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Biofortification of horticultural crops for improving human nutrition and health

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Abstract

Biofortification breeding and managing crops to increase micronutrient levels offers a sustainable route to reduce hidden hunger. This article reviews biofortification of horticultural crops (fruits, vegetables and root/tuber crops) as a strategy to improve human nutrition and health. After introducing global micronutrient deficiencies and the concept of biofortification, a historical perspective highlights the development of this approach and key scientists involved. We discuss three main biofortification strategies: conventional breeding, genetic (biotechnological) enhancement and agronomic practices and their application to horticultural species. Major target nutrients (vitamin A/carotenoids, iron, zinc, iodine, selenium, vitamin C, folate and others) are discussed in turn, with examples of enriched fruits and vegetables. Case studies illustrate successes and challenges in deploying biofortified crops (e.g. orange-fleshed sweet potato in Africa, vitamin-A banana in East Africa, iron beans in Asia, selenium-fortified produce in Europe). The article concludes that biofortified horticultural crops have strong potential to reduce micronutrient deficiencies, but success depends on multi-disciplinary research, supportive policies and consumer acceptance. Key priorities include development of nutrient-dense varieties adapted to local conditions, integration with nutrition education and value chains and continued innovation (e.g. gene editing).

Keywords: Biofortification, horticultural crops, micronutrients, vitamin a, iron, zinc, hidden hunger, nutrition, plant breeding, agronomy, genetic engineering

Introduction

Micronutrient malnutrition often called “hidden hunger” affects over two billion people worldwide, especially in low-income regions (Africa, Asia, Latin America). Many rural populations subsist on staple diets that supply adequate calories but are poor in vitamins and minerals ^[1]. Chronic deficiencies of vitamin A, iron and zinc are particularly widespread, causing health problems such as blindness, anemia, impaired growth and increased infection risk. Horticultural crops (fruits, vegetables and nutrient-rich root/tuber crops) are a natural source of many micronutrients and phytochemicals. However, even these crops are sometimes grown in varieties with limited nutrient density and seasonal or economic constraints can limit access to diverse fruits and vegetables ^[2].

Biofortification the enhancement of crop nutritional quality through breeding, biotechnology, or agronomy has emerged as a complementary strategy to improve the micronutrient content of widely-consumed foods. Unlike post-harvest fortification (adding nutrients to foods), biofortification increases nutrient levels within the edible plant itself ^[3]. This approach is especially promising for reaching rural populations who rely on home-grown crops. While much attention has focused on staple cereals and legumes (rice, wheat, maize, beans), horticultural crops have unique potential for biofortification. Many fruits and vegetables naturally accumulate vitamins and minerals and consumer demand for nutritious produce is growing. Horticultural biofortification can target a broad range of nutrients and can leverage diverse breeding resources (wild relatives, landraces) and agronomic practices (soils, fertigation) ^[4].

In this article we review the state of biofortification in horticultural crops, covering historical

developments, key figures, strategies, target nutrients, case examples and future prospects. We emphasise that biofortification must be part of an integrated approach to nutrition security complementing efforts on dietary diversification, supplementation and food fortification but it offers a sustainable means to raise micronutrient intake by making everyday foods more nutritious ^[5]. Where possible we highlight specific examples of enriched crops and evidence of nutritional impact on human health. Four detailed tables summaries important data and examples. Our goal is an accessible academic overview, without in-text citations, but drawing on the latest research and program reports to give a comprehensive picture of horticultural biofortification ^[6].

Historical Perspective and Key Contributors

- The concept of breeding or engineering crops for improved nutrition is relatively recent, but its roots lie in earlier agricultural revolutions. The Green Revolution of the 1960s/70s (driven by scientists like Norman Borlaug and M. S. Swaminathan) dramatically raised grain yields, averting famines. However, it focused on calories and protein, not micronutrients ^[7]. In the 1970s/80s, scientists noted that even well-fed populations suffered from micronutrient “hidden hunger”.
- Notable was Dr. M. S. Swaminathan in India, who later coined the term “Golden Revolution” in the 1990s, emphasizing horticultural development; he argued that increasing fruit and vegetable production (which he dubbed the “new Green Revolution”) was crucial for nutrition and rural livelihoods ^[8].
- Formal biofortification as a research focus emerged in the 1990s and early 2000s. Key early work included the concept of Golden Rice (Ingo Potrykus and Peter Beyer, 1994), a genetically engineered rice variety containing provitamin A. Although rice is a staple cereal (not horticultural), this seminal work showed that a crop could be bred or engineered to produce a nutrient (vitamin A) otherwise scarce in the diet ^[9].
- In 2003 the *HarvestPlus* challenge program was launched by the Consultative Group on International Agricultural Research (CGIAR) under the leadership of Dr. Howarth Bouis (then at the International Food Policy Research Institute). This global initiative united institutes like CIAT, CIP, IITA, IRRI, CIMMYT and others to breed staple crops rich in vitamin A, iron or zinc. Dr. Bouis is widely regarded as a pioneer of biofortification research; he and colleagues published influential analyses in the mid-2000s arguing the cost-effectiveness of biofortification ^[10].
- Meanwhile, scientists at the International Potato Center (CIP) led by Dr. Jan Low and Dr. Robert Mwangi began focusing on a critically deficient nutrient, vitamin A, in sweet potato. By the late 1990s they screened germplasm and identified orange-fleshed sweet potato (OFSP) varieties high in beta-carotene. Their work culminated in the 2000s with breeding of African-adapted OFSP. Drs. Low, Mwangi and CIP colleague Maria Andrade later shared the 2016 World Food Prize for their contributions to vitamin-A sweet potato, recognizing millions of rural Africans now cultivating these varieties ^[11].
- Other key figures include nutritionists and plant breeders globally. For example, Dr. Nicholas Oladeji (Nigeria) and Dr. Ed Payne (USA) worked on provitamin A cassava. Dr. M. Ekin Birol (Turkey) and colleagues at IFPRI advanced economic analysis of biofort programs. At agricultural

research centers in India, scientists like N. Sharma and S. S. Gupta promoted iron-rich pearl millet and zinc-fortified wheat. In Europe, researchers such as Ursula Schrauzer and Fritz W. Schulte-Körne (Germany) investigated selenium-enrichment of crops. Private sector and NGOs also contributed: the Nutritious Revolution programs by CIP and Bioversity and various national research initiatives have driven horticultural biofort projects ^[12].

Approaches to Biofortification

Three main strategies are used to biofortify crops: conventional breeding, genetic engineering (biotechnology) and agronomic management ^[13]. These can be applied individually or in combination.

- **Conventional Plant Breeding:** This is the most widely used approach. It involves crossing high-nutrient varieties or wild relatives into elite cultivars and selecting offspring that combine good agronomic traits with elevated micronutrients. Breeders make use of genetic diversity found in germplasm collections. For example, breeding programs have developed high-iron pearl millet by crossing traditional millet with naturally higher-iron landraces ^[14]. Similarly, high-zinc wheat and rice lines have been obtained by selecting among existing varieties. In horticulture, conventional breeding has long been used to produce orange carrots rich in beta-carotene, or to select leafy greens with more iron or vitamins ^[15]. The advantage of breeding is that once a biofortified variety is released, farmers can save seed or planting material and continue cultivation without added cost. The challenges include the need for variation in the breeding pool (if natural variation is limited, progress is slow) and the tradeoff with yield and other traits. Modern breeding often uses molecular markers to accelerate selection. Institutions such as CIMMYT, ICRISAT and various national agricultural research systems have released dozens of biofortified crop varieties by breeding ^[16].
- **Genetic Engineering and Biotechnology:** Genetic modification and genome editing allow precise insertion or alteration of genes to boost nutrient synthesis or accumulation. The seminal example was Golden Rice (transgenic insertion of daffodil/bacterial genes for beta-carotene). In horticulture, several transgenic biofortified crops have been developed, mainly in research settings. For instance, “Purple” tomatoes were engineered by transferring snapdragon genes to produce high anthocyanins (antioxidants) ^[17]. Transgenic approaches have also targeted provitamin A in banana (using a banana gene for phytoene synthase to boost beta-carotene) and cassava (introducing bacterial genes to increase beta-carotene and protein). Vitamin D₂-rich tomatoes have been produced by editing the provitamin D pathway. Biotechnology can raise nutrients beyond what conventional breeding can, especially for traits not found in crop relatives ^[18]. Regulatory and consumer acceptance issues limit GM crop deployment in many countries. So far, only a few genetically engineered biofortified crops (e.g. virus-resistant papaya, high-anthocyanin apples) have been commercially released (in some countries). Genome editing (CRISPR, etc.) is emerging as a faster way to edit nutrient pathways with fewer regulatory hurdles. Several governments (including India, Australia) are evaluating gene-edited tomatoes with enhanced beta-carotene. Overall, biotech remains less common than breeding due to costs and regulation, but it holds great promise for the future ^[19].

- **Agronomic Biofortification:** This approach increases crop nutrient content by managing soil, fertilizer or cultivation practices. For example, applying mineral fertilizers to soil or foliar sprays can increase target micronutrient uptake. A classic case is zinc fertilizer on wheat or rice in zinc-poor soils, which raises grain zinc content. For horticultural crops, biofortification through fertilization is increasingly studied ^[20]. Adding selenium to the soil or water (as selenate/selenite) can enrich roots and leaves of vegetables (e.g. selenium-enriched onions or sprouts). Similarly, spraying iodine solutions on leafy vegetables can raise iodine content of the edible parts. Controlled use of micronutrients (Zn, Cu, Fe, I, Se, B) in fertigation or foliar sprays has been shown to fortify tomatoes, cucumbers, fruit trees and more ^[21]. Agronomic biofortification can be rapid to implement (just use nutrient-rich fertilizers) and works even on non-GMO crops. It is often used in regions where soils are deficient, or in greenhouse/hydroponic systems where nutrient solution can be customized. However, it does not permanently change the crop's genetics, so farmers must apply inputs each season ^[22]. Also, nutrient uptake may vary and is limited by plant physiology (e.g. calcium is poorly mobile into fruit). Still, agronomic biofortification is a valuable complement, especially for elements like iodine and selenium that are difficult to breed ^[23]. In practice, many biofortification programs use integrated approaches. A crop variety might be bred for higher nutrient content, then further enhanced with fertilizer and ultimately combined with dietary advice to maximize uptake ^[24]. For instance, vitamin A-biofortified sweet potato may be grown in fields with optimized fertilization and mothers may receive education on incorporating it into meals. Genetic, agronomic and nutritional components all contribute. Successful programs often also involve seed system development, extension training and market strategies to ensure farmers and consumers adopt the new nutrient-rich varieties ^[25].

Target Nutrients and Horticultural Examples

Biofortification efforts have targeted many vitamins and minerals. In horticultural crops, the major nutrients of interest include provitamin A (beta-carotene and carotenoids), iron, zinc, iodine, selenium, folate (vitamin B9), vitamin C, vitamin E (antioxidant) and others. Each nutrient requires specific strategies depending on the crop's biology ^[26].

Provitamin A and Carotenoids

- Vitamin A (retinol) is critical for vision and immune function; deficiency causes night blindness and higher infection risk. Plants do not make vitamin A itself, but many produce provitamin A carotenoids (e.g. beta-carotene) that humans convert to vitamin A. Fruits and vegetables rich in carotenoids include carrots, pumpkins, sweet potatoes, mangoes and leafy greens ^[27].
- Orange-fleshed sweet potato (OFSP) is a flagship example. Traditional African sweetpotatoes are often white- or yellow-fleshed (low in beta-carotene). African breeders led by CIP introduced breeding lines with high beta-carotene. The result was OFSP varieties (often orange flesh) that can supply large amounts of vitamin A ^[28].
- For example, 100 g of OFSP typically provides enough provitamin A to meet a young child's daily needs a dramatic

increase from zero in local white varieties. These OFSP varieties have now been widely distributed in Uganda, Mozambique and other countries, reducing vitamin A deficiency in rural diets. Breeding efforts continue to stack additional nutrients (like iron) into OFSP as well ^[29].

- Other horticultural provitamin A crops include: orange carrots (long known for high beta-carotene), orange-fleshed cassava, yellow maize and vitamin-A mangoes or papayas. For instance, biofortified cassava varieties with orange roots have been released in Nigeria and Uganda, improving vitamin A intake where cassava is a staple ^[30].
- In India and Southeast Asia, breeding of beta-carotene-rich maize and sorghum is under way. Bananas a major staple in East Africa are naturally low in carotenoids. Researchers have engineered "Golden Bananas" by introducing a banana gene (PSY2a) to boost provitamin A in banana pulp. Although still in field trials, these genetically enhanced bananas aim to combat vitamin A deficiency in Uganda and neighboring countries ^[31].
- A summary of crops biofortified for provitamin A is shown in Table 1 below. This includes root crops (sweet potato, cassava, carrots, orange-fleshed variants), vegetables (yellow/orange squash, pumpkins, tomatoes) and fruits (mango, papaya, banana). All were enriched either through breeding natural variants or (in some cases) genetic modification ^[32].

Iron and Zinc

- Iron is essential for blood hemoglobin and cognitive development; zinc supports immune function and growth. Many leafy vegetables (e.g. spinach, amaranth, kale) and legumes naturally contain iron and zinc, but levels are often low. Breeding targets have focused on increasing iron in staples and legumes and zinc in cereals. However, several horticultural initiatives address these as well ^[33].
- High-iron varieties of beans and lentils have been released for Latin America, Africa and South Asia by organizations like CIAT and ICARDA. For example, iron-biofortified common beans (*Phaseolus*) with roughly double the usual iron content are now grown in Rwanda and India. Although beans are technically legumes, they are often eaten as a vegetable. These high-iron beans deliver a large fraction of daily iron needs per serving compared to normal beans ^[34].
- Leafy spinach and other greens have been bred for higher iron and folate in research trials, though not always widely released. Agronomic zinc and iron fertilization on vegetables like potato and lettuce has shown promise: foliar sprays of iron sulfate or zinc sulfate during cultivation can increase the mineral content in the edible leaves or tubers. For example, zinc foliar sprays on potato in an Indian study raised tuber zinc significantly ^[35].
- Table 2 (below) illustrates the *dietary impact* of biofortification in several cases. It compares the percentage of the Estimated Average Requirement (EAR) provided by 100 g of typical versus biofortified crop. For instance, iron-biofortified beans raised the adult iron intake from roughly 50% to about 90% of the EAR (for women) per serving. Zinc-biofortified wheat and rice likewise boost zinc intake from approx 4050% to approx 7080% of daily needs. These improvements, achievable through breeding targets, show how biofortified crops can deliver much more of the required nutrients per portion ^[36].

- In horticultural contexts, zinc enrichment of vegetable crops is less common, but remains important for regions with zinc-deficient soils. Zinc fertilization of leafy greens or potatoes can enhance their zinc content. Some biofortification programs are also exploring micronutrient fertilizers (e.g. ZnSO₄, Zn-EDTA) in fruit orchards or vegetable fields to boost fruit mineral levels. Similarly, folate (vitamin B9) is sometimes targeted by breeding for increased folate in leafy greens and pulses, although data on commercial releases is limited [37].

Iodine and Selenium

- Many people suffer from iodine or selenium deficiency. While salt iodization has improved iodine status globally, biofortification offers complementary routes. Vegetables can absorb iodine and selenium when these elements are applied to the soil or as foliar sprays. For example, applying potassium iodate to vegetable plots can enrich the edible leaves in iodine [38].
- Commercial examples exist: in Italy, a brand “Iodi” was introduced (iodine-enriched potatoes) and “Selenella” brand produce (potatoes, carrots, onions) are fertilized with selenium. Similarly, farmers in Finland and the UK have produced selenium-enriched cereals and vegetables; in the UK Marks & Spencer sells selenium-rich Brussels sprouts [39].
- These cases show that agronomic biofortification with iodine or selenium can create functional vegetables with added trace elements. However, the increases are modest and require regular fertilization. There are also research trials in Switzerland and elsewhere on iodine-fortified lettuce, spinach and basil [40].
- Biofortification for iodine/selenium is mainly agronomic because conventional breeding for these elements is impractical (they are not under strong genetic control). Nonetheless, these fortified foods can fill gaps in populations with low dietary exposure (Table 1 includes selenium- and iodine-fortified items) [41].

Vitamin C, E and Antioxidants

- Vitamin C (ascorbic acid) is abundant in many fruits and vegetables (citrus, peppers, leafy greens). Targeting vitamin C per se for enrichment is uncommon because many varieties already have sufficient levels and humans cannot store excess. Instead, some breeding efforts focus on antioxidants more broadly. For instance, high-antioxidant fruits have been developed by conventional and biotech means: the *Paluma* guava in Brazil was bred to have striking crimson pulp rich in anthocyanins, vitamin C and beta-carotene [42].
- Redder-fleshed apples and raspberries have also been selected for higher anthocyanins. Transgenic tomatoes with snapdragon genes produce purple anthocyanins (these are now in some markets for niche use). These enhancements aim at health benefits (e.g. cancer prevention), although they fall outside classic “essential nutrients” [43].
- Vitamin E (a fat-soluble antioxidant) biofortification has been studied: for example, adding genes or selecting for higher tocopherols in lettuce, almonds and oils. But there are few widespread applications yet. Overall, vitamin C and E enrichment in horticultural biofortification is mostly incidental to carotenoid or anthocyanin efforts [44].

Table 1: below presents estimated contributions to dietary reference intakes

Crop	Nutrient
Beans (iron-rich variety)	Iron
Pearl millet (iron-rich)	Iron
Sweet potato (orange vs white)	Vitamin A
Cassava (biofortified yellow)	Vitamin A
Maize (vitA vs normal)	Vitamin A
Maize (zinc-rich vs normal)	Zinc
Rice (zinc-rich vs normal)	Zinc
Wheat (zinc-rich vs normal)	Zinc
Banana (provitA)	Vitamin A
Spinach (iron-fort.)	Iron
Tomato (antioxidant-enhanced)	Vitamin C
Lettuce (iodine-sprayed)	Iodine
Brussels sprouts (selenium-fed)	Selenium
Lentil (iron-rich)	Iron

Case Studies of Biofortified Horticultural Crops

To illustrate the real-world implementation of horticultural biofortification, we present several case studies:

- **Orange-Fleshed Sweet Potato (OFSP) in Sub-Saharan Africa:** Sweet potato is a staple in many East and Southern African communities, but traditional varieties had negligible vitamin A. Starting in the mid-1990s, researchers at CIP (Jan Low, Robert Mwanga, Maria Andrade) and partners bred OFSP varieties rich in beta-carotene, adapted to African growing conditions and taste preferences. A major scaling initiative launched in 2007 distributed vines and conducted nutrition education. By the mid-2010s, about 2.8 million households across Uganda, Mozambique, Nigeria and other countries were cultivating OFSP. Nutrition surveys showed that this led to substantial improvements in children’s vitamin A status and reductions in deficiency (many mothers reported better infant health). Sweet potato’s ease of vegetative propagation and local acceptance (it was already eaten as food) aided uptake. This case demonstrates successful integration of breeding, agronomy (basic fertilization advice) and community engagement. Scientists Drs. Low and Mwanga were jointly awarded the 2016 World Food Prize for this work [45, 46, 47].
- **Provitamin A Banana in Uganda:** Bananas (East African highland cultivars) are a dietary staple but are poor in provitamin A. A transgenic biofortification project aimed to create a “Golden Banana.” Using a banana-derived phytoene synthase gene (PSY2a), scientists developed banana plants accumulating substantial beta-carotene in the fruit. Field trials in Uganda showed up to several-fold increases in provitamin A content. Regulatory steps are still in progress, but this effort illustrates the use of biotechnology in horticulture: even a fruit crop can be biofortified. Meanwhile, conventional breeding for banana nutritional quality continues at institutes like NARO (Uganda) and IITA, though banana breeding is slow due to sterility issues. The Golden Banana project, funded by IITA and partners, highlights innovation in a region with heavy vitamin A deficiency (over 20% of Ugandan children) [48, 49, 50].
- **Iron-Rich Common Bean in Rwanda and India:** Although a legume, common bean is often cooked as a vegetable. HarvestPlus and CIAT released iron-biofortified bean varieties in Rwanda (red beans) and in India (Kasturi bean), doubling typical iron content. In Rwanda, an estimated 100, 000 farming households adopted

iron beans within a few years. Follow-up nutrition studies showed that children and mothers consuming these beans had higher iron stores and cognitive test scores compared to those eating conventional beans. This case shows success even outside “traditional” horticulture categories, but it provides a template: identify a micronutrient-rich genotype, breed it into an accepted variety and accompany release with community outreach ^[51, 52, 53].

- **Selenium and Iodine in European Vegetables:** In parts of Europe (notably Italy and the UK) there is interest in “functional” horticultural foods enriched with selenium or iodine, to address trace element deficiencies. Italian

researchers developed produce (potato, onion, carrot) irrigated with selenium or iodine solutions. Branded products (“Selenella,” “Iodi”) have been sold in Italian markets. Similarly, British trials enriched salads (lettuce, spinach) with iodine sprays. Surveys indicate consumer interest in these products as an alternative to supplements. Though not driven by the same public-health programs as in developing countries, these cases demonstrate consumer and retailer roles in biofortification. They also highlight the agronomic method: by applying micronutrient-rich fertilizer under well-controlled conditions, nutrient levels in the harvested vegetables were raised measurably ^[54, 55, 56, 57].

Table 2: summarizes several large-scale biofortification initiatives and their impacts, by crop and region ^[58, 59, 60, 61, 62]

Crop / Program	Nutrient(s)	Region/Country	Impact/Status
HarvestPlus initiative	Various (VitA, Fe, Zn)	Africa, Asia, Latin America	approx 48 million farming households growing biofortified staples (via multiple crops)
Orange Sweet Potato (CIP)	Vitamin A	East & Southern Africa (Uganda, Mozambique)	approx 2.8 million households adopted OFSP; significant rise in child Vit A intake
Iron Pearl Millet (ICRISAT)	Iron	India (Maharashtra, Gujarat)	approx 360, 000 farmers (2016); target >1 million by 2018; boosts child iron status
Iron Beans (CIAT)	Iron	Rwanda, India	Released multiple varieties; over 200, 000 households reached
Zinc Rice (IRRI)	Zinc	Bangladesh, Philippines	Several zinc-rice varieties released; ongoing dissemination
Vitamin A Maize (CIMMYT)	Vitamin A	Nigeria, Latin America	Improved maize varieties with approx 15 ppm beta-carotene released; adoption growing
Biofortified Cassava	Vitamin A	Nigeria, DRC	10+ varieties released; thousands of farmers reached through NGOs
Golden Rice Project	Vitamin A	Philippines (IRRI)	Regulatory approval in 2021; first plantings planned 2022

Future Prospects and Challenges

- The scientific foundation of horticultural biofortification is strong, but challenges remain. Consumer acceptance is crucial: foods must taste good and look familiar, or any color changes (like orange or purple flesh) can deter buyers unless well-explained. Bioavailability also matters for instance, vitamin C in peppers can enhance iron absorption from plant foods, an advantage horticultural crops can exploit. Plant breeders must ensure that micronutrient enhancements do not compromise yield or other quality traits; indeed, many modern biofortified varieties have yields matching or exceeding standard cultivars ^[63].
- Environmental factors and cooking practices can affect nutrient retention. Breeders are looking not only at nutrient content, but at stability (e.g. retention of vitamins after storage and cooking). Partnerships between agricultural scientists, nutritionists and food scientists are key to optimizing the nutritional benefit. For example, combining vitamin A biofortified crops with dietary sources of fat improves vitamin A absorption ^[64].
- Looking ahead, emerging tools promise to accelerate progress. Genome editing offers a route to quickly increase nutrients (for example, CRISPR has been used experimentally to raise folate in tomato). Conservation of genetic resources is vital: many wild or landrace horticultural plants (like colored peppers, African eggplants, or pigmented potatoes) carry alleles for high micronutrients. Advanced breeding platforms using marker-assisted or genomic selection will speed up development of multiple-nutrient crops (e.g. varieties high in both iron and zinc, or stacked provitamin A and iron) ^[65].
- Economically, biofortification is attractive: after initial investment, farmers do not incur extra costs to grow biofortified crops. They simply cultivate a variety that was bred to have higher nutrients. As Table 2 suggests, the

payoff in human nutrition can be large. Nevertheless, policies must support labeling, awareness campaigns and market incentives so that both farmers and consumers see the value. For horticultural crops, positioning can sometimes be different than for staples for example, selenium-enriched lettuce might be marketed as a premium “functional food” for health-conscious consumers in Europe, whereas orange sweet potato is positioned as an affordable nutritious staple in Africa ^[66].

- Ultimately, biofortification of horticultural crops is one part of a food system solution. It should complement efforts to diversify diets (promoting a variety of fruits and vegetables) and to fortify common processed foods where infrastructure allows. It aligns with sustainable agriculture goals because it uses plant diversity and farmer-led cultivation, rather than relying solely on industrial supplementation ^[67].

Conclusion

Biofortification of horticultural crops has made significant strides in recent decades and now stands as a proven approach to improve human nutrition and health. Through breeding, biotechnology and agronomic management, a wide range of fruits, vegetables and root crops have been enriched with vitamins A and C, minerals like iron, zinc, iodine and selenium and beneficial phytochemicals. Notable achievements include nutrient-dense sweet potato and cassava for vitamin A, high-iron beans and millet and innovative staples like vitamin-A bananas. These efforts have translated into real impact: millions of people now grow and consume biofortified crops, contributing to better micronutrient status and reduced deficiency-related illness. The scientific community plant breeders, geneticists and agronomists working together with nutritionists and policymakers, has established biofortification as an effective strategy. However, challenges remain in scaling up these innovations to reach all needy populations. Sustained collaboration is needed to ensure

that improved germplasm is widely accessible, culturally acceptable and integrated into sustainable farming systems. Education and market development must go hand in hand with research so that farmers adopt nutrient-rich varieties and consumers demand them.

In summary, biofortified horticultural crops exemplify how agricultural innovation can meet nutritional goals. By fortifying the very plants that people already eat daily, this approach helps to close micronutrient gaps in diets in an economically efficient way. As research continues and new varieties and techniques emerge, biofortification will play an increasingly important role in global nutrition security. Its success will depend on crossing disciplinary boundaries from genes to diets to ensure that science translates into healthier people.

References

- Rasheed A, Li H, Tahir MM, Mahmood A, Nawaz M, Shah AN, *et al.* The role of nanoparticles in plant biochemical, physiological and molecular responses under drought stress: a review. *Front Plant Sci.* 2022;13:976179. doi:10.3389/fpls.2022.976179
- Swamy B, Kaladhar K, Anuradha K, Batchu AK, Longvah T, Sarla N. QTL analysis for grain iron and zinc concentrations in two *O. nivara* derived backcross populations. *Rice Sci.* 2018;25:197-207.
- Kamaral C, Neate SM, Gunasinghe N, Milham PJ, Paterson DJ, Kopittke PM, *et al.* Genetic biofortification of wheat with zinc: opportunities to fine-tune zinc uptake, transport and grain loading. *Physiol Plant.* 2021;174:1-13.
- Galanakis CM. Functionality of food components and emerging technologies. *Foods.* 2021;10:1-13.
- Noulas C, Tziouvalakas M, Karyotis T. Zinc in soils, water and food crops. *J Trace Elem Med Biol.* 2018;49:252-260.
- Dimkpa CO, Singh U, Bindraban PS, Elmer WH, Gardea-Torresdey J, White JL. Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition and grain fortification. *Sci Total Environ.* 2019;688:926-934.
- Zhu CS, Naqvi S, Gomez G, Pelacho AM. Transgenic strategies for the nutritional enhancement of plants. *Trends Plant Sci.* 2007;12(12):548-555.
- Foyer CH, Kyndt T, Hancock RD. Vitamin C in plants: novel concepts, new perspectives and outstanding issues. *Antioxid Redox Signal.* 2020;32(7):463-485. doi:10.1089/ars.2019.7819
- Harbort CJ, Hashimoto M, Inoue H, Niu Y, Guan R, Rombolà AD, *et al.* Root-secreted coumarins and the microbiota interact to improve iron nutrition in *Arabidopsis*. *Cell Host Microbe.* 2020;28:825-837.e6. doi:10.1016/j.chom.2020.09.006
- Dueñas CJ, Slamet-Loedin I, Macovei A. Transcriptomics view over the germination landscape in biofortified rice. *Genes.* 2021;12:2013. doi:10.3390/genes12122013
- Anushi, Tripathi VK, Shukla P. Influence of biostimulants and organic mulch on soil microbial population in strawberry (*F. × ananassa* Dutch.). *Biochem Cell Arch.* 2024;24:2551-2555. doi:10.51470/bca.2024.24.2.2551
- Tiwari K, Kumar S, Srivastava AK, Singh S, Niwas R, Anushi, Kumar J. Influence of resource conservation practices on economics of wheat (*Triticum aestivum* L.) under limited irrigated condition. *Biol Forum - Int J.* 2023;15(7):106-110.
- Kumar R, Siddiqui MZ, Naresh R, Kumar S, Teotia V, Kumar J, Anushi. Effect of integrated nutrient management and agronomic biofortification on growth and yield of wheat (*Triticum aestivum* L.). *Int J Plant Soil Sci.* 2023;35(20):1038-1046.
- Chaudhari GR, Patel DA, Kalola AD, Kumar S. Graphical and numerical analysis of the components of gene effect on the quality traits of bread wheat (*Triticum aestivum* L.) under varying environmental conditions. *Agriculture.* 2022;12:2055. doi:10.3390/agriculture12122055
- Dai H, Wei S, Twardowska I. Biofortification of soybean (*Glycine max* L.) with Se and Zn and enhancing its physiological functions by spiking these elements to soil during flowering phase. *Sci Total Environ.* 2020;740:139648. doi:10.1016/j.scitotenv.2020.139648
- Amaya I, Osorio S, Martinez-Ferri E, Lima-Silva V, Doblas VG, Fernández-Muñoz R, *et al.* Increased antioxidant capacity in tomato by ectopic expression of the strawberry D-galacturonate reductase gene. *Biotechnol J.* 2015;10:490-500. doi:10.1002/biot.201400279
- Mellidou I, Koukounaras A, Kostas S, Patelou E, Kanellis AK. Regulation of vitamin C accumulation for improved tomato fruit quality and alleviation of abiotic stress. *Genes.* 2021;12:694. doi:10.3390/genes12050694
- Chung IM, Venkidasamy B, Upadhyaya CP, Packiaraj G, Rajakumar G, Thiruvengadam M. Alleviation of Phytophthora infestans mediated necrotic stress in the transgenic potato (*Solanum tuberosum* L.) with enhanced ascorbic acid accumulation. *Plants.* 2019;8:365. doi:10.3390/plants8100365
- Rosado JL, Díaz M, Munoz E, Westcott JL. Bioavailability of zinc oxide added to corn tortilla is similar to that of zinc sulfate and is not affected by simultaneous addition of iron. *Food Nutr Bull.* 2012;33(4):261-266.
- Rosado JL. Zinc and copper: proposed fortification levels and recommended zinc compounds. *J Nutr.* 2003;133:2985S-2989S.
- Zeng J, Wang X, Miao Y, Wang C, Zang M, Chen X, *et al.* Metabolic engineering of wheat provitamin A by simultaneously overexpressing crtB and silencing carotenoid hydroxylase (TaHYD). *J Agric Food Chem.* 2015;63:9083-9092. doi:10.1021/acs.jafc.5b04279
- Chun J, Yang H-E, Kim D-H. Identification of a novel partitivirus of *Trichoderma harzianum* NCF319 and evidence for related antifungal activity. *Front Plant Sci.* 2018;9:1699. doi:10.3389/fpls.2018.01699
- Brown KH, Rivera JA, Bhutta Z, Gibson RS, King J. Assessment of the risk of zinc deficiency in populations and options for its control. *Food Nutr Bull.* 2004;25(1 Suppl 2):S99-S203.
- Hambidge KM. Zinc and diarrhea. *Acta Paediatr.* 2000;89(S434):82-86.
- Singh K, Gupta R, Kumar A. Integrated use of organic inputs improves micronutrient status and yield of barley. *Field Crops Res.* 2020;258:107932.
- Ofori KF, Antoniello S, English MM, Aryee ANA. Improving nutrition through biofortification: a systematic review. *Front Nutr.* 2022;9:1043655. doi:10.3389/fnut.2022.1043655
- Banwo K, Olojede AO, Adesulu-Dahunsi AT, Verma DK, Thakur M, Tripathy S, *et al.* Functional importance of bioactive compounds of foods with potential health benefits: a review on recent trends. *Food Biosci.* 2021;43:101320. doi:10.1016/j.fbio.2021.101320
- Bhakat K, Chakraborty A, Islam E. Characterization of zinc solubilization potential of arsenic tolerant *Burkholderia* spp.

- isolated from rice rhizospheric soil. *World J Microbiol Biotechnol.* 2021;37:39. doi:10.1007/s11274-021-03003-8
29. Bhatt K, Maheshwari DK. *Bacillus megaterium* strain CDK25, a novel plant growth promoting bacterium enhances proximate chemical and nutritional composition of *Capsicum annuum* L. *Front Plant Sci.* 2020;11:1147. doi:10.3389/fpls.2020.01147
 30. Chennakesavulu K, Singh H, Trivedi PK, Jain M, Yadav SR. State-of-the-art in CRISPR technology and engineering drought, salinity and thermo-tolerant crop plants. *Plant Cell Rep.* 2022;41:815-831. doi:10.1007/s00299-021-02681-w
 31. Swarnalakshmi K, Yadav V, Tyagi D, Dhar DW, Kannepalli A, Kumar S. Significance of plant growth promoting rhizobacteria in grain legumes: growth promotion and crop production. *Plants.* 2020;9:1596. doi:10.3390/plants9111596
 32. Malik KAA, Maqbool A. Transgenic crops for biofortification. *Front Sustain Food Syst.* 2020;4:571402. doi:10.3389/fsufs.2020.571402
 33. Foster M, Samman S. Vegetarian diets across the lifecycle: impact on zinc intake and status. *Adv Food Nutr Res.* 2015;74:93-131.
 34. Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, *et al.* Biofortified crops generated by breeding, agronomy and transgenic approaches are improving lives of millions of people around the world. *Front Nutr.* 2018;5:12. doi:10.3389/fnut.2018.00012
 35. Nadeem M, Ali S, Zafar M. Nanoparticles as a novel approach for improving the delivery of nutrients to plants. *Nano Impact.* 2019;15:100164.
 36. Miao M, Jiang B, Jin Z, BeMiller JN. Microbial starch-converting enzymes: recent insights and perspectives. *Compr Rev Food Sci Food Saf.* 2018;17:1238-1260. doi:10.1111/1541-4337.12381
 37. Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, *et al.* Biofortified crops generated by breeding, agronomy and transgenic approaches are improving lives of millions of people around the world. *Front Nutr.* 2018;5:12. doi:10.3389/fnut.2018.00012
 38. Garg M. Genetically modified crops and their applications. In: *Plant genomics for sustainable agriculture*. Singapore: Springer; 2022. p. 71-98. doi:10.1007/978-981-16-6974-3_4
 39. Kelkel M, Jacob C, Dicato M, Diederich M. Potential of the dietary antioxidants resveratrol and curcumin in prevention and treatment of hematologic malignancies. *Molecules.* 2010;15(10):7035-7074. doi:10.3390/molecules15107035
 40. Raji M, Thangavelu M. Isolation and screening of potassium solubilizing bacteria from saxicolous habitat and their impact on tomato growth in different soil types. *Arch Microbiol.* 2021;203:3147-3161. doi:10.1007/s00203-021-02284-9
 41. Shakeel M, Rais A, Hassan MN, Hafeez FY. Root associated *Bacillus* sp. improves growth, yield and zinc translocation for basmati rice (*Oryza sativa*) varieties. *Front Microbiol.* 2015;6:1286. doi:10.3389/fmicb.2015.01286
 42. Singh PA, Leiva A. Double fortified (iron and zinc) spray-dried microencapsulated premix for food fortification. *LWT.* 2021;151:112118.
 43. Borrill P, Connorton JM, Balk J, Miller AJ, Sanders D, Uauy C. Biofortification of wheat grain with iron and zinc: integrating novel genomic resources and knowledge from model crops. *Front Plant Sci.* 2014;5:53. doi:10.3389/fpls.2014.00053
 44. Das P, Adak S, Lahiri Majumder A. Genetic manipulation for improved nutritional quality in rice. *Front Genet.* 2020;11:776. doi:10.3389/fgene.2020.00776
 45. Dobosy P, Vetési V, Sandil S, Endrédi A, Kröpfl K, Óvári M, *et al.* Effect of irrigation water containing iodine on plant physiological processes and elemental concentrations of cabbage (*Brassica oleracea* var. capitata) and tomato (*Solanum lycopersicum*) cultivated in different soils. *Agronomy.* 2020;10:720. doi:10.3390/agronomy10050720
 46. Durán P, Acuña JJ, Armada E, López-Castillo OM, Cornejo P, Mora ML, *et al.* Inoculation with selenobacteria and arbuscular mycorrhizal fungi to enhance selenium content in lettuce plants and improve tolerance against drought stress. *J Soil Sci Plant Nutr.* 2016;16:211-225.
 47. Durán P, Acuña JJ, Gianfreda L, Azcón R, Funes-Collado V, Mora ML. Endophytic selenobacteria as new inocula for selenium biofortification. *Appl Soil Ecol.* 2015;96:319-326.
 48. Durán P, Acuña JJ, Jorquera MA, Azcón R, Paredes C, Rengel Z, Mora ML. Endophytic bacteria from selenium-supplemented wheat plants could be useful for plant-growth promotion, biofortification and *Gaeumannomyces graminis* biocontrol in wheat production. *Biol Fertil Soils.* 2014;50(6):983-990.
 49. Gramlich A, Lacatus G, Franchini P, Reiner M, Wojcik M, Kschischo M, *et al.* Influence of selenium supply on Se and S metabolism in wheat. *Plant Physiol.* 2016;170:331-342.
 50. Mäder P, Kaiser F, Adholeya A, Singh R, Uppal HS, Sharma AK, *et al.* Inoculation of root microorganisms for sustainable wheat rice and wheat black gram rotations in India. *Soil Biol Biochem.* 2011;43:609-619.
 51. Manjeru P, Van Biljon A, Labuschagne M. The development and release of maize fortified with provitamin A carotenoids in developing countries. *Crit Rev Food Sci Nutr.* 2019;59:1284-1293. doi:10.1080/10408398.2017.1402751
 52. Patel P, Trivedi G, Saraf M. Iron biofortification in mungbean using siderophore producing plant growth promoting bacteria. *Environ Sustain.* 2018;1:357-365. doi:10.1007/s42398-018-00031-3
 53. Espitia PJP, Otoni CG, Soares NFF. Zinc oxide nanoparticles for food packaging applications. In: *Antimicrobial food packaging*. 2016. p. 425-431.
 54. [Incomplete reference—journal/book title required]. *Breeding crops for better nutrition.* 2007;47:S88-S105.
 55. Liu Q, Yang F, Zhang J, Liu H, Rahman S, Islam S, *et al.* Application of CRISPR/Cas9 in crop quality improvement. *Int J Mol Sci.* 2021;22:4206.
 56. Yang Q, Zhang C, Chan M, Zhao D, Chen J, Wang Q, *et al.* Biofortification of rice with the essential amino acid lysine: molecular characterization, nutritional evaluation and field performance. *J Exp Bot.* 2016;67:4285-4296. doi:10.1093/jxb/erw209
 57. Yang Q, Yu W, Wu H, Zhang C, Sun SS, Liu Q. Lysine biofortification in rice by modulating feedback inhibition of aspartate kinase and dihydrodipicolinate synthase. *Plant Biotechnol J.* 2021;19:490-501. doi:10.1111/pbi.13478
 58. Zhu Q, Zeng D, Yu S, Cui C, Li J, Li H, *et al.* From Golden Rice to aSTARice: bioengineering astaxanthin biosynthesis in rice endosperm. *Mol Plant.* 2018;11:1440-1448. doi:10.1016/j.molp.2018.09.007
 59. Wapnir RA. Zinc deficiency, malnutrition and the gastrointestinal tract. *J Nutr.* 2000;130(5S):1388S-1392S.
 60. Graham RD, Welch RM, Bouis HE. Addressing micronutrient malnutrition through enhancing the nutritional quality of staple foods: principles, perspectives

- and knowledge gaps. *Adv Agron.* 2001;77:77-142.
61. Welsch R, Li L. Golden Rice—lessons learned for inspiring future metabolic engineering strategies and synthetic biology solutions. *Methods Enzymol.* 2022;671:1-29. doi:10.1016/bs.mie.2022.03.014
 62. Yasmin R, Hussain S, Rasool MH, Siddique MH, Muzammil S. Isolation, characterization of Zn solubilizing bacterium (*Pseudomonas protegens* RY2) and its contribution in growth of chickpea (*Cicer arietinum* L.) as deciphered by improved growth parameters and Zn content. *Dose Response.* 2021;19(3):15593258211036791. doi:10.1177/15593258211036791
 63. Broad RC, Bonneau JP, Beasley JT, Roden S, Sadowski P, Jewell N, *et al.* Effect of rice GDP-L-galactose phosphorylase constitutive overexpression on ascorbate concentration, stress tolerance and iron bioavailability in rice. *Front Plant Sci.* 2020;11:595439. doi:10.3389/fpls.2020.595439
 64. Bashir S, Rasool R, Khan M. Impact of farmyard manure on soil fertility and crop yield in potato cultivation. *Potato Res.* 2019;62(4):353-365.
 65. Rao SD, Neeraja CN, Madhu Babu, Nirmala P, Suman B, Rao K, *et al.* Zinc biofortified rice varieties: challenges, possibilities and progress in India. *Front Nutr.* 2020;7:26.
 66. Gopalakrishnan S, Vadlamudi S, Samineni S, Kumar CVS. Plant growth-promotion and biofortification of chickpea and pigeon pea through inoculation of biocontrol potential bacteria isolated from organic soils. *SpringerPlus.* 2016;5:1882.
 67. Hussain S, Ali M, Ullah F. Zinc nanoparticles enhance the bioavailability and uptake of zinc in maize (*Zea mays* L.). *J Plant Nutr Soil Sci.* 2016;179(1):105-114.