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Biofortified Crops: A Sustainable Approach for Nutritional Security

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Abstract

Today the major global health concern especially in the developing countries where the dietary requirements are met from the staple crops deprived of nutrient diversity is the "hidden hunger" which is generally caused by micronutrient deficiencies. Millions of people are severely affected with health problems like anemia, impaired immunity and vision disorders due to the deficiencies of essential micronutrients such as iron, zinc, and vitamin A. Biofortification is the sustainable strategy for enhancing the nutritional quality of food crops through plant breeding, agronomic practices, and modern biotechnological approaches. Biofortification enrich the crops with higher concentrations of essential vitamins and minerals in their edible parts, without any major changes in food consumption patterns. Many biofortified varieties in crops like rice, wheat, pearl millet and sweet potato were developed to combat the micronutrient deficiencies among the rural populations who mainly rely on the staple crops for their dietary requirements.

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1. Introduction

Food security emphasizes on the availability of sufficient calories to meet the dietary needs of a growing population. However, it has become increasingly clear that food security alone does not guarantee nutritional security. Around 165 million people of the world population suffers from deficiencies of essential micronutrients such as iron, zinc, vitamin A, and iodine, even on the uptake of adequate quantities of staple foods (Chakravorty et al., 2023). With the widespread micronutrient deficiencies in soils, the high prevalence of undernutrition across various age groups, and the challenging socioeconomic conditions in India where 21.9% of the population lives below the poverty line, biofortification emerges as a cost-effective, sustainable, and highly efficient strategy to address nutritional insecurity both in India and globally (Kundu et al., 2025).

Hidden hunger poses serious health threat to billions of people, especially in developing countries. According to global nutrition reports, most of the micronutrient deficiencies are seen in women,

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children, and low-income populations. Iron deficiency leads to anemia, zinc deficiency affects immune function and growth, and vitamin A deficiency can cause vision problems and increased risk of infections. Hidden hunger can also lead to stunted growth, hindered cognitive abilities, weakened immunity, and increased susceptibility to degenerative and chronic illnesses (Ibeanu et al., 2020). In developing countries like India, the problem is significant because a large proportion of the population depends heavily on staple crops such as rice, wheat, and maize, which provide calories but often lack sufficient micronutrients. Certain traditional approaches such as diet diversification, supplementation, and food fortification can be adopted to address this issue, but these strategies may not always reach rural populations effectively (Ginkel et al., 2023).

In this context, biofortification serves as an innovative and sustainable agricultural approach to enhance the nutritional quality of food crops. Biofortification is the process through which the essential micronutrients in crop plants are enhanced through certain plant breeding, agronomic practices, or modern biotechnological methods which improves the nutritional value of crops during their growth, making it a long-term and cost-effective solution to combat hidden hunger.Biofortified crops have the potential to significantly improve the nutritional status of the staple crops which serve as primary diet to billions of populations especially in the developing countries. With advances in plant breeding and biotechnology, several biofortified crop varieties have already been developed and released for cultivation.

2. Concept of Biofortification

Biofortification refers to the process of increasing the density of vitamins and minerals in crops through plant breeding and modern agricultural technologies. The primary aim is to develop crop varieties that naturally contain higher levels of essential nutrients in their edible parts.Unlike conventional fortification, which focuses on post-harvest fortification where nutrients are added to food during processing, biofortification enhances the nutritional status at the genetic level of the plant. Once a biofortified variety is developed and adopted by farmers, it continues to maintain the enhanced nutrition season after season without any additional interventions.

This concept of biofortification holds good for developing countries where majority of the people rely heavily on staple crops and have limited access to diversified diets. By incorporating nutritional traits into commonly consumed crops, biofortification provides a significant means of improving dietary quality without much changes in eating habits.

3. Methods of Biofortification

There are three main approaches through which biofortification can be achieved: conventional plant breeding, agronomic biofortification, and genetic engineering.

3.1. Conventional plant breeding

Conventional plant breeding is one of the most widely used methods for developing biofortified crops. It captures the naturally occuring genetic variation for micronutrient content existing within crop species and utilizing it in the selective breeding techniques to develop varieties with improved nutrient levels. It involves selection of plants with desirable traits, crossing them and repetitive evaluations for subsequent generations. Such methods offer a way to increase micronutrient levels without compromising crop yield (Pandey et al., 2016).

Plant breeders identify the superior nutrient concentrations in the crop through screening of the germplasm which are then crossed with high-yielding varieties to combine desirable agronomic traits with higher nutritional quality. This method is highly accepted, environmentally safe, and sustainable and pose no problem with the public adoption. Once developed, biofortified varieties can be cultivated by farmers without requiring any special inputs.

3.2. Agronomic biofortification

Agronomic biofortification process involves the external application of micronutrient fertilizers to the soil or foliage to enhance the nutrient status of the crops. For example, applying zinc fertilizers in zinc-deficient soils can increase the zinc concentration in cereal grains. This method is relatively easy, simple and provides quick results. However, the application of fertilizers is required for every season the crop is cultivated which infact increases the production costs. Agronomic biofortification is a promising method for enhancing crop nutrition by manipulating soil composition (Zulfiqar et al., 2021).

3.3. Genetic engineering and biotechnology

To meet the food and nutritional needs of the ever-increasing population the conventional approaches may not be sufficient. To expedite the development of biofortified varieties suitable for future climates, leveraging recent advancements in omics approaches becomes pivotal (Varshney et al., 2021). Various biotechnological tools such as genetic engineering and gene editing are available to enhance nutrient content in crops through introduction or modification of specific genes that are responsible for nutrient synthesis and accumulation.One well-known example is Golden Rice, which has been genetically engineered to produce beta-carotene, a precursor of vitamin A. Although biotechnology offers great potential, its adoption depends on regulatory approvals and public acceptance.

Evaluating existing germplasm accessions to assess micronutrient concentrations and utilizing genome-wide association studies (GWAS) to pinpoint high-fidelity molecular markers aids in identifying quantitative trait loci (QTLs), candidate genes, or alleles which are responsible for the desired nutritional traits. Subsequently, these identified QTLs/genes could be introduced into elite cultivars through genomics-assisted breeding or transgene-based methods, thereby boosting grain micronutrient content (Chandra et al., 2020). The convergence of various omics disciplines, including genomics, transcriptomics, proteomics, metabolomics, and ionomics, plays a pivotal role in creating biofortified crops tailored for the demands of the future.

4. Role of Biofortification in Nutritional Security

Biofortified crops play a crucial role in improving nutritional security, particularly in developing countries that are deprived of essential nutrients in the staple foods. Nutritional security means ensuring that people have access not only to sufficient food but also to nutritious food for healthy living.

Biofortification contributes to nutritional security in several ways:

1. It improves the nutritional quality of staple foods that are already widely consumed. Since, people need not change their dietary habits and hence holds the same place in the daily diets.

2. Biofortification is a simple, cost-effective and sustainable solution (Dhaliwal et al., 2022). Once farmers adopt biofortified varieties, the nutritional benefits continue over generations without requiring special inputs.

3. Biofortified crops which do not require any special efforts to grow can reach remote and rural populations where other nutrition interventions may not be effective. Smallholder farmers can grow these crops similarly like the regular crops and consume them directly and safely, thereby improving household nutrition.

4. Biofortification supports maternal and child health by reducing the risk of micronutrient deficiencies. Improved intake of iron, zinc, and vitamin A can significantly enhance overall health outcomes especially in children and women.

5. Global and National Initiatives

Several international organizations and national research institutes are adopting and actively promoting biofortification as a sustainable strategy to combat hidden hunger. One of the most important global initiatives is HarvestPlus, an international program that focuses on developing and promoting biofortified crops. HarvestPlus works in collaboration with national agricultural research systems to develop nutrient-rich crop varieties and ensure their adoption by farmers.In India, the role played by institutions such as the Indian Council of Agricultural Research (ICAR) and agricultural universities in developing biofortified crop varieties is appreciable. Several zinc-rich rice varieties, iron-rich pearl millet varieties, and nutrient-enhanced wheat varieties have been released for cultivation.

Government programs aimed at improving nutrition and food security are also incorporating biofortified crops into their strategies. These efforts aim to integrate agriculture with nutrition policies to achieve sustainable development goals.

6. Achievements in Various crops in India

ICAR through coordinated efforts and collaboration, with various national and international initiatives, improved the nutritional quality in cereals, pulses, oilseeds, vegetables and fruits using breeding methods which has led to the development of 87 improved varieties i.e., rice (8), wheat (28), maize (14), pearl millet (9), finger millet (3), small millet (1), lentil (2), groundnut (2), linseed (1), mustard (6), soybean (5), cauliflower (1), potato (2), sweet potato (2), greater yam (2) and pomegranate (1) (Table 1, Devendra et al., 2022).

7. Challenges in Biofortification

Despite its significant potential, biofortification faces

Table 1: List of biofortified varieties in various crops in India (Devendra et al., 2022)

Crop	Name of the cultivar	Nutrient	Year of Release
Rice	CR Dhan 310	Protein 10.3%	2016
	DRR Dhan 45	Zinc 22.6ppm	2016
	DRR Dhan 48	Zinc 24.0ppm	2018
	DRR Dhan 49	Zinc 25.2ppm	2018
	Zinco Rice MS	Zinc 27.4ppm	2018
	CR Dhan 311	Protein 10.1% Zinc 20.1ppm	2018
	CR Dhan 315	Zinc 24.9ppm	2020
	CR Dhan 411	Protein 10.1%	2021
Wheat	WB 02	Iron 40.0ppm Zinc 42.0ppm	2017
	HPBW 01	Iron 40.0ppm Zinc 40.6ppm	2017
	Pusa Tejas (HI 8759)	Protein 12.0% Iron 41.1ppm Zinc 42.8ppm	2017
	Pusa Ujala (HI 1605)	Protein 13.0% Iron 43.0ppm	2017
	HD-3171	Zinc 47.1ppm	2017
	HI 8777	Iron 48.7ppm Zinc 43.6ppm	2018
	MACS 4028	Protein 14.7% Iron 46.1ppm Zinc 40.3ppm	2018
	PBW 752	Protein 12.4%	2018
	PBW 757	Zinc 42.3ppm	2018
	Karan Vandana (DBW 187)	Iron 43.1 ppm	2018 & 2020
	DBW 173	Protein 12.5% Iron 40.7 ppm	2018
	UAS 375	Protein 13.8%	2018
	DDW 47	Protein 12.7% Iron 40.1 ppm	2020
	PBW 771	Zinc 41.4ppm	2020
	HI 8802	Protein 13%	2020
	HI 8805	Protein 12.8% Iron 40.4 ppm	2020
	HD 3249	Iron 42.5 ppm	2020
	MACS 4058	Protein 14.7% Iron 39.5ppm Zinc 37.8ppm	2020
	HD 3298	Protein 12.1% Iron 43.1 ppm	2020

Crop	Name of the cultivar	Nutrient	Year of Release
	HI 1633	Protein 12.4% Iron 41.6ppm Zinc 41.1ppm	2020
	DBW 303	Protein 12.1%	2020
	DDW 48	Protein 12.1%	2020
	DBW 332	Protein 12.2% Zinc 40.6ppm	2021
	DBW 327	Zinc 40.6ppm	2021
	HI 1636	Zinc 40.4ppm	2021
	HI 8823	Protein 12.1% Zinc 40.1ppm	2021
	HUW 838	Zinc 41.8ppm	2021
	MP 1358	Protein 12.1 % Iron 40.6ppm	2021
Maize	Vivek QPM-9	Lysine 4.19% Tryptophan 0.83%	2008
	Pusa HM-4 Improved	Lysine 3.62% Tryptophan 0.91%	2017
	Pusa HM-8 Improved	Lysine 4.18% Tryptophan 1.06%	2017
	Pusa HM-9 Improved	Lysine 2.97% Tryptophan 0.68%	2017
	Pusa Vivek QPM 9 Improved	Provitamin A 8.15ppm Lysine 2.67% Tryptophan 0.74%	2017
	Pusa VH 27 improved	Provitamin A 5.49ppm	2020
	Pusa HQPM 5 Improved	Provitamin A 6.77ppm Lysine 4.25% Tryptophan 0.94%	2020
	Pusa HQPM 7 Improved	Provitamin A 7.10ppm Lysine 4.19% Tryptophan 0.93%	2020
	IQHM 201 (LQMH 1)	Lysine 3.03% Tryptophan 0.73%	2020
	IQHM 202 (LQMH 2)	Lysine 3.04% Tryptophan 0.66%	2020
	IQHM 203 (LQMH 3)	Lysine 3.48% Tryptophan 0.77%	2020
	Malviya Swarn Makka 1	Lysine 3.89% Tryptophan 0.97%	2021
	Pusa HQPM 1 Improved	Provitamin A 7.02ppm Lysine 4.59% Tryptophan 0.85%	2021

Crop	Name of the cultivar	Nutrient	Year of Release
	Pusa Biofortified Maize Hybrid 1	Provitamin A 6.60ppm Lysine 3.37% Tryptophan 0.72%	2021
Pearl Millet	HHB 299	Iron 73.0ppm Zinc 41.0ppm	2017
	AHB 1200Fe	Iron 73.0ppm	2017
	AHB 1269Fe	Iron 91.0ppm Zinc 43.0ppm	2018
	ABV 04	Iron 70.0ppm Zinc 63.0ppm	2018
	Phule Mahashakti	Iron 87.0ppm Zinc 41.0ppm	2018
	RHB 233	Iron 83.0ppm Zinc 46.0ppm	2019
	RHB 234	Iron 84.0ppm Zinc 46.0ppm	2019
	HHB 311	Iron 83.0ppm	2020
	HHB 67 Improved 2	Protein 15.5% Iron 54.8ppm Zinc 39.6ppm	2021
Fingermillet	VR 929 (Vegavathi)	Iron 131.8 ppm	2020
	CFMV 1 (Indravathi)	Calcium 428 mg 100 g^{-1} Iron 58 ppm Zinc 44 ppm	2020
	CFMV-2	Calcium 454 mg 100 g^{-1} Iron 39 ppm Zinc 25 ppm	2020
Little Millet	CLMV 1	Iron 59.0ppm Zinc 35 ppm	2020
Lentil	Pusa Ageti Masoor	Iron 65 ppm	2017
	IPL 220	Iron 73 ppm Zinc 51 ppm	2018
Groundnut	Girnar 4	Oleic acid 78.5%	2020
	Girnar 5	Oleic acid 78.4%	2020
Linseed	TL 99	Linoleic acid 58.9%	2019
Mustard	Pusa Mustard 30	Erucic acid 1.2%	2013
	Pusa Double Zero Mustard 31	Erucic acid 0.76% Glucosinolates 29.41 ppm	2016
	Pusa Mustard 32	Erucic acid 1.32%	2020
	Pusa Double Zero Mustard 33	Erucic acid 0.58% Glucosinolates 15.17 ppm	2021
	RCH-1	Erucic acid 0.09% Glucosinolates 19.49 ppm	2021

Crop	Name of the cultivar	Nutrient	Year of Release
	PGHS 1699	Erucic acid 1.49% Glucosinolates 20.34 ppm	2021
Soybean	NRC-127	Kunitz Trypsin Inhibitor free	2018
	NRC-132	Lipoxigenase-2 free	2020
	NRC-147	Oleic acid 42%	2020
	NRC-142	Kunitz Trypsin Inhibitor free Lipoxigenase-2 free	2021
	MACS NRC 1667	Kunitz Trypsin Inhibitor free	2021
Cauliflower	Pusa Beta Kesari 1	Provitamin A 8-10 ppm	2015
Potato	Kufri Manik	Anthocyanin 0.68 ppm	2020
	Kufri Neelkanth	Anthocyanin 1.0 ppm	2020
Sweet Potato	Bhu Sona	Provitamin A 14 mg 100 g^{-1}	2017
	Bhu Krishna	Anthocyanin 90 mg 100 g^{-1}	2017
Greater Yam	Sree Neelima	Anthocyanin 50 mg 100 g^{-1} Protein 15.4% Zinc 49.8 ppm	2020
	Da 340	Anthocyanin 141.4 mg 100 g^{-1} Iron 136.2 ppm Calcium 1890 ppm	2020
Pomegranate	Solapur Lal	Iron 5.6-6.1 mg 100 g^{-1} Zinc 0.64-0.69 mg 100 g^{-1} Vitamin C 19.4-19.8 mg 100 g^{-1}	2017

several challenges. One major challenge is limited awareness among farmers and consumers which causes problem in adoption of the biofortified crops thus limited access to the nutritional benefits. Another challenge in cultivating and adopting the biofortified varieties is ensuring the maintenance of high yield, disease resistance, and other desirable agronomic traits. Farmers are more likely to adopt new varieties if they perform well under field conditions.

Consumer acceptance is also important, particularly when biofortified crops differ slightly in color or appearance from traditional varieties. For example, orange-colored sweet potatoes or maize may initially face resistance in communities accustomed to white varieties. In addition, strengthening seed distribution systems and ensuring the availability of biofortified seeds to farmers at the same time creating awareness among the farmers and consumers are essential for large-scale adoption.

8. Future Prospects

The future of biofortification is promising due to rapid advances in plant breeding, genomics, and biotechnology. Modern tools such as marker-assisted selection, genomic selection, and gene editing are enabling scientists to develop nutrient-rich crop varieties more effectively. Integration of biofortification with other agricultural innovations such as climate-resilient breeding and sustainable farming practices will further enhance its impact. As awareness increases among policy makers, farmers, and consumers, biofortified crops are likely to play an increasingly important role in global nutrition strategies. Expanding research and development efforts, strengthening public–private partnerships, and improving extension services will be crucial for accelerating the adoption of biofortified crops.

9. Conclusion

Biofortification represents a powerful and sustainable approach to addressing micronutrient deficiencies and improving nutritional security. By improving the nutritional status of staple crops through conventional breeding and modern biotechnological tools, it proves to be a cost-effective and long-term solution to combat hidden hunger. With continuous efforts in research, policy support, and farmer adoption, biofortification is the potential tool to significantly improve public health outcomes and can contribute to global food and nutrition security.

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