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BIOFORTIFIED CROPS IN INDIA: A SUSTAINABLE STRATEGY TO COMBAT HIDDEN HUNGER AND ENHANCE NUTRITIONAL SECURITY

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ABSTRACT

Despite significant strides in food-grain production and calorie availability in India, hidden hunger continues to be a serious nutritional and public-health problem. Iron, zinc, vitamin A, folate, calcium and other micronutrient deficiencies are ongoing and continue to impact children and adolescents, women, rural communities, tribal communities and socio-economically disadvantaged populations. Biofortification has proven to be a sustainable nutrition-sensitive and agriculture-based approach to enhance the nutrient quality of staple food crops. Biofortification increases the nutrient content, retention and bioavailability of edible parts of crops before they are harvested, and is different from supplementation and industrial food fortification, which add nutrients to or remove them from food products after harvest. This review covers the possibilities of biofortified crops for hidden hunger and the nutritional security in India. It covers the main methods such as conventional breeding, agronomic biofortification, molecular breeding, transgenic approaches, genome editing, microbial biofortification and strategies to mitigate anti-nutritional factors. It also reviews the current status of the biofortified agricultural, horticultural, tuber and underutilized crop varieties in India with focus on rice, wheat, maize, pearl millet, pulses, oilseeds, vegetables, fruits and tubers. Policy framework and government support in the form of ICAR based research, strengthening of seed system, extension services, POSHAN Abhiyaan, Anemia Mukt Bharat, PM POSHAN, ICDS and potential public distribution system are also highlighted in the review. India can make biofortification a major component of its agri-food system by improving seed systems, establishing public procurement systems, labelling, value addition and impact assessment.

KEYWORDS: Biofortification; Hidden hunger; Nutritional security; Micronutrient malnutrition; India

1. INTRODUCTION

Despite significant strides in increasing food-grain production and calorie availability in India, hidden hunger has continued to be one of the most entrenched nutrition issues in the country. It is a lack of micronutrients in a diet, where intake is sufficient to cover energy needs but not sufficient to allow for adequate growth, immunity, cognition, reproduction and productivity. Iron, zinc, folic acid, Vitamin A and other micronutrient deficiencies persist among children, adolescent girls, pregnant women, women of reproductive age, socio-economically vulnerable communities, rural communities and tribal communities in India. The situation indicates that food security should not be restricted to just ‘food coverage’ (staple grain) but should also cover ‘food quality' (nutrient density and equity of access to micronutrient rich foods).

India has implemented a number of nutrition-specific interventions to tackle micronutrient malnutrition. Iron and folic acid supplementations are still the mainstay of anemia control in Anemia Mukt Bharat. Although supplementation coverage has improved in 2017-2020, there are indications that coverage remains suboptimal, and that efforts to deliver, adhere, monitor and improve equity within states and population groups require strengthening (Joe et al., 2022). The introduction of POSHAN Abhiyaan and POSHAN 2.0 has led to better nutrition governance through convergence, life-cycle interventions, community participation, behavioural change communication and use of technology for monitoring (Vir, 2023). The effect of these programmes relies on continuous implementation and uptake of the programmes by households. Barriers to supplementation in vulnerable communities can include inconsistent availability, adherence, and awareness, as well as inconsistent service delivery.

Food fortification has become an important public-health tool in India. Fortification of staples (rice, wheat flour, edible oil, milk and salt) will contribute to the micronutrient availability at the population level, provided there is regulation, quality assurance and effective distribution. Thakur et al. (2023) have highlighted the role of fortification in reduction of malnutrition, if it is coupled with food-safety standards and public delivery system. But, industrial fortification requires processing facilities, industrial supply chains and access to fortified products by consumers. This situation may not apply to households who are buying and consuming locally produced, minimally processed food. Thus complementary agriculture based practices that enhance the intrinsic nutritional quality of crops before reaching the food system are needed in India.

In this context, biofortification has proven to be a potentially effective nutrition-oriented agricultural intervention. It means improving nutrient levels or availability in the edible parts of plants by conventional breeding, agronomic management, molecular breeding, transgenic or genome editing and microbial manipulation. Biofortification is the process of strengthening the crop itself before harvest, as compared to the industrial fortification process, which strengthens the food after harvest. After nutrient-rich varieties are introduced, multiplied and adopted by farmers, they have the potential to deliver ongoing nutrition benefits through local seed systems and household nutrition. Biofortified varieties are defined as a sustainable approach to address malnutrition due to their agricultural productivity and nutritional value by Yadava et al. (2017). The use of this approach is particularly applicable in India, where rice, wheat, maize, millets, pulses, tubers and horticultural crops form the staple food of the region.

Recent research indicates biofortification is progressing from the science to the practice. Efforts for dissemination, acceptance and consumption of biofortified varieties will lead to better human nutrition, if plant breeding and adoption is done well, (Kumar et al., 2023). Rice biofortification is significant especially for the large population in the Indian subcontinent relying on rice as a staple food. Sanjeeva Rao et al. (2020) conducted a review of the status of zinc-biofortified rice in India and found that although there had been some progress in breeding and rice varietal development, its dissemination, performance and adoption had been problematic. Jaldhani et al. (2025) also demonstrated that biofortification of rice has progressed further in India with respect to research, adoption potential and policy relevance, but the potential for nutritional impact on a large scale will rely on the availability of seeds, farmer participation and consumer acceptance.

Biofortification needs to also be linked to climate-resilient agriculture. Food production and nutritional values are vulnerable to climate variability, heat stress, drought, salinity, pests and soil degradation. Nutrient-rich varieties will only be grown if they offer yield stability, resistance to stress, and resistance to disease and/or desirable cooking or processing qualities. Yadava et al. (2025) highlighted the need for mainstreaming of climate smart crop varieties for enhanced yield and minimisation of risk for farmers. Likewise, biofortified and salt-tolerant sweet potato, taro and other tropical tubers could help provide nutrition security in less resilient environments where staple food crops are less reliable (Mukherjee, 2025).

Although there are potential benefits to biofortification, it is plagued with scientific and institutional obstacles. Karki et al. (2025) highlighted that the technological feasibility, sustainability, acceptance and effective delivery are biobased fortification approaches that need attention. With biofortified crops, important considerations are nutrient bioavailability, cooking losses, genotype-environment interactions, seed-system capacity, consumer awareness and market incentives and evidence of health outcomes. Biofortification should not be offered as a standalone solution, therefore. It should be used in addition to supplementation, food fortification, dietary diversification, sanitation, women's education and equitable food access.

2. Biofortification and Nutritional Security

Biofortification, which is a nutrition-sensitive approach in agriculture, refers to increase in the concentration, retention and bioavailability of essential nutrients in the edible parts of crops. Biofortification is different from supplementation, which involves producing foods with added nutrients in tablet, capsule or syrup form, and industrial food fortification, which involves fortification during food processing, as it enhances the nutritional value of the crop in the field before harvest. Therefore, it is particularly useful in communities that rely on highly processed staple foods, which are produced in-house and used in their diets. Biofortification can help increase the nutrient profile of regionally accepted foods, such as cereals, millets, pulses, tubers, fruits and vegetables, which are staples in the local diet in India, and therefore, help to enhance the nutritional security.

The main importance of biofortification is that it provides a link between agricultural productivity and public-health nutrition. Nutritional security goes beyond just having enough food available, it also means having access to food that supplies enough micronutrients for growth, immunity for better functioning, cognition or thinking, reproductive health and productivity. Biofortified crops can help achieve this by boosting the nutritional content of crops, including the iron, zinc, provitamin A, protein quality components, and essential amino acids. Since biofortification is targeting staple food crops that are eaten on a daily basis by the nutritionally vulnerable, it has tremendous potential to combat human malnutrition in developing countries, as noted by Kiran et al. (2022). Likewise, Dhaliwal and others (2022) defined biofortification as a “frontier” practice to enhance field crops with micronutrients and solve nutrition-security issues using agricultural methods.

Biofortification also plays an important role as it will offer a sustainable, recurring source of nutrients after the creation, release and uptake of improved varieties. Biofortified varieties can be incorporated into the seed system and grown in different seasons as opposed to supplementation programmes, which need to be procured and distributed on an ad hoc basis. But nutrient traits need to be integrated into the breeding program for a specific cultivar and not used as a single breeding target, if the traits are to be successful. Virk et al. (2021) suggested that biofortification should move from being based on targeted breeding projects and become part of more mainstream breeding pipelines in order to achieve combined breeding for nutritional traits with yield potential, disease resistance, climate resilience, grain quality and farmer preferred traits.

The nutrition impact of biofortification is a cascade of interrelated pathways. Development and release of improved varieties, dissemination via seed systems, acceptance by farmers, consumers and processors, retention during processing and cooking and assimilation and utilization by the human body are all prerequisites for improved varieties to be effective. Taking note of multiple impact pathways of biofortified foods, Huey et al. (2022) pointed out that biofortified foods impact nutrition at the production, market access, household consumption, nutrient retention and biological utilization levels. Consequently, one has to consider more than the nutrient content of raw grain or produce when assessing biofortification. Its true impact on nutrition security will only be realized if the biofortified food is available, affordable, accepted, and eaten on a regular basis, and provided to deliver the bioavailable nutrients.

In biofortification, bioavailability is an important scientific factor to take into account. Crops could be enriched with increased levels of iron or zinc but the nutrients would need to be stable on storage, processing and cooking and should be bioavailable following ingestion. Sometimes, the absorption of minerals is reduced in cereal- and pulse-based diets due to anti-nutritional factors, such as phytates. The amount of nutrients in crops is also affected by the agronomic situation. Biofortification in agronomic approach by incorporating the minerals into soil, foliar application, seed priming and nutrient management has the potential to enhance mineral levels in food crops, however, these effects are dependent on the genotype of the crop, fertility of soil, nutrient mobility, environmental conditions, and management practices (Bhardwaj et al., 2022). Therefore, the issues of crop biology and food-use need to be addressed in biofortification.

So far, from a public health point of view, it has been seen that when the biofortification implementation systems are robust, evidence shows that it can be used to support improved nutrition. Ofori et al. (2022) found that biofortification can be a part of the nutrition improvement, but that results will depend on the extent of adoption and consumption, nutrient bioavailability and programme design. The finding is pertinent in the Indian context where the dietary habits, agro climatic variations as well as the socio-economic differences necessitate biofortification in a region specific way. Biofortification of cereals (Rice and Wheat), dryland and tribal food systems (Millet), local food systems (Horticulture or tubers) with high dietary diversity of fruits, vegetables and tubers, and pulse biofortification in vegetarian diets may be relevant.

3. METHODOLOGIES OF BIOFORTIFICATION

Biofortification can be done by complementary breeding, agronomic, biotechnological and microbial methods leading to higher level of nutrients in edible parts of crops, nutrient retention, and nutrient bioavailability. The choice of an appropriate method depends on the crop, nutrient to be targeted, the level of the available genetic variability, soil conditions, cost, regulatory conditions and scale of adoption. Biofortification has been defined as a multi-disciplinary approach focusing on the improvement of crops, nutritional management, molecular biology, and planning for food systems to increase the nutritive value of crops while retaining yield and acceptability (Srivastav et al., 2022).

The most popular and accepted method is conventional breeding. It includes the selection of naturally rich micronutrient germplasm and hybridization of superior donors with high-yielding locally adapted cultivars. Over time, breeders can create iron, zinc, provitamin A, protein quality, and/or antioxidant-rich varieties by repeated selections without the use of foreign genes. This is a relatively low cost approach, which is scalable and acceptable to farmers and consumers. It is however dependent on the presence of natural variation and may take multiple generations. For wheat, donor identification and introgression and combination of mineral density with yield, grain quality and disease resistance have been the main approaches used for biofortification (Gupta et al., 2024). There are four main strategies to develop biofortified crops, as outlined in Figure 1: breeding-based, agronomic, molecular, biotechnological and microbial.

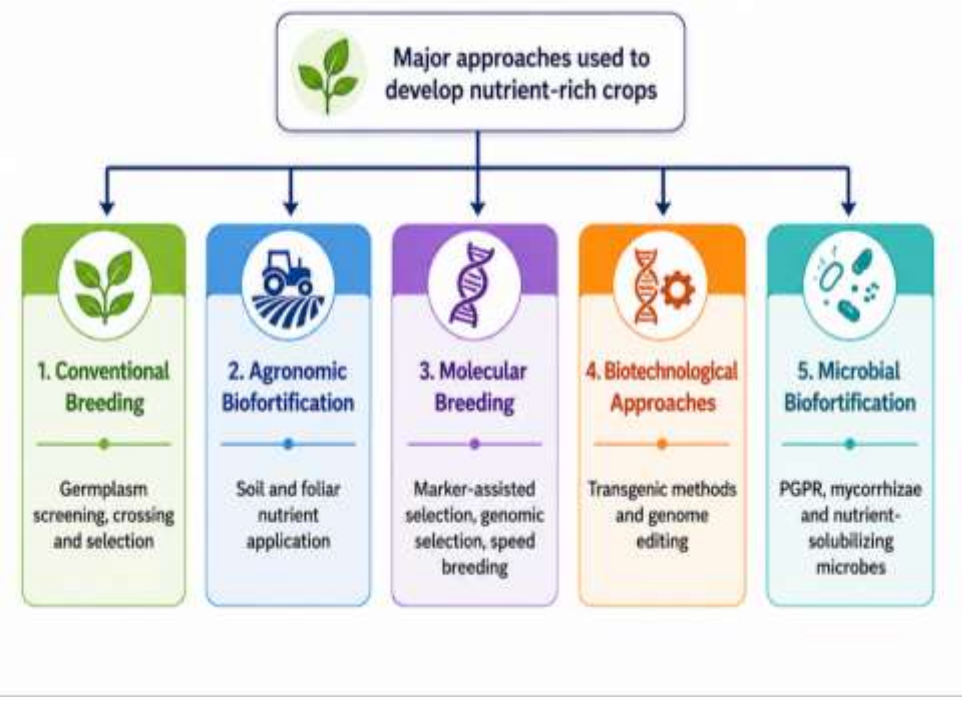

Figure 1. Strategic Approaches for Developing Biofortified Crops

Agronomic biofortification is the enhancement of nutrients using external nutrient management. It contains; soil application, foliar spray, fertigation, seed priming and use of mineral fertilizers, organic amendments or nutrient inputs integrated. This method is especially effective for those nutrients which tend to be deficient in the soil, such as zinc, iron, selenium and iodine. Jaiswal et al. (2022) reported that mineral biofortification can be a tool to sustain agriculture and human health in a way, if nutrient application can be synchronized to the requirement of the crop and soil chemistry and environmental factors. Agronomic approaches are likely to provide faster results than breeding, but effectiveness depends on the genotype(s), soil pH, moisture, and the type of fertilizer and capability of farmers to apply inputs repeatedly.

Using molecular breeding, the speed and accuracy of nutrient improvement is enhanced. Marker assisted selection can be used to monitor genomic regions linked to nutrient deposition and genome wide markers can be used to predict breeding value for complex traits (genomic selection). Speed breeding can reduce the length of generation cycles and speed up the development of the nutrient rich cultivars. When traits of nutrition need to be integrated with yield stability, resistance to stress and cooking quality and adaptation to region, these tools are helpful. They do need high sophistication in infrastructure, manpower and training, stable phenotyping and good breeding pipelines (Sheoran et al., 2022).

When desirable traits are not present, or can only be found, in the natural gene pool, transgenic and genome-editing techniques offer further possibilities. Transgenic biofortification can be used to incorporate genes related to nutrient biosynthesis, transport or storage, while genome editing can be used to precisely modify native genes associated with nutrient accumulation, metabolic pathways and/or anti-nutritional factors. Advanced biotechnological methods that involve modulation of the nutrient-homeostasis pathways can be used to improve the micronutrient content (Banerjee et al., 2023). These methods can enhance provitamin A, iron, zinc, folate, calcium or amino acid level, however, they must be determined as biosafe, regulated, and accepted by the public and address intellectual-property issues.

Microbial biofortification is a novel pathway that is relevant to the environment. The use of plant growth promoting rhizobacteria, mycorrhizal fungi and nutrient solubilizing microbes can enhance mineral mobilization, mineral uptake by roots, plant growth and mineral accumulation. These biological methods could lower reliance on synthetic fertilizers and promote low-input farming, but they will yield different outcomes on different soils, under different climates and with different crop varieties or cultivars (Jaiswal et al., 2022).

Finally, bioavailability and nutrient retention have to be considered for biofortification. More nutrients are not enough if nutrients are destroyed during milling, cooking or storage, or if anti-nutrient factors (e.g., phytates) interfere with nutrient absorption. Methods of reducing the phytate content, increasing the ability to chelate minerals and increasing the stability of minerals in the diet can complement the dietary strategy. Srivastav et al. (2022) stressed the importance of future biofortification to consider the technological feasibility, nutrition effectiveness and adoption barriers. In general, none of the methods are consistently better. It is conventional breeding that provides “acceptance” and “scale”, agronomic approaches that provide the flexibility, molecular tools that provide speed, precision through biotechnology and sustainability through microbial approaches. So, the concept of integrated biofortification is crucial for developing productive, affordable, acceptable and nutritionally effective crops. For India, the integration is particularly crucial because crops have to meet the nutritional requirements, farming preferences, and regional diets and various agroecological requirements.

4. Biofortified Agricultural Crop Varieties

Biofortified crops have emerged as a key element of India's nutrition-sensitive crop improvement program. They display unique development characteristics that have evolved from yield-centric breeding to varieties with the ability to be more productive, resilient and nutritious for climate change. In India, the major biofortification initiatives have been on rice, wheat, maize, pearl millet, sorghum, small millets, pulses and oilseeds due to their cultivation and consumption in various agroecological zones. Garg et al. (2018) highlighted that biofortified crops developed through breeding, agronomy and transgenic technologies are already having an impact on nutrition around the world, and have potential relevance for India, where staple based diets are prevalent.

The enrichment of zinc and iron in rice and wheat is important for India's food security and has been the focus of significant attention. The particular focus of biofortification has been on grain zinc and iron, with no compromise in yield, grain quality and adaptation to regional production systems. Roy et al. (2022) underlined the importance of the genomic tools for enhancing the zinc and iron levels in wheat such as molecular markers, Genome-Wide Association Studies (GWAS) and Genomic Selection (GW) selection. These tools can be valuable in promoting the development of nutrient rich cultivars that do not sacrifice agronomic traits. Rice biofortification also holds significant promise on the regional level, as rice is a staple food in eastern, southern and north-eastern India, and may be combined with a zinc deficient diet.

Quality protein maize and provitamin A enrichment are the biofortification areas that have been targeted with maize. QPM is a quality protein maize with a higher level of lysine and tryptophan, thus providing benefits for protein quality, and provitamin A maize can help address the vitamin A deficiency of maize consumers. Another success story is pearl millet, which is especially highlighted for iron and zinc enrichment. Iron-rich and zinc-rich pearl millet varieties can contribute to climate resilience and nutrition, as pearl millet is grown in dryland and semi-arid areas. Sorghum and small millets also present opportunities because they are naturally good sources of minerals, drought-tolerant and adaptable to marginal farming systems. VijayaKumar et al. (2025) pointed out that biofortification is a sustainable solution to micronutrient malnutrition in South Asia, particularly if nutrient-rich crops are integrated into the local diets and agricultural practices. Table 1 gives an overview of the current status and relevance of important groups of biofortified crops in India.

Table 1. Biofortified agricultural crop groups in India

Crop group	Major crops	Target traits	Key institutions	Current status and relevance

Cereals	Rice, wheat	Zinc, iron, protein, mineral density	ICAR, SAUs, AICRPs, HarvestPlus, CGIAR	Major staples; useful for improving micronutrient intake in cereal-dependent populations
Maize	Quality protein maize, provitamin A maize	Lysine, tryptophan, protein quality, provitamin A	ICAR, SAUs, maize research networks	Supports protein-quality improvement and vitamin A intake in maize-consuming regions
Millets	Pearl millet, sorghum, small millets	Iron, zinc, calcium, fibre, antioxidants	ICAR, ICRISAT, SAUs, AICRPs	Important for dryland, tribal and climate-vulnerable regions due to nutrient density and stress tolerance
Pulses and /oilseeds	Chickpea, lentil, pigeon pea, mungbean, groundnut, mustard, soybean	Protein, iron, zinc, folate, mineral density, fatty acid quality	ICAR, pulse/oilseed institutes, SAUs, AICRPs	Supports vegetarian diets, protein-micronutrient intake and dietary diversification
Climate-resilient crops	Cereals, millets, pulses, oilseeds	Nutrient density with drought, heat and disease tolerance	ICAR, SAUs, CGIAR, AICRPs	Combines biofortification with yield stability and climate resilience
Deployment systems	Released and pipeline varieties	Stable nutrient expression and farmer-preferred traits	ICAR, KVKs, seed agencies, FPOs	Adoption depends on seed supply, demonstrations, market linkages and consumer awareness

Note: ICAR = Indian Council of Agricultural Research; SAUs = State Agricultural Universities; AICRPs = All India Coordinated Research Projects; CGIAR = Consultative Group on International Agricultural Research; KVKs = Krishi Vigyan Kendras; FPOs = Farmer Producer Organizations.

In India, the pulses and oilseeds are also significant in the context of biofortification. Protein, iron, zinc and folate can be added to mostly vegetarian diets through pulse foods like chickpea, lentil, pigeon pea and mungbean. The minerals, fatty acids and other nutritional characteristics will depend on the crop type and breeding goal. According to Jaiswal et al. (2022), mineral biofortification can be a tool to foster sustainable farming and help combat malnutrition, in conjunction with soil fertility management and crop-specific approaches. Therefore it is important to consider biofortified pulses and oilseeds as part of a diverse nutrition security portfolio, not a secondary crop.

Support from institutions has played a key role in the success of biofortified agricultural varieties in India. ICAR, State Agricultural Universities, All India Coordinated Research Projects, Harvest Plus and CGIAR networks have made contributions in terms of germplasm evaluation, breeding, multi-location testing, varietal release, multiplication and extension. The advanced biotechnological approaches can further enhance micronutrient enhancement through better nutrient uptake, transport, storage and metabolic pathways, as demonstrated by Banerjee et al. (2023). Azeem et al. (2025) also highlighted the need for a combined approach of conventional breeding, agronomy, molecular tools, and policy support for sustainable biofortification in the future.

The situation of biofortified agricultural crops in India is encouraging though deployment is not uniform. Scale is critical for seed multiplication, regional adaptation, consumer awareness, acceptance and market demand. Biofortified crops, which are enriched with nutritional value, are particularly critical as they need to be able to cope with changing rainfall, heat, salinity, and pests. Thus future efforts in India should incorporate nutrient traits into the regular breeding programmes, with an added focus on biofortified varieties that are productive, localized, affordable and accepted by farmers and consumers. Greater integration with public procurement, school feeding and nutrition-sensitive extension and farmer producer groups will help enhance adoption. Similarly, participatory varietal selection can guarantee grain colour, taste, cooking quality, duration of maturity and local market preference are taken into account. If not so implemented, then such nutrition benefits that can happen in the breeding programme may not be reflected in the nutrition level of the household at the community level, in the vulnerable Indian communities, in the long run.

5. Biofortified Horticultural Crop Varieties

For India, biofortified horticultural, tuber and underutilized crops are emerging as critical crops in the future for nutritional security as it cannot be relied on solely from the cereals. Vitamins, minerals, antioxidants, dietary fibre and bioactive components are often missing or limited in staple-based diets, and these are abundant in fruits, vegetables, roots and tubers and indigenous crops. Although most initiatives in India on biofortification have traditionally involved rice, wheat, maize and pearl millet, the same logic of nutrition sensitivity applies to sweet potato, potato, greater yam, pomegranate, vegetables, fruits and underutilized species adapted to the local environment in India. These crops can enhance dietary diversity and household nutrition, particularly in areas of the country that lack access to markets for diversified products. Orange-fleshed sweet potato varieties have a high provitamin A carotenoid content while purple-fleshed varieties are high in anthocyanins and antioxidants, making them one of the most promising biofortified tuber crops. Valuable sweet potato varieties are available that can tolerate salt and are adapted to the particular region, and can be useful in regions under stress, in kitchen gardens and nutrition gardens. Potato biofortification is also applicable as coloured-flesh potato can provide anthocyanins, phenolics and antioxidant activity, and mineral enhanced potato can provide micronutrient intake. Greater yam and other tropical tubers are of high significance in tribal and rain-fed areas due to their adaptability and ability to supply energy and minerals like calcium and iron to the local population. The crops are particularly beneficial in situations where food security demands climate resilience, low input farming and culturally appropriate foods. They summarise the nutritional benefits that can be obtained from biofortified horticultural, tuber and underutilized crops which include provitamin A, vitamin C, iron, calcium, anthocyanins, antioxidants, dietary fibre, and other bioactive compounds which play a role in nutritional security.

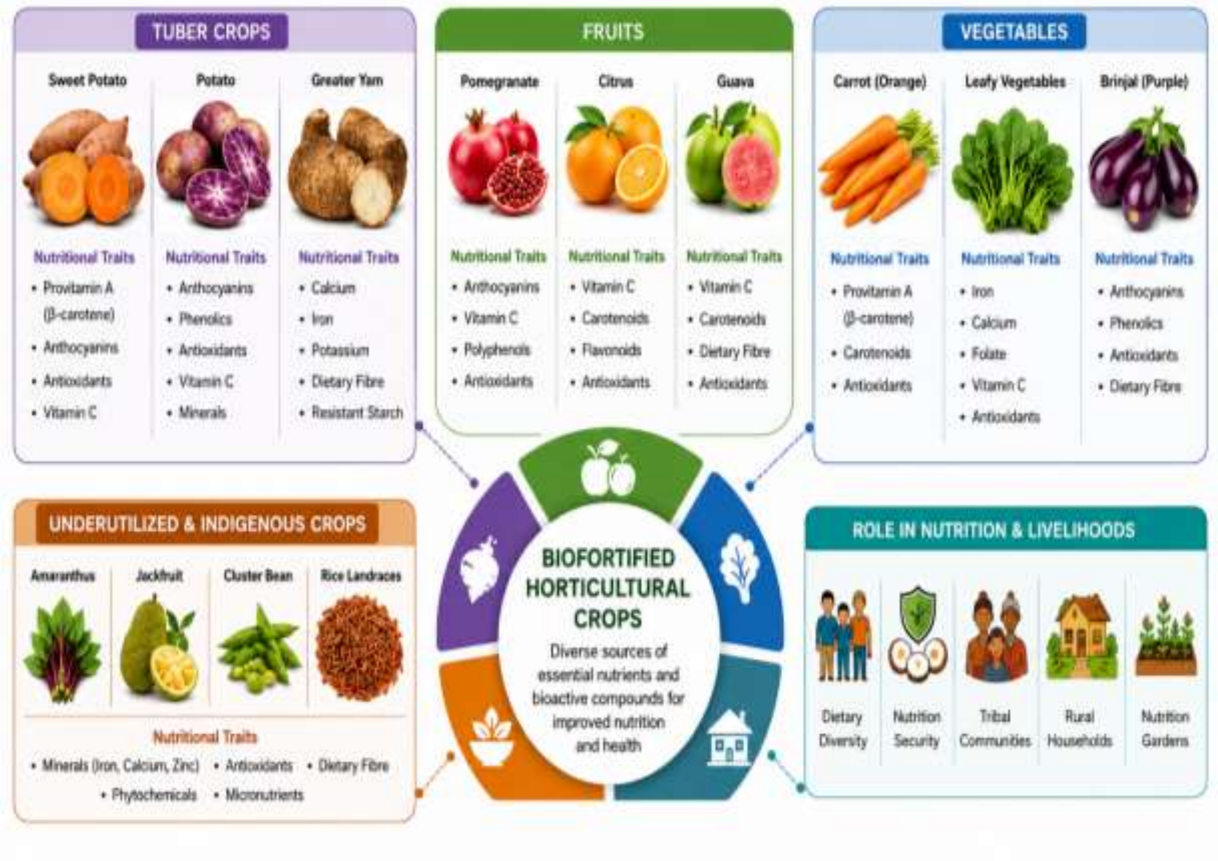

Figure 2. Biofortified Horticultural, Tuber and Underutilized Crops for Nutritional Security

Other biofortified horticultural crops contain fruits/vegetables with higher vitamin C, Anthocyanins, carotenoids, calcium, iron and other phytochemicals. Pomegranates rich in anthocyanin and ascorbic acid could provide antioxidant rich fruits, while the nutrient-rich vegetables can help to enhance micronutrient availability in the diets of people. Another category of less utilized indigenous crops are also relevant as the crops have natural nutrient density, stress resistance and local acceptability. The study by Longvah et al. (2022) demonstrated that rice landraces from Northeast India have a rich nutrient diversity and nutritional potential supporting the potential of exploring local genetic resources for nutritional enhancement. This is for rice but can be used for indigenous fruits and vegetables, underutilized tubers and minor crops.

Agricultural biofortification can provide lessons that will benefit the development of biofortified horticultural crops and biofortified tubers. ICAR's biofortified variety programme highlighted the importance of using nutrient-rich varieties as a sustainable approach to tackling malnutrition (Yadava et al., 2017). Biofortification has been used to improve provitamin A, lysine and tryptophan in maize, highlighting how biofortification can improve biofortification targets while maintaining agronomic traits (Gupta et al., 2015). Kaur (2018) also showed that carotenoid-pathway genes like crtRB1, LcyE could help to boost beta-carotene content in QPM.

By integrating nutrients with farmer and consumer demand, breeding biofortified varieties and hybrids can be beneficial for human nutrition and markets, as shown by Govindaraj et al. (2019). Therefore, agronomic biofortification was shown to enhance zinc and iron uptake in chickpea via nutrient application, implying that there is also a potential for nutrient management of horticultural crops. Thus, the importance of nutrient management in horticultural crops cannot be neglected, as Pal et al. (2019) found that this also has potential to boost zinc and iron uptake in chickpea through agronomic biofortification. In the case of fruits, vegetables and tubers, crop response, soil fertility, post-harvest stability and cost also need to be taken into account in addition to the improvement of the mineral content by agronomic practices.

There are some challenges to practical implementation of horticultural biofortified crops even though they hold great promise. A significant number of fruits and vegetables are perishable and need be stored, processed, transported and supported by the value chain. Shelf life, cooking quality, taste, colour and household preparation are all aspects that must be addressed in tubers. Colour change is important as carotenoids or anthocyanins could affect preference and consumer acceptance is therefore critical.

6. Policy Frameworks and Government Support

Policy-instruments and government support play a key role in making biofortification a nutrition policy at the population level. Biofortification needs a coordinated effort between agricultural research, the seed system, extension systems, food procurement, public nutrition programmes and platforms for consumer awareness in India. Biofortification needs to not be restricted to the labs or trials in experimental settings, as it is an agricultural issue and also a public health problem. It needs to be incorporated into nutrition sensitive agriculture, sustainable food systems and national nutrition programmes. Results from agronomic biofortification studies argue that the micronutrient availability from biofortified staple food crops including cereals, rice, wheat and pulses is enhanced through nutrient management, production and delivery when used in combination (Prasad et al., 2014).

The scientific backbone of biofortification in India is the Indian Council of Agricultural Research, the State Agricultural Universities, and the All India Coordinated Research Projects with institutes specializing in research on various crops. These institutions are engaged in germplasm screening, identification of traits, breeding, multilocation testing, varietal release, production of breeder seed and technical validation. Their function is particularly critical since biofortified varieties need to be high-yielding, resilient to climate change and disease, have cooking and quality grain, and be suitable for their region. Rice biofortification is a good example of such an institutional route. Along with varietal development, dissemination of these seeds, farmer participation, potential for adoption and policy mechanisms play pivotal role in advancing the progress of rice biofortification in India (Jaldhani et al., 2025).

To ensure high scale adoption of biofortified crops, seed multiplication and distribution play an important role. Once a variety has been released, breeder seed should be multiplied to foundation and certified seed via public seed agencies, private seed companies, farmer producer organizations and community-based seed systems. Government sponsored programmes, like Seed Village Programme, can contribute to increase local availability of quality seed especially in rural, tribal and marginal farming areas. Good seed systems are necessary if biofortified varieties are not to be confined to research plots and demonstration fields.

Extension is also crucial to the acceptance of farmer practices. Biofortified varieties can be introduced to farmers through a farmer participatory varietal selection, Krishi Vigyan Kendras, participatory demonstrations and farmer field schools, training programmes. The most important aspect of a demonstration is that farmers tend to look at yield, maturity, pest resistance, grain quality/market demand before nutrition. Extension agencies should, therefore, broadcast the message of biofortification as a health intervention and at the same time as a farmer-relevant technology that can boost productivity, resilience and market opportunities.

Convergence with the public nutrition programmes can also be enhanced in the context of biofortification. Biofortified cereals, millets, pulses and horticultural crops can be tied up with POSHAN Abhiyaan, Anemia Mukt Bharat, PM POSHAN services, ICDS services, Anganwadi services, National Food Security and Nutrition Mission and, if possible, Public Distribution System. This convergence can help to build a stable demand, as well as direct nutrient-rich food to children, women, and adolescents, and other nutritionally vulnerable groups. A series of foliar-application studies on wheat, rice and common bean in various countries demonstrate that biofortification can be implemented at the production level, and that its nutritional effects will be dependent on adoption, delivery and consumption system (Ram et al., 2016). Likewise, there is a need for coordination between the recommendations of fertilizer applications, crop management, farmer incentives, and food systems planning to implement cereal biofortification with zinc (Çakmak & Kutman, 2018).

Biofortified crops must also be procured, certified, labelled and have quality standards to be mainstreamed. Both certification and labelling can help to ensure consumer recognition and trust, as well as protection of varietal identity and nutrient claims. Market assurance for farmers can be offered by public procurement in schools, community nutrition programmes and local institutions. Farmer producer organisations, self-help groups and public private partnerships can provide support for aggregation, processing, branding and value addition, and local market linkages. While highlighting the potential of agronomic biofortification for achieving global nutrition security, Bhardwaj et al. (2022) pointed out that it would require a marriage of convenience with sustainable agriculture and institutional support.

7. Challenges and Future Prospects

Several scientific, agronomic, institutional and market-related challenges need to be overcome to scale-out the use of biofortified crops in India. Biofortification holds great promise for combating hidden hunger; however, this will rely on the ability to transfer nutrient-rich varieties from research systems to markets and farmers' fields and on to their household diets. This is one of the major challenges which is limited awareness to farmers, extension workers and consumers. Farmers generally face a choice between producing high-yielding crops, keeping crops for an extended period, resisting attacks from pests, earning a higher price for their grain or produce and providing nutrients (iron and zinc) that are invisible. Biofortified varieties may not be widely adopted without the support of strong extension and field demonstration activities, even if they are nutrition improved.

Another critical issue is the availability of weak seed. Many biofortified varieties have not yet been widely adopted due to lack of quality seed at the right time, in quantity and/or through trusted local supply lines. Seed multiplication, then, is of crucial importance for seed distribution, including access to the last mile. Other barriers to scaling up are suboptimal extension systems, especially in rainfed, tribal and marginal areas where biofortified crops may be of great nutritional importance. Farmer training and participatory varietal selection and local demonstrations are required to demonstrate that biofortified crops can be nutrient dense, high-yielding, and agronomically suitable.

The market also lacks price certainty and incentives for farmers to participate. Many micronutrient traits are not apparent to consumers; therefore, biofortified produce would not likely fetch premium prices without the backing of certification, labelling, branding and procurement systems. But consumer acceptance is not to be neglected. Household adoption is high for taste, cooking quality, texture, colour, shelf-life and regional food preferences. Biofortified vegetables and tubers could be subject to further challenges due to their perishability, requiring storage, processing and market linkages. According to Consentino et al. (2023) agronomic biofortification is possible for vegetable crops, which can result in yield and functional value improvement, but the response of the crops and market acceptance will depend on nutrient source, dose, application method, crop species and production environment. In the same way, Thakur et al. (2022) highlighted that enhancements of the vitamins, minerals and quality traits of vegetables should be coupled with consumer acceptance and food-use quality. The major challenges and future strategies for scaling biofortified crops in India are summarised in Table 2, which include constraints in awareness amongst the farmers, seed availability, consumer acceptance, bioavailability, agronomic limitations and impact evidence for long-term.

Table 2. Challenges and future prospects for scaling biofortified crops in India

Key challenge	Implication for scaling	Future prospect/strategy
Limited farmer awareness and weak extension	Low adoption despite nutritional benefits	Frontline demonstrations, farmer training and participatory varietal selection
Poor seed availability	Biofortified varieties remain limited to small areas	Stronger breeder, foundation and certified seed systems with local seed networks
Lack of price incentives and market uncertainty	Farmers may prefer conventional varieties	Procurement support, branding, certification and market linkages
Consumer acceptance issues	Taste, colour, cooking quality and regional food habits may limit use	Consumer education, recipe development, labelling and awareness campaigns
Bioavailability and cooking losses	Higher nutrient content may not translate into health benefits	Studies on nutrient retention, bio accessibility, cooking methods and dietary interactions
Soil and agronomic constraints	Micronutrient uptake varies across soils and environments	Site-specific nutrient management, microbial biofortification and climate-resilient varieties
Regulatory and policy barriers	Slow deployment of transgenic or genome-edited crops	Clear biosafety guidelines, transparent regulation and public communication
Limited health-outcome evidence	Weak policy confidence and limited investment	Long-term impact evaluation on adoption, intake, bioavailability and nutritional outcomes

Some science issues are still to be addressed. The higher the nutrient level in edible parts of crops, the better the nutritional outcomes may not be. All of the above must be taken into consideration, as well as nutrient losses as a result of food processing, nutrient interactions and bioavailability. Anti-nutritional factors, like phytates, can decrease iron and zinc absorption in cereal and pulse foods. Accumulation of minerals is also influenced by soil constraints. Crop uptake of the micronutrients iron, zinc and others are influenced by soil pH, organic matter, moisture, activity of microorganisms and interactions between nutrients. Debnath et al. (2026) discussed a zinc–iron interaction dilemma in agronomic biofortification where increased biofortification of one mineral may impact the uptake or accumulation of another mineral. In the case of biofortified crops, transgenic and genome edited ones are particularly affected by regulatory and public acceptance barriers. Biosafety assessment, regulatory clarity, intellectual property management and public trust are required to deploy modern biotechnology to provide nutrition improvement, and they are possible to be accelerated. There are other gaps, such as long-term health-outcome evidence. While many studies demonstrate the increase in nutrient concentrations in crops, fewer studies assess the nutrient intake, bioaccessibility, absorption, cost-effectiveness and measurable health benefits of vulnerable populations.

However, the future of biofortification in India is bright, given these difficulties. Biofortified crops that are resilient to climate change can tackle the multiple challenges of food and agricultural insecurity in the face of drought, heat, salt, and new pest challenges. Access to good quality seed can be enhanced by strengthening seed systems, decentralising seed multiplication, farmer producer organisations and farmer communities' seed networks. Promising opportunities are also available for microbial biofortification. Nazma et al. (2025) have reported that plant–microbe interaction can be used to boost the solubilization of nutrients, uptake at the roots, and plant growth, which can enhance iron and zinc biofortification, but more field trials are needed under different agro-climatic conditions.

Going forward, there is a need for better labelling, nutrition and consumer education, public procurement, and linking the nutritional initiatives with nutrition programmes like school meals, ICDS, Anganwadi and community nutrition programmes. Biofortified millets and pulses, vegetable and tubers have the potential to enhance market and acceptability through value added products. Traceability to the digital level can ensure the maintenance of the identity of the variety of product, help monitor the distribution of seeds and provide nutrient information. Long-term impact evaluation should consider: Adoption, Consumption, Bioavailability, health outcomes and equity. With robust science, robust seed systems, incentives, and consumer trust, and nutrition sensitive policy integration, biofortification can become a viable approach towards nutritional security in India.

8. CONCLUSION

Biofortification is a nutrition-driven, agriculture-based approach to the nutrition security of India to tackle hidden hunger and is a sustainable approach. Despite significant strides in food-grain production, micronutrient deficiencies have become a public-health problem for children, women, adolescents, rural households, tribal communities and other vulnerable groups in India. Biofortification can help increase the nutrient concentration, nutrient retention and nutrient bioavailability of staple crops and, consequently, the quality of the nutrient intake without significant changes in food practices. Biofortified rice, wheat, maize, pearl millet, pulses, oilseeds, vegetables, fruits and tubers have the potential to enhance intake of micronutrients such as iron, zinc, provitamin A, protein quality components, calcium, antioxidants and other essential nutrients. The impact of biofortification, however, is realised in the farmers' fields, through the food markets and households following the field-to-farmers' field translation process. To achieve large-scale success, biofortification should be supported by a robust seed system, farmer training, extension services, consumer awareness, public procurement, labelling, certification, incentives and integration in nutrition programmes. Going forward, breeding efforts should focus on long term bioavailability testing, dietary consumption and health effects. Biofortification is not a magic bullet for malnutrition but rather a component of food systems which should be combined with other approaches to malnutrition including dietary diversification, supplements, food fortification, sanitation, education and improving access to food for all people. Biofortification can be a major part of India's nutrition sensitive agri-food system, if scientific, institutional and policy measures are coordinated and implemented.

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