JOURNAL OF FOOD AND BIOTECHNOLOGY

Review Article ISSN 3041- 6299 Open Access

Biofortification Approaches for Enhancing Nutritional Quality of Horticultural Crops

Abhijit Debnath*[1], Abhik Sarkar[2], Moaakum Pongen[3], and H. Lembisana Devi[4]

[1]*Department of Horticulture and Post-Harvest Technology, Palli Siksha Bhavana, Visva-Bharati, Sriniketan, West Bengal, India*
[2]*Department of Community Health Nursing, Sambalpur University, Jyoti Vihar, Burla, Sambalpur, Odisha, 768019, India*
[3]*Department of Animal Science, ICAR KVK, Wokha, Nagaland 797111, India*
4Department of Horticulture, ICAR-KVK Tamenglong, ICAR RC for NEHR Manipur Centre, Lamphelpat, Imphal, Manipur 795001, India

Corresponding author: **Abhijit Debnath** | E-mail: **abhijitdebnathhorticulture@gmail.com**

Citation: Abhijit Debnath, Abhik Sarkar, Moaakum Pongen, and H. Lembisana Devi (2021). Biofortification Approaches for Enhancing Nutritional Quality of Horticultural Crops. *Journal of Food and Biotechnology.* **01 to 04. DOI: https://doi.org/10.51470/FAB.2021.2.2.01**

02 August 2021: Received | 04 September 2021: Revised | 06 October 2021: Accepted | 08 November 2021: Available Online

Abstract

Micronutrient malnutrition, commonly referred to as hidden hunger, affects billions of people worldwide and poses serious public health challenges, particularly in developing countries. Horticultural crops such as fruits and vegetables are rich sources of vitamins, minerals, antioxidants, and dietary fiber, making them essential components of human nutrition. Biofortification has emerged as a sustainable strategy to enhance the nutritional quality of crops by increasing the concentration and bioavailability of essential nutrients in edible plant parts. This review highlights recent advances in biofortification approaches applied to horticultural crops, including conventional breeding, agronomic biofortification, genetic engineering, and modern genome-editing technologies. The article also discusses the role of soil and nutrient management, microbial interventions, and precision agriculture tools in enhancing nutrient uptake and accumulation. Challenges associated with adoption, regulatory concerns, and consumer acceptance are examined along with future prospects for integrating biofortification with climate-smart horticulture. Biofortification of horticultural crops holds significant potential to improve global nutrition while supporting sustainable agricultural production systems.

Keywords: *biofortification, horticultural crops, micronutrients, nutrient enrichment, crop breeding, agronomic biofortification, genetic engineering, food security.*

1. Introduction

Horticultural crops play a critical role in ensuring global food and nutritional security due to their rich content of vitamins, minerals, antioxidants, and dietary fiber. Fruits and vegetables are indispensable components of a healthy diet and are known to reduce the risk of several non-communicable diseases, including cardiovascular disorders, diabetes, obesity, and certain cancers. In many developing countries, horticulture also contributes substantially to agricultural GDP, employment generation, and livelihood security, particularly for smallholder farmers and peri-urban producers. Increasing urbanization, rising income levels, and growing awareness of health and nutrition have further increased global demand for high-quality horticultural produce, the importance of fruits and vegetables, micronutrient deficiencies remain a major global challenge. Deficiencies of iron, zinc, vitamin A, iodine, and folate affect billions of people worldwide, particularly women and children in low- and middle-income countries [1]. This phenomenon, often described as "hidden hunger," occurs when diets provide sufficient calories but lack essential micronutrients required for healthy growth and immune function. Consequences include impaired cognitive development, increased susceptibility to infections, poor pregnancy outcomes, and elevated mortality rates.

In many regions, limited access to diversified diets, seasonal availability of fruits and vegetables, and economic constraints further exacerbate nutritional deficiencies [2]. Conventional strategies to combat micronutrient deficiencies include dietary diversification, food fortification, and supplementation programs. Although effective in certain contexts, these approaches often require continuous financial support, infrastructure, and effective distribution systems. In rural and resource-limited areas, maintaining long-term supplementation and fortified food supply chains can be challenging. Therefore, sustainable agricultural solutions that integrate nutritional improvement directly into crop production systems are increasingly being promoted.

Biofortification has emerged as a promising and sustainable strategy aimed at enhancing nutrient concentrations in crops during plant growth rather than through post-harvest fortification. By increasing nutrient levels in commonly consumed crops, biofortification ensures that populations receive improved nutrition through their regular diets without requiring major changes in food habits or additional financial burdens. This approach is particularly suitable for regions where horticultural crops form a significant part of daily diets [3]. Horticultural crops offer excellent opportunities for biofortification because of their naturally diverse nutrient composition, high consumer acceptance, and wide cultivation across agro-climatic regions. Advances in plant breeding, biotechnology, soil fertility management, and crop production practices have accelerated the development of nutrient-enriched horticultural varieties. Increasing integration of precision agriculture and sustainable farming practices further enhances nutrient efficiency in crop production. This review examines major biofortification approaches applied to horticultural crops, evaluates their benefits and limitations, and highlights emerging trends and future opportunities in improving nutritional quality through horticulture.

2. Concept and Importance of Biofortification

Biofortification refers to the process of increasing the concentration and bioavailability of essential micronutrients in edible portions of crops during plant growth. Unlike food fortification, where nutrients are added during food processing, biofortification integrates nutritional improvement directly into agricultural production systems. As crops accumulate higher nutrient levels in grains, fruits, or edible tissues, consumers benefit naturally through routine dietary consumption. The importance of biofortification lies in its long-term sustainability and cost-effectiveness. Once nutrient-dense crop varieties are developed and adopted by farmers, they can be cultivated repeatedly without requiring continuous intervention or additional processing costs. Farmers can use saved seeds or planting materials while maintaining improved nutritional quality in their produce. This makes biofortification particularly valuable for rural communities with limited access to fortified foods and nutritional supplements [4]. In horticultural crops, biofortification not only enhances micronutrient levels but can also improve concentrations of health-promoting phytochemicals such as carotenoids, flavonoids, vitamin C, and phenolic compounds. These compounds contribute to improved immunity, antioxidant protection, and disease prevention. Nutritionally enriched fruits and vegetables may also command higher market prices, providing economic benefits to farmers and strengthening value chains in horticulture, biofortification contributes to sustainable agricultural systems by promoting efficient nutrient use, reducing reliance on synthetic inputs, and encouraging environmentally friendly crop management practices. When combined with improved soil fertility and crop management strategies, biofortification can enhance both crop productivity and nutritional value simultaneously, biofortification offers a practical approach to simultaneously address malnutrition, agricultural sustainability, and economic development through nutrient-enriched horticultural production systems.

3. Approaches to Biofortification in Horticultural Crops

Biofortification strategies employ multiple approaches ranging from traditional breeding to advanced biotechnology and agronomic management practices. Each method has unique advantages and limitations, and integrated strategies often yield the best results.

3.1 Conventional Breeding Approaches

Conventional breeding utilizes natural genetic variation present in crop species to develop varieties with enhanced nutrient concentrations. Plant breeders screen germplasm collections, including wild relatives and traditional cultivars, to identify genotypes with superior nutrient profiles. These genotypes are then crossed with high-yielding or disease-resistant varieties to combine nutritional quality with desirable agronomic traits. In horticultural crops, breeding programs have successfully improved carotenoid levels in tomato and carrot, enhanced iron and zinc content in leafy vegetables, and increased antioxidant concentrations in berries and colored fruits [5]. Marker-assisted selection and genomic tools now enable breeders to identify nutrient-associated genes more efficiently, thereby accelerating breeding programs, breeding programs often require long development cycles and depend on the availability of sufficient genetic variability within crop species. In some crops, increasing nutrient concentration may also influence yield or quality traits, requiring careful breeding strategies to balance productivity and nutrition.

3.2 Agronomic Biofortification

Agronomic biofortification involves application of mineral fertilizers, soil amendments, and crop management practices to enhance nutrient uptake and accumulation in plants. Micronutrients such as zinc, iron, selenium, iodine, and boron can be applied through soil fertilization, foliar sprays, or fertigation systems. Foliar nutrient application has shown considerable success in horticultural crops because nutrients are absorbed directly through leaves and transported to edible plant parts [6]. Improved soil management practices, including addition of organic matter, compost, and biofertilizers, enhance nutrient availability and root absorption. Optimized irrigation practices further support efficient nutrient uptake. Agronomic biofortification offers rapid and flexible nutrient enhancement but requires repeated applications each season. Effectiveness may vary with soil type, climate, and crop species, necessitating location-specific management recommendations.

3.3 Genetic Engineering Approaches

Genetic engineering allows direct modification of plant genomes to enhance nutrient biosynthesis or storage pathways. Through transgenic approaches, genes responsible for nutrient production or accumulation can be introduced or overexpressed to significantly increase micronutrient levels. In horticultural crops, genetic modification has improved carotenoid accumulation in tomatoes and enhanced antioxidant and vitamin profiles in several fruits and vegetables [7]. Genetic engineering can also reduce anti-nutritional factors that limit nutrient absorption, commercialization of genetically engineered crops often faces regulatory challenges and consumer concerns regarding genetically modified organisms (GMOs). Public awareness and regulatory approval processes influence adoption across different regions.

3.4 Genome Editing Technologies

Genome editing technologies such as CRISPR-Cas systems provide precise tools to modify genes controlling nutrient metabolism without necessarily introducing foreign DNA.

These technologies enable targeted improvements, including enhancing nutrient biosynthesis, increasing nutrient storage, or reducing compounds that limit bioavailability [8]. Genome editing offers faster development compared to conventional breeding and avoids some regulatory concerns associated with transgenic crops. Recent research demonstrates successful modification of nutrient-related traits in fruits and vegetables, making genome editing a promising avenue for future horticultural biofortification programs and an advances in gene discovery, molecular biology, and plant transformation techniques are expected to further expand genome-editing applications in horticultural crops.

4. Role of Soil and Microbial Interactions

Soil health plays a fundamental role in determining nutrient availability and uptake in horticultural crops, thereby influencing the success of biofortification strategies. Healthy soils rich in organic matter improve soil structure, water-holding capacity, and nutrient retention, enabling plants to absorb essential micronutrients more efficiently. Balanced fertilization practices and maintenance of appropriate soil pH further support nutrient solubility and root absorption [9]. Soil microbial communities significantly contribute to nutrient cycling and availability. Beneficial microorganisms, including mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), enhance nutrient acquisition by expanding root absorption zones and facilitating solubilization of otherwise unavailable nutrients. For example, mycorrhizal fungi improve phosphorus and micronutrient uptake, while bacteria such as *Azospirillum*, *Bacillus*, and *Pseudomonas* species assist in nitrogen fixation and micronutrient mobilization. Biofertilizers and microbial inoculants are increasingly incorporated into horticultural production systems to enhance nutrient efficiency and reduce dependence on chemical fertilizers. These biological inputs not only improve nutrient uptake but also promote plant growth, stress tolerance, and soil sustainability. Integration of soil health management with microbial technologies thus strengthens agronomic biofortification efforts and supports environmentally sustainable horticultural production.

5. Biofortification Targets in Horticultural Crops

Biofortification programs in horticultural crops focus on enhancing concentrations of key micronutrients essential for human health. Major nutritional targets include iron, zinc, calcium, selenium, vitamin A precursors such as beta-carotene, vitamin C, folate, and various antioxidant compounds [10]. These nutrients play critical roles in immune function, cognitive development, bone health, and disease prevention. Several horticultural crops serve as ideal candidates for nutrient enhancement due to their widespread consumption and inherent nutritional richness. Tomato and carrot are important sources of carotenoids and antioxidants, while leafy vegetables such as spinach, amaranth, and lettuce provide iron and folate. Sweet potato varieties rich in provitamin A have shown success in addressing vitamin A deficiency. Citrus fruits, berries, and guava are valuable sources of vitamin C and phytochemicals, while cruciferous vegetables contribute beneficial minerals and antioxidants.

An important consideration in biofortification is improving nutrient bioavailability rather than simply increasing total nutrient concentration. Factors such as anti-nutritional compounds, dietary interactions, and food processing methods influence nutrient absorption in humans. Therefore, breeding and management strategies increasingly aim to enhance nutrient forms that are easily absorbed while reducing inhibitors of nutrient utilization.

6. Role of Precision Agriculture and Smart Technologies

Precision agriculture technologies are increasingly supporting biofortification efforts by enabling accurate and efficient nutrient management. Advanced sensing tools monitor soil nutrient status, plant health, and crop growth conditions in real time, allowing farmers to apply nutrients precisely where and when they are needed. Remote sensing technologies, drones, and satellite imagery help detect nutrient deficiencies and crop stress early, facilitating timely corrective measures. Smart fertigation systems integrated with drip irrigation enable targeted delivery of nutrients directly to plant roots, improving nutrient use efficiency while minimizing environmental losses through leaching or runoff [6]. Artificial intelligence (AI) and data-driven decision support systems further assist farmers in optimizing nutrient management strategies by analyzing historical and real-time data. Digital agriculture tools thus enhance crop productivity and nutritional quality simultaneously, making precision farming an important component of modern biofortification strategies.

7. Challenges and Limitations

The promising progress, biofortification faces several technical, economic, and social challenges. Genetic limitations in certain crops restrict the extent to which nutrient levels can be enhanced through breeding. Environmental conditions such as soil type, climate variability, and water availability can also influence nutrient accumulation in crops, leading to inconsistent results across regions. Nutrient stability during postharvest storage, processing, and cooking remains another concern, as some vitamins and micronutrients may degrade before consumption. Regulatory restrictions and lengthy approval processes for genetically engineered crops further limit adoption in certain countries. Consumer acceptance is another critical factor, particularly where genetically modified or unfamiliar crop varieties are involved. In addition, limited farmer awareness, lack of quality planting materials, and inadequate extension services may slow adoption of biofortified crops. Addressing these barriers requires coordinated efforts involving research institutions, policymakers, and agricultural extension agencies.

8. Conclusion

Biofortification represents a promising and sustainable strategy to enhance the nutritional quality of horticultural crops and combat widespread micronutrient deficiencies. Advances in breeding, biotechnology, agronomic practices, and digital agriculture technologies have expanded opportunities for improving nutrient density in fruits and vegetables. Integrating biofortification into horticultural production systems can simultaneously improve public health, agricultural sustainability, and farmer incomes. Nutrient-rich horticultural crops not only contribute to healthier diets but also offer economic advantages through increased market value and consumer demand for nutritious foods, and effective dissemination strategies will be essential to realize the full potential of biofortified horticultural crops in addressing global nutritional challenges and promoting sustainable food systems.

Table. Major Biofortification Approaches in Horticultural Crops

Approach	Method	Advantages	Limitations
Conventional Breeding	Selection and hybridization	Non-GMO, farmer-friendly	Time-consuming
Agronomic Biofortification	Fertilizer and soil management	Immediate impact	Requires repeated application
Genetic Engineering	Gene insertion/modification	High nutrient improvement	Regulatory concerns
Genome Editing	Targeted gene modification	Precise and fast improvement	Regulatory acceptance evolving
Microbial Biofortification	Biofertilizers and microbes	Sustainable nutrient uptake	Variable field performance

References

1. Buturi, C. V., Mauro, R. P., Fogliano, V., Leonardi, C., & Giuffrida, F. (2021). Mineral biofortification of vegetables as a tool to improve human diet. *Foods*, *10*(2), 223.
2. Shwetha, H. J., Shilpa, S., Arathi, B. P., Raju, M., & Lakshminarayana, R. (2020). Biofortification of carotenoids in agricultural and horticultural crops: a promising strategy to target vitamin A malnutrition. *Vitamins and Minerals Biofortification of Edible Plants*, 123-161.
3. Rouphael, Y., & Kyriacou, M. C. (2018). Enhancing quality of fresh vegetables through salinity eustress and biofortification applications facilitated by soilless cultivation. *Frontiers in plant science*, *9*, 1254.
4. D'Imperio, M., Parente, A., Montesano, F. F., Renna, M., Logrieco, A. F., & Serio, F. (2020). Boron biofortification of Portulaca oleracea L. through soilless cultivation for a new tailored crop. *Agronomy*, *10*(7), 999.
5. Gonzali, S., Kiferle, C., & Perata, P. (2017). Iodine biofortification of crops: agronomic biofortification, metabolic engineering and iodine bioavailability. *Current opinion in biotechnology*, *44*, 16-26.
6. Kumar, S., Palve, A., Joshi, C., & Srivastava, R. K. (2019). Crop biofortification for iron (Fe), zinc (Zn) and vitamin A with transgenic approaches. *Heliyon*, *5*(6).
7. Wang, M., Vasconcelos, M. W., & Carvalho, S. M. (2021). Role of calcium nutrition on product quality and disorder susceptibility of horticultural crops: processes and strategies for biofortification. In *Calcium transport elements in plants* (pp. 315-335). Academic Press.
8. Mimmo, Tanja, Raphael Tiziani, Fabio Valentinuzzi, Luigi Lucini, Carlo Nicoletto, Paolo Sambo, Matteo Scampicchio, Youry Pii, and Stefano Cesco. "Selenium biofortification in Fragaria× ananassa: implications on strawberry fruits quality, content of bioactive health beneficial compounds and metabolomic profile." *Frontiers in Plant Science* 8 (2017): 1887.
9. García-Bañuelos, M. L., Sida-Arreola, J. P., & Sánchez, E. (2014). Biofortification-promising approach to increasing the content of iron and zinc in staple food crops. *Journal of Elementology*, *19*(3).
10. Sujith Kumar, M. S., Mawlong, I., & Rani, R. (2020). Biofortification of Brassicas for quality improvement. In *Brassica Improvement: Molecular, Genetics and Genomic Perspectives* (pp. 127-145). Cham: Springer International Publishing.