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REVIEW ARTICLE

BIOFORTIFICATION: A STRATEGY TO COMBAT MICRONUTRIENT DEFICIENCY

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ABSTRACT

Micronutrient deficiency is a condition in which body lacks essential vitamins and minerals for proper growth and development. These nutrients are required by our body in small quantities. Micronutrient deficiency is commonly known as "hidden hunger" because it lacks visible sign at the early stages but can lead to poor health over time. In developing countries, micronutrient deficiency is more common. These micronutrients include vitamins (A, B, C, D, E, K), minerals (Iron, Calcium, Phosphorus, Iron, Zinc, Selenium and so on). The two-year-long COVID-19 pandemic refocused attention on micronutrition, with food fortification and micronutrient supplementation playing a prominent role in public health measures. Agronomic biofortification, which involves using fertilizers and other inputs to enrich crops with mineral micronutrients, is one of the solutions that has gained popularity because of its fast results and importance in the face of challenges like pandemics and climate change. Biofortification by agronomic, genetic, and transgenic approaches provides a sustainable solution to micronutrient deficiencies. Thus, the goal of biofortification is to increase the amounts of micronutrients in crops in order to improve their nutritional quality.

KEYWORDS

Micronutrient deficiency, hidden hunger, developing countries, Biofortification

1. INTRODUCTION

Hidden hunger, or chronic malnutrition, affects about two billion people worldwide and is associated with reduced cognitive function, stunted growth, and an increased risk of death (Sheoran et al., 2022). The Food and Agriculture Organization of the United Nations estimates that roughly 792.5 million people globally are malnourished, with approximately 780 million of them living in developing nations (McGuire, 2015). Micronutrient deficiency is generally caused by an insufficient supply or low quality of important nutrients in the daily diet (Mahto et al., 2022). Vegetables provide essential nutrients, and the Indian Council of Medical Research (ICMR) advises that individuals, regardless of their dietary preferences, should aim to consume 300 grams of vegetables daily. This includes 125 grams of leafy greens, 100 grams of tubers, and 75 grams of other varieties. To combat malnutrition, nutraceuticals can be utilized to enhance nutritional security through micronutrient supplementation. Biofortification serves as an economical method to elevate the nutrient levels in food crops, thereby producing more nutritious food for a vast population while optimizing land use. Additionally, biofortified crops can be transformed into 'designer foods' with enhanced nutrient profiles through genetic engineering and traditional breeding techniques (Sharma and Singh, 2020). Biofortification is an innovative approach to addressing common vitamin and mineral deficiencies by enhancing the nutritional value of crops. The word itself essentially means "strengthening life" and has Latin and Greek roots (Tripathy et al., 2020). Increasing the levels of micronutrients like zinc (Zn) and iron (Fe) in commonly consumed foods is crucial because of population requirements and nutritional supply imbalances, unequal distribution, differences in micronutrient bioavailability from foods, and restricted access to biofortified products. A multimodal strategy is required to address Zn and Fe shortages through biofortification, which includes raising soil mineral content, promoting plant uptake, boosting accumulation in edible crop sections, and ensuring adequate absorption in the human body (Shahane and Shivay, 2022).

Enhancing the micronutrient content in crops can be achieved through three primary methods: genetic engineering, conventional plant breeding, and agricultural strategies such as optimized fertilizer application. Although genetic engineering has been explored across various crop types, conventional breeding remains the most commonly employed method in actual biofortification efforts (Rasheed et al., 2023).

2. METHODS OF BIOFORTIFICATION

2.1 Agronomic biofortification

Agronomic biofortification comprises the direct administration of nutrients to plants, resulting in a temporary improvement in their nutritional and health quality, which, when consumed, helps to enhance human nutrition (Cakmak and Kutman, 2018a). Agronomic biofortification is regarded as one of the most effective strategies for combating micronutrient malnutrition because it increases mineral content in crops while also improving mineral bioavailability by reducing antinutritional factors and/or increasing levels of compounds that promote mineral absorption (Szerement et al., 2022). To enhance the concentration of essential nutrients in the edible parts of crops, agronomic biofortification utilizes fertilizers that are high in micronutrients. The primary micronutrients focused on by this technique include selenium (applied as selenium), iodine (administered through soil application of iodide or iodate), and zinc (generally applied via foliar sprays of $ZnSO_4$). Introducing micronutrients such as iron, zinc, and copper to plants through foliar application is considered a rapid and efficient strategy. Mycorrhizal fungi have been observed to significantly increase the levels of selenium, iron, copper, and zinc in crops due to their capacity to improve nutrient uptake. Additionally, it has been found that utilizing sulfur-oxidizing bacteria enhances the sulfur content in onions (Tripathy et al., 2020). Several factors influence the success of agronomic biofortification, as a significant proportion of nutrients are lost during the evolution from soil to plant, plant to edible food, and finally to human ingestion (Mohd

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Daud et al., 2016). Using expensive mineral fertilizers in agronomic biofortification boosts the cost of biofortified crops, limiting their accessibility to economically disadvantaged groups (Cakmak and Kutman, 2018b).

2.2 Conventional plat breeding

The most widely accepted approach to biofortification is conventional breeding, which provides a sustainable and economical substitute for agronomic and transgenic techniques. Plants with a high nutrient content and exceptional agronomic qualities are produced by crossing nutrient-rich parent lines with recipient lines that possess acceptable agronomic traits over many generations (Garg et al., 2018). In the past forty years, the primary objective of conventional plant breeding has been to enhance crop productivity and resistance to pests and diseases. Regrettably, this frequently implied that the nutritional quality of the crops was neglected. Consequently, numerous crop varieties currently have lower levels of iron, zinc, copper, and magnesium. Nevertheless, there is an increasing movement to emphasize the nutritional value of crops by boosting their amounts of vital vitamins, antioxidants, and micronutrients. This is accomplished by selecting inherently nutritious plant varieties from seed banks and hybridizing them with high-yielding varieties. To ensure that the resultant crops are genuinely more nutritious, nutritionists ought to be involved in supervising the breeding procedure (Tripathy et al., 2020).

2.3 Genetic engineering and transgenesis

Advanced methods of genetic engineering, including gene editing, transgenic techniques, and others, present significant opportunities for enhancing the nutritional quality of crops and tackling the deficiency of vital micronutrients (Tien Lea et al., 2016). Plant breeders can utilize genetically modified (GM) or transgenic crops to incorporate desired genes into high-quality varieties that were not previously accessible, thereby increasing their value. This approach presents unique benefits regarding the management of viruses, pests, and other detrimental organisms, as well as enhancing the nutritional content and health advantages of crops. In cases where a plant species has restricted natural genetic diversity for certain traits, or when traditional breeding methods are infeasible due to reproductive challenges, genetic engineering offers an effective solution to improve the concentration and bioavailability of micronutrients in the edible parts of the plant (Tripathy et al., 2020). Researchers have used biotechnology to create crops that are rich in iron, zinc, and beta-carotene, which the body uses to make vitamin A. Despite being essential for human health, people in developing countries usually do not get these nutrients in their diets. The introduction of golden rice, a type fortified with vitamin A to help minimize vitamin A deficiency in some areas, is a well-known example. Although there is much potential for improving the nutritional value of crops using this method, it is still up for debate, and more study is required to fully evaluate the risks and potential effects (Avnee et al., 2023).

3. ZINC BIOFORTIFICATION

A major public health concern, zinc (Zn) insufficiency affects over 17% of the world's population, with Africa and Asia having the highest prevalence (24% and 19%, respectively) (Chasapis et al., 2020). The worldwide average concentration of zinc (Zn) in wheat grains is 28. 2 mg/kg, with a range from 5. 0 to 82. 0 mg/kg. North America boasts the highest average at 34. 0 mg/kg, while Africa, Oceania, and South America share the lowest average at 18. 4 mg/kg. In contrast, Asia and Europe have average values of roughly 28. 0 mg/kg. This difference in zinc content among regions highlights the significance of biofortification in tackling deficiencies in micronutrients (Hui et al., 2025). Zinc fertilizer application influences Zn concentrations in wheat grains in various ways. Foliar or a mix of soil and foliar applications enhance grain Zn levels more effectively compared to soil applications alone. 1 Soil treatment elevated Zn by 29. 1% (5. 1 mg/kg), yet most grains still did not meet the nutritional requirement of 40 mg/kg. Foliar and combined methods raised Zn levels by 55. 2% (16. 2 mg/kg) and 62. 3% (15. 9 mg/kg, respectively), enabling roughly 67% of grains to meet the demand. Therefore, foliar and combined treatments are more effective for boosting grain Zn and addressing human zinc deficiency through biofortification (Hui et al., 2025).

4. SELENIUM BIOFORTIFICATION

As a vital mineral with important physical and antioxidant properties, studies have shown that selenium stimulates plant development and may mitigate the impacts of heavy metals (Adeel et al., 2019). Fertilization methods can be categorized into root fertilization and foliar fertilization, depending on the route by which plants take in nutrients (Niu et al., 2021).

Delivering nutrients directly to the above-ground parts of the plant, foliar fertilization minimizes the adverse impacts of fertilization on the soil and functions as an alternative approach (Fernandez and Eichert, 2009). It was observed that the use of selenium through foliar methods (0–40 μM) increased the selenium levels in the leaves of two lettuce varieties with different pigmentation, with the red variety demonstrating a 57% greater accumulation of selenium in comparison to the green variety. However, all selenium treatments caused a 9% decrease in the fresh weight of green lettuce, whereas the concentrations of 32 and 40 μM resulted in a reduction in the fresh weight of red lettuce by 11% and 22%, respectively (Pannico et al., 2019).

Marker-assisted breeding may be utilized to incorporate high-selenium chromosomal areas from high-yielding yet low-selenium edible plant varieties into breeding populations (Wu et al., 2015). One significant drawback of conventional and marker-assisted plant breeding is the requirement for extra agronomic biofortification, particularly the use of selenium fertilizers, in areas where the natural selenium content in the soil is minimal (Wang et al., 2017).

5. IRON BIOFORTIFICATION

In humans, iron (Fe) plays a crucial role in growth, development, and numerous physiological functions, such as facilitating the transport of oxygen from the lungs to body tissues, aiding in the development of the immune system, and synthesizing proteins that carry oxygen, including hemoglobin and myoglobin (Jomova et al., 2022). Using traditional breeding methods, the International Rice Research Institute (IRRI) created a biofortified rice variety that, after processing and boiling, has five times the iron content (3.21 μg/g dry weight) of locally available kinds in the Philippines (Gregorio, 2001). 192 non-anemic Filipino women who consumed this biofortified variety on a daily basis for nine months improved their iron status by 20% (as determined by ferritin levels and body iron). However, it only increased their iron consumption from 46% to 56% of the recommended daily allowance (Haas et al., 2005).

Iron deficiency is uncommon in mineral soils due to its low solubility, particularly in calcareous soils that have elevated pH and bicarbonate (HCO_3^-) concentrations, which restricts its accessibility (Aciksoz et al., 2011). In case of conventional breeding, improvements in traits like iron (Fe) accumulation have been slower. Navigating the complex regulatory networks that control Fe homeostasis is crucial for efficient biofortification in order to raise Fe concentrations in specific plant tissue.

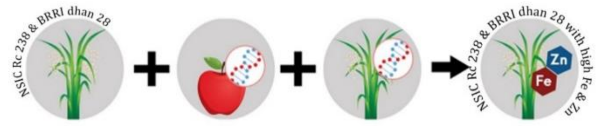

Figure: Biofortified rice with high iron and zinc

Source: https://www.irri.org/biofortification

6. IODINE BIOFORTIFICATION

Iodine deficiency is a serious global health issue, and it is recognized as the primary cause of intellectual disability. It is a common cause of thyroid issues such as goiters and underactive thyroid. The hazards are especially high during pregnancy, when inadequate iodine can cause brain damage in the unborn child and influence the baby's development through breastfeeding (Patrick, 2008). The food chain carries iodine from plants to humans, so biofortifying crops is a key strategy to guarantee that people consume adequate amounts of this essential nutrient. The capacity of plants to absorb and store iodine, as well as the amount of bioavailable iodine in the soil and water, largely determine how much iodine is present in food (Jaiwal et al., 2019). Using inorganic iodine salts to raise iodine levels in crops is the most researched method. Specialized transport proteins allow plants to absorb iodate (IO_3^-) and iodide (I^-) from soil or nutrient solutions. Iodate is generally a more effective soil amendment than iodide at increasing plant iodine levels. This is most likely because iodate has a higher stability and delivers iodine to plants more effectively (Lawson et al., 2015).

6.1 Agronomic biofortification of crops

Crop	Treatment	References
Rice	Microbial application to biofortify wheat with selenium and iron Increased selenium and iron uptake in wheat	(Li et al., 2024)
Wheat	Foliar + soil application of zinc sulfate and/or iron sulfate Improved wheat performance under water deficit	(Bana et al., 2022a)
Tomato	Selenium Sodium selenite (5 mg L^{-1}) Boosted selenium accumulation in tomato by 53%	(Rahim et al., 2020)
Cowpea	Four foliar application levels (0, 25, 50, and 100 μM L^{-1}) of both iron chelates and ferrous sulfate	(Márquez-Quiroz et al., 2015)
Eggplant	Foliar application of MNENPK (N, P, K, Fe, Zn, B) Increased fruit nutrients (Fe +26%, Zn +34%)	(Bana et al., 2022b)
Chickpea	Foliar $FeSO_4 \cdot 7H_2O$ application Raised grain iron by 21–22%	(Hidoto et al., 2017)
Lentil	Pre-flowering foliar $ZnSO_4 \cdot 7H_2O$ (0.5%) Raised grain Zn by 10.5 mg/kg	(Dhaliwal et al., 2021)
Potato	Application of KIO_3 at 2.0 kg iodine/ha Enhanced iodine content in potato	(Ledwożyw-Smoleń et al., 2020)
Broccoli	Soil+foliar treatment Increased growth and Zn content in florets and leaves	(Rivera-Martin et al., 2020)
Quinoa	Fe applied by root, foliar spray, combined root and foliar Improved growth, productivity, Fe, protein, ascorbic acid, and manganese	(Lata-Tenesaca et al., 2023)

7. SCOPES OF BIOFORTIFICATION

7.1 Improve the nutrition of rural populations

Biofortified crops are excellent way to provide necessary nutrients to rural populations that often lack access to varied diets and organized nutrition programs. These crops are created with a particular micronutrient profile that is precisely suited to the nutritional requirements of women and children, considering their typical eating habits (Bouis and Saltzman, 2017).

7.2 Economic sustainability

An additional important benefit of biofortification is its financial advantage. After the investment in creating nutrient-dense plant varieties is made, subsequent costs remain low. These enhanced seeds can be exchanged among nations, and after farmers adopt them, they can preserve the seeds and cultivate biofortified crops annually. This ongoing usage over time and in various regions generates economies of scale, rendering biofortification a highly sustainable and cost-effective method (Stein, 2010).

7.3 Cost effectiveness

The World Bank in 2010 identifies biofortification as one of the most economically efficient public health strategies, costing only about $15 to $20 per disability-adjusted life year (DALY) averted (Bouis and Saltzman, 2017)

8. CHALLENGES

8.1 GM Crop Perception

The possible health effects of genetically modified (GM) crops have been the subject of an ongoing discussion. The advantages of using genetically modified seeds are not widely understood. In rural India, a large number of farmers hold the view that genetically modified crops are dangerous to consume as a result of these continuous debate (Chaudhary et al., 2024). Despite the pressing need to address widespread vitamin A deficiency, Golden Rice took 15 years to receive regulatory approval, highlighting these difficulties. This regulatory burden is particularly noticeable in Africa, where systems are costly, opaque, and excessively cautious. The established risks of current nutritional deficiencies may be outweighed by regulatory caution (Shohael et al., 2025)

8.2 Balancing micronutrient absorption and antinutrients

Iron absorption has traditionally been improved by lowering antinutritional substances like phytic acid and polyphenols. It is crucial to create alternate biofortification techniques that can increase iron absorption without negating the positive effects of these compounds, though, because they also provide health advantages like antioxidant qualities and support for gut health (Singh et al., 2016).

8.3 Gaps in Evidence on Public Health Impact

While it is known that food fortification increases nutrient intake and improves nutrient status in the body, there is still little data showing how it affects observable health outcomes like disease prevention, cognitive development, and child growth (Das et al., 2013).

8.4 Inequitable Access for Low-Income Populations

Although the goal of mass fortification programs is usually to benefit the entire population, the poorest people are often not adequately reached. Additional costs like import taxes on fortification supplies and equipment may make fortified products unaffordable for low-income households (Darnton-Hill et al., 2005).

9. CONCLUSION

Micronutrient deficiency, commonly called as "hidden hunger," remains as significant worldwide health concern, especially in developing countries where access to nutrient-rich foods is limited. Biofortification offers a sustainable and cost-effective approach to combat this by enriching the nutritional content of staple crops through agronomic methods, traditional breeding, and genetic engineering. Each technique provides distinct advantages: agronomic practices deliver immediate nutritional boosts, conventional breeding ensures long-term improvements, and genetic engineering allows for targeted nutrient enhancement, especially where genetic diversity is restricted. Examples like zinc-enriched wheat, selenium-fortified lettuce, and iron-rich rice highlight the efficacy of biofortified crops in addressing nutritional deficiencies. Despite these successes, obstacles like public resistance to genetically modified crops, the presence of antinutrients, a lack of comprehensive long-term health data, and uneven distribution to vulnerable populations continue to hinder progress. Therefore, realizing biofortification's full potential to alleviate hidden hunger and enhance global nutrition demands collaborative efforts across various fields, supportive policy frameworks, and fair distribution systems.

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