JOURNAL OF CURRENT RESEARCH IN FOOD SCIENCE

E-ISSN: 2709-9385
P-ISSN: 2709-9377
Impact Factor (RJIF): 5.71
JCRFS 2025; 6(2): 240-246

www.foodresearchjournal.com
Received: 02-09-2025
Accepted: 06-10-2025

All Author details are given below the references Section

Biofortification of vegetable crops for micronutrient enhancement: Advances and challenges

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DOI: https://www.doi.org/10.22271/foodsci.2025.v6.i2d.281

Abstract
Biofortification of vegetable crops is an emerging, sustainable strategy to combat "hidden hunger" by enhancing the concentration and bioavailability of essential micronutrients such as iron, zinc, selenium, iodine, provitamin A carotenoids, folates and vitamin C in edible tissues. Vegetables are particularly suitable targets owing to their inherently high nutrient density, short crop cycles and broad inclusion in daily diets, offering substantial potential to complement staple-crop biofortification and conventional supplementation or industrial fortification programmes. This review consolidates recent advances in agronomic practices, conventional and molecular breeding, and modern biotechnological tools including genetic engineering, genome editing and synthetic biology for micronutrient enhancement across major vegetable groups such as leafy vegetables, brassicas, solanaceous crops, cucurbits, root and tuber vegetables, and alliums. It further highlights the emerging role of soil-plant-microbe interactions, hydroponic and controlled-environment systems, and crop-wise case studies demonstrating substantial (often multi-fold) increases in target micronutrients without compromising yield or quality.
Biofortification of vegetable crops is an emerging, sustainable strategy to combat "hidden hunger" by enhancing the concentration and bioavailability of essential micronutrients such as iron, zinc, selenium, iodine, provitamin A carotenoids, folates and vitamin C in edible tissues. Vegetables are particularly suitable targets owing to their inherently high nutrient density, short crop cycles and broad inclusion in daily diets, offering substantial potential to complement staple-crop biofortification and conventional supplementation or industrial fortification programmes. This review consolidates recent advances in agronomic practices, conventional and molecular breeding, and modern biotechnological tools including genetic engineering, genome editing and synthetic biology for micronutrient enhancement across major vegetable groups such as leafy vegetables, brassicas, solanaceous crops, cucurbits, root and tuber vegetables, and alliums. It further highlights the emerging role of soil-plant-microbe interactions, hydroponic and controlled-environment systems, and crop-wise case studies demonstrating substantial (often multi-fold) increases in target micronutrients without compromising yield or quality.
Key constraints such as genotype × environment interactions, limited high-throughput phenotyping, uncertain human bioavailability, fragmented seed systems, regulatory and biosafety hurdles for engineered cultivars, and low consumer awareness are critically examined alongside policy and governance gaps that hinder large-scale deployment. The article concludes by outlining research and policy priorities for integrating biofortified vegetables into horticultural value chains, home and peri-urban gardens, school and institutional feeding programmes and public procurement schemes, underscoring their potential to strengthen nutrition-sensitive horticulture and contribute meaningfully to the reduction of micronutrient malnutrition.

Keywords: Biofortification, vegetable crops, micronutrient enrichment, agronomic and genetic approaches

1. Introduction
Micronutrient malnutrition or "hidden hunger" affects nearly two billion people worldwide, mainly due to inadequate intake of essential minerals and vitamins such as iron (Fe), zinc (Zn), selenium (Se), iodine (I), folate and provitamin A carotenoids (Bouis and Saltzman, 2017; Bouis and Goveta, 2023) [2, 3]. Conventional interventions like supplementation and post-harvest food fortification have had notable success but often face challenges related to recurrent costs, infrastructure and weak delivery systems in low- and middle-income countries (Talsma *et al*., 2022) [23].

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Biofortification, defined as the enhancement of micronutrient concentration and/or bioavailability in edible plant tissues through agronomic measures, conventional breeding or modern biotechnological tools, has emerged as a cost-effective and sustainable strategy to address hidden hunger (Bouis and Saltzman, 2017 [3]; Rehan *et al.*, 2024) [18]. While the majority of early biofortification programmes focused on staple cereals and roots, there is growing recognition that vegetables owing to their inherently high nutrient density, short crop cycles and wide dietary inclusion can play a pivotal role in micronutrient enhancement (Mehmood *et al.*, 2023) [14]; Datta *et al.*, 2025 [5].

This review synthesizes recent advances in the biofortification of vegetable crops for micronutrient enhancement, with emphasis on agronomic, breeding and molecular approaches, in (Fig. 1) and critically discusses the key challenges and future prospects for mainstreaming biofortified vegetables into horticultural production systems.

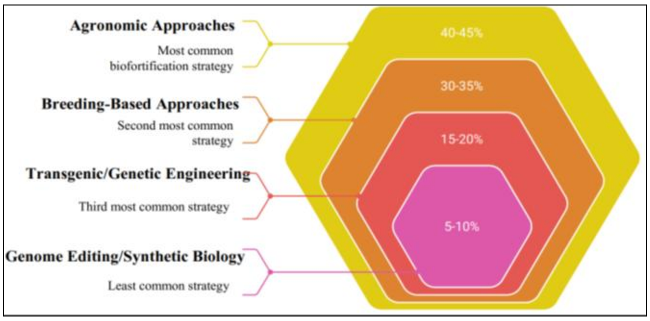

Fig 1: Relative distribution of biofortification strategies in vegetables

2. Micronutrient malnutrition and the role of vegetables

Micronutrient deficiencies compromise immune function, cognitive development, work capacity and maternal-child health, thereby imposing major social and economic burdens (Muthayya *et al.*, 2013) [16]; Talsma *et al.*, 2022 [23]. In many regions, diets are dominated by low-diversity cereal-based staples that supply sufficient calories but insufficient micronutrients, and access to animal-source foods and supplements is constrained by affordability and cultural preferences (Bouis and Saltzman, 2017) [3].

Vegetables are rich in minerals, vitamins, dietary fibre and diverse phytochemicals, and thus have been promoted as indispensable components of healthy diets (Cakmak and Kutman, 2018) [4]; Di Gioia *et al.*, 2021 [7]. Leafy vegetables such as spinach, amaranth and kale are good sources of Fe, Zn, folate and vitamin C, while fruit vegetables like tomato, chilli, capsicum and pumpkin provide provitamin A carotenoids, lycopene and other antioxidants (Mehmood *et al.*, 2023; Rehan *et al.*, 2024) [14, 18]. Brassicas and alliums are recognized for their Se accumulation and glucosinolate content, contributing to both micronutrient intake and functional health benefits (White and Broadley, 2009) [24]; Di Gioia *et al.*, 2021 [7].

Because vegetables can be produced in home gardens, peri-urban systems and intensive commercial horticulture, their biofortification has strong potential to deliver micronutrients to diverse population groups, including urban poor and rural households (Datta *et al.*, 2025; Ajsspn, 2025) [1, 5].

3. Target micronutrients and priority vegetable crops

Key micronutrients targeted in vegetable biofortification include Fe, Zn, Se, I, provitamin A carotenoids (β-carotene, α-carotene, β-cryptoxanthin), lycopene, folates and vitamin C, as well as health-promoting phytochemicals synergistic with micronutrient functions (Mehmood *et al.*, 2023) [14]; Rehan *et al.*, 2024 [18]. Priority vegetable groups include leafy vegetables (spinach, amaranth, fenugreek, kale), brassicas (cabbage, broccoli, kale, mustard), solanaceous crops (tomato, chilli, brinjal), cucurbits (pumpkin, bottle gourd, bitter gourd, cucumber), bulb crops (onion, garlic) and root/tuber vegetables (carrot, beetroot, sweet potato) (Gomathi and Vethamoni, 2017; Ajsspn, 2025) [1, 10].

Substantial genetic variation for micronutrient concentration has been documented within vegetable germplasm. For example, wide ranges for leaf Fe and Zn have been reported in amaranth and spinach; β-carotene content varies markedly among carrot and pumpkin genotypes; and Se accumulation differs significantly among broccoli and garlic cultivars (White and Broadley, 2009 [24]; Di Gioia *et al.*, 2021 [7]; Mehmood *et al.*, 2023) [14]. Such diversity provides a foundation for breeding and selection, complemented by agronomic biofortification to exploit plant uptake and partitioning mechanisms (Cakmak and Kutman, 2018 [4]; Rengel *et al.*, 2022) [19] (Table 1.).

Table 1: Representative target micronutrients, vegetable crops and biofortification approaches

Vegetable	Major micronutrient	Genetic or agronomic response	Main biofortification approaches	References
Leafy vegetables (spinach, amaranth, kale, fenugreek)	Fe, Zn, folate, vitamin C	Large genotypic variation in leaf Fe and Zn; foliar Zn and Fe sprays increase tissue concentration and sometimes yield.	Agronomic (soil and foliar fertilization), conventional breeding, hydroponic solution management.	Cakmak and Kutman (2018) [4]; Rengel *et al.* (2022) [19]; Mehmood *et al.* (2023) [14].
Brassicas (broccoli, cabbage, mustard)	Se, I, Zn	Strong Se accumulation; Se and I fertilization enhances shoot content and human dietary supply.	Agronomic Se/I fertilization, breeding for Se-efficient genotypes.	White and Broadley (2009 [24]; Di Gioia *et al.* (2021) [7].
Solanaceous vegetables (tomato, chilli, brinjal)	Provitamin A carotenoids, lycopene, vitamin C, Zn	High variability in carotenoids; transgenic and edited lines show >2-3-fold increases in β-carotene and folate.	Conventional and molecular breeding, transgenic modification, CRISPR/Cas editing.	Giuliano (2017); Ajsspn (2025 [1, 9]; Zhu *et al.* (2024) [26].
Root and tuber vegetables (carrot, sweet potato, beetroot)	β-carotene, Fe, Zn	Orange-fleshed types rich in β-carotene; micronutrient fertilizers raise Fe/Zn in roots.	Breeding for high carotenoid; agronomic micronutrient fertilization.	HarvestPlus (2025); Rehan *et al.* (2024) [18].
Alliums (onion, garlic)	Se, Zn	Efficient Se uptake from soil and solution; Se-rich bulbs developed under field conditions.	Agronomic Se fertilization and fertigation.	White and Broadley (2009 [24]; Di Gioia *et al.* (2021) [7].

4. Biofortification strategies in vegetable crops

4.1 Agronomic biofortification

Agronomic biofortification entails the application of mineral fertilizers, soil amendments, fortified organic inputs or foliar sprays to improve the supply, uptake and partitioning of target micronutrients in crops (Cakmak and Kutman, 2018) [4]. In vegetables, soil or fertigation application of $ZnSO_4$, Fe chelates, Se and iodine salts, together with foliar sprays, have been widely explored to increase tissue concentrations in leaves, fruits and bulbs (Rengel *et al.*, 2022) [19]; Datta *et al.*, 2025 [5].

Systematic reviews conclude that agronomic biofortification is particularly effective for Zn and Se, with typical 1.5-3-fold increases in plant tissue concentrations under optimized management, and often with concomitant yield benefits (Cakmak and Kutman, 2018) [4]; Rengel *et al.*, 2022 [19]. For example, Se fertilization in broccoli and garlic markedly increases Se content in edible portions, while foliar Zn sprays in leafy vegetables and cucurbits significantly enhance leaf Zn and improve growth (White and Broadley, 2009) [24]; Di Gioia *et al.*, 2021 [7].

Nevertheless, response to agronomic biofortification is strongly modulated by soil properties, including pH, texture, organic matter and carbonate content, as well as interactions with macronutrients and other cations (Cakmak and Kutman, 2018) [4]. Challenges such as nutrient immobilization, leaching and poor translocation from vegetative tissues to fruits or storage organs may limit effectiveness, underscoring the need to couple fertilizer strategies with appropriate cultivars and soil-health management (Rengel *et al.*, 2022 [19]; Mehmood *et al.*, 2023) [14].

4.2 Conventional and molecular breeding

Breeding for micronutrient-dense vegetables exploits natural variation in germplasm collections, landraces and wild relatives, aiming to increase micronutrient concentrations without compromising yield, disease resistance or quality traits (Bouis and Saltzman, 2017) [3]; Rehan *et al.*, 2024 [18]. Screening programmes have identified high-Fe and high-Zn genotypes in leafy amaranths and spinach, high-carotenoid carrots and pumpkins, and tomato lines with elevated lycopene and β-carotene, which serve as donors in crossing schemes (Gomathi and Vethamoni, 2017; Di Gioia *et al.*, 2021) [7, 10].

Molecular tools-including marker-assisted selection, quantitative trait loci (QTL) mapping, genome-wide association studies and, more recently, genomic selection-are increasingly being deployed to dissect the genetic architecture of micronutrient traits and to accelerate the introgression of favourable alleles into elite horticultural backgrounds (Pfeiffer and McClafferty, 2007; Bouis and Goveta, 2023) [2, 17]. The concept of mainstreaming-embedding biofortification targets as routine selection criteria in breeding pipelines-has been successfully implemented in several staples and is now being extended to horticultural crops such as tomato, sweet potato and leafy greens (Pfeiffer and McClafferty, 2007 [17]; HarvestPlus, 2025).

However, breeding for micronutrient traits can encounter trade-offs with yield and organoleptic quality, and phenotyping for mineral and vitamin content is often laborious and costly, especially when multi-environment trials are required to account for genotype × environment interactions (Di Gioia *et al.*, 2021 [7]; Rehan *et al.*, 2024) [18]. Advances in high-throughput phenotyping (e.g. X-ray fluorescence for minerals, near-infrared spectroscopy for carotenoids) and metabolomics are helping to overcome some of these constraints (White and Broadley, 2009 [24]; Cakmak and Kutman, 2018) [4].

4.3 Genetic engineering, genome editing and synthetic biology

Genetic engineering allows the addition, overexpression or silencing of specific genes involved in nutrient uptake, transport, storage or biosynthesis, enabling biofortification even when suitable natural variation is limited (Giuliano, 2017; Bouis and Goveta, 2023) [2, 9]. Transgenic tomatoes with elevated β-carotene, lycopene or folate have been generated through overexpression of carotenogenic genes or folate biosynthesis enzymes, demonstrating substantial increases in these micronutrients in fruits (Giuliano, 2017) [9]; Zhu *et al.*, 2024 [26]. Similarly, overexpression of ferritin or metal transporter genes has been proposed to increase Fe accumulation in edible tissues of various crops (White and Broadley, 2009) [24].

Genome editing tools such as CRISPR/Cas9 provide more precise modification of endogenous genes, enabling targeted knockouts or base edits to redirect metabolic flux, reduce antinutritional factors or up-regulate micronutrient biosynthesis (Zhu *et al.*, 2024) [26]; Siddiqi *et al.*, 2025 [22]. In vegetables, CRISPR/Cas-mediated edits have been reported for carotenoid pathway genes in tomato and pepper, leading to enhanced provitamin A content without foreign DNA integration (Zhu *et al.*, 2024) [26]. Synthetic biology extends these approaches by redesigning entire pathways or introducing synthetic modules for multi-nutrient enhancement, although most applications remain at proof-of-concept research stages (Siddiqi *et al.*, 2025) [22].

Despite their potential, genetically engineered and genome-edited biofortified vegetables face regulatory uncertainty and varying levels of public acceptance across countries, influencing their near-term deployment (Bouis and Goveta, 2023) [2]; Siddiqi *et al.*, 2025 [22].

4.4 Role of soil-plant-microbe interactions in vegetable biofortification

Beyond direct fertilizer inputs, soil biological properties and plant-microbe interactions significantly influence micronutrient acquisition by vegetables (Cakmak and Kutman, 2018) [4]; Rengel *et al.*, 2022 [19]. Mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR) can mobilize sparingly soluble forms of Zn, Fe and Se through acidification, siderophore production and enzymatic mechanisms, thereby enhancing root uptake and translocation to shoots and edible organs (Rengel *et al.*, 2022) [19]; Di Gioia *et al.*, 2021 [7].

Recent studies show that inoculation of leafy vegetables and brassicas with selected mycorrhizal consortia or Zn-solubilizing bacteria can increase micronutrient content more efficiently than mineral fertilizer alone, particularly in low-input systems (Cakmak and Kutman, 2018 [4]; Mineral Biofortification of Vegetables, 2021) [15]. Combining microbial inoculants with moderate doses of micronutrient fertilizers represents an emerging strategy that may lower input requirements while improving nutrient use efficiency and soil health.

5. Recent advances and case examples

Several recent reviews and case studies highlight progress in the biofortification of vegetables. Mehmood *et al.* (2023) [14] and Rehan *et al.* (2024) [18] summarize advances in Fe and Zn biofortification of leafy vegetables, reporting significant increases in leaf micronutrient contents through both agronomic management and selection of superior genotypes. Di Gioia *et al.* (2021) [7] documented successful Se biofortification in broccoli and garlic using Se-enriched nutrient solutions and soil applications, enhancing Se concentrations to levels that can substantially contribute to dietary requirements.

In solanaceous crops, tomato has emerged as a model for carotenoid and folate biofortification. Transgenic and edited varieties with two- to five-fold higher β-carotene and folate have been reported, demonstrating the feasibility of stacking multiple nutritional traits without major yield penalties (Giuliano, 2017) [9]; Zhu *et al.*, 2024 [26]. In root crops, orange-fleshed carrot and sweet potato lines with high provitamin A content are now being promoted in several countries as part of broader nutrition-sensitive agriculture initiatives (HarvestPlus, 2025; Bouis and Goveta, 2023) [2] (Fig. 2).

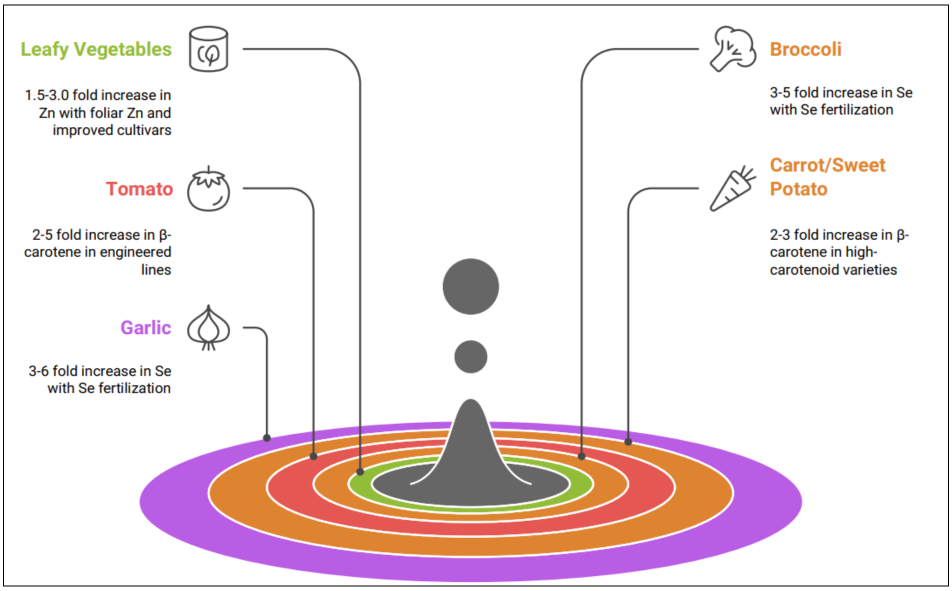

Fig 2: Indicative fold increase in micronutrient concentration following biofortification in selected vegetables.

6. Crop-wise advances in vegetable biofortification

6.1 Leafy vegetables

Leafy vegetables such as spinach (Spinacia oleracea), amaranth (Amaranthus spp.), fenugreek (Trigonella foenum-graecum) and kale (Brassica oleracea var. acephala) are prime targets because leaves are directly consumed and show high mineral density (Cakmak and Kutman, 2018) [4]; Mehmood *et al*., 2023 [14]. Screening trials have reported two- to four-fold variation in Fe and Zn concentrations among genotypes of amaranth and spinach, providing scope for selection of biofortified lines within existing germplasm (Gomathi and Vethamoni, 2017 [10]; Rehan *et al*., 2024) [18].

Agronomic interventions such as soil application of $ZnSO_4$ and Fe chelates, combined with foliar sprays at key vegetative stages, generally increase leaf micronutrient concentrations and can improve yield and leaf area index (Cakmak and Kutman, 2018) [4]; Rengel *et al*., 2022 [19]. Hydroponic and soilless culture systems allow fine-tuning of nutrient solution composition and have been used to successfully enrich baby leafy vegetables in Zn, I and Se while maintaining quality traits such as colour, texture and shelf life (Di Gioia *et al*., 2021 [7]; Biofortification of baby leafy vegetables, 2022).

6.2 Brassicas

Brassicas (broccoli, cabbage, kale, mustard greens) possess inherent capacity to accumulate Se and, to a lesser extent, I, making them attractive vehicles for human intake of these micronutrients (White and Broadley, 2009; Di Gioia *et al*., 2021) [7, 24]. Field and controlled-environment experiments demonstrate that soil or foliar application of selenate or selenite can raise Se content in broccoli heads and cabbage leaves several-fold without detrimental effects on yield, provided that doses are kept below phytotoxic thresholds (Di Gioia *et al*., 2021) [7]; Mineral Biofortification of Vegetables, 2021 [15].

Breeding for Se-efficient brassica genotypes is in its infancy but early work suggests genetic differences in root uptake, xylem loading and vacuolar storage of Se that could be exploited for long-term improvement (White and Broadley, 2009) [24]. Integration of Se biofortification with production of glucosinolate-rich broccoli and kale may deliver dual benefits by supporting both micronutrient adequacy and chronic disease risk reduction (Di Gioia *et al*., 2021; Bouis and Goveta, 2023) [2, 7].

6.3 Solanaceous vegetables

Tomato (Solanum lycopersicum) is a leading solanaceous model for carotenoid and vitamin biofortification. Natural and induced variation in genes controlling the carotenoid pathway (e.g. Psy1, CrtR-b2, Lcy-b) has been used to develop high-lycopene and high-β-carotene lines, while transgenic and genome-edited approaches have produced "Golden" tomatoes with multiple-fold increases in provitamin A (Giuliano, 2017) [9]; Zhu *et al*., 2024 [26]. Vitamin C biofortification has also been attempted by overexpressing key enzymes of the Smirnoff-Wheeler pathway, resulting in fruits with enhanced ascorbic acid content (Giuliano, 2017) [9].

In capsicum and chilli (Capsicum spp.), selection of high-carotenoid genotypes and CRISPR-guided edits in carotenoid biosynthetic genes show promise for developing biofortified peppers that deliver substantial provitamin A per serving (Zhu *et al*., 2024 [26]; Siddiqi *et al*., 2025) [22]. Parallel agronomic strategies, such as balanced N-K fertilization and optimized light management, can further influence carotenoid composition and must be considered in production packages (Mineral Biofortification of Vegetables, 2021) [15].

6.4 Root and tuber vegetables

Carrot (Daucus carota) and sweet potato (Ipomoea batatas) are established sources of provitamin A, and biofortified lines with elevated β-carotene have been widely promoted (HarvestPlus, 2025; Bouis and Goveta, 2023) [2]. In carrots, both conventional breeding and selection among landraces have yielded orange and purple types with high carotenoid and anthocyanin content, while agronomic management (N-K fertilization, irrigation) modulates pigment accumulation (Mineral Biofortification of Vegetables, 2021) [15].

Orange-fleshed sweet potato varieties have been shown in human intervention trials to improve vitamin A status in children and women, providing compelling evidence for the public-health relevance of root-crop biofortification (De Moura *et al*., 2015 [6]; WHO, 2017). Extension of such programmes to other root vegetables, including biofortified beetroot with enriched Fe and folate, is an area of current research.

6.5 Alliums and other specialty vegetables

Onion (Allium cepa) and garlic (Allium sativum) have high capacity to accumulate Se when supplied in available forms and are thus useful for Se biofortification in regions where dietary Se intake is low (White and Broadley, 2009; Di Gioia *et al*., 2021) [7, 24]. Se-enriched bulbs not only increase Se intake but may also influence organoselenium compound profiles, which have been associated with potential anticancer and cardioprotective effects (Di Gioia *et al*., 2021) [7].

Other speciality vegetables, such as microgreens, baby leaf salads and exotic leafy herbs, are emerging as candidates for intensive biofortification using hydroponics, vertical farming and controlled-environment agriculture (Mineral Biofortification of Vegetables, 2021) [15]. Their short growth cycles and high value can justify precision supplementation of micronutrients in nutrient solutions, enabling the production of highly enriched products for niche markets and functional foods.

7. Challenges

7.1 Bioavailability, processing and culinary practices

The nutritional impact of biofortified vegetables depends not only on tissue concentration but also on the bioaccessibility and bioavailability of micronutrients after cooking and digestion (La Frano *et al*., 2014 [13]; Mineral Biofortification of Vegetables, 2021) [15]. Antinutritional factors such as oxalates, phytates and tannins can complex with Fe and Zn, reducing absorption; conversely, organic acids and vitamin C can enhance non-heme Fe bioavailability (La Frano *et al*., 2014) [13].

Processing and culinary methods, including boiling, steaming, stir-frying and fermentation, differentially affect micronutrient retention. For example, boiling may leach water-soluble vitamins and minerals, whereas steaming often preserves them better; carotenoids can be more bioaccessible after mild cooking with oil but may degrade under prolonged heating (De Moura *et al*., 2015 [6]; Mineral Biofortification of Vegetables, 2021) [15]. Designing biofortification programmes must therefore consider typical local cooking practices and promote preparation methods that retain and make best use of the enhanced micronutrient content.

7.2 Seed systems, quality control and labelling

Effective deployment of biofortified vegetables requires robust seed systems capable of producing and distributing high-quality biofortified seed and planting material (HarvestPlus, 2025; Saltzman *et al*., 2025) [21]. In many low- and middle-income countries, vegetable seed sectors are fragmented, with a mixture of public, private and informal systems, making consistent quality control and certification challenging (Bouis and Goveta, 2023) [2].

Standardized protocols for verifying micronutrient levels in candidate varieties, maintaining genetic purity during seed multiplication and clearly labelling biofortified seed are essential to maintain farmer and consumer trust (Saltzman *et al*., 2025) [21]. Development of national or regional standards for "biofortified" claims, aligned with Codex and WHO/FAO guidance, would help avoid misuse of the term and support market development.

7.3 Consumer perception, willingness-to-pay and market integration

Consumer studies indicate that awareness and understanding of biofortification remain limited in many contexts, and willingness-to-pay for biofortified vegetables depends on attributes such as appearance, taste, perceived safety and price (Saltzman *et al*., 2013; Farming First, 2025) [8, 20, 21]. For traits that alter visible characteristics (e.g. deeper orange colour, intense green leaves), some consumers may initially resist change, but targeted information campaigns about health benefits can improve acceptability (WHO, 2017).

Integrating biofortified vegetables into existing value chains-wholesale markets, supermarkets, institutional procurement, processing industries-will be crucial to generate stable demand and price incentives for farmers (HarvestPlus, 2025; Datta *et al*., 2025) [5]. Partnerships with food processors to develop branded, biofortified vegetable products (e.g. sauces, purees, dried powders) can further extend reach and improve year-round availability.

8. Policy, governance and cross-sectoral integration

Governance analyses highlight that biofortification has historically been framed within agricultural research and development, while nutrition, health and education sectors have only gradually begun to engage (Improving Nutrition through Biofortification, 2022; Saltzman *et al*., 2025) [21]. Mainstreaming biofortified vegetables in national nutrition strategies requires explicit recognition in policies, budg*et al*locations and multi-sector coordination mechanisms linking agriculture, health, education and social protection (Farming First, 2025; Bouis and Goveta, 2023) [2, 8].

Key policy instruments include:

- Inclusion of biofortified vegetable varieties on recommended variety lists and subsidy catalogues. (HarvestPlus, 2025).
- Procurement of biofortified vegetables for school feeding, hospitals, correctional facilities and public canteens. (Farming First, 2025) [8].
- Support for public-private partnerships to develop and market biofortified seeds and consumer products. (Bouis and Goveta, 2023) [2].
- Risk-proportionate regulatory frameworks for genome-edited biofortified vegetables that differentiate them from transgenic GMOs where appropriate. (Siddiqi *et al*., 2025) [22].

Ultimately, scaling biofortification of vegetable crops will depend on aligning incentives for breeders, seed companies, farmers, traders, retailers and consumers, within an enabling policy environment that values nutritional outcomes alongside yields and profitability (Saltzman *et al*., 2025) [21].

9. Conclusion

Biofortification of vegetable crops represents a sustainable and effective approach to addressing micronutrient deficiencies and hidden hunger. Significant progress has been made through conventional and molecular breeding, agronomic practices, and emerging technologies such as genome editing and nanotechnology to enhance micronutrient content and bioavailability. However, challenges including complex trait inheritance, environmental interactions, bioavailability constraints, regulatory issues, and limited adoption remain. Integrating genetic, agronomic, and nutritional strategies, along with supportive policies and awareness programs, will be essential to fully realize the potential of biofortified vegetables in improving global nutritional security.

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