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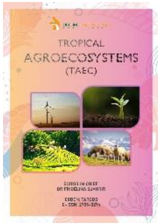

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RESEARCH ARTICLE

BIOFORTIFICATION: ENHANCING NUTRITIONAL VALUE IN CROPS

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ABSTRACT

Biofortification is a sustainable solution to the micronutrient malnutrition problem in the world through enhancing the nutritional density of staple foods using different approaches. It mainly deals with the issue of hidden hunger which affects billions of people, especially from the developing world where their diets lack micronutrients. Crops like rice, wheat, maize, beans and others fortified with iron, zinc and vitamins among others assist in increasing the bioavailability of these nutrients in economic terms. Agronomic biofortification involves the use of fertilizers with micronutrients, conventional breeding involves choosing crop varieties with high nutrient density from a pool of germplasm while genetic engineering has the added advantage of precise nutrient enhancement seen in the case of golden rice – beta-carotene. Obstacles include socio-economic ones, culture, and regulatory factors present are the facts, but organizations such as HarvestPlus have proven the ability of biofortified crops in the fight against malnutrition. The prospects involve scaling up and shifting to multi-nutrient biofortification, as well as other types of genetic engineering in order to meet the nutritive needs. Changes in the policy and sharpening the community's perception of the importance of the cultivation of biofortified crops within agricultural systems are central to improving dietary quality and thus the well-being across the human population.

KEYWORDS

Agronomic practices, Biofortification, Genetic engineering, Micronutrient deficiencies, Nutritional enhancement

1. INTRODUCTION

Biofortification is the process to improve the bioavailability of essential nutrients in crop plant edible portions via agronomic methods or genetic manipulation. This strategy could be a critical answer to malnutrition and hidden hunger(Singh et al., 2016). Biofortification is a new and promising method of delivering essential vitamins and minerals for those who do not have access to a diverse range of foods or other sources of nutrition. It is a cost-effective and future option for increasing nutrition in these people (Garg et al., 2018). We've grown a lot more food since the Green Revolution, but the nutritional value of these crops hasn't kept up with the demands of growing populations food. This has resulted in a variety of malnutrition issues, particularly in developing and underdeveloped countries where daily diets are imbalanced. Malnutrition, sometimes referred to as hidden hunger, has become a major concern, as noted by the Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs) (Chaudhary et al., 2022).

Around 148 million children under 5 are too short for their age (stunted), and 45 million are too thin for their height (wasted). For older children and teenagers aged 5-19, about 190 million are underweight. Among adults, roughly 350 million are underweight. Globally, 22.3% of children are affected by stunting, and 6.8% by wasting (WHO, 2024). Micronutrient deficiencies, also known as hidden hunger, afflict more than 2 billion people worldwide, many of people live in underdeveloped nations. This means that the diets of many individuals lack in essential vitamins and minerals (Sumithra Muthayya et al., 2013). A deficiency of vitamin A, zinc, iron, and iodine causes the deaths of approximately 20% of children under the age of five (Prentice, 2017). Micronutrient deficiency affects almost half of the world's population, primarily those living in developing countries. Clearly, this is a serious problem that affects a greater proportion of the world's population than any other health problem (Banik, 2024a). Human body need 22 essential nutrients. However, many people, particularly those who depend heavily on cereals or live in areas with poor soil, are frequently short of essential minerals such as iron, zinc, calcium, magnesium, copper, iodine, and selenium. Traditional treatments, like as supplements and fortified foods, have not always been effective in correcting these deficits. A more promising technique is biofortification, which involves increasing the mineral content of the foods we eat. This can be accomplished through improved fertilization or selective breeding of plants. Crops have a high genetic diversity, making them ideal for long-term biofortification efforts(White and Broadley, 2005). To tackle micronutrient deficiencies needs a comprehensive approach that includes eating a diversified foods, taking supplements, and fortifying common foods with essential vitamins and minerals (Rai et al., 2024). However, these types of initiatives face challenges such as limited access, high expenses, and sustainability concerns, particularly in low-income communities (Zimmermann and Boelaert., 2015). Biofortification improves nutritional levels in staple crops by traditional breeding or genetic engineering. And emerge as a cost-effective and sustainable strategy to combat nutrient deficiencies and assure global food security(Bouis and Saltzman, 2017). Biofortification provides various advantages over other approaches. It focuses on staple crops that are regularly consumed by people at risk of nutrient deficiencies, to make sure improved nutrition reach those who needed it the most (Wessells and Brown, 2012). Biofortification is a one-time investment with long-term advantages. When crops are enhanced with nutrients, these qualities are passed down to future generations, thereby enhancing nutrition. This strategy is especially useful for communities with limited resources because it provides a long-term solution that does not require constant involvement (Bouis et al., 2011). Farmer with their current farming

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methods, may cultivate biofortified crops without any additional inputs or new infrastructure. This makes it a simple and affordable method of enhancing nutrition communities (Garg et al., 2018). Biofortification can be achieved using a variety of approaches, the most common of which are agronomic biofortification, breeding, and genotype selection. Breeding techniques include traditional and mutation breeding, molecular markers, and genetic engineering. Agronomic approaches include providing nutrients to the soil or plants, incorporating helpful microbes, and modifying irrigation procedures (Sunusi et al., 2019).

This review will look at the various approaches, benefits, and challenges of biofortification and highlight how it can be a sustainable answer to worldwide nutritional deficiencies. It explores numerous strategies, provides actual examples of successful biofortification, and explores future opportunities and advancements in this field. It also discusses the importance of policy and community engagement in the effectiveness of biofortification efforts. The research also examines the financial implications and long-term impacts on public health.

2. Needs for Biofortification

The world population is expected to grow from 8.1 billion in 2024 to 8.6 billion by 2030 and 9.8 billion by 2050. With the rapid growth of the world population, there is an increasing need to provide healthy and nutritious food for everyone. Many global crises, such as climate change and pandemics could threaten large parts of both agriculture production and human life and health. These factors will disrupt food supplies and increase hunger and malnutrition, especially in developing countries (Sheoran et al., 2022).

Today, there continue to be significant challenges with malnutrition being one of the biggest areas of concern with regard to universal health care in different parts of the world. Malnutrition remains a major killer of children under five years, and accounts for almost half of the children under five years deaths in poor countries. In 2022 there are 148 million children under five years of age affected by stunting, 45 million affected by wasting, and 37 million overweight or obese (WHO, 2024). Likewise, the deficiencies in the macronutrients and micronutrients, including iodine, vitamins, zinc and iron, persist in the present day as they mostly affect children and pregnant women. These deficiencies when missing out can cause serious health problems in children and other people in society such as; stunted growth, weak immune system, complications during pregnancy and even during childbirth.

Biofortification is recognized more as the essential approach towards the micronutrient deficiencies, which are known as 'hidden hunger,' affecting billions of people in the world. Unfortunately, many people suffering from malnutrition cannot afford to consume a wide variety of foods. They depend on a few foods that are basic and thus they may lack some nutrients that are necessary for the body. The goal of biofortification is simple: to increase the nutritional content of these staple crops through various methods of biofortification (Meenakshi et al., 2010). Biofortification of crops enhances the bioavailability of several micronutrients including zinc, iron, carotenoids and selenium in the edible portions of crops to mitigate nutrient-deficiency related health issues (Naik et al., 2024). Biofortification is best known for increasing the nutritional quality in high-yielding popular crops and creating new popular varieties with high nutrition quality. This two-fold system nutrient intake and addresses food scarcity issues (Taylor et al., 2012). This approach is particularly beneficial for populations with limited access to diverse diets and other micronutrient interventions. Traditional food crops may not always contain adequate micronutrient densities for proper growth, but the use of modern breeding techniques other agronomic practices and post-harvest technologies supported by biotechnologies show the desired micronutrient densities can be achieved. Thus, using these techniques, breeders are able to rapidly generate nutrient-dense crop varieties, which significantly reduces malnutrition and stabilizes the quality of human life (Banoriya and Keerthana, 2024). Besides, the rationale for the bio fortification is to increase, the availability of vitamins and minerals, and food security in the world to eradicate malnutrition and related diseases. Food biofortification eliminates dietary deficiencies by increasing nutrient density in crops that are commonly eaten around the world. It is particularly important when such a population has a limited choice of food products available to them. Altogether, biofortification guarantees the availability of sufficiently nutrient-dense food while supporting sustainable agriculture (Banik, 2024b).

3. Types of Biofortification

3.1 Agronomic approach

Agronomic biofortification is a faster and easier method to enhance the level of good nutritional foods crops. This includes the use of mineral fertilizers which contain micronutrients that can be applied to the soil or the photoreceptors of the food crops, to increase the micronutrient content in the edible parts of the food crops (Yadav et al., 2024). Micronutrient fertilizers containing Iron, Zinc, Copper, Manganese, Iodine, Selenium, Molybdenum, Cobalt, Nickel etc. have been proved to increase not only the quality but the yield of crops as well. This exercise not only increases nutrient density in produce and food crops but also greatly contributes to alleviating the problem of human malnutrition by enriching basic nutrients in consumable products through the produce from the farm (Cakmak, 2008). Agronomic biofortification has value in various crops as a fast, successful approach to raising micronutrients, yields, and nutrition. However, it involves constant buy-in of fertilizers and is capable of incurring environmental effects (Singh et al., 2016). Different techniques of agronomic biofortification.

3.1.1 Soil application

Mineral fertilizers containing one or more of the essential micronutrients are spread over the soil to help make the micronutrients available to the plant and help improve the quality of the plant. Zinc, iron, selenium and iodine which are required by plants are also administered to the soils through application of fertilizers where they are taken by the plant root systems and transported to the above-ground plant organs (Ray and Sairam, 2024).

3.1.2 Foliar application

Foliar fertilization is the most frequent and efficient biofortification technique on the field since it highly increases the micronutrients in the part of the plants which are edible. Fertilizers are applied by spraying on the plants somewhere in the foliage. This method is fast and effective in fixing nutrient deficiencies and enhancing the quality of nutrients in the crops. Different research indicated that food crops including pulses indicated an improvement of micronutrients like iron, zinc and selenium by foliar application where the micronutrients were applied to the plant foliage which helped in an increase of these micronutrients in the harvested grain (Jha and Warkentin, 2020).

3.1.3 Seed priming

Nutri priming where by seeds are immersed in nutrient solutions before planting. This results in the stimulation of metabolism within the seed and hence enhanced germination rates, shorter germination durations, and enhanced shoot vigor (Lazim and Ramadhan, 2023). Application of micronutrient seeds treatment increases yield of the crop and content of micronutrients in many crop breeds thus more economical and friendly to the environment. Seed priming with $ZnSO4$ and $ZnCl2$ at a rate of 1.25g Zn per kg of seed increased grain zinc content by 21-35 per cent and boosted grain production by 33-55 per cent (Dogra et al., 2024).

3.2 Conventional Plant breeding approach

Conventional breeding is a breeding method that has the potential to improve the nutritional value, taste, and yield potential of major staple crops (Singh et al., 2016). This involves using plants that substantially have high inherent amounts of micronutrients that need to be enhanced. This method builds on genetic variation already found within a crop species and requires relatively simple selection procedures. So, the plant breeders look for nutrient-rich types of the crop, and then these are crossed with high-yield strains to incorporate both qualities. The resulting offspring are then selected for further breeding cycles as their superior traits are sought after (Rai et al., 2024). Enhancement of the natural nutrient quality by plant breeding guarantees healthy crops that come with breeding solutions that are specific to the particular region and solve certain nutritive inadequacies within the area. IPB can be easily incorporated and done in plant breeding programs, making it cheaper compared to marker-assisted selection (Chhetri and Santosh, 2024). However, unlike the other methods, conventional breeding takes a long time, sometimes it may take several years to come up with a new variety of biofortified food.

3.3 Genetic engineering approach

Transgenic biofortification, on the other hand, entails the direct genetic modification of plants through engineering to increase the nutrient density of their tissues. Transgenic methods involve the selection of special genes from one organism to another in order to produce plants that are nutritive. This can be done through techniques like genetic engineering and gene editing amongst other techniques. It is faster and more accurate than the basic breeding method that opens up the possibility of introducing properties that are absent in the aim species of crops (Hina et al., 2023). In this way, the utility of genetic engineering is that it can obtain manyfold enhancement in nutrient levels, which is very hard or even not possible through ordinary breeding. Another successful instance of the genetic engineering of plants to increase their levels of essential nutrients is the creation of Golden Rice. Golden Rice has been designed as a result of genetic engineering by placing genes of the precursor of vitamin A into the rice DNA. This genetic modification enables the development of Beta-carotene within rice grains to help combat diseases associated with vitamin A deficiency, in areas in which rice is the main staple diet (Białowąs et al., 2024).

4. BENEFITS OF BIOFORTIFICATION

Table 1: Benefits of biofortification among the various sector

Sector	Benefits	References
Agriculture	Deeper root growth allows plants to absorb more nutrients, which is especially useful in soils that lack essential trace metals.	(Bouis, 1996)
	It improves resource efficiency by increasing drought resilience, minimizing the demand for irrigation, and decreasing the use synthetic fertilizers and pesticides. This improves plant growth and contributes to more sustainable agriculture.	(Bouis, 2002; Rana et al., 2012)
	Biofortification improves disease resistance by enriching crops with important micronutrients such as zinc and selenium, which promote immune function and reduce vulnerability to infections.	(Lyons and Graham, 2004)
	Even in harsh conditions, biofortification increases crop yields by enhancing their nutritional value and overall productivity. With the use of genetic technology, this approach provides more nutrient-dense food options.	(Timmer, 2003)
	Breeding for iron, zinc, and provitamin A has been successful, with HarvestPlus generating 393 biofortified cultivars in 63 countries, benefiting millions.	(Virk et al., 2021)
Economic	Biofortification stands out as a cost-effective technique since it only requires the one large investment in research to create nutrient-dense cultivars.	(Nestel et al., 2006)
	Biofortification focuses on rural areas, ensuring that they have access to nutrient-dense foods when fortified alternatives in urban are unavailable.	(Bouis, 2002)
	Farmers can cultivate biofortified crops with their existing techniques, without the need for additional inputs or new infrastructure, making it a simple and cost-effective solution to improve nutrition in their communities.	(Garg et al., 2018)
	In order to treat nutritional deficiencies, biofortification enhances the efficacy of established approaches like supplementation and fortification.	(Underwood, 1999)
Population	Biofortification is viable since it relies on familiar staple crops and requires no changes in food habits or farming practices.	(Bouis, 1996)
Program	Biofortified seeds are sustainable because they naturally retain improved nutrients, giving long-term advantages.	(Bouis, 1996)
Health benefits	Biofortification benefits human health by increasing the nutrients in staple crops, addressing deficiencies such as anemia and visual impairments, improving immunity, and promoting cognitive function, particularly in inadequate in nutrients populations.	(King, 2002)

5. TARGETED NUTRIENTS FOR BIOFORTIFICATION

5.1 Iron (Fe)

Iron is crucial, for the functioning of hemoglobin in blood cells helping in the transport of oxygen and playing important roles in producing energy and synthesizing DNA (Zaib et al., 2023). iron deficiency is an issue globally resulting in conditions like microcytic anemia, negative pregnancy outcomes decreased work capacity and compromised immune and endocrine functions as highlighted by (Bailey et al., 2015). The goal of iron biofortification is to boost the iron levels in crops such, as rice, wheat and beans.

5.2 Zinc (Zn)

Zinc differently participates in such processes as enhancing immunity, DNA synthesis, healing of tissues, and cell division. Zinc deficiency has become such a major and severe problem that it can no longer be overlooked. These diseases include skin and kidney disorders, illnesses of the immune system, susceptibility to infections, slowed healing of tissues, and child growth retardation (Wenegieme et al., 2024).

5.3 Vitamin A (Carotenoids)

Vitamin A is crucial for maintaining healthy vision, immune function, and skin health. It supports the functioning of the heart, lungs, kidneys, and other organs (Stephens et al., 1996). Deficiency in Vitamin A leads to night blindness, corneal scarring and it can increase the susceptibility of severe infections especially in children. Vitamin A deficiency can also cause Xerophthalmia, a condition which may culminate to blindness (Stein et al., 2005).

5.4 Folate (Vitamin B9)

Folate also known as vitamin B9, is involved with the synthesis of DNA, its repair and replication. It is most important during periods of rapid cell replication such as in pregnancy and fetal development (Dey et al., 2024). Anemia, heart diseases, homocysteine elevation, neural tube birth disorders, pregnancy complications and possibly, more chances of neurological diseases are some of the effects of folate deficiency (Jha and Warkentin, 2020).

5.5 Selenium

Selenium is an essential micronutrient plays a vital role in the process of growth, development and immunity. It protects against infections and oxidative stress through the redox-regulating activity of selenoproteins, such as glutathione peroxidase, and helps prevent cancer progression (Razaghi et al., 2021). Poor selenium intake can impair the body's immune systems, thyroid gland functions and the reproductive system. Besides, it may develop a vulnerability to some diseases and health conditions including the Keshan disease, which is characterized by heart diseases, and the Kashin-Beck disease, which causes joints diseases, in people (Thomson, n.d.).Agronomic biofortification also enables enhancing se levels in food crops by using enhanced se foliar and soil fertilizers (Rasheed et al., 2023).

5.6 Iodine

Iodine is important for synthesizing and secreting hormones that keep thyroid function at optimal levels: T3 (triiodothyronine) and T4 (thyroxine). These hormones are further crucial for normal growth, development, and regulation of metabolic processes across every organ in the body (Vasiljev et al., 2022). Lack of iodine results in thyroid disorders and where untreated, generalized goiter, cretinism, mental retardation, reduced fertility rates, high rate of perinatal deaths and increased infant mortalities (Delange, 1994).

6. TARGETED TABLE CROPS FOR BIOFORTIFICATION

Cereals comprise the foundation of most nutrition plans around the globe across the worldwide. Biofortification involves breeding of popular staple food crops to increase the micronutrient density, with an intention of making access to micronutrient-dense foods more affordable for low income-third world consumers in Africa, Asia and Latin America. The first goal is to make certain reasonable quantities of vitamin A, iron, and/or zinc are consumed through these crops given prevalent dietary practices (Andersson et al., 2017). The main crops that are most often prioritized for biofortification include:

6.1 Rice

Rice, which is a primary sustenance for over the majority of the planet's individuals(Bhullar & Gruissem, 2013) and particularly for people in Asia(Zeigler & Barclay, 2008). It is a key focus for biofortification with zinc (Zn), iodine (I), iron (Fe), and selenium (Se) due to the widespread deficiencies of these nutrients among rice-eating populations. Thus, boosting the levels of these micronutrients in rice grains offers a sustainable solution to combat hidden hunger (Prom-U-Thai et al., 2020).

6.2 Wheat

Wheat has historically been a staple meal for a large section of the world's population. It is grown in all sorts of climates and geographical locations(Dixon et al., 2009). Biofortification efforts aimed at enhancing iron and zinc as these deficiencies are common in proportion in wheat grains (Borrill et al., 2014).

6.3 Maize

Maize is most important staple food crop of many regions of the world(Rouf Shah et al., 2016). Global design of maize biofortification projects has focused on producing various cultivars with high amounts of provitamin A, lysine, tryptophan, Zn and Fe to combat nutrient deficiencies (Goredema-Matongera et al., 2021).

6.4 Pearl Millet

Pearl millet (Pennisetum glaucum) is a warm season grain crop grown on approximately 28 million ha in the arid and semi-arid tropics of Asia and Africa. Biofortification of pearl millet intends to enhance Fe and Zn content as these nutrient deficiencies are observed as a major health concern in the developing countries(Rai et al., 2013).

6.5 Cassava

Cassava is grown in over 100 countries and is the staple daily energy source for many people living in the tropical parts of America, Africa, and Asia (Parmar et al., 2017). Biofortification seeks to enhance Fe and Zn content in cassava as these micronutrient deficiencies are rampant in sub-Saharan Africa (Okwuonu et al., 2021).

6.6 Sweet Potato

In particular, sweet potato is a food security crop in sub-Saharan Africa and some part of Asia(Low et al., 2017). OFSPs are rich sources of beta-carotene and are bio-fortified provitamin A crops that can help prevent vitamin A deficiency in many under-served countries (van Jaarsveld et al., 2005).

7. Challenges/Limitations of Biofortification

Biofortification, that includes both conventional breeding and genetic engineering, is a potential technique to alleviate global malnutrition and enhance public health (H. E. Bouis et al., 2011). However, this strategy faces numerous hurdles across socio-economic, cultural, and environmental issues.

Table 2: Challenges and Limitations of Biofortification Across Various Sectors

Category	Challenges/limitation	Description
Social	Awareness and education	Socio-economic factors, such as access to resources and education, play a crucial role in the success or failure of biofortification programs (Talsma et al., 2017).
	Cultural preferences	Cultural preferences and traditional farming methods may prevent acceptance, which requires culturally specific awareness campaigns to overcome these challenges (Bouis et al., 2011).
	Adoption Challenges	Farmers may be unwilling to adapt to new varieties if they are concerned, they will get lower yields or if the crops lack the attributes that they are used to from traditional varieties (Birol et al., 2015).
Economic	Financial limitation	Financial limitations among smallholder farmers can hinder the widespread adoption of biofortified crops. To overcome this, targeted support through subsidies and instructional programs is necessary (Saltzman et al., 2013).
	Research and Outreach Costs	To ensure that biofortified crops reach communities, extensive investment in research, breeding, and extension programs for communities are required (Nestel et al., 2006).
	Market acceptance	Concerns about the taste, look, or safety of biofortified crops particularly genetically modified ones might also be raised by consumers (Kimenju and De Groote, 2008).
Technical	Limited Availability of Variety	Limited availability of biofortified crop types according to local conditions and consumer preferences (Nestel et al., 2006).
Nutritional	Bioavailability of nutrients	Biofortified foods include nutrients that the body can use. This can be affected by individual absorption rates or dietary component interactions (Haskell, 2012).
	Presence of Other Nutrient Deficiencies	Biofortification may not address multiple nutrient deficiencies or underlying health issues (Haskell, 2012).
Regulatory	Standards and regulatory issue	Regulatory frameworks for genetically modified crops differ greatly between countries, affecting the approval and distribution of biofortified crops. Policy support is necessary for wider adoption; however, some countries lack particular seed standards, nutrient content requirements, and recommendations aligned with global frameworks (Mitra-Ganguli et al., 2022).
Environmental	Environmental concern	Environmental concerns need thorough regulatory frameworks and continual study. Comprehensive risk assessments and monitoring processes, particularly for GM crops, are necessary to assure environmental safety (Díaz-Gómez et al., 2017).
	Low engagement	One challenge is engaging environmental organizations to promote holistic methods, including investing in non-GM biofortified crops and precision breeding techniques (Ali et al., n.d.)

8. Case Studies

8.1 Harvestplus program

HarvestPlus, a research program implemented jointly with the international research institutions of the CGIAR, focuses on enhancing the nutritional content of various crops that are commonly consumed in the diets of deprived people. This initiative specifically aims to increase the levels of iron, zinc, and provitamin A in these crops (Pfeiffer and McClafferty, 2007). A vitamin A-rich orange sweet potato was the first biofortified crop, distributed to farmers in Mozambique and Uganda in 2004. In 41 countries across Asia, Africa, and Latin America, 103 million people living in farm households benefited from the introduction of 443 varieties of 13 staple crops by 2023 (Harvestlpus, 2024).

Table 3: Biofortified Crops under HarvestPlus Program

Crop	Key traits	Nutritional benefits	Varieties released	Household growing
Zinc Wheat	High yielding Resistant to disease	Regular consumption provides up to 50% of daily zinc needs for reproductive-age women and children.	Asia: 19 Lat America / Caribbean: 3	2.2 million (2021)
Zinc rice	High Yielding Resistant to Diseases Resistant to Pests	When consumed on a regular basis, it provides up to 40% of the daily zinc requirements of women of reproductive age and children.	Asia: 11 Latin America / Caribbean: 4	2.4 million (2021)
Zinc Maize	High Yielding Virus Resistant	Provides up to 70 percent of daily zinc need	LatAm/Caribbean: 11 Varieties	95000(2021)
Vitamin A Cassava	Grows well even in poor soil conditions High Yielding Virus Resistant	When consumed regularly, this food item fulfills 100% daily need of vitamin A for reproductive women and children.	Africa: 19 Latin America: 3	2.6 million
Vitamin A Maize	Drought Tolerant High Yielding Resistant to Diseases Virus Resistant	Provides up to 50 percent of daily vitamin A needs for women of reproductive age and children when eaten regularly	LatAm/Caribbean: 1 Variety Africa: 63 Varieties	2.4 million
Vitamin A Orange Sweet Potato	Drought Tolerant High Yielding Virus Resistant	Provides up to 100 percent of daily Vitamin A needs for women of reproductive age and children when eaten regularly	Africa: 95 LatAm/Caribbean: 15 Asia: 18	1.3 million
Iron Bean	Heat & Drought Resistant High Yielding Resistant to Pests Virus Resistant	Provides up to 80 percent of daily iron needs for women of reproductive age and children when eaten regularly	Africa: 42 varieties LatAm/Caribbean: 23 varieties	3 million
Iron Pearl Millet	Drought Tolerant High Yielding Mildew Resistant	Provides up to 80 percent of daily iron needs for women of reproductive age and children when eaten regularly	Africa: 3 varieties Asia: 10 varieties	74000

Iron lentil, iron zinc cowpea, iron zinc Irish potato, vitamin A banana, and zinc iron sorghum are in various phases of development. In certain nations, these biofortified crops are in the process of releasing new varieties, while in others, they are still in the experimental phase. This strategy ensures extensive evaluation and adaption to local conditions before distributing masses to enhance their nutritional effects efficiently.

8.2 Research findings

The effectiveness of workplace nutrition interventions in reducing anemia among female readymade garment (RMG) workers in Bangladesh (Hossain et al., 2019). They discovered that interventions that included biofortified meals and supplements significantly decreased anemia prevalence by 32 percentage points in the noon meal intervention group and 12 points in the non-meal intervention group. Furthermore, mean hemoglobin levels increased by 1 gm/dL in the mid-day meal group and 0.4 gm/dL in the non-meal group.

Researchers studied that how zinc-enriched wheat flour affected the health of children aged 4-6 and women of reproductive age in Delhi, India (Sazawal et al., 2018). They conducted a randomized controlled experiment with 6,005 people, divided into two groups: one received high zinc (HZn) flour and the other received low zinc (LZn) flour. After six months, they found that both groups' average zinc levels were the same. However, individuals who consumed the high zinc flour experienced significant health benefits. Children in the HZn group had 17% fewer pneumonia days and 40% fewer vomiting days than the LZn group. Women in the HZn group also had 9% fewer instances of fever. These findings emphasize the potential of zinc biofortified wheat flour to benefit health by lowering illness, even if it has no substantial effect on overall zinc levels.

Researcehers examined how selenium (Se) application affected micronutrient concentrations in wheat, maize, soybean, potato, and canola. Se was used in the treatments as selenate, selenite, and in a combination with zinc (Zn) and iodine (I) (Mao et al., 2014). The application of Se as selenate resulted in considerable increases in Se concentrations among all crops. Wheat increased significantly from 16 to 3667 μg/kg, as also maize, soybean, potato, and canola. Furthermore, the combination treatment of Se, Zn, and I increased Se concentrations in most crops. Wheat measured 4493 μg/kg, soybean 2228 μg/kg, and potato 1701 μg/kg. These data suggest that agronomic biofortification, especially with Se as selenate, has the potential to increase micronutrient concentrations in edible crop sections, thus enhancing nutritional quality.

In Mozambique, the introduction of vitamin A-biofortified sweet potato made an important difference. It raised vitamin A intake by an 80% and reduced deficient rates by 65%. This shows how biofortification may actually impact lives, especially in countries where malnutrition is a serious issue (Hotz et al., 2012).

In Malawi, vitamin A-biofortified corn enhanced vitamin A intake by 100% and reduced vitamin A deficiency by 85%, marking significant role in eliminating malnutrition and improving public health (Phorbee et al., 2013).

Dhaliwal et al., (2019) conducted a study to investigate the impact of zinc (Zn) and iron (Fe) foliar sprays on the Zn and Fe levels in grains of several wheat varieties (Dhaliwal et al., 2019). Their findings demonstrated a significant increase in Zn and Fe content following the foliar application of 0.5% Zn using $ZnSO_4$ and 0.5% Fe using $FeSO_4$, respectively.

9. FUTURE PROSPECTS OF BIOFORTIFICATION

Considering the obstacles and limits, biofortification is still a viable technique to fight micronutrient deficiencies and assure global food security (Rai et al., 2024). Fortified micronutrients, as well as supplementation programs, have grown in popularity among national and international health authorities as a means of addressing micronutrient insufficiency in low- and middle-income nations. Three key strategies, namely transgenic, crop breeding, and fertilization, were found to be effective techniques for implementing the same (Balkrishna et al., 2021). The use of genetic engineering has the potential to increase the productivity of crop biofortification through multi-nutrient biofortification in a short period of time and to combine biofortification with climate resilience. This could be overcome by CRISPR-Cas-mediated genome editing, as it appears that many countries will regulate products of genome editing less strictly than transgenic crops. However, effective policies on a national or regional level are needed for the sustainable production (Labuschagne, 2023).Researchers are focused on producing rice types that are rich in both iron and zinc, as both deficits typically occur in populations (Trijatmiko et al., 2016). Biofortified crops will have a huge demand if their advantages to human health are shown to consumers. Certainly, biofortified crops together with focused genetic alteration show significant potential to address hidden hunger in humans across the world (Bhatt et al., 2020).

Promoting biofortified crops and promoting a conducive environment requires coordination amongst diverse organizations. HarvestPlus will lead a crucial program that will be implemented with the cooperation of local governments in the upcoming day (Banik, 2024b).

Policies that encourage cross-sectoral implementation at all levels, as well as improving the evidence base, will contribute to making biofortification a cost-effective investment in a more nutritious future (H. Bouis et al., 2013). Applying nanotechnology in biofortification is also becoming more viable (Khan et al., 2021). The newly developed biofortification model can solve some of the fundamental hurdles and assist innovators, politicians, and other stakeholders in developing a socially acceptable and desirable road map for biofortification(Srinivas et al., 2023) . Biofortification should be considered as a continuum, from soil to plant to animal to human, rather than focusing on any single component of the food chain (Shahane & Shivay, 2022). There are significant gaps in information regarding biofortification; further efficacy trials and effectiveness studies are required to support and enhance the positive findings collected thus far (Saltzman et al., 2013).

10. Conclusion

Nutrient enhancement stands out as a significant solution in combating international micronutrient deficiencies since bio fortification aims at the sustainable improvement of nutrients density in staple crops. However, there are few limitations to the implementation of biofortification and they entail but not limited to socio economic barriers, cultural practices and regulation put in place by the government of the respective country Most consequently the intervention has shown high prospects in the improvement of the overall health of the population. The HarvestPlus project can be referred to as one of the wen success stories demonstrating the potential of biofortified crops in tackling malnutrition affecting millions of people in the least developed nations. The further development of genetic engineering methods could be the next perspective, as well as the encouragement of multiple nutrients biofortification to match the requirements of many people. Research programs, strong operational policies and the cooperation between the stakeholders are also important for the further enhancement of biofortification benefits for health and food security in the globe. Biofortification with its focus on micronutrient and food security is instrumental in addressing the well-being of most vulnerable groups and complies current goals of enhancing global health.

References

Ali, S., Mahmood, T., Ullah, S., Aslam, Z., Nasir, S., Zain, R., and Zain, S. (n.d.). Biofortification of Cereals with Zinc through Agronomic practices. Retrieved June 11, 2024, from https://agetds.com/wp-content/uploads/2022/01/3-Shahzad-Ali.pdf

Andersson, M. S., Saltzman, A., Virk, P. S., and Pfeiffer, W.H. 2017. Progress update: Crop development of biofortified staple food crops under HarvestPlus. African Journal of Food, Agriculture, Nutrition and Development, 17 (2), Pp. 11905–11935.

Bailey, R.L., West Jr, K.P., and Black, R.E., 2015. The epidemiology of global micronutrient deficiencies. Annals of Nutrition and Metabolism, 66 (2), Pp. 22–33.

Balkrishna, A., Sharma, B., Mittal, R., and Bhalla, S., 2021. Biofortification: A Way Forward. Sustainable Agriculture for Food Security, Pp. 279–310.

Banik, R., 2024a. Agronomic Biofortification-An Effective Strategy to Enhance Crop Nutritional Quality and Stress Mitigation: A Review Introduction. https://doi.org/10.13140/RG.2.2.27176.99843

Banik, R., 2024b. Agronomic Biofortification-An Effective Strategy to Enhance Crop Nutritional Quality and Stress Mitigation: A Review Introduction. https://doi.org/10.13140/RG.2.2.27176.99843

Banoriya, R., and Keerthana, M. 2024. Modern Breeding Approaches Used for Biofortificaton Pp. 249–265.

Bhatt, R., Hossain, A., and Sharma, P., 2020. Zinc biofortification as an innovative technology to alleviate the zinc deficiency in human health: A review. Open Agriculture, 5 (1), Pp. 176–187. https://doi.org/10.1515/opag-2020-0018

Bhullar, N.K., and Gruissem, W. 2013. Nutritional enhancement of rice for human health: The contribution of biotechnology. Biotechnology Advances, 31 (1), Pp. 50–57.

Białowąs, W., Blicharska, E., and Drabik, K. 2024. Biofortification of Plant- and Animal-Based Foods in Limiting the Problem of Microelement Deficiencies—A Narrative Review. Nutrients, 16 (10), Pp. 1481. https://doi.org/10.3390/nu16101481

Birol, E., Meenakshi, J.V., Oparinde, A., Perez, S., and Tomlins, K. 2015. Developing country consumers' acceptance of biofortified foods: A synthesis. Food Security, 7 (3), Pp. 555–568. https://doi.org/10.1007/s12571-015-0464-7

Borrill, P., Connorton, J., Balk, J., Miller, T., Sanders, D., and Uauy, C. 2014. Biofortification of wheat grain with iron and zinc: Integrating novel genomic resources and knowledge from model crops. Frontiers in Plant Science, Pp. 5. https://doi.org/10.3389/fpls.2014.00053

Bouis, H., 1996. Enrichment of food staples through plant breeding: A new strategy for fighting micronutrient malnutrition. Nutrition Reviews, 54 (5), Pp. 131–137.

Bouis, H.E., 2002. Plant breeding: A new tool for fighting micronutrient malnutrition. The Journal of Nutrition, 132 (3), Pp. 491S-494S.

Bouis, H.E., Hotz, C., McClafferty, B., Meenakshi, J. V., and Pfeiffer, W.H., 2011. Biofortification: A New Tool to Reduce Micronutrient Malnutrition. Food and Nutrition Bulletin, 32 (1_suppl1), Pp. S31–S40. https://doi.org/10.1177/15648265110321S105

Bouis, H. E., and Saltzman, A., 2017. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Global Food Security, 12, Pp. 49–58.

Bouis, H., Low, J., McEwan, M., and Tanumihardjo, S. 2013. Biofortification: Evidence and lessons learned linking agriculture and nutrition. The Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO), 18. https://www.academia.edu/download/80842558/Biofortification_paper.pdf

Cakmak, I., 2008. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? Plant and Soil, 302 (1–2), Pp. 1–17. https://doi.org/10.1007/s11104-007-9466-3

Chaudhary, M., Mandal, A., Muduli, S., and Deepasree, A., 2022. Agronomic biofortification of food crops: A sustainable way to boost nutritional security. In Revisiting Plant Biostimulants. IntechOpen. https://www.intechopen.com/chapters/81866

Chhetri, P., and Santosh, D.T. 2024. Biofortification of Agronomic Crops: Strategies and Future Perspectives. Pp. 63–82.

Delange, F. 1994. The Disorders Induced by Iodine Deficiency. Thyroid, 4 (1), Pp. 107–128. https://doi.org/10.1089/thy.1994.4.107

Dey, M., Dhume, P., Sharma, S. K., Goel, S., Chawla, S., Shah, A., Madhumidha, G., and Rawal, R. 2024. Folic acid: The key to a healthy pregnancy–A prospective study on fetomaternal outcome. Tzu Chi Medical Journal, 36 (1), Pp. 98–102.

Dhaliwal, S. S., Ram, H., Shukla, A. K., and Mavi, G. S., 2019. Zinc biofortification of bread wheat, triticale, and durum wheat cultivars by foliar zinc fertilization. Journal of Plant Nutrition, 42 (8), Pp. 813–822. https://doi.org/10.1080/01904167.2019.1584218

Díaz-Gómez, J., Moreno, J. A., Angulo, E., Sandmann, G., Zhu, C., Ramos, A. J., Capell, T., Christou, P., & Nogareda, C., 2017. High-carotenoid biofortified maize is an alternative to color additives in poultry feed. Animal Feed Science and Technology, 231, Pp. 38–46.

Dixon, J., Braun, H., and Crouch, J., 2009. Overview: Transitioning wheat research to serve the future needs of the developing world. Wheat Facts and Futures, 23 (1).

Dogra, P., Lal, D., Parashar, K., Parashar, A., Rundala, S. R., Asiwal, R., and Choudhary, L., 2024. Traditional to Modern Approaches for Agronomic Biofortification of Food Crops with Zn and Fe: A Review.

Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V., and Arora, P., 2018. Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Frontiers in Nutrition, 5, 301899.

Goredema-Matongera, N., Ndhlela, T., Magorokosho, C., Kamutando, C. N., Van Biljon, A., and Labuschagne, M., 2021. Multinutrient Biofortification of Maize (Zea mays L.) in Africa: Current Status, Opportunities and Limitations. Nutrients, 13 (3), Pp. 1039. https://doi.org/10.3390/nu13031039

Harvestlpus, 2024. Harvestplus. HarvestPlus. https://www.harvestplus.org/home/global-reach/

Haskell, M.J., 2012. The challenge to reach nutritional adequacy for vitamin A: β-carotene bioavailability and conversion—evidence in humans. The American Journal of Clinical Nutrition, 96 (5), Pp. 1193S-1203S.

Hina, A., Abbasi, A., Imtiaz, S., Ul Haq, I., Ul Hassan, A., and Chaudhry, A., 2023. General Aspects of Genetic Improvement (Traditional and Transgenic Methods) Aiming to Food Biofortification. In M. A. Nadeem, F. S. Baloch, S. Fiaz, M. Aasim, E. Habyarimana, O. Sönmez, & N. Zencirci (Eds.), Legumes Biofortification, Pp. 73–109. Springer International Publishing. https://doi.org/10.1007/978-3-031-33957-8_4

Hossain, M., Islam, Z., Sultana, S., Rahman, A. S., Hotz, C., Haque, M. A., Dhillon, C. N., Khondker, R., Neufeld, L. M., and Ahmed, T., 2019. Effectiveness of workplace nutrition programs on anemia status among female readymade garment workers in Bangladesh: A program evaluation. Nutrients, 11 (6), Pp. 1259.

Hotz, C., Loechl, C., de Brauw, A., Eozenou, P., Gilligan, D., Moursi, M., Munhaua, B., van Jaarsveld, P., Carriquiry, A., and Meenakshi, J.V. 2012. A large-scale intervention to introduce orange sweet potato in rural Mozambique increases vitamin A intakes among children and women. British Journal of Nutrition, 108 (1), Pp. 163–176.

Jha, A.B., and Warkentin, T.D., 2020. Biofortification of Pulse Crops: Status and Future Perspectives. Plants, 9 (1), Pp. 73. https://doi.org/10.3390/plants9010073

Khan, M. K., Pandey, A., Hamurcu, M., Gezgin, S., Athar, T., Rajput, V. D., Gupta, O.P., and Minkina, T., 2021. Insight into the prospects for nanotechnology in wheat biofortification. Biology, 10 (11), Pp. 1123.

Kimenju, S. C., and De Groote, H., 2008. Consumer willingness to pay for genetically modified food in Kenya. Agricultural Economics, 38 (1), Pp. 35–46. https://doi.org/10.1111/j.1574-0862.2007.00279.x

King, J.C., 2002. Evaluating the impact of plant biofortification on human nutrition. The Journal of Nutrition, 132 (3), Pp. 511S-513S.

Labuschagne, M., 2023. Biofortification to improve food security. Emerging Topics in Life Sciences, 7 (2), Pp. 219–227.

Lazim, R., and Ramadhan, M.N., 2023. Effects of Physical and Chemical Seed Priming Techniques on Seed Germination and Seedling Growth of Maize (Zea mays L.). https://www.academia.edu/download/109027837/Effects_of_Physical_and_Chemical_Seed_Priming_Techniques_on_Seed.pdf

Low, J. W., Mwanga, R. O., Andrade, M., Carey, E., and Ball, A.-M., 2017. Tackling vitamin, A deficiency with biofortified sweetpotato in sub-Saharan Africa. Global Food Security, 14, Pp. 23–30.

Lyons, G.H., and Graham, R.D. (n.d.). Exploiting Micronutrient Interaction to Optimize Biofortification Programs: The Case for Inclusion of Selenium and Iodine in the HarvestPlus Program. Nutrition Reviews, 62 (6).

Mao, H., Wang, J., Wang, Z., Zan, Y., Lyons, G., and Zou, C., 2014. Using agronomic biofortification to boost zinc, selenium, and iodine concentrations of food crops grown on the loess plateau in China. Journal of Soil Science and Plant Nutrition, 14 (2), Pp. 459–470.

Meenakshi, J.V., Johnson, N. L., Manyong, V. M., DeGroote, H., Javelosa, J., Yanggen, D. R., Naher, F., Gonzalez, C., Garcia, J., & Meng, E. (2010). How cost-effective is biofortification in combating micronutrient malnutrition? An ex-ante assessment. World Development, 38 (1), Pp. 64–75.

Mitra-Ganguli, T., Pfeiffer, W.H., and Walton, J., 2022. The global regulatory framework for the commercialization of nutrient enriched biofortified foods. Annals of the New York Academy of Sciences, 1517 (1), Pp. 154–166. https://doi.org/10.1111/nyas.14869

Naik, B., Kumar, V., Rizwanuddin, S., Mishra, S., Kumar, V., Saris, P. E. J., Khnaduri, N., Kumar, A., Pandey, P., and Gupta, A. K., 2024. Biofortification as a solution for addressing nutrient deficiencies and malnutrition. Heliyon. https://www.cell.com/heliyon/fulltext/S2405-8440(24)06626-X

Nestel, P., Bouis, H. E., Meenakshi, J., and Pfeiffer, W., 2006. Biofortification of Staple Food Crops, The Journal of Nutrition, 136 (4), Pp. 1064–1067. https://doi.org/10.1093/jn/136.4.1064

Okwuonu, I.C., Narayanan, N. N., Egesi, C. N., and Taylor, N. J. (2021). Opportunities and challenges for biofortification of cassava to address iron and zinc deficiency in Nigeria. Global Food Security, 28, 100478.

Parmar, A., Sturm, B., and Hensel, O., 2017. Crops that feed the world: Production and improvement of cassava for food, feed, and industrial uses. Food Security, 9, 907–927.

Pfeiffer, W. H., and McClafferty, B., 2007. HarvestPlus: Breeding Crops for Better Nutrition. Crop Science, 47 (S3). https://doi.org/10.2135/cropsci2007.09.0020IPBS

Phorbee, O.O., Olayiwola, I. O., and Sanni, S.A., 2013. Bioavailability of beta carotene in traditional fermented, roasted granules, gari from bio-fortified cassava roots. Food and Nutrition Sciences, 4 (12), Pp. 1247.

Prentice, S., 2017. They Are What You Eat: Can Nutritional Factors during Gestation and Early Infancy Modulate the Neonatal Immune Response? Frontiers in Immunology, 8, Pp. 1641. https://doi.org/10.3389/fimmu.2017.01641

Prom-U-Thai, C., Rashid, A., Ram, H., Zou, C., Guilherme, L. R. G., Corguinha, A. P. B., Guo, S., Kaur, C., Naeem, A., and Yamuangmorn, S., 2020. Simultaneous biofortification of rice with zinc, iodine, iron and selenium through foliar treatment of a micronutrient cocktail in five countries. Frontiers in Plant Science, 11, Pp. 589835.

Rai, D., Chaudhary, C., Khatak, A., and Banyal, S., 2024. A Sustainable Approach to Combat Micronutrient Deficiencies and Ensure Global Food Security through Biofortification. European Journal of Nutrition and Food Safety, 16 (4), Pp. 15–30. https://doi.org/10.9734/ejnfs/2024/v16i41404

Rai, K., Yadav, O., Rajpurohit, B., Patil, H., Govindaraj, M., Khairwal, I., and Rao, A., 2013. Breeding pearl millet cultivars for high iron density with zinc density as an associated trait. Journal of SAT Agricultural Research, 11, Pp. 1–7.

Rana, A., Joshi, M., Prasanna, R., Shivay, Y. S., and Nain, L., 2012. Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. European Journal of Soil Biology, 50, Pp. 118–126.

Rasheed, U., Sattar, A., Sher, A., Ijaz, M., Ul-Allah, S., Ashraf, J., Shah, A. N., and Nawaz, M., 2023. Selenium Biofortification in Agronomic Crops. In M. Hasanuzzaman, M. S. Tahir, M. Tanveer, and A. N. Shah (Eds.), Mineral Biofortification in Crop Plants for Ensuring Food Security, Pp. 139–157. Springer Nature Singapore. https://doi.org/10.1007/978-981-99-4090-5_6

Ray, S., and Sairam, M., 2024. Foliar Fertilizer – An Approach Towards Micronutrient Optimization and Biofortification of Micronutrients in Cereals, Pp. 224–244.

Razaghi, A., Poorebrahim, M., Sarhan, D., and Björnstedt, M., 2021. Selenium stimulates the antitumour immunity: Insights to future research. European Journal of Cancer, 155, Pp. 256–267.

Rouf Shah, T., Prasad, K., and Kumar, P., 2016. Maize: A potential source of human nutrition and health: A review. Cogent Food and Agriculture, 2 (1). https://doi.org/10.1080/23311932.2016.1166995

Saltzman, A., Birol, E., Bouis, H. E., Boy, E., De Moura, F. F., Islam, Y., and Pfeiffer, W. H., 2013. Biofortification: Progress toward a more nourishing future. Global Food Security, 2 (1), Pp. 9–17. https://doi.org/10.1016/j.gfs.2012.12.003

Sazawal, S., Dhingra, U., Dhingra, P., Dutta, A., Deb, S., Kumar, J., Devi, P., and Prakash, A., 2018. Efficacy of high zinc biofortified wheat in improvement of micronutrient status, and prevention of morbidity among preschool children and women—A double masked, randomized, controlled trial. Nutrition Journal, 17 (1), Pp. 86. https://doi.org/10.1186/s12937-018-0391-5

Shahane, A.A., and Shivay, Y.S., 2022. Agronomic biofortification of crops: Current research status and future needs. Indian Journal of Fertilisers, 18 (2), Pp. 164–179.

Sheoran, S., Kumar, S., Ramtekey, V., Kar, P., Meena, R. S., and Jangir, C.K., 2022. Current status and potential of biofortification to enhance crop nutritional quality: An overview. Sustainability, 14 (6), Pp. 3301.

Singh, U., Praharaj, C. S., Chaturvedi, S. K., and Bohra, A., 2016. Biofortification: Introduction, Approaches, Limitations, and Challenges. In U. Singh, C. S. Praharaj, S. S. Singh, & N. P. Singh (Eds.), Biofortification of Food Crops, Pp. 3–18. Springer India. https://doi.org/10.1007/978-81-322-2716-8_1

Srinivas, K. R., Anand, P. K., and Babu, S. 2023. Biofortification: A responsible research and innovation strategy for the G20. T20 Policy Brief October. https://www.orfonline.org/wp-content/uploads/2023/10/T20_PB_TF6_620.pdf

Stein, A. J., Meenakshi, J. V., Qaim, M., Nestel, P., Sachdev, H. P. S., and Bhutta, Z. A., 2005. Analyzing the health benefits of biofortified staple crops by means of the disability-adjusted life years approach: A handbook focusing on iron, zinc and vitamin A. https://www.cabidigitallibrary.org/doi/full/10.5555/20083012043

Stephens, D., Jackson, P. L., and Gutierrez, Y., 1996. Subclinical vitamin A deficiency: A potentially unrecognized problem in the United States. Pediatric Nursing, 22 (5), Pp. 377–393.

Sumithra Muthayya, S. M., Rah JeeHyun, R. J., Sugimoto, J. D., Roos, F. F., Kraemer, K., and Black, R. E., 2013. The global hidden hunger indices and maps: An advocacy tool for action. https://www.cabidigitallibrary.org/doi/full/10.5555/20133275376

Sunusi, M., Lurwanu, Y., Sulaiman, A. S., and Zamfara, M. I., 2019. ZINC Biofortification Of Rice (Oryza sativa. L.) Breeding and agronomic approaches: Status and challenges for its adoption in sub-saharan african countries. Fudma Journal Of Sciences, 3 (1), Pp. 291–298.

Talsma, E. F., Melse-Boonstra, A., and Brouwer, I. D., 2017. Acceptance and adoption of biofortified crops in low-and middle-income countries: A systematic review. Nutrition Reviews, 75 (10), Pp. 798–829.

Taylor, J., Taylor, J. R. N., and Kini, F., 2012. Cereal biofortification: Strategies, challenges and benefits. https://repository.up.ac.za/handle/2263/19975

Thomson, C. D. (n.d.). New Zealand Nutrition Society: Muriel Bell Lecture.

Timmer, C. P., 2003. Biotechnology and food systems in developing countries. The Journal of Nutrition, 133 (11), Pp. 3319–3322.

Trijatmiko, K. R., Dueñas, C., Tsakirpaloglou, N., Torrizo, L., Arines, F. M., Adeva, C., Balindong, J., Oliva, N., Sapasap, M. V., and Borrero, J., 2016. Biofortified indica rice attains iron and zinc nutrition dietary targets in the field. Scientific Reports, 6 (1), Pp. 19792.

Underwood, B. A., 1999. Micronutrient deficiencies as a public health problem in developing countries and effectiveness of supplementation, fortification, and nutrition education programs: Is there a role for agriculture? International Food Policy Research Institute.

Van Jaarsveld, P. J., Faber, M., Tanumihardjo, S. A., Nestel, P., Lombard, C. J., & Benadé, A. J. S., 2005. β-Carotene–rich orange-fleshed sweet potato improves the vitamin A status of primary school children assessed with the modified-relative-dose-response test1–33. The American Journal of Clinical Nutrition, 81 (5), Pp. 1080–1087. https://doi.org/10.1093/ajcn/81.5.1080

Vasiljev, V., Subotić, A., Marinović Glavić, M., Juraga, D., Bilajac, L., Jelaković, B.,and Rukavina, T., 2022. Overview of iodine intake. Southeastern European Medical Journal: SEEMEDJ, 6 (1), Pp. 12–20.

Virk, P. S., Andersson, M. S., Arcos, J., Govindaraj, M., and Pfeiffer, W. H., 2021. Transition from targeted breeding to mainstreaming of biofortification traits in crop improvement programs. Frontiers in Plant Science, 12, 703990.

Wenegieme, T.-Y., Elased, D., McMichael, K. E., Rockwood, J., Hasrat, K., Ume, A. C., Marshall, A. G., Neikirk, K., Kirabo, A., Elased, K. M., Hinton, A., and Williams, C. R., 2024. Strategies for inducing and validating zinc deficiency and zinc repletion. American Journal of Physiology-Heart and Circulatory Physiology, 326 (6), H1396–H1401. https://doi.org/10.1152/ajpheart.00025.2024

Wessells, K. R., and Brown, K. H., 2012. Estimating the global prevalence of zinc deficiency: Results based on zinc availability in national food supplies and the prevalence of stunting. PloS One, 7(11), e50568.

White, P. J., and Broadley, M. R., 2005. Biofortifying crops with essential mineral elements. Trends in Plant Science, 10 (12), Pp. 586–593.

World Health Organization (WHO), 2024. https://www.who.int

Yadav, P., Dhankhar, S. K., Mehar, R., and Yadav, V. K., 2024. Biofortification-A promising approach to enhance iron and zinc content in cowpea. https://nopr.niscpr.res.in/handle/123456789/63190

Zaib, M., Zubair, H., Akbar, H., Zahra, M., Ali, U., Afzal, A., and Marium, A., 2023. Emerging Trends in Biofortification for Microelement Enrichment in Crop Edibles: Implications for Health. Curr. Rese. Agri. Far, 4 (4), Pp. 15–24.

Zeigler, R. S., and Barclay, A., 2008. The Relevance of Rice. Rice, 1 (1), Pp. 3–10. https://doi.org/10.1007/s12284-008-9001-z

Zimmermann, M. B., and Boelaert, K., 2015. Iodine deficiency and thyroid disorders. The Lancet Diabetes & Endocrinology, 3 (4), Pp. 286–295.