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Biofortified crop for long-term agricultural development and nutritional security

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Abstract
Nutritional deficiencies remain a major concern in many developing countries, affecting both human and animal health. Diets in these regions are often dominated by cereal-based foods with limited diversity, resulting in inadequate intake of essential macro- and micronutrients. Although cereals and pulses serve as staple crops, they frequently lack vital nutrients, contributing to disorders such as anemia, rickets, and scurvy. Biofortification of these crops has emerged as a sustainable strategy to enhance their nutritional value and combat malnutrition. Recent advances in New Breeding Techniques (NBTs), including gene editing, transgenic approaches, and utilization of wild genetic resources, offer promising opportunities to develop nutrient-rich crop varieties. This study highlights the importance of biofortification in improving food quality and nutritional security. It also emphasizes how modern breeding technologies can accelerate the development of fortified crops, ultimately support agricultural sustainability and improve public health outcomes in resource-limited regions.

Keywords: Dietary deficits, biofortified crop/pulses, nutritional security, biofortification

Introduction
Nutritional security requires consuming adequate amounts of foods high in vital nutrients. Staple crops make up the majority of daily meals, especially in underdeveloped nations (ASLAM *et al*., 2023) [3]. This emphasizes the critical importance of producing highly nutritious meals in order to attain nutritional security. Bio fortification is an effective method recommended for alleviating hunger since it allows the establishment of certain nutrients into the edible sections of specific crops, allowing them to be consumed by both people and livestock (Sandhu *et al*., 2023) [37]. This approach focuses on creating crop types with naturally increased quantities of key nutrients. Despite of traditional ways of tackling malnutrition, such as vitamin supplementation, biologically crop fortification entails actively changing the genetic composition of crops with elevated yields to achieve targeted nutritional values. The
nutritional status of plants may be improved by using the variety of biotechnological tool, such as genetically modified crops. These approaches have the capacity to disperse micronutrients within plant tissues, optimise metabolic pathways, increase the availability of nutrients, and reduce antinutrient absorption (Sandhu *et al*., 2023) [37]. The development of CRISPR-based gene-editing techniques has opened up new avenues for crop biofortification, that enable targeted alterations of pathways in crops such as cereals to raise levels of beta-carotene and key amino acids (Saeed *et al*., 2024) [36].Agronomic biofortification uses mineral fertilizers, soil amendments, or a foliar application method to produce an immediate but transitory increase in nutrient content, with the goal of improving nutrient availability and absorption (Rajput *et al*., 2025) [34]. This article discusses advances in the biological fortification of vegetables, fruits, and grains for a variety of vital minerals, including magnesium (Mg), calcium (Ca), iodine (I), zinc (Zn), selenium (Se), iron (Fe), copper (Cu), and silicon (Si), which are often lacking or underutilized in human nutrition(Zulfiqar *et al*., 2020) [55] .Before introduction, these varieties go through three years of rigorous, multi-locational research to assure continuous yielding efficiency, targeted nutritional content in polished rice, and acceptable cereal and cooking texture.

What is biofortification?
Multiple approaches are employed to address deficiency in micro nutrients, with product fortification and medical supplementation being the most common (Buturi *et al*., 2021) [6]. Biofortification is a technique that entails employing plant breeding to boost micronutrients. Biofortification has the potential to alleviate the worldwide issue of malnutrition based on micro nutrients, or a "hidden which impacts more than 2 billion individuals (Siwela *et al*., 2020) [44]. Inadequate intake of vital minerals and vitamins, like iron, zinc, vitamin A, and iodine, can lead to serious health hazard such as impaired cognitive development, diminished immune response, higher mortality and morbidity rates in children and women (Paul *et al*., 2024) [33]. "Fortification" is a term which means incorporation of vital nutrients like folic acid to wheat flour or iodine to salt (Faye *et al*., 2025) [20]. The term "biofortification" refers to a genetically engineered crop variety to boost the concentration of specific micronutrients in the crop's consumable components (Van *et al*., 2023). Agronomic biofortification is the process of addition of nutrients to soil or leaves to increase their concentration in food (De Valença *et al*., 2017) [17]. Biological Fortification has primarily been achieved by conventional crop breeding and selection, although direct genome alteration has sometimes been performed, as in the case of Golden Rice (Senguttuvel *et al*., 2023) [39]. In any case, the creation of an exclusive product with better nutritional value, capable of meeting new customer demand, and willing to pay for a healthier way of eating, compensates the greater expenses that associated with biofortified vegetable growing in industrialized nations (Timpanaro *et al*., 2020) [47].

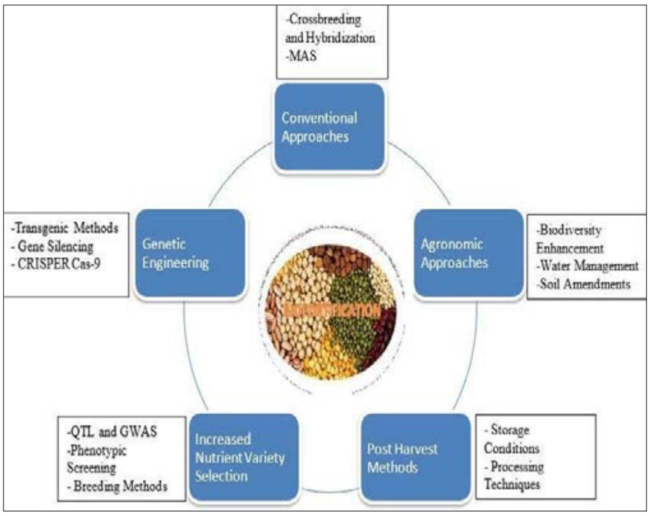

Fig 1: Different ways to produce bio-fortified crop

a. Genetically engineered crop production:

Genetically modified (GM) plants are plants used in agriculture who's DNA has been changed through biotechnological method to impart certain features such as insect resistance, herbicide tolerance, or increased nutritive value. As of early 2026, worldwide demand for these crops is steadily growing, with the release of future generation characteristics aimed at climate resistance and pest control (Nagar *et al*., 2024, Sedeek *et al*., 2019; Garg *et al*., 2024) [22, 31, 45].

- New Pest Resistance BASF introduced the "Nemasphere" trait in June 2024[36], the first GMO approach to tackle the soybean cyst nematode, a key pest (Saeed *et al* 2024) [36].
- Climate Resilience to assist farmers in adapting to changing climatic circumstances, fresh breeds are being developed with drought and salt resistance in mind.
- Regulatory Changes To improve local output, countries such as Australia and China have lately granted additional permissions for genetically modified crops such as bananas, Indian mustard and soyabeans(Faye *et al* 2025) [34]
- Bt Cotton is the only commercially certified genetically modified crops in India, accounting for more than 96% of the country's cotton acreage as of 2025/2026 (Jha *et al* 2025) [16, 25, 34].
- Extensive genetic diversity for nutrient improvement has also been stated in tomato, cassava, and potato germplasm, providing valuable resources for breeding programs (Chavez *et al*., 2005; Mazzucato *et al*., 2008) [12, 28]

b. Agronomic Approaches

An agronomic approach is the scientific and technical application of strategies for growing plants for food, fuel, and fibre while improving soil health and ecological sustainability (Wang *et al* 2025[52]. As of early 2026, the strategy has moved from traditional yield-orientated approaches to "Climate-Smart" and "Data-Driven" systems that solve worldwide food poverty by combining biological processes with modern technology (Chen *et al* 2024, Paul *et al*2024[13],). The effectiveness of agronomic biofortification depends on soil properties, nutrient mobility, and genotype–environment interactions (Haynes *et al*., 2012; Hillel & Hatfield, 2005) [23, 24].

Leading agricultural trends for 2026

- **AI-Driven Prescriptive Advisory:** AI has progressed from "behind the scenes" to a field-ready decision-making partner. Tools like the Bharat VISTAAR platform leverage multilingual AI to make field-specific suggestions in real time.

- **Bio-Digital Integration:** To improve nutrition programs and decrease synthetic residue, biological fertilizers and bio stimulants are being directly linked into digital agronomy systems.

- **Climate Resilience Stack:** Agronomists are deploying a "resilience stack" including moisture sensors, heat-resilient genetics (e.g., using CRISPR-Cas9), and precision fertilization calibrated for variable rainfall.

- **Skilled Field Robotics:** Automation is becoming a specific task, with modular robots created for specialized situations such as orchards or vineyards rather than "one-size-fits-all" platforms.

- **Global policies and trends:** India's Union Budget 2026 proposes ₹1.63 lakh crore for the agricultural sector, focusing on digital public facilities and high-value commodities such as sandalwood and cocoa. Biofortified crops have previously upgraded the lives of millions of people wide-reaching by increasing dietary intake of vital micronutrients (Garg *et al*., 2018; Bouis & Welch, 2010) [7, 21].

Table 1: Various approaches to Crop Bio-fortification (Nagar *et al*., 2024) [31]

Approach	Time-frame	Cost	Regulatory Acceptance	Sustainability	Key Strengths	Key Limitations
Conventional Breeding	Long	Low	High	High	Durable, farmer-accepted	Slow progress
Agronomic biofortification	Short	Moderate	High	Moderate	Rapid impact, flexible	Input-dependent
Transgenic approaches	Long	High	Low–moderate	High	High nutrient gains	Regulatory barriers
Genome editing	Medium	Moderate	Variable	High	Precision, speed	Policy uncertainty

Table 2: Different biofortified vegetable crops developed through conventional in Different countries

Crop	Variety	Content Rich	Released Country
Tomato	Sunblack Black galaxy	Anthocyanin	Israel
Potato	INIA321 Kawsay	Iron and zinc	Peru
Sweet potato	Ejumula, Kakamega Vita kabode	Vitamin-A	Uganda

Table 3: Biofortified vegetables crop developed through genetic engineering method

Sl. No.	Crop	Gene	Content
1.	Potato	-AmA1 -Strawberry d-galacturonic acid reductase (GaIUR) -PsY phytotene desaturase and lycopene Beta cyclase -beta carotene hydroxylase gene (bch)	- Protein - Vitamin-C -Vitamin- A -Beta carotene
2.	Tomato	-Tomato pds-beta Lyc -CaMV35s:Crtl	Beta carotene Beta carotene
3.	Cauliflower	Or gene	Beta carotene
4.	Lettuce	Soyabean ferritin Gene	Iron
5.	Carrot	CAXI	Clcium

"Several successful examples of transgenic biofortification have been reported in potato and other vegetable crops, including enhancement of protein content, provitamin A accumulation, carotenoid enrichment, and vitamin C biosynthesis (Chakraborty *et al*., 2010; Diretto *et al*., 2006[11, 19]; Römer *et al*., 2002; Van Eck *et al*., 2007) [48]."

Role of biologic fortification in addressing international malnutrition as an issue

In agricultural techniques, biofortified seeds may be readily distributed and duplicated, leading to increased nutritional availability. Improved crops can reach even remote places, benefiting farmers who survive on subsistence. Bio-fortified orange fleshed sweet potatoes (OFSP) with high vitamin A content have been found to enhance vitamin levels considerably examined the consumption and status of rural communities in Sub-Saharan Africa (Paul *et al*., 2024; Low *et al*., 2017) [26, 33]. Biofortification has been recognized as one of the most cost-effective strategies for reducing micronutrient deficiencies at the population level (Meenakshi *et al*., 2010; Bouis & Saltzman, 2017) [8, 30]. Conventional farming technique can enhance the nutritive value of plant-based foods to some extent, but biological fortification is the technique of introducing essential nutrients into agricultural crops using conventional, agronomic, and genetically modified breeding methods to tackle the long-lasting and advantageous impact of vitamin and mineral deficiency (an Ginkel & Cherfas 2023) [49]

"Consortia Research Platform (CRP) on Biofortification in Certain Grains for Nutritional Security" at the ICAR-Indian Institute of Rice Research (IIRR) for the planned period 2014-2017[1] aims to improve the dietary benefits of staple foods like as rice, wheat, maize, sorghum, pearl millet, and small millets through collaboration between ICAR institutions, Indian Council of Medical Research (ICMR) institutions, state agricultural universities, and conventional universities (Satyavati *et al*., 2021). The effort has been expanded into two phases (2017 - 2020 and 2021 - 2026) [16], using genomes and gene experimental research in biological fortification. ICAR helps to achieve these aims by producing highly productive biofortified varieties of crops (Neeraja *et al*., 2022) [32]. The CGIAR's Harvest Plus research scheme, which focuses on increasing vitamin A, iron, and zinc in many starchy grains, root, and tuber crops, has played a significant role in the global biological fortification study (Van *et al*., 2023) [49].

Table 4: Global scenario of malnourishment (Source: Saeed *et al*., 2024; Shetty, 2003; Akombi *et al*., 2017) [1, 36, 43]

Area	Frequency of malnourishment	Types	Key factor	Impact
Sub-Saharan Africa	34% of children under 5 are stunted, 6.9% are wasted	Stunting, wasting, Anaemia	Food insecurity, poverty, limited healthcare access, poor dietary diversity	Increased child mortality, reduced workforce productivity, hindered economic growth
South Asia	34.7% of children under 5 are stunted, 14.3% are wasted	Stunting, underweight, vitamin A and	Poverty, poor sanitation, gender disparities in food	High healthcare costs, compromised
		iron deficiencies, obesity	access, rapid urbanization	workforce development, intergenerational poverty
Middle east and North Africa	16% of women of reproductive age have anaemia	Obesity, anaemia, vitamin D deficiency	Sedentary lifestyle, limited sun exposure, high-calorie diets, social and economic inequalities	Increased risk of chronic diseases, reduced life expectancy, economic strain
Europe and Central Asia	20% of adults are obese; 6.5% of children under 5 are overweight	Obesity, vitamin D deficiency, iron deficiency	Sedentary lifestyle, high intake of processed foods, aging population	Healthcare burden due to non-communicable diseases, reduced workforce efficiency
North America	36.2% of adults are obese with vitamin D deficiency	Obesity, vitamin D and iron deficiencies	High-calorie diets, limited physical activity, socio-economic disparities in food access	Increased healthcare spending, reduced quality of life, economic productivity losses

Beyond crop development, the success of biofortification also depends on effective dissemination, consumer acceptance, and supportive policy frameworks. Organizations such as Harvest Plus and national programs under Indian Council of Agricultural Research have emphasized integrating biofortified crops into public food systems, including school feeding programs and mid-day meal schemes, to ensure wider reach among vulnerable populations (Aslam *et al* 2023) [3]. Furthermore, awareness campaigns and nutrition education are crucial to promote the adoption of biofortified foods, particularly in rural and low-income communities where hidden hunger is prevalent. With advancements in genomics, gene editing, and precision breeding (Minello *et al* 2025) [29], biofortification is evolving as a sustainable, cost-effective, and long-term strategy to combat micronutrient deficiencies globally, complementing traditional interventions such as dietary diversification and supplementation (White & Broadley 2009, Bashir *et al* 2026) [4, 51].

Difficulties with Biofortification

- **Yield Penalty:** Increased the amount of micro nutrients can occasionally result in a "yield penalty," in which the plant develops fewer grains or smaller harvests because it devotes more energy to nutrient synthesis (Cakmak 2008) [9] For example, boosting beta-carotene in sweet potatoes may compete with carbohydrate synthesis, thereby lowering overall dietary amount. Numerous examples of biofortification combine of greater yields elevated micronutrient levels, such as High Zinc Maize (Anwar *et al*., 2022, Debnath *et al* 2026) [2, 16] and Zinc and Iron enhanced wheat (Velu *et al*., 2020) [50], etc.

- **Genetic Uniformity:** Backcrossing into a small number of highly productive parent lines is frequently used to generate biofortified cultivars. This can result in genetic uniformity, increasing crop vulnerability to large-scale losses due to pests, diseases, or changing the climate (Chen *et al* 2026) [14].

- **Climatic Variability:** A crop's nutritional content is significantly influenced by soil composition and ph. For example, iron and zinc absorption is frequently reduced in alkaline or nutrient-depleted soils, therefore a bio fortified variety may not function consistently across locations.

- **Antinutrients:** Many regular meals include chemicals called phytates, which link to micronutrients like iron and zinc and inhibit the body from consuming these. Limiting these antinutrients while preserving the plant's own growth is a difficult breeding problem.(Singh *et al* 2016) [46].

- **Impact on heath:** In 2016, the World Health Organization created a committee to investigate the dietary impacts of biofortification (CGIAR, 2018). In January 2022[2, 10], the World Health Organization (WHO) classified biological fortification as a "Category 3 Intervention" on its website, citing a lack of systematic studies and insufficient data. Further study is needed to make particular suggestions (World Health Organization, 2022) [53].

Strategies for overcoming Difficulties

- **Interdisciplinary collaborations:** Plant breeders create nutrient-rich crop types, while nutritionists provide insights on dietary requirements and health benefits of biofortified food. Social scientists study the cultural, economic, and behavioural variables that influence consumer acceptance and adoption of biofortified crops (Sandhu *et al*., 2023) [37]. Interdisciplinary collaboration may produce biofortified crops that are nutritious, agronomically feasible, and socially acceptable. This can improve community health as well as food availability by combining diverse perspectives. (Bouis & Welch 2010,2017) [7, 8].

- **Breeding techniques:** Crop biofortification involves traditional breeding, marker assisted selection (MAS), and genetic modification. The use of genetics can modify plant genomes to enhance nutrient-rich traits. While this technology provides for precise control over needed qualities, it also requires rigorous regulatory oversight and widespread use. Identifying and using genetic characteristics that promote accumulation of nutrients in crops (Senguttuve *et al* 2023, Sandhu *et al* 2023 [37].

- **Agronomic practices:** Correct irrigation systems, such as drip irrigation or fertigation, distribute water and nutrients directly to plant roots, reducing loss of nutrients and increasing absorb efficacy. Crop management practices such as intercropping, cover crops, and rotation can improve soil fertility, nutrient cycling and soil nutrient availability, which boosts plant nutrient absorption (Sandhu *et al*., 2023) [37]. Maximising these ingredients can help farmers improve the nutritive value of their goods, increase nutrient content, and promote sustainable agricultural systems (Neeraja *et al* 2022, Anwar *et al* 2022) [2, 32].

Conclusion

Global biofortification initiatives are the crucial and effective way to achieving the objective of eliminating hunger and malnutrition. It aims to address hidden hunger in underdeveloped nations by increasing the nutritive value of basic foods like vegetables and grains. By this method the farmers may multiply seeds at nearly zero marginal cost over the course of a few years. Over the past few years, considerable advancement has been made with the development of numerous biofortified crop kinds that help in the target population's recovery from vitamin deficiencies (Costas *et al*., 1994) [15]. Right now, different variety of crops have been fortified, providing an optimal nutrition to the people all over the world while also combating hunger and malnutrition. Further research should prioritize the improvement of nutritional bioavailability, mitigate the environmental consequences, and strengthen legislative support for wider adoption. Maximizing the effect of biological fortification requires integrating it with other dietary initiatives and engaging the community with it. Biofortification may contribute significant role to the global food and nutrition security with proper assistance and coordination. The most recent innovative techniques used in genetic biology allow for the lowering of the antinutrients like as phytic acid or tannins in order to boost micronutrient content. ZFN, TALENS, CRISPR-Cas9, and other genome editing techniques can be used to change or eliminate undesirable genes, as well as used in biofortify crops with also leads to future crop sustainability and provide key support to stabilize food nutrition security.

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