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REVIEW ARTICLE

Ameliorating nutrition through biofortification: A strategy to combat hidden hunger - A review

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Abstract

More than 60 % of the world population suffers from iron deficiency and over 30 % of the global population has zinc deficiency. Micronutrient deficiency leads to compromised health like stunted growth, weakened immunity, cognitive impairment and increased susceptibilty to infection and results in economic losses. It is prevalent in populations depending on non-diversified plant-based diets. The most common micronutrient deficiencies are vitamin A deficiency, iron deficiency anemia and iodine deficiency disorders, which affect one-third of the world's population. Food fortification is an important strategy endorsed by the World Health Organization to combat this public health challenge,also referred to as "hidden hunger" (an individual is suffering from micronutrient deficiency). Increasing mineral content of staple food crops through biofortification is a promising and sustainable strategy of combating micronutrient malnutrition. Additionally, it will also enhance the agronomic efficiency of crops on poor mineral soils. A multipronged strategy towards enhancing mineral content of cereal grains should involve increased uptake of minerals from soil, enhanced partitioning towards grain and improved sequestration in the edible tissues of grains. At the same time, it is essential to improve mineral absorption of minerals in the human body from cereal-based diets. Both conventional and modern breeding approaches and genetic engineering are being employed for biofortification of crop plants. With increased understanding of mineral uptake and transport mechanisms in plants, it is becoming ever more possible to engineer biofortified crop plants, with the ultimate goal of overcoming hidden hunger.

Keywords: biofortification; food fortification; health; hidden hunger; micronutrient

Introduction

The introduction effectively establishes the context around global micronutrient deficiency and introduces biofortification as a solution (1). Despite advances in food production, an estimated two billion people worldwide-particularly in low-income countries -suffer from micronutrient malnutrition, also known as "hidden hunger" (2). This condition arises from the inadequate intake or poor bioavailability of key micronutrients such as vitamin A, iron, zinc and calcium. Micronutrient deficiencies can affect individuals of all ages across both developed or developing countries (3).

The most affected populations are found in regions of Africa, South Asia and Latin America, where diets are often monotonous and heavily plant-based (4). Whereas, rapid food might be relief from starvation, but there is an extensive problem of "hidden hunger" which is one and only satisfied by nutritionally enriched food. However, an individual has balanced diet is a far-fetched dream for the unprivileged people of the world (5). Moreover, micronutrient deficiencies are a silent epidemic situation which steadily diminish the immune system, hinders intellectual and physical growth and even leads to death. Hidden hunger is often termed as a "silent epidemic" as its impacts-impaired immunity, stunted growth, cognitive delays and increased mortality -are not always immediately visible (6).

Common deficiencies, including iron deficiency anemia (IDA), zinc deficiency, iodine deficiency and vitamin A deficiency, are widespread and not restricted to developing nations. Reports indicate rising incidences even in developed countries like the USA, Canada and across Europe (7, 8). These deficiencies often result from poor dietary intake and low nutrient absorption or assimilation (9, 10). Thus, the consequences of malnutrition as well as hidden hunger became rigorous; both of them had been calamitous especially among newborns evaluated annually 1.1 million out of 3.1 million infantile death allocated to deficiency of micronutrients (11, 12). To combat these deficiencies, food fortification strategies have been implemented globally, including supplementation, dietary diversification and modification of food processing systems (6).

According to World Health Organization (WHO) as well as Food and Agriculture Organization (FAO) of the United Nations, 149 million children under 5-years of age are stunted, 47 million are wasted including 462 million are underweight; moreover 50 % child deaths under 5-years of age in developing countries are linked with under-nutrition (13). The World Bank estimated that loss in GDP because of hidden hunger is up to 12 billion for India alone (14). One of the most promising and sustainable approaches to address hidden hunger is biofortification or biological fortification. This strategy involves enhancing the nutrient content and bioavailability of food crops through conventional plant breeding, agronomic interventions and modern biotechnology tools (15). Though, providing biofortified crops can help to address micronutrient deficiencies by increasing the daily adequacy of micronutrient intake among individuals through supplementation programme by international health organization (16). Since 2003, the CGIAR-led Harvest Plus program has been global leader in biofortification research, targeting iron, zinc and vitamin A, the three most commonly deficient micronutrients worldwide (17).

Historical background of biofortification

The concept of "biofortification" can be traced back the era of the Green Revolution (1966-1985), when the focus was primarily on enhancing crop yields and calorie sufficiency (18). However, by the 1990s, attention began to shift toward addressing hidden hunger and micronutrient deficiencies. American economist Howarth E Bouis began working on micronutrient malnutrition in the early 1990s. At that time, nutrition programs mostly prioritized calorie intake, but groundbreaking research by Bouis and Lawrence Haddad between 1984 and 1990 demonstrated that inadequate micronutrient intake was a primary barrier to improving overall nutritional outcomes.

In 2001, Steve Beebe coined the term "biofortification". Following this, Dr. Bouis successfully mobilized significant funding to advance the concept. In 2003, the CGIAR's Biofortification Challenge Program was rebranded as HarvestPlus (16). Between 2003 and 2008, target populations were identified and proof-of-concept research was conducted to validate the effectiveness of biofortified crops in combating micronutrient deficiencies (19).

Moreover, in 2013, the first biofortified crops were bred as well as approved for release by national varietal release committees and nutritional efficacy trials were carried out. Since 2014, the delivery of biofortified crops has been improved and more than 140 varieties of ten crops that are biofortified with vitamin A, iron and zinc have been released in 30 different countries. Furthermore, in 2016, Bouis was awarded the World Food Prize for his groundbreaking work on biofortification.

The burden of micronutrient deficiencies and its effects

Vitamin A

India bears a significant burden of vitamin A deficiency, primarily due to factors such as poverty, illiteracy and lack of nutritional awareness. It is estimated that 62 % of preschool-aged children and about 5 % of pregnant women exhibit symptoms of vitamin A deficiency (20). The deficiency of vitamin A leads to Xeropthalmia, which includes a spectrum of visual disturbances ranging from night blindness to Keratomalacia and ultimately Corneal scar. Thus, government of India numerous programs related to women and child welfare; vitamin A prophylaxis programme covers all preschool children in the community they receive a single oral dose of 200000 IU of vitamin A in every six months (21). According to NFHS-5, only 72.2 % of children aged 9-35 months in Maharashtra received vitamin A supplementation-down from 73.6 % previously. Coverage in other states such as Assam (58 %), Bihar (56 %) and Lakshadweep (44 %) remains suboptimal (22).

Iron

The occurrence of anemia was much higher in India among females of reproductive age group (23). As per NFHS-5, anemia has more worsened and increasing day by day over the last five years, with 68.4 % of children as well as 66.4 % of women suffering from anemia (24). In children, anemia impairs growth, cognitive development and immune function, while in adults, it causes fatigue and reduced work capacity (25, 26). Moreover, iron deficiency throughout the gestation period leads to fetal growth retardation and low-birth-weight (LBW) child. The blood loss among pregnant women suffering from anemia is fatal during childbirth. Even with a dedicated government programme like the "National Nutritional Anemia Control Programme", the burden of anemia in females at the childbearing generation in India remains high.

Iodine

Iodine deficiency is associated with a spectrum of disorders collectively known as iodine deficiency disorders (IDDs). These include goiter, cretinism, hypothyroidism, deaf-mutism, impaired mental development and muscular weakness (27). IDDs are the most frequent preventable factor of mental retardation (28). Thus, whole population of India is prone to developing IDDs in India as the sub continental soil deficient in iodine content, the deficiency of iodine is mostly common in hilly regions where rainfall is extreme which removes layers of soil containing iodine and onto which crop grown having lower content of, thereafter consumption of food crop deficient in iodine leads to deficiency symptoms. IDDs are the most frequent preventable cause of mental retardation (29).

Folic acid and vitamin B12

The folic acid insufficiency is more frequent in expectant mothers and reproductive females, however, vitamin B12 also plays a vital role in human reproduction and child development. Though insufficiency also associated to neural tube defects, megaloblastic anemia and low birth weight (LBW), stillbirths including abortion (13 -15). The Indian population, having vegetarian diet, is largely susceptible to vitamin B12 deficiency symptoms. A cross-sectional study found about 47 % of urban population in North India lacks vitamin B12 (30). A meta-analysis in 2015 revealed that high prevalence of neural tube defects in India (31). Some micronutrients and macronutrients need for better health (Table 1).

Food fortification

Food fortification is defined by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) as the deliberate addition of essential micronutrients and trace elements to food, aiming to improve its nutritional quality and confer health benefits with minimal risk (14). Historically, food fortification practices date back to ancient Persia, where iron filings were added to wine to improve soldier strength (33). Food Fortification of items began in the 1920s in Switzerland and the United States, where iodine was added to salt to treat endemic goiter and cretinism (34). Moreover, vitamin A and D were added to dairy products and the addition of iron as well as folic acid to flour started in 1930s and 40s in Western countries. Nowadays, with the commercial fortification of foods, a variety of foods are fortified

Table 1. Micronutrients and macronutrients needs for better health (32)

Micronutrients		Macronutrients		
Micro-minerals	**Vitamins**	**Amino acids (Essential)**	**Fatty acids (Essential)**	**Macrominerals**
Fe	A (Retinol)	Histidine	Linoleic acid	K
Zn	D (Calciferol)	Isoleucine	Linolenic acid	Ca
Cu	E (Tocopherol)	Leucine		Mg
Mn	K	Lysine		S
I	C	Methionine		P
Se	B-complex	Phenylalanine		Na
Mo		Threonine		Cl
Co		Tryptophan		
Ni		Valine		

with different micronutrients.

In contrast, biofortification is a newer approach that involves enhancing the nutrient content of crops during plant growth, using conventional breeding, genetic engineering or agronomic methods. However, there are various benefits of using food fortification to reduce micronutrient deficiency disease. The foods which are fortified with various nutrients provide micronutrients in ample amounts that are non-toxic in nature to those who have sufficient nutrients while providing for those with deficiencies (10), which are as close to natural levels as are found in a well-balanced diet, not in case of supplements. However, both approaches have limitations. Fortified foods may not reach impoverished populations without strong distribution systems and they also cannot substitute for a well-balanced diet rich in both macro- and micronutrients.

Malnutrition and hidden hunger

Malnutrition is a broad term that refers to a pathological condition resulting from an imbalance of nutrient intake. When nutrient intake exceeds the body's requirement, it leads to overnutrition while undernutrition occurs when essential nutrients are consumed in insufficient quantities-both conditions can result in adverse health outcomes (35). Hidden hunger, on the other hand, refers specifically to micronutrient deficiencies-a form of malnutrition that occurs even when caloric needs are met. Individuals may consume enough calories to feel full, but their diets lack vital vitamins and minerals such as iron, zinc, vitamin A and iodine (36, 37). This form of malnutrition often remains undetected until clinical symptoms manifest.

Several interrelated factors contribute to hidden hunger and malnutrition, particularly in developing countries. These include climate change, which affects agricultural productivity through altered weather patterns, droughts and floods; rising food prices, which reduce access to nutritious foods among low-income populations; and chronic illnesses such as kidney disease and cancer, which increase nutritional demands and reduce absorption. Both developed and developing nations face overlapping challenges of poverty, food insecurity and malnutrition. These issues are often intertwined in what is described as the "poverty trap"-a cyclical condition where poverty leads to hunger and hunger further entrenches individuals in poverty (38).

Biofortification of plant-based foods

Vegetables and other plant-based foods play a vital role in addressing undernutrition, hunger and poverty, particularly in low-income regions, due to their adaptability for local cultivation and consumption (39). A list of selected biofortified crop varieties and their nutrient targets is presented in Table 2. The article effectively supports the feasibility of biofortification as a sustainable solution, it is important to look for the inclusion of recent case studies or real-world implementations-especially involving staple crops like rice, maize and wheat (e.g. HarvestPlus, International Rice Research Institute, International Maize and Wheat Improvement Center).

- **Golden Rice**: Genetically engineered to produce provitamin A (beta-carotene); deployed in countries like the Philippines.
- **Iron-rich Beans and Zinc-enhanced Wheat:** Developed through conventional breeding, distributed via HarvestPlus programs.
- **Provitamin A Maize**: Successfully tested and distributed in Sub-Saharan Africa and parts of Latin America.

Interventions to reduce hidden hunger and malnutrition

Dietary diversification

One of the most sustainable strategies for addressing hidden hunger is dietary diversification. This involves increasing the variety of foods consumed, especially incorporating foods rich in micronutrients such as iron (Fe), zinc (Zn) and vitamins (40). In many developing countries, diets are heavily reliant on staple foods with limited micronutrient content, which contributes to hidden hunger. Diversifying diets by including fruits, vegetables, pulses, animal products and fortified foods can help prevent multiple deficiencies, strengthen the immune system and improve overall health (41). Dietary diversification is culturally acceptable, cost-effective and feasible; however, it requires nutritional awareness, dietary behavior change and access to diverse food sources. Additionally, the presence of anti-nutritional factors (e.g., phytates) in some plant foods may impair nutrient absorption, limiting the effectiveness of this strategy (1, 36).

Food supplementation

Food supplementation involves the use of medicinal-grade nutrient preparations-such as tablets, syrups, or capsules-to meet

Table 2. Adapted biofortified crops (32)

Biofortified crops	Target micronutrient	Countries where crops have been tested
Orange sweet Potato	Vitamin A	Uganda; Zambia
Beans	Iron	Uganda; Zimbabwe; Rwanda
Cassava	Vitamin A	Nigeria; Democratic Republic of Congo; Kenya
Maize	Vitamin A	Nigeria; Democratic Republic of Congo; Zambia; Zimbabwe
Pearl millet	Iron	India
Wheat	Zinc	India; Pakistan
Rice	Zinc	Bangladesh

dietary requirements, especially when nutrient intake from food alone is insufficient (42, 43). These supplements may include proteins, vitamins, essential fatty acids, amino acids, minerals and dietary fiber (43, 44). The food supplements are generally targeted to limited populations with acute lack of nutrients among developing countries. Food supplementation too is a straight, temporary as well as manageable plan that can be tailored to fulfill the particular requirements of a targeted people. It capitulates positive results quickly and is inexpensive in contrast to other interventions like diet diversification (44, 45). Food supplementation might also cause toxicity that has serious adverse effects among the health of people (46).

Food fortification

Food fortification refers to the process of adding essential micronutrients-such as vitamins and minerals-to food products to improve their nutritional quality and help populations meet their Recommended Dietary Allowance (RDA) (46, 47). However, food fortification and enrichment both devote to increasing nutritional composition of foods, even so a major variation between them (48). Food enrichment participates in restoring the loss of nutrients during processing, whilst food fortification contemplate replacing lost nutrients and connecting to those ones (nutrients) which are already present into the food in inadequate amounts. Though, there are numerous types of food fortification; target fortification, mass fortification, voluntary fortification in addition to mandatory fortification (46). For instance, voluntary fortification practices in countries like Gambia, the UAE and Qatar include adding vitamin A and iron to flours and breakfast cereals (46, 48). Mass fortification has proven effective in preventing large-scale deficiencies within specific populations (47, 48).

Conclusion

Biofortification of crops is a feasible and most economical approach for overcoming "hidden hunger". Enhancing the mineral concentration in the edible parts of cereal crops requires a comprehensive approach involving improved nutrient uptake from the soil, efficient translocation to grains and effective sequestration within the endosperm. Genetic diversity can be utilized to enhance micronutrient composition through conventional and modern breeding approaches. At the same time genetic engineering approaches can progress based on increased understanding of metabolic pathways and expression patterns of metal transporters, chelators and associated compounds. The most promising work plan to successfully alleviate micronutrient malnutrition will be to increase mineral content in the crops and simultaneously enhance their bioavailability by reducing anti-nutritional compounds and/or enhancing concentration of mineral absorption promoters. To effectively combat hidden hunger through biofortification, even after the development of biofortified varieties, it will be essential to address various socio-economical and socio-political challenges to popularize their cultivation by farmers and ultimately their consumption by the end users. A coordinated, multi-tiered approach-integrating research, policy, extension and community engagement-will be essential to scale up biofortification and achieve long-term nutritional security.

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Authors' contributions

AY conceived the study, gathered the relevant material and drafted the review. DG performed the sequence alignment and contributed to drafting the manuscript. SS revised the study. BS assisted with the technical work. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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