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Biofortification: An Ideal Approach for Nutritional Upliftment

Meenakshi Gupta[1], Shipra Srivastava[1], Ghizal Fatima[2], Mohd Mursal[2]
[1]Department of Food and Nutrition, Era University, Lucknow, UP, India
[2]Department of Biotechnology, Era University, Lucknow, UP, India

Abstract
The process of improving the nutrient density of food crops by modern biotechnology, improved agronomic practices, and/or traditional plant breeding is known as biofortification. It does this bereft of compromising any attribute that farmers or consumers value most. It has been recognized as a nutrition-sensitive farming method that helps reduce deficiencies in certain micronutrients. Iron-biofortification of beans, cowpea, and pearl millet; zinc-biofortification of maize, rice, and wheat; and provitamin A carotenoid-biofortification of cassava, maize, rice, and sweet potatoes are now under development and in differing stages of development. Over half the world's population lacks adequate levels of essential micronutrients, including iron, zinc, and various vitamins. Although, food fortification and supplementation have helped to reduce micronutrient deficiencies, but new strategies are still required, particularly to reach the impoverished in rural areas. Biofortification is an approach to uplift the nutritional quality of crops as well as improve their productivity. In under-developed nations, bio-fortification is the practice of enhancing nutrients in food crops offers a lasting, sustainable method of providing rural populations with access to micronutrients. Studies on the feasibility and effectiveness of biofortification, along with recent advancements in delivery, indicate that this approach holds potential in the fight against hidden hunger.

***CORRESPONDENCE:**
Meenakshi Gupta
(dt.meenakshigupta@gmail.com)

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INTRODUCTION

Biofortification is the process of producing micronutrient-dense staple crops through the application of contemporary biotechnology and the best traditional breeding techniques, with the aim of creating staple crops such as millets, maize, rice, and wheat. The overarching goal of the biofortification approach is to lower the rates of death and morbidity associated with micronutrient malnutrition and to improve food security, productivity, and the standard of living for underprivileged populations in developing nations by breeding staple crops that yield higher levels of bioavailable micronutrients in a way that is sustainable over time at a low cost.

Hidden hunger is characterized when someone consumes enough calories to sustain themselves, but their basic diet is deficient in important vitamins and minerals that are necessary for both physical and mental well-being. It affects children's and teenagers' mental and physical growth and can cause blindness, stunting, and a lower IQ; mothers and children are particularly sensitive. Because it increases the danger of disease and limits one's ability to work, hidden hunger also lowers adult men's and women's productivity. Up to 2 billion people are thought to be suffering from "hidden hunger" worldwide. Three major nutrients have been linked to these effects: zinc (Zn), iron (Fe), and Magnesium.[6]

A population with limited access to varied meals and other micronutrient interventions may benefit from the introduction of biofortification, a new, promising, affordable, and sustainable method of supplying micronutrients. Unfortunately, major food crops don't provide enough of the micronutrients needed for healthy human growth.

By improving the dietary intake of vital micronutrients, a number of tactics could be employed to lessen micronutrient deficits.[12] These consist of crop biofortification, food fortification, pharmacological supplements, and diet diversification. Crop biofortification is the most acceptable and sustainable approach to addressing the worldwide problem of hidden hunger. Micronutrients are already abundant in potatoes, particularly when eaten with the peel. Those with micronutrient deficits may benefit from its fortification.[20]

This review enlightens all the possible aspects of crop biofortification, including different methods- conventional breeding, agronomy, and transgenic approaches.

Based on various studies, it can be said that biofortification of the crop with different nutrients proved to be an effective way to bout micronutrient malnutrition and combat latent nutrient deficiency. Because biofortification is low-cost and sustainable, it benefits both citizens and governments. In order to address micronutrient deficiencies, this can support ongoing efforts at food fortification and nutritional supplementation. Furthermore, biofortification helps those who struggle to alter, their eating habits because of monetary, cultural, regional, or religious constraints.

Conventional Breeding Technique

Conventional breeding techniques provide for the necessary modifications needed to raise the micronutrient content of newly developed cultivars when combined with sophisticated phenotyping techniques and biotechnological procedures. The inherent genetic variety for important nutrient content that is now available should allow for breeding strategies to boost crop levels of vitamins and minerals (Shukla *et al.*, 2024). Conventional breeding has long sought to maximise cultivar production potential, and it has mainly succeeded in doing so by utilising heterosis to boost grain output and by creating genes that provide resistance against a variety of pests, and diseases in crops that are cross-pollinated.

With partners from the public and private sectors, such as the National Agricultural Research System (NARS), and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), considerable effort has been made in the field of pearl millet to generate high-iron pearl millet cultivars, according to a study titled "Conventional and Molecular Breeding Approaches for Biofortification of Pearl Millet".[8] Only when biofortified cultivars maintain high yield productivity and higher nutrient levels, benefiting both grower and consumer, can such initiatives be successful and sustained. It's fascinating to note that, similar to other cereals, pearl millet's micronutrient characteristics are comparatively more stable than grain harvest and its constituent parts.[11,16]

Agronomic Biofortification Technique

Agronomic biofortification is the progression of applying mineral fertilizer containing micronutrients to the soil and/ or plants to raise the micronutrient contents of the edible portion of food crops. Utilizing micronutrient-enriched fertilizers, agronomic and millets based bio-fortification is a quick and easy way to improve a crop's nutritional quality. Eating these crops also improves human nutrition status.[21] The main techniques used in agronomic bio-fortification include fertilizer application, mineral element solubilisation, and mobilization from source to sink (i.e., consumable plant parts). Higher-yielding objectives are aided by the macro minerals nitrogen (N), phosphorus (P), and potassium (K).

The efficacy of agronomic biofortification with mineral fertilizers is demonstrable by the applications of Se fertilization in Finland,[1] Zn fertilization in Turkey,[4] and E-fertilization in China.[14] In numerous crops, agronomic biofortification is effective. The primary goal of enhancing selenium (Se) in the mustard crop has been achieved by the use of rhizospheric bacteria and their formulations, which have improved Se uptake in the plant.[29] By applying foliar zinc spray, the zinc concentration in the potato flesh and skin increased. Based on the results of the trials, it was determined that ZnO and $ZnSO_4$ were more effective than $ZnNO_3$ at increasing zinc concentration while preserving harvests.[27]

The use of mineral and organic fertilisers in agronomic biofortification of staple and non-staple crops with different micronutrients has great potential to combat hidden hunger globally. The review is centered on the most recent developments in the application of Zn, Se, and Fe fertilisers. This includes the choice of fertilizer types, such as bio-fertilizers and nano-fertilizers, the kind and dosage of applied micronutrients, and the accumulation of these minerals by particular crops. Numerous studies on Zn, Se, and Fe fertilization and the impact of various parameters on the efficacy of agronomic biofortification have been published, but there is still a lack of clarity on this subject. Agronomic biofortification performance is dependent on a number of critical factors.

Transgenic Biofortification

Through genetic engineering, new cultivars with desired traits can be created. By using an infinite gene pool, it can transfer and express desired traits from one taxonomically and evolutionary distinct organism to another. Transgenic techniques continue to be the sole practical means of supplying crops lacking a certain micronutrient with the necessary ingredients. The ability to identify and describe gene function and then utilize these genes to design plant metabolism has been crucial to the development of transgenic crops. Additionally, transgenic techniques continue to be the only practical means of supplementing crops lacking a certain vitamin. Novel gene introduction, over expression of already-existing genes, down regulation of specific gene expression, and disruption of inhibitor manufacturing pathway genes have all been used to create transgenic crops. Furthermore, it is possible to use genetic alterations to redistribute micronutrients among tissues, improve the concentration of micronutrients in the edible parts of commercial crops, boost the effectiveness of biochemical pathways in edible tissues, or even reconstruct specific pathways.

Transgenically, bio-fortified crops initially demand a large amount of time, effort, and expenditure during the research and development stage, in contrast to nutrition-based organizational and agronomic biofortification projects. Nevertheless, it is a sustainable and economical strategy over the long term.[9,25] Moreover, there are no taxonomic restrictions on genetic engineering, and synthetic genes can be created and utilized. It may be possible to lessen micronutrient deficiency in consumers of transgenic crops, particularly in the impoverished in developing nations, by using crops with higher micronutrient concentrations.[10]

Micronutrient Malnutrition

Micronutrient Malnutrition is the absence of vital vitamins and minerals, which the body needs in trace amounts for healthy growth and development. (Fatima *et al*, 2025) Deficiencies in these micronutrients pose a serious threat to world health. They may cause children's physical and mental development to suffer, diseases to become more susceptible or worse, mental retardation, blindness, and general losses in potential and productivity. The following are examples of essential micronutrients: iron, zinc, calcium, iodine, vitamin A, B vitamins, and vitamin C. Micronutrients are compounds found in food that are necessary in small amounts for human health. They include every known vitamin and necessary trace mineral. When intakes of bioavailable micronutrients fall short of needs, micronutrient malnutrition occurs. Micronutrients are essential for the development of microbial pathogenicity as well as for cellular and humoral immune responses, cellular signaling and function, work capacity, reproductive health, learning, and cognitive processes.

Micronutrients must be obtained through diet because the body is unable to produce them. All ages are affected by micronutrient deficiencies, but pregnant women and children especially young infants see the most severe consequences. One of the greatest concerns for public health, especially in developing nations, is malnutrition, which includes shortages in several micronutrients.[3] 2011 recorded about 6.9 million deaths globally among children under the age of five years (UNICEF report 2012) 52 million children under five are wasted, 101 million are underweight, and 165 million children under five suffer from stunting. About 90% of them reside in just 36 nations, with Southeast Asia and sub-Saharan Africa having the highest frequency. India alone accounts for 36.3% of the world's population that are stunted.[2]

Numerous micronutrients have immune-modulating properties that affect a host's susceptibility to infectious diseases as well as the course and outcome of such infections. These include vitamin A, beta-carotene, folic acid, vitamin B12, vitamin C, riboflavin, iron, zinc, and selenium. Some of these micronutrients also have antioxidant properties that affect the microorganisms' genomes, especially those of viruses, and change the host's immunological homeostasis such as citrus foods.[5] These changes can have serious repercussions, such as the return of previously treated infectious disorders or the formation of new infections. Because of the nutrients and other bioactive ingredients that foods deliver, food systems are related to the health and nutritional well-being of individuals and populations. All food systems are based on agriculture because the majority of nutrients come from agricultural products.

Role of Biofortification in Combating Micronutrient Malnutrition

In regions where cereal grains make up a major component of the diet, dietary diversification is limited, and/or supplementation/fortification programs are weak, the prevalence and devasting effects of micronutrient deficiencies are amplified. Micronutrient deficits have long-lasting effects on immune system performance, growth, and cognitive development. Thus, there are numerous negative effects of this "hidden hunger" on human health, economic progress, and the ability to reduce poverty. Food demand is rising sharply due to changing lifestyles and a constantly expanding population, but there is not enough land for agriculture, which results in the heavy use of natural resources and frequently low-quality agricultural output. Enhancing the nutritional content of consumable and fodder crops for cattle could be one way to improve human nutrition, particularly in developing nations.

Biofortification, which is the practice of enhancing the nutritional value of edible crops via selected conventional breeding, mineral fertilization, or sophisticated transgenic techniques, is one way to lessen micronutrient deficits. Developing nations can benefit greatly from biofortification through a variety of techniques, such as the engineering of staple crops. In order to boost the most popular crops, such as corn, wheat, and rice, research and programs like Harvest Plus are concentrating on iron (Fe), zinc (Zn), and vitamin A, which the World Health Organization deems to be the most scarce micronutrients.

In conclusion, hidden hunger is a serious health issue for communities in underdeveloped nations and is caused by inadequate vitamin absorption. They frequently can only afford staple items, which results in a diet that is boring. When ingested in excess, staple foods may include anti-nutrients as well as insufficient amounts of important nutrients. In addition, to lowering the disadvantages of staple meals, staple food biofortification is a sustainable way to lessen malnutrition. However, to maintain soil fertility and attain adequate micronutrient concentrations in the produce, a combination with the application of micronutrient fertilizer may be required, depending on the crop and the soil where it is grown.

CONCLUSION

While reviewing numerous studies, it has been observed that crop biofortication is an ideal solution to improve food quality on grassroot level. Although micronutrient deficiency has been identified as a public health concern, interventions are being carried out in poor nations with differing degrees of success; despite this, progress has been slow. It may be possible to combat micronutrient deficiencies by using mineral fertilisers, transgenic plants, and plant breeding techniques. In order to effectively battle hidden hunger, it is also important to remember that, even once biofortified varieties are produced, a variety of socio-political and economic challenges need to be overcome in order to encourage their production and, eventually, consumer adoption.

An individual's micronutrient security level is determined by the type and quantity of food that is available for consumption. The main causes of deficits in macronutrients and micronutrients are inadequate food supplies, both in terms of quantity and quality. To end hidden hunger in underdeveloped countries, bio-fortification is a newly developed technique that raises the micronutrient content of crops. In order to combat micronutrient malnutrition in poor nations, this research explains how biofortification plays a role. Globally, the distinctiveness of biofortification methods should address local nutritional issues and be selected according to the possibility that customers will accept cultural differences. In general, biofortification is a potential set of methods that can enhance nutritional welfare worldwide and bring us one step closer to reducing hunger and malnutrition.

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