



Bio-fortified Crops: Impacts on Human Health and Environmental Sustainability

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Abstract

Bio-fortification is a trans-formative approach to combating hidden hunger by enhancing the nutritional quality of staple crops through agronomic practices, conventional breeding, and genetic modification. It significantly improves micro-nutrient availability, leading to reduced anemia, better cognitive performance, and enhanced immunity in vulnerable populations. Environmentally, bio-fortified crops offer a sustainable alternative to traditional fortification, with studies showing lower ecological footprints and improved resilience to abiotic and biotic stresses. They also support climate-smart agriculture and soil health, contributing to a circular food economy. However, challenges such as consumer acceptance, regulatory barriers, and the need for interdisciplinary scaling must be addressed for wider adoption.

Keywords: Hidden-hunger, Micro- nutrient, Sustainability, Vitamins

Introduction

Bio-fortification is the process of increasing the nutritional value of food crops by improving the concentration of vitamins and minerals during plant growth. The traditional food fortification, which adds nutrients during processing or supplementation that relies on clinical interventions. Contrary, the bio-fortification targets the source of nutrition through crops it-self by employing agronomic practices, conventional plant breeding approaches, and genetic modification in the targeted crops. This strategy is particularly vital for resource-constrained populations in developing regions who rely heavily on staple crops for their daily caloric intake but suffer from hidden hunger due to a lack of required dietary diversity. Probably, the flagship Golden rice bio-fortification project carried out by genetic modification in rice for producing provitamin A. These bio-fortified crops are meant to reduce socio-economic burden of malnutrition and are considered as an alternative interest in industrialized countries. At the present scenario, the bio-fortified crops have been released in 30 countries globally (Bouis and Saltzman, 2017). There



are around 150 varieties of ten crops including Iron beans, Iron pearl millet, Zinc maize, Zinc rice, Zinc wheat, Vit. A Banana, Vit. A Cassava, Vit. A Maize, Vit. A Orange sweet potato, Iron/Zinc cowpea, Iron/Zinc potato, Iron/Zinc lentils, Iron/Zinc sorghum have been released. The importance of bio-fortification has grown in the context of global challenges such as climate change and the COVID-19 pandemic, which have disrupted food systems and exacerbated nutritional vulnerabilities. By integrating nutritional goals into agricultural productivity, the bio-fortification aligns with the "One Health" approach, recognizing the interconnectedness of soil, plant, animal, and human health. As a sustainable and cost-effective intervention, it offers a long-term solution to malnutrition that requires minimal recurring investment once bio-fortified crop varieties are adopted by farmers.

Nutritional and human health impacts

Bio-fortification targets the enrichment of essential micronutrients such as iron, zinc, vitamin A, iodine, and selenium to combat hidden hunger and associated health problems. Vitamin A deficiency (VAD), a major cause of childhood blindness and increased infection-related mortality, can be addressed through crops like Golden Rice and orange-fleshed sweet potato (OSP), which supply bioavailable provitamin A. Similarly, iron- and zinc-biofortified crops, including beans and pearl millet, improve iron intake and nutritional status, especially among women and adolescents, while zinc-rich varieties like DRR Dhan 45 (28-45 ppm zinc) and Dhanshakti enhance immune function and growth. In addition, selenium-bio-fortified crops such as potatoes help reduce risks of cancer, infections, and oxidative stress by supporting antioxidant and thyroid functions. Folate-bio-fortified crops are also being developed to prevent neural tube defects by improving maternal nutrition. Overall, bio-fortification provides a sustainable, cost-effective strategy to reduce micro-nutrient deficiencies and improve global health outcomes.

Clinical and functional outcomes

Clinical trials and bio-availability assays are essential to evaluate the effectiveness of bio-fortified crops in improving human health. Evidence from such studies shows that consumption of iron-rich crops like pearl millet and beans enhances cognitive performance, including attention and memory, by improving serum ferritin and total body iron levels. Similarly, intake of orange-fleshed sweet potato (OSP) has been associated with reduced duration and incidence of diarrhea in children and improved growth in populations with nutrient-poor diets. Overall, bio-fortified crops significantly improve micro-nutrient status by providing bio-available nutrients, thereby reducing the prevalence of deficiencies in target populations.

Role in immune support and disease prevention

Recent advancements, such as nano bio-fortification, have highlighted the role of micro-nutrients in supporting the immune system. Particularly, zinc and selenium are vital for immune health, their enhancement through bio-



fortified crops may help reduce viral loads and support recovery in individuals affected by infectious diseases. Additionally, the selenium-rich crops are noted for their potential protective effects against certain types of cancer and allergies.

Environmental sustainability and ecological footprint

Biofortification plays an important role in promoting environmental sustainability by enhancing resource use efficiency, improving soil health, and reducing the ecological footprint of agricultural practices. Agronomic biofortification approaches, including the application of microbial inoculants and nano-fertilizers, help optimize nutrient uptake and enable controlled nutrient release, thereby minimizing nutrient losses and reducing reliance on excessive chemical fertilizers. These practices not only improve crop productivity but also contribute to maintaining soil fertility and long-term agricultural sustainability. In addition, many biofortified crops are developed with climate resilience in mind, exhibiting tolerance to abiotic stresses such as drought, salinity, and heat, which is essential under changing climatic conditions; for example, selenium biofortification has been reported to enhance plant tolerance to both abiotic and biotic stresses. Furthermore, Life-Cycle Assessment (LCA) studies indicate that biofortified crops, such as selenium-enriched potatoes, often have a lower environmental impact compared to conventional crop production systems, offering a more sustainable alternative. However, the introduction of biofortified crops, particularly those developed through genetic modification, raises concerns regarding biodiversity, including risks of gene flow to wild relatives and potential reduction in local crop diversity, emphasizing the need for careful management to ensure that biofortification strategies do not negatively impact ecosystem balance.

Implementation strategies and technologies

Biofortification can be achieved through integrated strategies involving agronomic practices, breeding approaches, and modern biotechnology. Agronomic biofortification includes the application of mineral fertilizers, nano-formulations, and seed or foliar treatments, along with beneficial microorganisms such as plant growth-promoting rhizobacteria, to enhance nutrient uptake from the soil, particularly for minerals like zinc and selenium. Conventional breeding remains a widely adopted and cost-effective approach, where nutrient-dense landraces or wild varieties are crossed with high-yielding cultivars; however, this process is time-consuming and may involve genetic drift, which is why molecular breeding techniques are increasingly used to accelerate selection through marker-assisted identification of nutrient-related traits. In cases where desired nutrients are absent or limited within the crop gene pool, genetic modification and biotechnological interventions are applied to modify metabolic pathways, as demonstrated by Golden Rice developed for enhanced provitamin A content. Additionally, such approaches can contribute to reduced pesticide use and improved soil health, making biofortification a sustainable and technologically advanced solution for improving crop nutritional quality.



Challenges and limitations

Despite the strong potential of biofortified crops to enhance nutritional security, several challenges limit their large-scale adoption. Consumer acceptance remains a key barrier, as changes in sensory traits, such as the orange color of orange-fleshed sweet potato and Golden Rice, may discourage adoption without awareness campaigns. Regulatory and ethical concerns, particularly around genetically modified crops, also create hurdles due to strict policies and public skepticism. In addition, technical and agronomic factors, including soil nutrient variability and region-specific suitability, can affect their effectiveness and sustainability. Ensuring nutrient stability during storage and processing, along with maintaining bio-availability, further remains a critical challenge.

Future perspective

To maximize the impact of bio-fortification, future research should adopt interdisciplinary approaches integrating agronomy, nutrition, and social sciences to ensure both nutritional effectiveness and cultural acceptance. Emphasis should also be placed on circular economy strategies, including valorization of crop residues through bio-refineries and AI-based resource management for sustainability. Long-term monitoring supported by well-designed clinical trials is essential to assess health outcomes and ecological impacts. Additionally, scalable, cost-effective delivery models must be developed to reach vulnerable rural populations, while integrating climate-resilient traits into bio-fortified crops to ensure sustainable food and nutrition security under changing environmental conditions.

Conclusion

The bio-fortification stands at the intersection of agriculture, nutrition and environmental science. It offers a powerful tool to combat micro-nutrient malnutrition while promoting sustainable agricultural practices. By enhancing the nutritional potential of staple crops, the bio-fortification improves human health outcomes, from cognitive development to immune support. Concurrently, the adoption of bio-fortified varieties can enhance crop resilience, improve soil health, and reduce the environmental footprint of food production. While challenges related to regulation, acceptance, and technical stability persist, the evidence supports bio-fortification as a scalable and cost-effective intervention. As part of a broader "One Health" and circular economy framework, bio-fortified crops are essential for achieving a more resilient and nourished global population.

References

J. Lungelo, 2024. Potential Risks and Benefits Associated With the Genetic Modification of Crops for Improved Nutritional Content in South Africa. *International Journal of Food Sciences* 7(2): 22-32.



- Jaiswal, D. K., Krishna, R., Chouhan, G. K., de Araujo Pereira, A. P., Ade, A. B., Prakash, S. and J. P. Verma, (2022). Bio-fortification of minerals in crops: current scenario and future prospects for sustainable agriculture and human health. *Plant Growth Regulation* 98(1), 5-22.
- Sharma, A. and R. K. Verma, (2019). Biofortification: a promising approach toward eradication of hidden hunger. In *Microbial Interventions in Agriculture and Environment: Volume 1: Research Trends, Priorities and Prospects* (313-327). Singapore: Springer Singapore.
- Bouis, H. E. and A. Saltzman, (2017). Improving nutrition through biofortification: a review of evidence from HarvestPlus, 2003 through 2016. *Global food security* 12, 49-58.
- Scuderi, A., Cammarata, M., Via, G. L., Pecorino, B. and G. Timpanaro, (2021). Life-Cycle Assessment of Biofortified Productions: The Case of Selenium Potato. *Applied System Innovation* 4(1), 1.