepticism in many countries. Lengthy approval processes, biosafety concerns and ethical debates can delay the release and adoption of genetically modified biofortified crops (Zhu *et al.*, 2013) ^[23]. Even non-transgenic biofortification initiatives require supportive policy frameworks, coordinated institutional efforts and sustained funding to achieve large-scale impact.

6.6 Monitoring and Impact Assessment

Evaluating the long-term nutritional and health impacts of biofortification programs presents methodological challenges. Accurate assessment requires interdisciplinary approaches combining agriculture, nutrition and public health data. Limited monitoring and evaluation capacity in low-resource settings can hinder evidence-based scaling of biofortification interventions (Bouis & Saltzman, 2017) ^[5]. While biofortification holds significant promise as a sustainable solution to micronutrient malnutrition, its success depends on addressing challenges related to bioavailability, agronomic variability, adoption, regulation and impact assessment. Overcoming these limitations through integrated research, policy support and stakeholder engagement will be critical for realizing the full potential of biofortification in improving global food and nutritional security.

7. Biofortification in the Indian Context

India faces a significant burden of micronutrient malnutrition, with deficiencies of iron, zinc and vitamin A remaining widespread across different population groups. Iron-deficiency anemia affects a large proportion of women of reproductive age, adolescent girls and young children, while zinc deficiency contributes to impaired immune function, growth retardation and increased susceptibility to infections. These nutritional challenges are closely linked to dietary patterns dominated by cereal-based staples and limited intake of micronutrient-rich foods (FAO *et al.*, 2023; NITI Aayog, 2021) ^[7, 15]. In this context, biofortification has emerged as a strategic intervention to improve nutritional outcomes through the agricultural sector.

Recognizing the potential of biofortification, India has taken proactive steps to integrate nutrition-sensitive agriculture into national food and nutrition security frameworks. The Indian Council of Agricultural Research (ICAR), in collaboration with national and international partners, has developed and released several biofortified crop varieties enriched with iron, zinc and provitamin A. These include biofortified varieties of rice, wheat, maize, pearl millet and sorghum, which are widely grown and consumed across the country (ICAR, 2021) ^[11]. Iron- and zinc-rich pearl millet varieties, in particular, have shown promising results in improving dietary iron intake in rural populations (Rai *et al.*, 2016) ^[16].

Agronomic biofortification has also gained importance in India due to widespread micronutrient deficiencies in agricultural soils, especially zinc-deficient soils affecting cereal productivity and grain quality. Soil and foliar application of zinc and iron fertilizers has been shown to enhance both crop yield and micronutrient concentration in grains, offering a dual benefit for farmers and consumers (Cakmak, 2008; Alloway, 2009) ^[6, 2]. These practices are increasingly being promoted through extension programs and integrated nutrient management strategies.

Biofortification in India is further supported by its alignment with national nutrition and development initiatives such as the National Nutrition Mission (Poshan Abhiyaan), the Public Distribution System (PDS), the Mid-Day Meal Scheme and the Integrated Child Development Services (ICDS). Incorporating biofortified staples into these large-scale food-based programs has the potential to significantly improve micronutrient intake among vulnerable populations,

particularly children and women (NITI Aayog, 2021; Bouis & Saltzman, 2017) ^[15, 5].

Despite these advancements, challenges remain in scaling biofortification across diverse agro-ecological zones and socio-economic contexts in India. Limited awareness among farmers and consumers, constraints in seed multiplication and distribution and the need for robust monitoring and evaluation systems continue to affect adoption rates. Addressing these challenges will require coordinated efforts among research institutions, policymakers, extension agencies and the private sector to mainstream biofortified crops into India's agricultural and food systems.

Biofortification holds substantial promise in the Indian context as a sustainable and inclusive strategy to address micronutrient malnutrition. By leveraging India's strong agricultural research infrastructure and extensive food distribution networks, biofortification can play a pivotal role in improving national nutritional security and achieving long-term public health goals.

9. Future Prospects and Research Needs

The future of biofortification lies in its ability to evolve as a science-driven, policy-supported and farmer-adopted intervention that effectively addresses emerging nutritional and environmental challenges. While significant progress has been achieved, expanding the scope and impact of biofortification will require continued research, technological innovation and systemic integration across agriculture, nutrition and public health sectors.

One of the important future prospects of biofortification is the development of multi-nutrient biofortified crops. Most existing varieties focus on enhancing a single micronutrient, whereas deficiencies often coexist in vulnerable populations. Advances in plant breeding, genomics and molecular biology offer opportunities to simultaneously enhance multiple nutrients such as iron, zinc and provitamin A within a single crop without compromising yield or agronomic performance (Kumar *et al.*, 2023; Singh *et al.*, 2021) ^[4, 19]. Such multi-nutrient crops could provide broader nutritional benefits and greater public health impact.

Emerging tools such as marker-assisted selection, genomic selection and gene editing technologies, including CRISPR/Cas systems, hold substantial promise for accelerating biofortification efforts. These approaches enable precise manipulation of genes involved in nutrient uptake, transport and storage, thereby improving efficiency and reducing the time required to develop biofortified varieties (Zhu *et al.*, 2013; Garg *et al.*, 2018) ^[23, 8]. Importantly, gene-editing approaches may overcome some regulatory and public acceptance challenges associated with transgenic crops.

Another critical research need lies in improving nutrient bioavailability. Future biofortification strategies must not only focus on increasing micronutrient concentration but also on reducing anti-nutritional factors such as phytates and enhancing synergistic compounds that promote absorption. Integrating biofortification with food processing techniques, dietary diversification and nutrition education will further enhance its effectiveness at the population level (Hurrell & Egli, 2010; Gibson & Ferguson, 2008) ^[10, 9].

The role of soil health and microbial interactions represents an emerging frontier in biofortification research. Greater emphasis on microbial-assisted biofortification using beneficial rhizobacteria and mycorrhizal fungi can improve

nutrient solubilization, uptake and plant resilience, while aligning biofortification with sustainable and organic farming systems (Singh *et al.*, 2021) ^[19]. Long-term studies are needed to assess the stability and scalability of such approaches under diverse agro-ecological conditions.

From a policy and implementation perspective, future efforts should focus on mainstreaming biofortified crops into national food systems. Strengthening seed systems, enhancing farmer awareness and ensuring market incentives for biofortified produce are critical for widespread adoption. Additionally, integrating biofortified crops into public nutrition programs, such as school feeding and food distribution schemes, can significantly amplify their impact (Bouis & Saltzman, 2017; NITI Aayog, 2021) ^[5, 15].

Robust monitoring and impact assessment frameworks are essential to evaluate the long-term nutritional, economic and environmental outcomes of biofortification interventions. Interdisciplinary research linking agriculture, nutrition and health indicators will help generate evidence needed to guide policy decisions and scale successful models.

The future success of biofortification depends on continuous innovation, supportive policies and coordinated action across sectors. By addressing existing research gaps and embracing emerging technologies, biofortification can play a central role in building resilient, nutrition-sensitive and sustainable food systems for the future.

10. Conclusion

Biofortification is a sustainable and agriculture-based strategy to combat micronutrient malnutrition and hidden hunger. It improves the nutritional quality of staple crops that are widely consumed by vulnerable populations. Unlike supplementation and industrial fortification, biofortification offers long-term benefits with minimal recurring costs. Biofortified crops contribute to improved intake of essential nutrients such as iron, zinc and vitamin A. The approach also enhances crop productivity, nutrient use efficiency and resilience to environmental stresses. In countries like India, biofortification aligns well with national nutrition and food security programs. Advances in breeding, biotechnology and microbial interventions further strengthen its potential. However, challenges related to bioavailability, adoption and awareness must be addressed. Strong policy support and farmer participation are crucial for scaling biofortification efforts. Overall, biofortification represents a key pathway toward sustainable food and nutritional security.

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