



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(2): 161-172
Received: 02-11-2025
Accepted: 09-01-2026

Upayan Sarkar
Department of Agronomy, School
of Agriculture, Lovely Professional
University, Phagwara, Punjab,
India

Shailja Sharma
Department of Agronomy, School
of Agriculture, Lovely Professional
University, Phagwara, Punjab,
India

Dr. Amandeep Kaur
Department of Agronomy, School
of Agriculture, Lovely Professional
University, Phagwara, Punjab,
India

Corresponding Author:
Upayan Sarkar
Department of Agronomy, School
of Agriculture, Lovely Professional
University, Phagwara, Punjab,
India

Advances in biofortified crops for combating hidden hunger and micronutrient deficiency: A review

Upayan Sarkar, Shailja Sharma and Amandeep Kaur

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i2c.4847>

Abstract

Malnutrition as well as micronutrient deficiencies (often called “hidden hunger”) are serious public health issues in low and middle-income countries. They are caused by inadequate intake of critical, yet preventively needed nutrients needed for growth, development and well-being. Increasing the nutritional quality of staple food crops, or biofortification, is achieved through either conventional plant breeding, genetic engineering, or agronomic approaches like crop management - all decriers of hidden hunger. Biofortification is a successful method of delivering nutrition by developing rice, wheat and other staples plants with levels of iron, zinc, vitamin A and vitamin C. In the future, it is essential to mainstream biofortification into national agricultural and nutrition policies, raise public awareness, and encourage farmers and consumers to adopt it. Biofortification continues to be a valuable, cost-effective, and underused strategy to address micronutrient malnutrition and improve food security worldwide. The adoption of the food-based recommendation, along with other nutrition and health measures, provides an effective and climate-resilient long-term means of linking agriculture and public health to foster a healthier world population which is more productive as well. In order to increase nutrition, this review outlines the latest developments, health effects, economic viability, and future prospects of improved crop biofortification initiatives.

Keywords: Agronomic biofortification, biofortification, crop nutrition, genome editing, hidden hunger, micronutrients, nutritional security

1. Introduction

Malnutrition in all its forms remains a serious global problem, especially in developing countries, where undernutrition and micronutrient deficiencies afflict millions of people. The term “hidden hunger,” which refers to micronutrient deficiencies, describes the absence of vital vitamins and minerals even when one consumes enough calories. Over 372 million preschool-aged children, along with nearly 1.2 billion non-pregnant women of reproductive age, suffer from at least one micronutrient deficiency. This highlights the phenomenon that hidden hunger is already a reality for millions of children and women across the world (Bourassa and Brown 2023) ^[13]. These deficiencies, although not as immediately visible as undernutrition, have significant long-term consequences on human health, development, and productivity.

Micronutrients are essential for health and proper metabolic function. Deficiencies, even below recommended levels, can lead to chronic disorders, reduced productivity, and economic losses. Over 2 billion people worldwide (Weininger 2019) ^[66] especially pregnant women and children under five suffer from micronutrient deficiencies, with iron, folate, zinc, iodine, and vitamin A being the most common (Bailey *et al.* 2015) ^[8]. These deficiencies contribute to poor growth, cognitive impairment, pregnancy complications, and increased disease risk. The need to correct this menace in the world using supplementation and food-based interventions such as dietary diversity and biofortification to enhance health conditions and sustainable development particularly in the underprivileged segment of the population is highly imperative (Bailey *et al.* 2015) ^[8].

Fortification and supplementation have been used as interventional frameworks to curtail the deficiency of micronutrients. Supplements have targeted effects and they face problems of high costs, logistics issues and less than optimal compliance. Supplementation would compensate by

upping the intake in fortified staples but was highly infrastructure reliant and confined with food habits. The need to diversify food to achieve balanced nutrition is not possible in most low-income/rural areas due to poor access and affordability of nutrient-dense food sources; therefore, achieving dietary diversity could also be quite difficult on a massive scale among the most vulnerable populations. (Labuschagne 2023) ^[31].

Given the drawbacks of conventional interventions, biofortification has emerged as a viable, cost-effective, sustainable, and efficient substitute to guarantee that micronutrient sufficiency can be attained (Avnee *et al.* 2023) ^[7]. Biofortification is simply the method that raises the degree of micronutrients in cultivated crops using either breeding strategies or biotechnological strategies.

In contrast to supplementation and fortification, biofortification addresses the source of nutrition i.e. the food which is eaten by peoples on a regular basis. This ensures that it is an effective plan to enhance nutritional status at the population level particularly where the people live in the countryside where there might be barriers to access to fortified foods or supplements. In conjunction with other global nutrition initiatives, such as the Sustainable Development Goals (SDGs) of the United Nations, particularly SDG 2, which aims to end hunger, provide food security and nutrition, and promote resilient agriculture, biofortification is becoming an increasingly important component (Ramadas *et al.* 2020) ^[48].

Giving a thorough overview of the idea, significance, and impact of biofortification as an intervention to guarantee improvements in global micronutrient deficiencies is the primary objective of this review. This article will look at different approaches to biofortification, including genetic engineering, agronomic, and conventional breeding techniques. It will also discuss the advantages, disadvantages, and potential applications of these methods in different situations (Paul *et al.* 2024) ^[43]. The effectiveness of biofortified crops in improving nutritional outcomes will also be examined, along with the socioeconomic, cultural, and policy-related factors that affect the adoption and expansion of biofortification initiatives (Mannar and Hurrell 2018) ^[32]. This review offers a synthesized overview of genetic, agronomic, and biotechnological strategies of biofortification and shows future research needs in the area of sustainable nutritional security.

2. Overview of micronutrient malnutrition and hidden hunger

Malnutrition, sometimes referred to as the "hidden hunger," and micronutrient deficiencies are serious worldwide health issues that affect billions of people. Such conditions feature insufficient food intake of necessary vitamins and minerals, even when the intake of the number of calories is sufficient.

Hidden hunger is a serious issue, and it may cause serious health conditions because it influences human development, growth and immunity. Deficits in iron, vitamin A, and iodine are the most prevalent forms of hidden hunger, which affecting over two billion people globally (Abeywickrama *et al.* 2018) ^[1] (Yilmaz and Yilmaz 2025) ^[68]. The highest occurrences of hidden hunger can be found in Sub-Saharan Africa, India, and Afghanistan with high health consequences, including the stunting and iron deficiency anaemia issues (Muthayya *et al.* 2013) ^[34].

The absence of dietary diversity in these areas contributes to the prevalence of nutritional inadequacies, even if many homes do not consume food in a diverse manner (Nair *et al.* 2016) ^[36]. To solve the problem of hidden hunger, one has to combine dietary

diversification planning, biofortification, and sustainable farming. Long-term maternal health enhancements can be achieved through the promotion of a variety of diets that include high concentrations of micronutrients as well as fortified foods (Teklu *et al.* 2023) ^[60]. Nevertheless, the interventions have to consider local circumstances, such as the state of agriculture, socioeconomic background, and food culture (Yilmaz and Yilmaz 2025) ^[68].

3. Historical context and need for biofortification

The history of biofortification research and development can be traced back to the recent realization of the multiplicity of hidden hunger amongst the world population induced by micronutrient deficiencies. The population that is affected by this deficiency is rather large, especially in developing nations, where the main staple crops do not provide people with the necessary micronutrients (Birol and Bouis 2023) ^[11]. Biofortification has been found as the feasible, sustainable, and economical approach that will counter it by naturally increasing the concentrations of micronutrients in crops on a genetic and agronomic level due to the food fortification process (Garg *et al.* 2018) ^[19] (Srivastav *et al.* 2022) ^[57].

Concept was made by research and development efforts under international initiatives like HarvestPlus, which was concerned with enriching staple crops. This was achieved by adopting interdisciplinary research involving plant breeding, nutrition as well as the socio-economic studies to make it to be effectively implemented and scaled up (Virk *et al.* 2021) ^[64], (Douthwaite *et al.* 2022) ^[17].

Some early victories in biofortification include crops that have been fortified with quality protein maize, which contains high levels of essential amino acids lysine and tryptophan, and was one of the first biofortified crops to have international traction. Other successes that followed are the vitamin A-rich orange sweet potato that was used to tackle the problem of vitamin A deficiency in much of Africa (Labuschagne 2023) ^[31]. Additional highlights include the availability of rice, wheat, and corn varieties that are high in iron and zinc, which have benefited millions of people, mostly in developing countries (Stangoulis and Knez 2022) ^[58], (Saltzman *et al.* 2017) ^[52].

Although such successes had been achieved, there were a number of challenges in the biofortification movement. The long breeding network that is usually needed to come up with the new biofortified ones has historically taken 810 years (Labuschagne 2023) ^[31]. Also there exists a resistance in taking up new biofortified varieties because of ignorance or acceptability among the consumers and the farmers. On the one hand, there are regulatory barriers, particularly barriers to genetically modified organisms that limit large-scale implementation of biofortified crops to some regions (Virk *et al.* 2021) ^[64].

Biofortification has progressively entered into mainstreaming where traits are introduced into the private and the public crop-breeding agendas. Through this mainstreaming approach, competition can be realized through the development of biofortified hybrids and varieties (Virk *et al.* 2021) ^[64]. As much as awareness and knowledge of importance of biofortified crops increase, they remain integrated in the world strategies of curtailing micronutrient deficiencies and sustainable enhancement of food security.

4. Objectives and scope of biofortification research

Currently, research on biofortification aims to address the issue of hunger by improving the nutritional content of basic crops and providing a more affordable and sustainable means of

ending malnutrition globally. According to many research, biofortification is the process of increasing the concentration of essential vitamins and minerals, like iron, zinc, and vitamin A, in crops by agronomic, biotechnological, and conventional plant breeding techniques (Stangoulis and Knez 2022)^[58], (Das *et al.* 2023)^[16], (Ashoka *et al.* 2023)^[5].

The aim of biofortification is one of the most significant to enhance the health of the population by decreasing the rate of micronutrient deficiencies often described as hidden hunger that form a major problem in countries with low and medium incomes where diets tend to be low in variance. It is regarded as a long-term intervention with initial costs on research and development but a huge payoff in the form of mass production and adoption of nutrient-rich varieties (Labuschagne 2023)^[31] (Bouis *et al.* 2024)^[12].

Millions of families, especially in developing nations, have been consuming biofortified staple crop varieties including maize, wheat, rice and legumes since the development and commercialization of these products because of biofortification research. The list of such biofortified crops includes high-iron beans, vitamin A-rich sweet potatoes, etc., which have proved to have positive effects on the reduction of deficiencies (Stangoulis and Knez 2022)^[58], (Das *et al.* 2023)^[16].

Development of fortified crops is not the only area that comes to mind when biofortification research is discussed because it also involves interdisciplinary research involving agricultural researchers, nutritionists and socio-economics researchers to optimize the usefulness and widespread use of these crops. These are being aware of patterns of farmers and consumers, handling the regulatory and policy issues, and the sustainable incorporation of biofortified crops into food systems (Birol and Bouis 2023)^[11] (Bouis *et al.* 2024)^[12].

With a focus on the future, the biofortification research is taking a different turn by including more innovative forms of genetic engineering that strengthen the multiple-nutrient strength and add climate-smartness attributes to crops. The purpose of such advancements is to enhance the nutritional effects of biofortification and surmount technical and logistical obstacles (Labuschagne 2023)^[31] (Bouis *et al.* 2024)^[12].

5. Approaches to biofortification

5.1 Genetic biofortification via conventional breeding

The use of natural genetic variability lying in crop germplasm is exploited to increase nutrient levels through traditional cross breeding and this process is known as genetic biofortification. The practice involves i) the selection of genotypes with better micronutrient content and ii) introduction of such traits in the elite cultivars through normal plant breeding methods. This has long been impeded using molecular markers, which have significantly reduced the time required to identify the molecular markers used in marker-assisted selection, which targets quantitative trait loci (QTL) that confer accumulation of micronutrients such as iron and zinc (Terera and Mcebisi 2023)^[61].

Breeders have succeeded in increasing the micronutrient content of legumes like chickpeas and lentils as well as grains like wheat and maize. For instance, biofortified maize, such as quality protein maize (QPM), has been developed with increased lysine and tryptophan levels, improving both the concentration of micronutrients and the quality of the protein (Gautam *et al.* 2021)^[21]. Pearl millet genotypes have been found too with high content of iron and zinc with positive correlation between the nutrition content and yield attributes present to contribute to the increased improvement of both nutrition as well as productivity concurrently (Pujar *et al.* 2020)^[46].

Such traditional breeding initiatives are advantaged by the fact that they are not GMO solutions, which may help better acceptance by consumers and facilitation by governments. Nevertheless, genetic barriers are presented in some crops because of low differences or complicated genes alternation in micronutrient traits. To overcome these obstacles, it involves utilizing landraces, crop wild relatives and bringing multidisciplinary tools to expand genetic pools that can be used in breeding (Terera and Mcebisi 2023)^[61].

5.2 Genetic engineering and genome editing techniques

Advancements in genetic engineering have introduced powerful tools for biofortification beyond the scope of conventional breeding (Fig 2). Transgenic technologies enable direct introduction of genes responsible for micronutrient biosynthesis, transport, or storage into crop genomes. A flagship example is Golden Rice, genetically modified to biosynthesize beta-carotene (provitamin A) in rice endosperm, addressing vitamin A deficiency prevalent in Asia and Africa. Without significantly changing agronomic features, this transgene-driven biofortification raises the nutritional content of rice, a staple food for billions of people (Kumari 2024)^[29].

CRISPR-Cas9 (Fig 2) and other genome editing methods, which offer accurate and effective target gene alterations without introducing foreign DNA sequences, are examples of further advances. Such precision breeding emerges as a promising approach to manipulate micronutrient pathways while circumventing some regulatory hurdles and public apprehension associated with GMOs (Sisodiya and Tiwari 2024)^[55]. Emerging genome editing applications in biofortification include editing genes that control nutrient accumulation, phytate reduction (to enhance mineral bioavailability), and stress tolerance to ensure stable nutrient content under variable environments.

Despite their promise, these genetic engineering approaches face challenges in regulatory approval, biosafety assessments, and acceptance, particularly in developing countries. Societal concerns about GM crops, potential unforeseen ecological effects, and complex approval systems have delayed widespread adoption. An integrated process characterized by strong risk communication and transparent safety assessments, as well as policy frameworks can be of critical importance to the future development of genetic engineering-mediated biofortification (Rout *et al.* 2023)^[50].

5.3 Agronomic biofortification practices

Agronomic biofortification is the use of farming techniques to increase the concentration of micronutrients in edible portions (Fig 1). This is done by applying micronutrient fertilizers topically and in the soil, which will immediately replenish the deficient nutrients in the soil and boost plant uptake. The technique can be of worth in areas where soils are metallurgically insufficient or ones with environmentally congested forces to restrict nutrition accessibility (Gautam *et al.* 2025)^[20].

Biofertilizers are composites that contain beneficial living organisms, mainly plant growth-promoting microorganisms that could be rhizobacteria and actinomycetes and those microbes promote better availability and uptake of nutrients like iron, zinc and selenium by improving soil health and cycling of nutrients. These biofertilizers are safe, environmentally friendly, and biofortification agents that can be used together with chemical fertilizers to minimize the effects the fertilizers have on the environment (Gautam *et al.* 2025)^[20].

The use of nano-fertilizers is also one of the new frontiers in agronomic biofortification (Fig 2). Engineered nanoparticles that target to deliver micronutrients in effective, yet controlled manners reduce leaching or volatilization losses, in turn increasing nutrient use and enhancing the nutrition of crops. Research contrasting zinc oxide nanoparticles with conventional zinc sulphate fertilizers in wheat has been shown to increase the vigour, yield aspects, and grains accumulation of zinc, which emphasizes the importance of nano-fertilizers as an important next-generation biofortification system (Chaudhary *et al.* 2022) ^[14], (Yadav *et al.* 2023) ^[67].

Combining these agronomic techniques could offer quick and inexpensive solutions to improve the nutritional value of food crops and could be seen as an adjunct to the genetic biofortification methodology (Table 1). The levels of optimization, however, must be regarding type of nutrients, when to use them, effects on the environment and their uptake by farmers to achieve maximum returns.

6. Biofortified crops' effects on human health

6.1 Addressing iron and zinc deficiencies

One of the most common nutritional illnesses in the world is iron and zinc deficiency, particularly in low-income people who rely on cereals with naturally low micronutrient concentrations. Iron deficiency anaemia remains a leading cause of morbidity in women and children, while zinc deficiency compromises immune function and growth (Rai *et al.* 2024) ^[47]. Biofortified crops are designed to alleviate these deficiencies through enhanced nutrient concentration and improved bioavailability, reducing the incidence and severity of associated health outcomes.

Multiple clinical trials and community-based interventions have demonstrated the efficacy of biofortified cereals. For instance, it has been demonstrated that iron-biofortified pearl millet improves iron absorption and lowers the incidence of anemia in children after intake. Cultivars of wheat that have been biofortified with zinc have enhanced serum zinc levels and helped reduce stunting in susceptible groups (Rai *et al.* 2024) ^[47]. Similarly, genetic and agronomic biofortification of wheat has been linked to increased iron and zinc grain content with positive implications for human health when consumed at scale (Sharma *et al.* 2020) ^[53].

Furthermore, agronomic biofortification enhances zinc concentration in wheat grains, while influencing crop yield and quality, resulting in nutritional and socioeconomic benefits (Singh *et al.* 2023) ^[54]. However, these health outcomes depend on factors such as nutrient bioavailability, crop intake quantity, and presence of inhibitory compounds. Biofortification strategies also integrate efforts to reduce antinutritional factors like phytate, which impair mineral absorption. Collectively, through increasing micronutrient content in widely consumed staples, biofortification represents a cornerstone intervention to mitigate iron and zinc deficiencies globally (Table 2).

6.2 Vitamin A biofortification and carotenoid enhancement

A public health issue, vitamin A deficiency has been linked to blindness, which is an avoidable immune system impairment and a risk factor for child mortality. The strategy of biofortifying crops in terms of their increased content of provitamin A carotenoids has also become a crucial aspect in the fight against VAD in rural Africa and Asia. Some crops, which are biofortified with carotenoid, like Golden Rice, orange-fleshed sweet potatoes, and provitamin A maize varieties, provide an achievable source of the nutrient (Ashoka *et al.* 2023) ^[5].

There have been breakthroughs in breeding carotenoid rich crops and in Africa breeding is aimed at supplementing vitamin A using staple crops. Nevertheless, it is not all crops and all regions that become successful because of genetic and agronomic and social cultural factors that impact acceptance and utilization rates (Nuwamanya and Atwijukire 2019) ^[38]. Moreover, the techniques used in processing affect the retention of vitamin A where some heating techniques lead to losses of the nutrient. It is recommended that protocols that allow the preservation of carotenoids should be optimized on a crop-specific manner leading to maximum health benefit (Nuwamanya and Atwijukire 2019) ^[38], (Pessu *et al.* 2020) ^[44]. The orange-coloured-fleshed sweet potatoes varieties, notably, have shown better biochemical and antioxidant properties than the cream-coloured fleshed version and can yield significant benefits towards vitamin A intake in Africa with inclusion in local food systems (Oluniyo *et al.* 2021) ^[40]. In order to maximize the operational use of biofortified crops to enhance vitamin A nutrition, it is crucial for food scientists to ensure carotenoid bioavailability stability during processing.

6.3 Additional micronutrients: Selenium, iodine, and others

In addition to iron and zinc, micronutrients that have biofortification work, include selenium, iodine, folate, and others, which are deemed essential to human health. Selenium is an essential trace mineral that also possesses antioxidative properties, and emerging interest in biofortification of selenium lies in its role in decreasing the risk of chronic disease development and strengthening immune responses. Selenium supplemented using hydroponics and fertilizer methods in crops such as strawberries have been promising to elevate the selenium levels and improve active compounds related to health merits (Mimmo *et al.* 2017) ^[33].

Similarly, iodine biofortification remains crucial for preventing goitre and cognitive impairments caused by iodine deficiency. Folate biofortification, though less widespread, is gaining research interest owing to its critical involvement in preventing neural tube defects during pregnancy. Biofortification also contributes to enhancing antioxidant properties in foods, potentially mitigating the incidence of chronic diseases like cardiovascular conditions and certain cancers (Roy 2022) ^[51]. Research continues to explore the optimization of biofortification techniques for these nutrients, balancing increased micronutrient levels with crop yield and quality, while addressing potential accumulation of toxic elements. The broadening scope of biofortification thus represents an important stride toward comprehensive nutritional security and chronic disease prevention (Nagar *et al.* 2024) ^[35].

7. Biofortification of staple cereals and legumes

7.1 wheat biofortification: Iron and zinc focus

For many people around the world, particularly in South Asia and some regions of Africa, wheat is a staple diet, yet it is often low in bioavailable iron and zinc, contributing to micronutrient deficiencies. Biofortification of wheat via genetic and agronomic approaches aims to enhance these micronutrients in the grain. Agronomic techniques include applying micronutrient fertilizers topically and, in the soil, to enhance grain uptake and accumulation, whereas genetic approaches entail breeding programs that discover and incorporate genetic loci linked to greater Fe and Zn content (Sharma *et al.* 2020) ^[53]. Some commercially released biofortified wheat varieties have high concentrations of micronutrients; in India, Pakistan and Bangladesh, the improved biofortified wheat varieties have

helped the various populations obtain a better nutritional status. Yet it is emphasized in a systematic review that the topic of science should evaluate bioavailability of mentioned nutrients and their physiological effect after being consumed further, which has been understudied (Gupta *et al.* 2024) ^[24].

Clinical trials of changes, presented by consumption of biofortified zinc wheat flour in adolescent girls showed some decisive changes in levels of some thyroid hormones which showed physiological effects despite no such impact witnessed on levels of zinc in blood plasma over the period. This evidence reflects the multi-factorial nature of micronutrient absorption and metabolism after the intake of biofortified foods (Fatima *et al.* 2025) ^[18]. Multidisciplinary research is essential in how to address these challenges so as to maximize on the focus of wheat biofortification as well as its public health impact.

7.2 Maize biofortification: Quality protein and provitamin a

Maize can be considered one of the major staples in most of the sub-Saharan nations, and it is a major source of calories. However, traditional maize crops typically lack key amino acids like tryptophan and lysine in appropriate amounts, which results in protein-energy malnutrition. Smaller amounts of these amino acids are found in Quality Protein Maize (QPM), a product developed by CIMMYT and other organizations, which has better protein quality and has even led to changes in undernutrition in populations that rely on maize as a staple crop (Gautam *et al.* 2021) ^[21].

Provitamin A-rich maize cultivars, sometimes known as "Provitamin A maize," have been biofortified to assist prevent vitamin A deficiency, which is the main cause of blindness and child mortality that may be avoided otherwise. Adoption and utilization surveys Seval 2016 (Carried out in Nigeria) shows that there is great awareness and acceptance of biofortified maize to use because of its health properties and its agricultural characteristics such as resistance to pests and high yields. However, limitations, such as labour expenses, seed availability, and storage issues, pose restraints to adoption indicating the demand of enhanced market connections and, and support (Oluwaseun and Chidiebere-Mark 2024) ^[41].

The Zambian context was used to determine consumer willingness to pay on the different biofortified orange maize varieties through adopting innovative auctioning methods of determining the demand in knowing the attitude towards risks and forms a strong basis to help in the deployment and promotion process. The orange coloration study is also part of consumer perception research that might prove to have some issues regarding the visual change of traditional white maize (Nyakurwa *et al.* 2017) ^[39].

7.3 Biofortification in pulses and legumes

Legumes, lentils, chickpeas, etc., are part of diversifying diets because of their protein and micronutrients. Due to the popularity of cereal-based diet in producing countries, iron and zinc deficiencies have become center-stage factors of focus on biofortification using these crops. According to studies, nutritional stability is impacted by ambient and genotype-by-environment interactions, and there is significant genetic heterogeneity in iron and zinc levels among lentil genotypes (Aski *et al.* 2023) ^[6].

In the case of chickpea, genetically modified methods have been applied to increase iron concentration through manipulation of the genes that are encoded in iron homeostasis like nicotinamide synthase and ferritin. Preliminary achievements point at the possibility of further cultivation of nutritionally supplemented

cultivars. Genetic enhancement, as well as agronomic practices, to biofortify grain legumes, is promising to enhance micronutrient consumptions and sustain agriculture diversification and sustainability (Tan 2023), (Janila *et al.* 2016) ^[25].

8. Biofortification of vegetables and horticultural crops

8.1 Nutritional enhancement in leafy and root vegetables

Vegetables are key constituents in a balanced diet because they contain high proportions of vitamins, minerals, antioxidants and phytochemicals. Biofortification programs with leafy and root vegetables pursue the objectives of correcting hidden hunger by increasing concentrates of iron, zinc and compounds like carotenoids and phenolics. These are done by use of agronomic measures such as micronutrient fertilization and genetic measures which include breeding and application of biotechnological techniques (Das *et al.* 2023) ^[16], (Vignesh *et al.* 2025) ^[63].

Conventional breeding has not been very successful in the biofortification of vegetables owing to the complex nature of inheritance involved in nutrient traits. To address these obstacles, modern molecular techniques and high-throughput phenotyping are being applied more to create varieties that are more nutrient-rich (Nagar *et al.* 2024) ^[35].

In addition, micronutrient bioavailability is increased by decreasing antinutrients in vegetables and hence their health effects are amplified. It is imperative that such holistic approaches be incorporated to foster vegetable biofortification as one of the sustainable solutions to enhancing grain-based diets (Krishnamoorthy *et al.* 2022) ^[27].

8.2 Biofortified sweet potato and pumpkin varieties

Historically, orange-fleshed sweet potato types have been the biofortified crops utilized to alleviate vitamin A deficiency in sub-Saharan Africa. The varieties exhibit high beta-carotene content, enhanced antioxidant activity, and desirable biochemical characteristics in comparison with the conventional cream-fleshed varieties and help address the problem of malnutrition in a child population (Nuwamanya and Atwijukire 2019) ^[38].

In biofortified sweet potato products, processing methods influence the retention of vitamin A and related nutrients. Research reveals there are differences in sensory and nutritional quality between fried and boiled products, requiring optimal processing parameters to provide the greatest nutritional quality and product acceptability, as desired by the consumer (Pessu *et al.* 2020) ^[44].

The incorporation of such potato sweet potato varieties in the food security programmes indicates the contribution of such varieties as a source of enhancing the dietary quality of vulnerable populations.

8.3 Selenium and micronutrient biofortification in fruits

Biofortification of antioxidant capacity of fruits like strawberries through selenium has also been brought in as a potential area to increase the consumption of this trace micronutrient. Research with selenium in boosted nutrition on fertilizers has portrayed successful absorption of selenium in the fruit pulp without affecting the productivity. The metabolomic profiling shows the elevated flavonoid and polyphenol chemical compounds that are sure to bring improvement in their organoleptic qualities, and their health-promoting effects on antioxidant activity (Mimmo *et al.* 2017) ^[33].

Rearranging biochemical processes and exploiting the concept

of biofortification, the nutritive status of fruits can be improved, which is another way of dealing with micronutrient deficiency. There is also a complementary role of biofertilizers and bio-stimulants in horticultural crops that affect plant health, uptake of micronutrients, and yields which improves the availability of nutrient-dense fruits to the consumers (Krishnamoorthy *et al.* 2022) ^[27], (Tiwari *et al.* 2023) ^[62].

9. Socioeconomic and policy aspects in biofortification adoption

9.1 Farmer and consumer acceptance

Biofortification programs should gain acceptance by farmers and consumers in order to be successful. Awareness and the overall preparedness to plant biofortified crops like maize among farmers is considered high in Nigeria and other parts of the world according to studies that have been conducted on the matter. Age, education, level of contact with extension, farm size and income are some of the factors at play to determine utilization such as access to inputs and dissemination of knowledge (Oluwaseun and Chidiebere-Mark 2024) ^[41].

The influence of consumer preferences is based on organoleptic properties, culture, and health perceived benefits. For instance, Indian farmers have been ready to pay more for biofortified rice varieties, particularly younger and better-educated women (Waris *et al.* 2019) ^[65], which suggests a role of demographics in the acceptance and demand. On the same note, the consumer willingness to pay to consume orange maize in Zambia and their attitudes to risk have been assessed through new experimental auction designs that help in guiding promotional interventions (Gupta 2015) ^[23].

Moreover, barriers of poor access to quality seed, expensive labour, cold storage space and capital restrict widespread implementation. There are also gender dynamics and educational inequalities that influence uptake, and thus there is a need to develop specific awareness and support initiatives that increase equity and market penetration.

9.2 Regulatory and biosafety frameworks

There are complex regulatory problems associated with developing and deploying genetically modified, biofortified crops. On the continent of Africa, countries like Kenya are taking steps towards the development of biosafety policies and institutions like National Biotechnology Policies and Biosafety Acts, but they are not yet widely using GM biofortified crops in their food system because of the safety issues, the lack of information passed on to the citizens and the slow implementation of laws (Zannah and Cyrus 2019) ^[69].

The opportunity of GM biofortified crops to generate significant health benefits is not lost on scientists and stakeholders, and yet there has been cynicism by the consumer and regulatory bodies. To increase public trust and facilitate commercialization, the regulatory environment must be harmonized and the risks and benefits must be communicated clearly. As the experience of the Bio Cassava Plus and other programs show, the principle of transparency of structures and the involvement of stakeholders is critical in the process of breaking down the adoption barriers (Adenle *et al.* 2012) ^[12].

Also, the journey towards making biosafety a viable option implies that adequate investments should be made in research and monitoring infrastructure, development of capacity, and adherence to international standards so that the deployment should be safe and equitable, and this deployment should have a chance to reduce malnutrition (Rout *et al.* 2023) ^[50].

9.3 Economic benefits and food security contributions

There is substantial evidence that biofortification can enhance farmer livelihoods and promote food security. Enhanced nutritional quality of staple crops reduces the disease burden associated with micronutrient deficiencies, leading to improved productivity and reduced medical expenses within populations (Ashoka *et al.* 2023) ^[5]. Biofortified crops can increase household income through surplus production and premium pricing, contributing to rural economies.

Economic evaluations highlight biofortification as a cost-effective intervention relative to supplementation and fortification, particularly due to its sustainable, self-propagating nature once biofortified seeds are adopted and disseminated (Bamji 2016) ^[9]. Moreover, integrating biofortification into nutrition-sensitive agricultural value chains creates opportunities for market development, farmer empowerment, and systemic improvements addressing hidden hunger (Kumar *et al.* 2022) ^[28]. Cross-sectoral collaborations and policy support are essential to maximize biofortification's economic impact, necessitating inclusion in national nutrition and agriculture plans and linkages with social protection programs to enhance accessibility and affordability.

10. Technological innovations and future directions

10.1 Advances in molecular breeding and omics technologies

Molecular breeding techniques have revolutionized biofortification by enabling identification and manipulation of genes by controlling nutrient biosynthesis and accumulation. The generation of nutrient-dense crop varieties is accelerated by quantitative trait loci (QTL) mapping and genomic selection, which enable simultaneous selection for several traits, including as yield, stress tolerance, and micronutrient content (Nasim *et al.* 2025) ^[37].

Genomic tools also aid in dissecting complex trait inheritance and interactions with environmental factors. Advances in transcriptomics, proteomics, and metabolomics provide insights into crop nutritional pathways, assisting in targeted breeding and genetic engineering strategies (Tererai and Mcebisi 2023) ^[61]. Combining these omics approaches with high-throughput phenotyping expedites the breeding pipeline, fostering the rapid release of improved cultivars for diverse agro-ecological zones. In order to address the problems presented by climate change and changing nutritional requirements, biofortification initiatives will continue to improve in efficiency, precision, and efficacy through the combination of multi-trait selection, gene editing, and marker-assisted breeding approaches (Aski *et al.* 2023) ^[6].

10.2 Nanotechnology and biofertilizers in biofortification

Nanotechnology applications in agriculture, notably nano fertilizers, offer innovative pathways for efficient micronutrient delivery, minimizing losses and environmental impacts. Zinc nano-fertilization in wheat has shown promising results in enhancing grain nutrient content and yield, optimizing nutrient use efficiency via precise applications (Al-Juthery *et al.* 2022) ^[3].

At the same time, biofertilizers based on plant growth-promoting microbes improve the soil health and nutrient availability stages, which are fortified with the achievements in the nano-tech sphere. These biological amendments alter soil microbial populations, enhance nutrient cycling, and promote plant nutrient uptake, which forms the basis of sustainable methods of biofortification (Gautam *et al.* 2025) ^[20].

Innovation of integrated use of nano-fertilizers and biofertilizers is paramount in the context of the climatic crisis, and such

approaches to nutrient biofortification and agricultural initiative resilience are guaranteed. The implementation strategies ought to be monitored in regards to environmental safety, economic feasibility, and scalability (Tiwari *et al.* 2023) ^[62].

10.3 Post-harvest handling and food processing

Post-harvest processes have significant effects on bioavailability and nutrient retention of micronutrients in biofortified food. According to a number of studies, the traditional method of cooking, drying and storing can lead to significant losses in the number of vitamins and minerals unless they are not optimized (Pessu *et al.* 2020) ^[44].

Formulation of the value-added food products like nutritionally fortified cookies using biofortified pearl millet provides the scope of consuming the micronutrients by ensuring the shelf life and palatability of the products (Bansal *et al.* 2022) ^[10].

Similarly, there are also examples of biofortified wheat and soybean products that are found to improve the protein, iron, and zinc in foods that are readily consumed to overcome the issue of malnutrition. Without appropriate methods of processing that maintain and improve nutrient composition, there is little point in applying biofortification until it ultimately gets to the consumer, and having the desired effect (Kumari *et al.* 2023) ^[30]. Further studies to optimise the post-harvest technologies, support market associations and enhance the logistics of the use of biofortified crops should be promoted to fully utilise them as a national nutrition intervention programme.

11. Challenges and limitations of biofortification

11.1 Technical constraints

Another underlying issue in biofortification has to do with limitations inherent in genetics, such as a lack of variability in the genes of certain micronutrient characteristics of major crops, a situation that may hinder breeding efforts. Inheritance, interactions of the environment, and presence of antinutritive factors like phytates have negative effects on the accumulation and availability of nutrients (Ashoka *et al.* 2023) ^[5].

The issue of bioavailability is a crucial concern such that the increase of nutrients in the food might not be directly proportional to the absorption behaviour in humans because of the chemical forms, food matrix interactions and physiological factors. Therefore, breeding tactics propose a step-by-step approach to silencing the inhibitors and increasing nutrient solubility at the same time, yet the science behind it is already developing (Sharma *et al.* 2020) ^[53].

The process of micronutrient accumulation is also subject to agronomic factors (i.e., soil type, climate, and crop management practices) and these preconditions need to be accounted when adopting the biofortification intervention in one place or another (Roy 2022) ^[51].

11.2 Socioeconomic and cultural barriers

The process of adopting biofortification is heavily dependent on the socioeconomic aspects. The major drawbacks in utilisation of biofortified varieties among farmers include limited access to good seeds, poor capital, and extension services, and inadequate market infrastructure. Also, the sociocultural taste, colour, and traditional ways of food consumption can restrict the acceptance by consumers. As an example, the product of provitamin A maize usually has a special orange colour, which is not given, as compared to the normal white maize (Oluwaseun and Chidiebere-Mark 2024) ^[41].

Also, there is low awareness and education level, especially among women, who in most cases are the ones controlling food choices at the house. These barriers call upon a thorough education outreach, engagement solution, and gender friendly methods to ensure acceptance and continuity of biofortified crops in the community (Govindaraj 2015) ^[22].

11.3 Policy and regulatory challenges

By causing a delay in the commercialization of genetically modified biofortified crops, regulatory delays and widespread fear among people can be seen as a limitation. Risk communication effectively balancing benefits and potential small risks is essential to build public trust. Fragmented and inconsistent biosafety frameworks across regions further complicate commercialization processes (Smyth 2017) ^[56].

Harmonization of regulations and transparent stakeholder engagement are necessary to facilitate introduction and scaling of biofortified GM crops. Governments and policymakers must prioritize biofortification in national nutrition and agricultural agendas to overcome administrative bottlenecks and enable broad access to biofortified foods (Zennah and Cyrus 2019) ^[69].

Experience from African countries reveals that while policy frameworks exist, active integration of biofortification in food systems requires further capacity building and enforcement (Adenle *et al.* 2012) ^[2].

12. Case studies of biofortification programs and impact assessments

12.1 Biofortified wheat and rice programs

South Asian countries have implemented extensive programs releasing zinc- and iron-biofortified wheat varieties, backed by agronomic and genetic research. Evaluations indicate improvements in micronutrient intake and associated health parameters, particularly reducing anaemia in women and children (Fatima *et al.* 2025) ^[18].

In India, farm-level willingness to pay for biofortified rice varieties reflects encouraging market potential, emphasizing the importance of demographic targeting and awareness creation for scaling interventions. Supplementation trials and community interventions further validate the positive health impacts of consuming biofortified cereals (Waris *et al.* 2019) ^[65].

Porridge and other value-added foods derived from biofortified wheat and soybean have shown nutritional enhancements, underscoring integration of biofortified crops into diets beyond raw grain consumption (Kumari *et al.* 2023) ^[30].

12.2 African sub-Saharan regions' biofortification of maize

Due to farmer involvement and market acceptability, biofortified maize cultivars such as orange maize and QPM have become popular in Nigeria and Zambia. Awareness programs and extension services have increased uptake, positively affecting micronutrient status and livelihoods (Oluwaseun and Chidiebere-Mark 2024) ^[41].

Consumer acceptance research also indicates the need to overcome negative attitudes concerning the colour and taste of the product. Premium prices willingness and better market opportunities are given as economic incentives to adopt (Gupta 2015) ^[23].

Collaboration strategies based on market networks and community training lead to increased biofortified maize dependent on expanded distribution and long-term utilization, which slows down the lack of regional nutrition security (Nyakurwa *et al.* 2017) ^[39].

12.3 Biofortified vegetables and root crops in nutritional security

An example of effective implementation of biofortified vegetables into diet patterns is the use of orange-fleshed sweet potato as an element of nutrition intervention in Africa. The improved micronutrient consumption of these varieties can normalize the vitamin A level, which has noticeable effects in eye health and immunity, respectively ((Nuwamanya and Atwijukire 2019) ^[38]. Biofortification of vegetables enhances diet diversification and can contribute to the solution of many micronutrient deficiencies without affecting only one at a time. It is recommended that lessons learnt in these programs focus on supporting policies, supply chains, and creating awareness in relation to enhancing adoption (Das *et al.* 2023) ^[16]. Dietary diversification supported by homestead production of biofortified vegetables and animal-source foods complements biofortification efforts, leading to more sustainable nutritional outcomes (Bamji 2016) ^[9].

13. Summary of key advances and findings

Through genetic, agronomic, and biotechnological means, biofortification has proven to be an effective and long-term method of addressing micronutrient deficiencies on a worldwide scale. The creation of biofortified horticulture crops, legumes, and cereals with higher levels of Fe, Zn, vitamin A, and other micronutrients significantly reduces deficits with broad socioeconomic and public health advantages (Ashoka *et al.* 2023) ^[5]. Interdisciplinary efforts integrating molecular breeding, agronomy, and food science have improved biofortification methodologies, facilitating the release of nutritionally enhanced crop varieties with demonstrated efficacy in clinical and field settings (Rai *et al.* 2024) ^[47]. The approach aligns with sustainable development goals by contributing to resilient food systems, enhanced nutrition, and economic empowerment of farming communities (Sharma *et al.* 2020) ^[53].

14. Future research needs and opportunities

Future research priorities include multi-nutrient biofortification targeting combinations of micro- and macronutrients, improving trait stability under diverse environmental conditions, and addressing nutrient bioavailability concerns through reduction of antinutrients and enhancing absorption. Technological innovations such as CRISPR-based genome editing, nanotechnology applications, and advanced omics methodologies promise to accelerate biofortification progress (Fig 3). However, interdisciplinary collaborations bridging plant science, nutrition, social sciences, and policy research are essential to optimize outcomes (Tererai and Mcebisi 2023) ^[61]. Expanding consumer-centric research focusing on acceptance, behavioral factors, and socio-cultural dynamics will further enhance adoption and impact (Chaudhary *et al.* 2022) ^[14]. Integrative approaches combining agronomic practices with genetic biofortification also warrant intensified study to realize synergistic benefits (Gautam *et al.* 2025) ^[20].

15. Policy and implementation strategies

Scaling biofortification requires supportive policy frameworks that incorporate these interventions into national nutrition and agricultural plans. Emphasis on public-private partnerships, effective extension services, education, and capacity building is crucial to surmount existing socioeconomic barriers. Timely deployment of biofortified varieties, especially those created through genetic engineering, will be made easier by coordinated biosafety rules, clear regulatory processes, and risk communication (Smyth 2017) ^[56]. Nutrition-sensitive value chains and market integration strategies must be developed to ensure equitable access and sustainable utilization (Bamji 2016) ^[9]. Biofortification is a key instrument to tackle hidden hunger all over the world if multi-stakeholder coordination involving governments, research institutions, NGOs and farmer organizations happens in a coordinated manner (Kumar *et al.* 2022) ^[28].

Table 1: Agronomic Biofortification Approaches for Combating Micronutrient Deficiencies

Micronutrient deficiency	Agronomic biofortification method	Examples of crops
Iron (Fe) Deficiency	Application of iron-rich fertilizers and foliar sprays	Biofortified rice, wheat, and maize (Rashid <i>et al.</i> 2025) ^[49] .
Zinc (Zn) Deficiency	Use of Zn-based fertilizers (soil and foliar application)	Biofortified rice and wheat; Zn-rich genotypes developed (Paharaj <i>et al.</i> 2021) ^[45] .
Vitamin A Deficiency	Enhancing carotenoid content via biofortification + agronomic support	Golden Rice, provitamin A-rich bananas (Paharaj <i>et al.</i> 2021) ^[45] , (Amah <i>et al.</i> 2019) ^[4] .
General Micronutrient Deficiencies	Integrated nutrient management combining mineral fertilizers, organic inputs, and improved varieties	Fortified cereals and legumes with enhanced mineral and vitamin content (Koç and Karayığit 2022) ^[26] .

Table 2: Biofortification Approaches in Staple Crops: Nutrient Targets, Methods, and Global impact

Crop	Nutrients enhanced	Biofortification method	Potential impact and regions
Rice	Iron, Zinc, and other micronutrients	Breeding, Genetic Engineering	Significant increase in daily micronutrient intake; beneficial in rice-consuming regions (Das <i>et al.</i> 2023) ^[16] .
Golden Rice	β-Carotene (Provitamin A)	Biotechnology (Development of Golden Rice)	Aims to combat vitamin A deficiency effectively (Paharaj <i>et al.</i> 2021) ^[45] .
Bananas	Provitamin A Carotenoids (pVACs)	Conventional Breeding, Transgenic Approaches	Tackles vitamin A deficiency in tropical and subtropical regions where bananas are staple (Amah <i>et al.</i> 2019) ^[4] .
Cereals	Iron, Zinc	Agronomic Biofortification, Breeding	A viable strategy to increase mineral content of staple crops, combatting iron and zinc deficiencies (Rashid <i>et al.</i> 2025) ^[49] .
General	Various Micronutrients	Agronomic, Plant Breeding, Genetic Engineering (CRISPR-Cas9)	Sustainable solution; effective in reducing hidden hunger globally (Koç and Karayığit 2022) ^[26] .

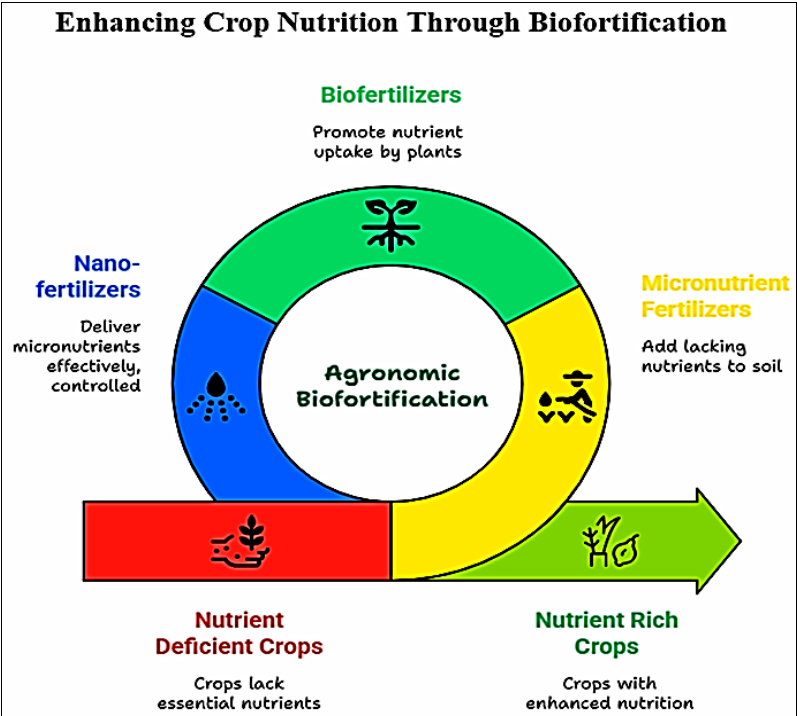


Fig 1: Biofortification Approaches to Enhance Nutrient Content in Crops

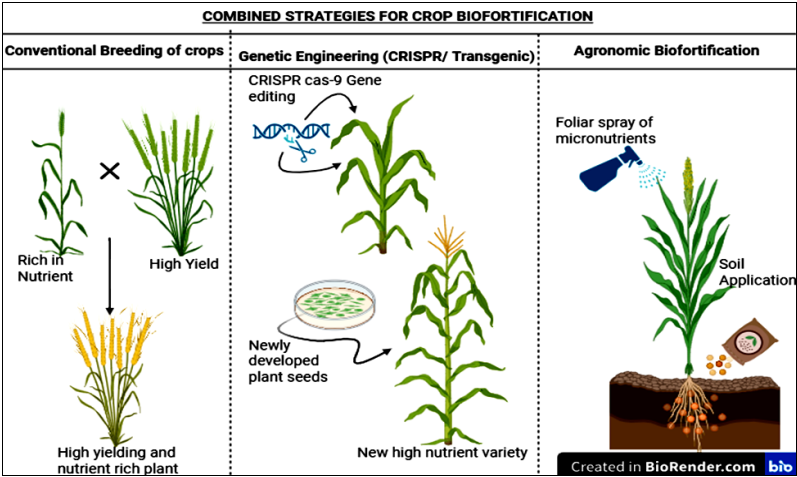


Fig 2: Combined Crop Biofortification Approaches to Combat Micronutrient Deficiencies (BioRender n.d.)

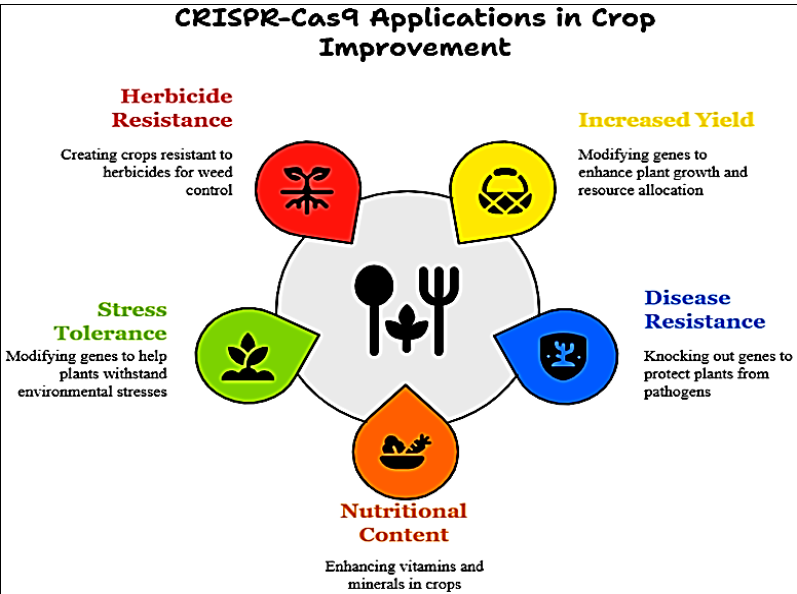


Fig 3: CRISPR- Cas9 Applications in Crop Improvement

16. Conclusion

Biofortification has also become a viable and economical approach to solving micronutrient malnutrition especially in areas where dietary diversification has not yet been achieved. The additional work on the breeding, agronomic, and biotechnological interventions has provided the possibility to design nutritionally enriched varieties of crops and influence the outcomes of population health to a significant extent. However, biofortification can succeed only with a concerted effort of researchers, policymakers, extension systems, and farmers. It will be important to reinforce the networks of seed distribution, improve consumer awareness and promote evidence-based policies to make it adopted on a large scale. Bio fortified crops can transform the world food and nutritional security with further innovation and institutional support.

References

1. Abeywickrama HM, Koyama Y, Uchiyama M, Shimizu U, Iwasa Y, Yamada E, *et al.* Micronutrient status in Sri Lanka: a review. *Nutrients*. 2018;10(11):1583. <https://doi.org/10.3390/nu10111583>
2. Adenle AA, Awoh OC, Akromah R, Parayil G. Developing GM super cassava for improved health and food security: future challenges in Africa. *Agriculture & Food Security*. 2012;1(1):11. <https://doi.org/10.1186/2048-7010-1-11>
3. Al-Juthery HW, Lahmoud NR, Alhasan AS, Al-Jassani NA, Houria A. Nano-fertilizers as a novel technique for maximum yield in wheat biofortification. *IOP Conference Series: Earth and Environmental Science*. 2022;1060(1):012043. <https://doi.org/10.1088/1755-1315/1060/1/012043>
4. Amah D, van Biljon A, Brown A, Perkins-Veazie P, Swennen R, Labuschagne M. Recent advances in banana (*Musa* spp.) biofortification to alleviate vitamin A deficiency. *Critical Reviews in Food Science and Nutrition*. 2019;59(21):3498-3510. <https://doi.org/10.1080/10408398.2018.1495175>
5. Ashoka P, Sangeeta B, Spandana DRK, Saikanth D, Kesarwani A, Nain M, *et al.* Bio-fortification and its impact on global health. *Journal of Experimental Agriculture International*. 2023;45(10):106-115. <https://doi.org/10.9734/jeai/2023/v45i102203>
6. Aski MS, Mishra GP, Tokkas JP, Yadav PS, Rai N, Bansal R, *et al.* Strategies for identifying stable lentil cultivars (*Lens culinaris* Medik) for combating hidden hunger, malnourishment and climate variability. *Frontiers in Plant Science*. 2023;14:1102879. <https://doi.org/10.3389/fpls.2023.1102879>
7. Avnee, Sood S, Chaudhary DR, Jhorar P, Rana RS. Biofortification: an approach to eradicate micronutrient deficiency. *Frontiers in Nutrition*. 2023;10:1233070. <https://doi.org/10.3389/fnut.2023.1233070>
8. Bailey RL, West KP Jr, Black RE. The epidemiology of global micronutrient deficiencies. *Annals of Nutrition and Metabolism*. 2015;66(Suppl 2):22-33. <https://doi.org/10.1159/000371618>
9. Bamji MS. Food-based approach to combat micronutrient deficiencies. *Proceedings of the Indian National Science Academy*. 2016. <https://doi.org/10.16943/ptinsa/2016/48885>
10. Bansal T, Kawatra A, Sangwan V. Sensorial, nutritional and shelf-life evaluation of bio-fortified millet-based cookies supplemented with carrot powder and sesame. *Asian Journal of Dairy and Food Research*. 2022;41(1):83-88. <https://doi.org/10.18805/ajdfr.dr-1696>
11. Birol E, Bouis HE. Role of socio-economic research in developing, delivering and scaling new crop varieties: the case of staple crop biofortification. *Frontiers in Plant Science*. 2023;14:1099496. <https://doi.org/10.3389/fpls.2023.1099496>
12. Bouis H, Foley J, Lividini K, Jumrani J, Reinke R, Van Der Straeten D, *et al.* Biofortification: future challenges for a newly emerging technology to improve nutrition security sustainably. *Current Developments in Nutrition*. 2024;8(12):104478. <https://doi.org/10.1016/j.cdnut.2024.104478>
13. Bourassa M, Brown K. Minding the micronutrient data gap. Washington (DC): Micronutrient Forum; 2023.
14. Chaudhary M, Mandal A, Muduli S, Deepasree A, Abshiba. Agronomic biofortification of food crops: a sustainable way to boost nutritional security. In: *Revisiting Plant Biostimulants*. IntechOpen; 2022. <https://doi.org/10.5772/intechopen.103750>
15. Created with BioRender.com.
16. Das K, Roy P, Tiwari RK. Biofortification of rice, an impactful strategy for nutritional security: current perspectives and future prospect. *Plant-Based Diet*. 2023. <https://doi.org/10.5772/intechopen.110460>
17. Douthwaite B, Johnson N, Wyatt A. Using outcome trajectory evaluation to assess HarvestPlus' contribution to the development of national biofortification breeding programs. *European Journal of Development Research*. 2023;35(2):426-445.
18. Fatima S, Nazli R, Malik O, Khan S. Effect of bio-fortified zinc wheat flour on serum levels of thyroid hormones among adolescent girls. *Journal of Saidu Medical College Swat*. 2025;15(1):16-20. <https://doi.org/10.52206/jsmc.2025.15.1.983>
19. Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, *et al.* Biofortified crops generated by breeding, agronomy and transgenic approaches are improving lives worldwide. *Frontiers in Nutrition*. 2018;5:12. <https://doi.org/10.3389/fnut.2018.00012>
20. Gautam A, Sharma V, Chauhan C, Thakur A, Pandey MK, Priscilla K, *et al.* Fortifying crops with micronutrients for sustainable global nutritional security. *Agronomy Journal*. 2025;117(3):e70086. <https://doi.org/10.1002/agj2.70086>
21. Gautam D, Shrestha B, Subedi B. Bio-fortified maize: cornerstone in plant breeding to combat hidden hunger in developing countries. *Archives of Agriculture and Environmental Science*. 2021;6(1):100-107. <https://doi.org/10.26832/24566632.2021.0601013>
22. Govindaraj M. Is fortification or biofortification of staple food crops a simple solution to complex nutritional disorders in developing countries? *Journal of Nutrition and Food Sciences*. 2015;5(2):1-4. <https://doi.org/10.4172/2155-9600.1000351>
23. Gupta N. Estimation of consumers' risk attitudes and willingness to pay for bio-fortified orange maize in rural Zambia using Becker-DeGroot-Marschak mechanism. *SSRN Electronic Journal*. 2015. <https://doi.org/10.2139/ssrn.2612794>
24. Gupta OP, Singh A, Pandey V, Sendhil R, Khan MK, Pandey A, *et al.* Critical assessment of wheat biofortification for iron and zinc. *Frontiers in Nutrition*. 2024;10:1310020. <https://doi.org/10.3389/fnut.2023.1310020>
25. Janila P, Rupavatharam S, Kumar CS, Samineni S, Gaur PM, Varshney RK. Technologies for intensification of

- production and uses of grain legumes for nutrition security. Proceedings of the Indian National Science Academy. 2016;82:1541-1553.
<https://doi.org/10.16943/ptinsa/2016/48887>
26. Koç E, Karayiğit B. Assessment of biofortification approaches to improve micronutrient-dense plants as a sustainable solution to hidden hunger. *Journal of Soil Science and Plant Nutrition*. 2022;22(1):475-500.
<https://doi.org/10.1007/s42729-021-00663-1>
 27. Krishnamoorthy V, Easwaran S, Thangaselvabai T. Influence of biostimulants and micronutrients as foliar spray on growth, yield and quality of chow chow (*Sechium edule*). *International Journal of Plant & Soil Science*. 2022;34(24):804-811.
<https://doi.org/10.9734/ijpss/2022/v34i242704>
 28. Kumar S, Das A, Kasala K, Ravula P. Micronutrient-sensitive food value chains: a systematic review of intervention strategies and impact pathways. *CABI Reviews*. 2022;2022:1-15.
<https://doi.org/10.1079/cabireviews202217012>
 29. Kumari K. Adoption of golden rice: a boon for children suffering from vitamin A deficiency. *Journal of Advanced Scientific Research*. 2024;15(2):6-10.
 30. Kumari S, Dixit AK, Singh SRK. Bio-fortified wheat and soybean varieties: a sustainable approach for food and nutritional security. *International Journal of Multidisciplinary Research*. 2023;5(6):284-296.
<https://doi.org/10.36948/ijfmr.2023.v05i06.8002>
 31. Labuschagne M. Biofortification to improve food security. *Emerging Topics in Life Sciences*. 2023;7(2):219-227.
<https://doi.org/10.1042/etls20230066>
 32. Mannar MV, Hurrell RF, editors. Food fortification in a globalized world. London: Academic Press; 2018.
 33. Mimmo T, Tiziani R, Valentinuzzi F, Lucini L, Nicoletto C, Sambo P, *et al.* Selenium biofortification in *Fragaria* × *ananassa* and its impact on fruit quality and metabolomic profile. *Frontiers in Plant Science*. 2017;8:1887.
<https://doi.org/10.3389/fpls.2017.01887>
 34. Muthayya S, Rah JH, Sugimoto JD, Roos FF, Kraemer K, Black RE. Global hidden hunger indices and maps. *PLoS One*. 2013;8(6):e67860.
<https://doi.org/10.1371/journal.pone.0067860>
 35. Nagar BL, Thakur SS, Goutam PK, Prajapati PK, Kumar R, Kumar S, Singh R, Kumar A. Role of bio-fortification in enhancing nutritional quality of vegetables. *Advances in Research*. 2024;25(4):64-77.
<https://doi.org/10.9734/air/2024/v25i41082>
 36. Nair MK, Augustine LF, Konapur A. Food-based interventions to modify diet quality and diversity to address multiple micronutrient deficiency. *Frontiers in Public Health*. 2016;3:277.
<https://doi.org/10.3389/fpubh.2015.00277>
 37. Nasim A, Hao J, Tawab F, Jin C, Zhu J, Luo S, *et al.* Micronutrient biofortification in wheat: QTLs, candidate genes and molecular mechanism. *International Journal of Molecular Sciences*. 2025;26(5):2178.
<https://doi.org/10.3390/ijms26052178>
 38. Nuwamanya E, Atwijukire E. Advances in carotenoid increments in storage parts of African staple crops. *Journal of Plant Breeding and Crop Science*. 2019;11(3):68-79.
<https://doi.org/10.5897/JPBCS2018.0776>
 39. Nyakurwa CS, Gasura E, Mabasa S. Potential for quality protein maize for reducing protein-energy undernutrition in maize-dependent sub-Saharan African countries: a review. *African Crop Science Journal*. 2017;25(4):521-537.
<https://doi.org/10.4314/acsj.v25i4.9>
 40. Oloniyo RO, Omoba OS, Awolu OO. Biochemical and antioxidant properties of cream and orange-fleshed sweet potato. *Heliyon*. 2021;7(3):e06533.
<https://doi.org/10.1016/j.heliyon.2021.e06533>
 41. Oluwaseun AA, Chidiebere-Mark NM. Preferences and utilization of bio-fortified maize among farming households in Imo State, Nigeria. *Journal of Agriculture and Food Sciences*. 2024;22(2):298-319.
<https://doi.org/10.4314/jafs.v22i2.21>
 42. Palmer AC. Golden rice: a quarter-century of innovation, challenges and the promise of better nutrition. *Journal of Nutrition*. 2025;155(7):1-12.
<https://doi.org/10.1016/j.tjnut.2025.06.025>
 43. Paul M, Thriveni V, Niharika M, Upadhyay DK, Kiro D, Verma A, *et al.* Biofortification of crops: a nutritional strategy for combating malnutrition. *European Journal of Nutrition and Food Safety*. 2024;16(11):63-77.
<https://doi.org/10.1007/s10722-020-00956-x>
 44. Pessu PO, Akande SA, Abel GI, Gbabe EK, Adarabierin IG, Olagunju OD, *et al.* Influence of processing methods on the quality attributes of bio-fortified sweet potato products. *Agrosearch*. 2020;20(1):133-143.
<https://doi.org/10.4314/agrosh.v20i1.12s>
 45. Prahara S, Skalicky M, Maitra S, Bhadra P, Shankar T, Brestic M, *et al.* Zinc biofortification in food crops could alleviate zinc malnutrition in human health. *Molecules*. 2021;26(12):3509.
<https://doi.org/10.3390/molecules26123509>
 46. Pujar M, Govindaraj M, Gangaprasad S, Kanatti A, Shivade H. Genetic variation and diversity for grain iron, zinc, protein and agronomic traits in advanced breeding lines of pearl millet (*Pennisetum glaucum* L.) for biofortification breeding. *Genetic Resources and Crop Evolution*. 2020;67(8):2009-2022.
<https://doi.org/10.1007/s10722-020-00956-x>
 47. Rai D, Chaudhary C, Khatak A, Banyal S. A sustainable approach to combat micronutrient deficiencies and ensure global food security through biofortification. *European Journal of Nutrition and Food Safety*. 2024;16:15-30.
<https://doi.org/10.9734/ejnf/2024/v16i41404>
 48. Ramadas S, Vellaichamy S, Ramasundaram P, Kumar A, Singh S. Biofortification for enhancing nutritional outcomes and policy imperatives. In: *Wheat and Barley Grain Biofortification*. Cambridge: Woodhead Publishing; 2020. p. 309-327.
<https://doi.org/10.1016/B978-0-12-818444-8.00013-4>
 49. Rashid A, Zeshan MA, Ghafoor N, Bashir H, Mehmood F, Hameed MA, *et al.* Biofortification of wheat, rice and maize with zinc: combating hidden hunger. *Plant and Environment*. 2025;6(1):1-23.
<https://doi.org/10.54219/plantenviro.06.01.2025.169>
 50. Rout GR, Swain R, Sahoo DP. Journey of genetically modified crops: status and prospects. *Magna Scientia Advanced Research and Reviews*. 2023;7(1):103-128.
<https://doi.org/10.30574/msarr.2023.7.1.0030>
 51. Roy B. Bio-fortification: future challenges toward nutritional security. *Plant Archives*. 2022;22(1):1-6.
<https://doi.org/10.51470/plantarchives.2022.v22.no1.036>
 52. Saltzman A, Birol E, Oparinde A, Andersson MS, Asare-Marfo D, Diressie MT, *et al.* Availability, production and consumption of crops biofortified by plant breeding. *Annals of the New York Academy of Sciences*. 2017;1390(1):104-

114. <https://doi.org/10.1111/nyas.13314>
53. Sharma D, Ghimire P, Bhattarai S, Adhikari U, Khanal S, Poudel PB. Biofortification of wheat: genetic and agronomic approaches to combat iron and zinc deficiency. *International Journal of Environment, Agriculture and Biotechnology*. 2020;5(4):1077-1088. <https://doi.org/10.22161/ijeab.54.29>
54. Singh S, Kaur J, Ram H, Singh J, Kaur S. Agronomic biofortification of wheat (*Triticum aestivum* L.) to alleviate zinc deficiency in humans. *Reviews in Environmental Science and Bio/Technology*. 2023;22(2):505-526. <https://doi.org/10.1007/s11157-023-09653-4>
55. Sisodiya AS, Tiwari S. Biotechnology's benefits to agriculture: increasing crop production and quality. *Current Research in Agriculture and Farming*. 2024;5(4):1-15. <https://doi.org/10.18782/2582-7146.215>
56. Smyth SJ. Genetically modified crops, regulatory delays and international trade. *Food and Energy Security*. 2017;6(2):78-86. <https://doi.org/10.1002/fes3.100>
57. Srivastav P, Vutukuru M, Ravindran G, Awad MM. Biofortification: present scenario, possibilities and challenges. *Sustainability*. 2022;14(18):11632. <https://doi.org/10.3390/su141811632>
58. Stangoulis JC, Knez M. Biofortification of major crop plants with iron and zinc: achievements and future directions. *Plant and Soil*. 2022;474(1):57-76. <https://doi.org/10.1007/s11104-022-05330-7>
59. Tan ZH. The characterisation of CaNAS2 and biofortification of chickpea. Brisbane: Queensland University of Technology; 2021.
60. Teklu D, Gashu D, Joy EJ, Amede T, Broadley MR. Effectiveness of agronomic biofortification strategies in fighting hidden hunger. *Agronomy*. 2023;13(8):2173. <https://doi.org/10.3390/agronomy13082173>
61. Tererai T, Mcebisi M. Genetic bio-fortification of cereals from a plant breeding perspective. *Journal of Plant Breeding and Crop Science*. 2023;15(1):42-56. <https://doi.org/10.5897/JPBCS2022.0997>
62. Tiwari AK, Moond V, Choudhari RJ, Badekhan A, Tejasree P, Baral K, *et al.* Optimizing bio-fertilizers to address food security and advance nutritional sustainability. *Journal of Experimental Agriculture International*. 2023;45:235-249. <https://doi.org/10.9734/jeai/2023/v45i122284>
63. Vignesh M, Esakkiammal SD, Varman KM. Biofortification of vegetable crops: a mechanism to optimize hidden hunger. *Asian Journal of Soil Science and Plant Nutrition*. 2025;11(2):329-342. <https://doi.org/10.9734/ajsspn/2025/v11i2532>
64. Virk PS, Andersson MS, Arcos J, Govindaraj M, Pfeiffer WH. Transition from targeted breeding to mainstreaming of biofortification traits in crop improvement programs. *Frontiers in Plant Science*. 2021;12:703990. <https://doi.org/10.3389/fpls.2021.703990>
65. Waris A, Neeraja CN, Azam MM. Farm women's willingness to pay for bio-fortified rice varieties. *Oryza*. 2019;56(2):236-241. <https://doi.org/10.35709/ORY.2019.56.2.9>
66. Weininger J. Nutritional disease. *Encyclopaedia Britannica*. 2019.
67. Yadav AK, Seth A, Kumar V, Datta A. Agronomic biofortification of wheat through fertilizer management to alleviate zinc malnutrition. *Communications in Soil Science and Plant Analysis*. 2023;54(2):154-177. <https://doi.org/10.1080/00103624.2022.2110892>
68. Yilmaz H, Yilmaz A. Hidden hunger in the age of abundance: nutritional pitfalls of modern staple crops. *Food Science & Nutrition*. 2025;13(2):e4610. <https://doi.org/10.1002/fsn3.4610>
69. Zennah K, Cyrus K. Potential uses, perceptions and policy issues of genetically modified crops in Africa: a case study of Kenya. *African Journal of Food, Agriculture, Nutrition and Development*. 2019;19(1):13946-13958. <https://doi.org/10.18697/AJFAND.84.BLFB1029>