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Breeding Vegetables for Nutritional Security: Addressing Malnutrition and Hidden Hunger

Johar Singh, Garima Verma, Madhu Sharma*, Jiffinvir Singh Khosa and A. S. Dhatt

Department of Vegetable Science, Punjab Agricultural University, Ludhiana – 141001, Punjab, India; madhusharma@pau.edu

Abstract

Malnutrition, particularly "hidden hunger" (micronutrient deficiency), remains a persistent global health crisis, disproportionately affecting vulnerable populations. Vegetables, often termed "protective foods," play a vital role in alleviating these problems due to their richness in essential vitamins, minerals, and bioactive compounds. However, the nutritional quality of vegetable crops has been overlooked in research and breeding programs. This review examines the strategies to enhance the nutritional density of vegetables to secure public health. Global and national nutrition programs play a foundational role in the extensive inclusion of vegetables in daily diets. The current strategies range from agronomic biofortification (using enriched fertilisers) and conventional breeding (hybridisation and selection) to advanced technologies like molecular breeding (MAS, GS) and genome editing (CRISPR-Cas9), enabling the targeted improvement of key nutrients. Moreover, interdisciplinary collaboration, standardised nutrient screening, and the utilisation of underutilised, nutrient-rich local crops are the need of the hour. Collectively, these innovations offer promising routes to develop nutrient-dense, climate-resilient cultivars that can contribute substantially to dietary diversification and nutritional security, thereby addressing the global challenge of micronutrient deficiencies.

Keywords: Hidden hunger, Malnutrition, Micronutrients, Vegetables, Vitamins and minerals

Malnutrition remains one of the most persistent public-health challenges worldwide, affecting nearly 733 million people globally, making it about one in eleven people (Anonymous 2024). Despite substantial increases in global food supply over recent decades, "hidden hunger" with diets deficient in essential micronutrients remains a pervasive challenge. This problem is severe in low-income regions characterised by less diverse but cereal-heavy diets (Yilmaz & Yilmaz 2025). Recent global intake-based estimates of 15 essential nutrients reveal that over half of the world's population has inadequate intake of at least one key micronutrient, causing high deficiencies of vitamin A (48%), vitamin C (53%), iron (65%), and zinc (46%) (Passarelli *et al.* 2024). Women are disproportionately affected by low intake of iodine, vitamin B12, iron, and selenium. The present scenario indicates that 800 million people across the globe are undernourished, of which 98% belong to the developing nations (Thakur *et al.* 2022), and also, a broader group of this population is suffering from hidden hunger. Therefore, addressing hidden hunger requires targeted strategies to enhance the micronutrient content of food rather than merely increasing caloric availability.

Micronutrients, though needed in minute quantities, are essential compounds for sustaining healthy growth, development, immunity, and metabolic balance (Savarino *et al.* 2021). They support a wide range of physiological processes, from energy production and tissue repair to cognitive function and disease resistance. Deficiencies in these vital compounds can lead to serious health consequences, including impaired growth, developmental delays, anaemia, and compromised immunity (Kiani *et al.* 2022). Nearly

*Author for correspondence

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one-fifth of school-age children and adolescents nationwide suffer from vitamin A deficiency, with some preschool-based investigations estimating a prevalence of about 18% (Reddy *et al.* 2022). According to NFHS-5 (2019-21), anaemia remains alarmingly high in India, affecting 67% of children (6–59 months), nearly 57% of women of reproductive age, and about 52% of pregnant women, while nationally representative biochemical surveys indicate zinc deficiency in ~17% of preschoolers, ~16% of school-aged children, and ~31% of adolescents (Khura *et al.* 2023). Deficiencies in these nutrients disproportionately affect infants, children, and women of reproductive age, so increasing the micronutrient density of commonly consumed crops will be a highly cost-effective and sustainable public-health approach (Ashraf 2025).

Vegetables occupy a unique place in the human diet as "protective foods," owing to their dense concentration of vitamins, minerals, dietary fibre, and bioactive compounds (Saiwal *et al.* 2019). Along with nutritional edge, vegetables are also widely consumed, versatile in diets, and culturally embedded across diverse dietary and food systems. The term vegetables includes various kinds of leafy greens, roots, tubers, legumes, and fruit vegetables, which make them a complete source of nutrition. They also contain a wide mix of plant chemicals that act as antioxidants and anti-inflammatory agents, helping the body fight off damage that can lead to long-term illnesses (Lee 2018).

Globally, the nutritional role of vegetables is gaining renewed importance within the effort to meet the United Nations Sustainable Development Goals. "Zero Hunger" and "Good Health and Well-being" are novel projects under the UNSDG that emphasise the need for diverse, nutrient-rich diets and farming systems that directly improve nutrition (Grosso *et al.* 2020). To move in that direction, several strategies are being explored, starting from breeding vegetables that naturally contain higher levels of micronutrients (biofortification), improving their nutritional quality through processing, and then linking vegetable-based foods with school meal plans and public health programs. In addition, modern biotechnological tools are expanding the possibilities even further, pointing toward a future in which vegetables play a central role in food systems designed not only to feed people but to keep them healthy. Studies on bioencapsulation and edible vaccines have created a possibility of delivering nutritional compounds orally (Mishra *et al.* 2008). Culinary versatility and high acceptance of vegetables make them an intriguing candidate for novel nutrient or health-product delivery systems.

When seen from a broader nutritional perspective, vegetables are often underestimated to tackle malnutrition and hidden hunger. (Peter *et al.* 2021). Numerous studies have shown health benefits of phytochemicals, which cannot be ascribed to a single vegetable alone. Consumption of diverse vegetables offers consumers the full range of health benefits (Singh *et al.* 2025). Making vegetables a routine part of meals not only improves dietary diversity but also helps make key micronutrients available to people at a lower cost. This review looks at how vegetables contribute to better nutrition, the part they play in reducing micronutrient deficiencies, and what strategies can further enhance their impact in fighting malnutrition. It also reflects on future possibilities of how vegetable-based approaches could be linked with national and global nutrition efforts in building sustainable diets.

Role of vegetables in national and global nutrition security programs

Vegetables play a crucial role in addressing hidden hunger and improving nutritional outcomes globally and nationally. In India, several initiatives have been launched to integrate vegetables into nutrition-sensitive programs and public health frameworks. Poshan Abhiyaan (National Nutrition Mission), launched in 2018, aims to improve nutrition for children, adolescent girls, pregnant women, and lactating mothers, with an emphasis on dietary diversification and behaviour change communication. Under this program, vegetables are promoted through community nutrition gardens and Anganwadi Centres, while kitchen and nutrition gardens at household and community levels ensure a year-round supply of fresh vegetables, particularly leafy greens, to combat micronutrient deficiencies (Pooja 2022). State-specific initiatives have further supported home production through the distribution of vegetable seed kits. The Mid-Day Meal Scheme, now PM POSHAN,

is the world's largest school feeding initiative and incorporates vegetables into daily meals to enhance micronutrient intake. Green leafy vegetables, carrots, beans, and other seasonal vegetables are increasingly included to provide iron, vitamin A, and vitamin C, with states such as Tamil Nadu and Karnataka demonstrating positive impacts on child growth and anaemia reduction (Vir 2013). Additionally, the Government of India, through ICAR and Krishi Vigyan Kendras (KVKs), has promoted kitchen and *Poshan Vatikas* (nutrition gardens), empowering women and self-help groups while ensuring dietary diversity through the integration of local landraces and indigenous vegetables such as drumstick, amaranths, and cowpea (Selvarani & Subathra 2024).

At the global level, several initiatives have increasingly recognised the potential of vegetables in addressing malnutrition and promoting nutrition security. Programs such as HarvestPlus, part of the CGIAR network, have traditionally focused on biofortification of staple cereals and legumes to combat micronutrient deficiencies (Bouis & Saltzman 2017). However, there is growing attention on vegetables as natural sources of essential vitamins and minerals, and partnerships with national programs, including ICAR in India, are now facilitating targeted breeding efforts to enhance nutrient content in vegetable crops. The World Vegetable Centre (AVRDC), based in Taiwan, plays a pivotal role by conserving over 65,000 vegetable accessions and supporting breeding programs for nutrient-dense crops such as tomato, amaranth, mung bean, and various indigenous vegetables (Ebert 2020). AVRDC also actively promotes home and school gardens, linking vegetable production with improved dietary quality and nutritional outcomes in smallholder farming systems across Asia and Africa (Chadha *et al.* 2011).

In parallel, CGIAR research programs have prioritised vegetable biofortification within broader nutrition and health initiatives (Douthwaite 2020). These programs emphasise the use of genetic diversity, low-cost biofortification strategies, and value chain integration, ensuring that nutrient-rich vegetables reach vulnerable populations while maintaining agronomic performance and market acceptability. Vegetables are therefore integrated not only as a source of essential nutrients but also as a key component of sustainable and resilient food systems. Campaigns such as the International Year of Fruits and Vegetables (2021), promoted by the UN and FAO, have highlighted vegetables as central to achieving Sustainable Development Goal 2 of Zero Hunger, while promoting nutrition-sensitive agriculture through community, school, and household gardens (Kunlere 2025). By combining biofortification, genetic resource utilisation, and nutrition-sensitive interventions, such initiatives provide a robust framework for integrating vegetables into strategies aimed at achieving global nutrition security.

Strategies to enhance the nutritional quality of vegetables

Enhancing the nutritional quality of vegetables is central to combating hidden hunger and meeting the micronutrient requirements of populations. Since vegetables already provide a wide array of vitamins, minerals, and bioactive compounds, systematic improvement through agronomical interventions, genetic resources, breeding, and molecular tools can further enhance their nutrient density. Strategies include the exploitation of natural variation, conventional and pre-breeding approaches, and the application of modern molecular breeding and biotechnological interventions (Figure 1).

Nutritional diversity in vegetables

Vegetables serve as rich sources of both macronutrients and micronutrients, including vitamins and minerals, that collectively support growth, immunity, metabolism, and disease prevention. Unlike staple cereals or tuber crops that mainly supply energy, vegetables provide nutrient density rather than caloric bulk, making them indispensable in achieving balanced and health-promoting diets. The nutritional diversity among vegetables arises from their wide taxonomic range, encompassing leafy greens, legumes, root and tuber crops, fruit vegetables, and underutilised traditional species, which provides opportunities for selection and breeding to enhance specific nutritional traits. Therefore, understanding and utilising the inherent nutritional variability in vegetables is the foundation for developing improved varieties with enhanced nutrient content.

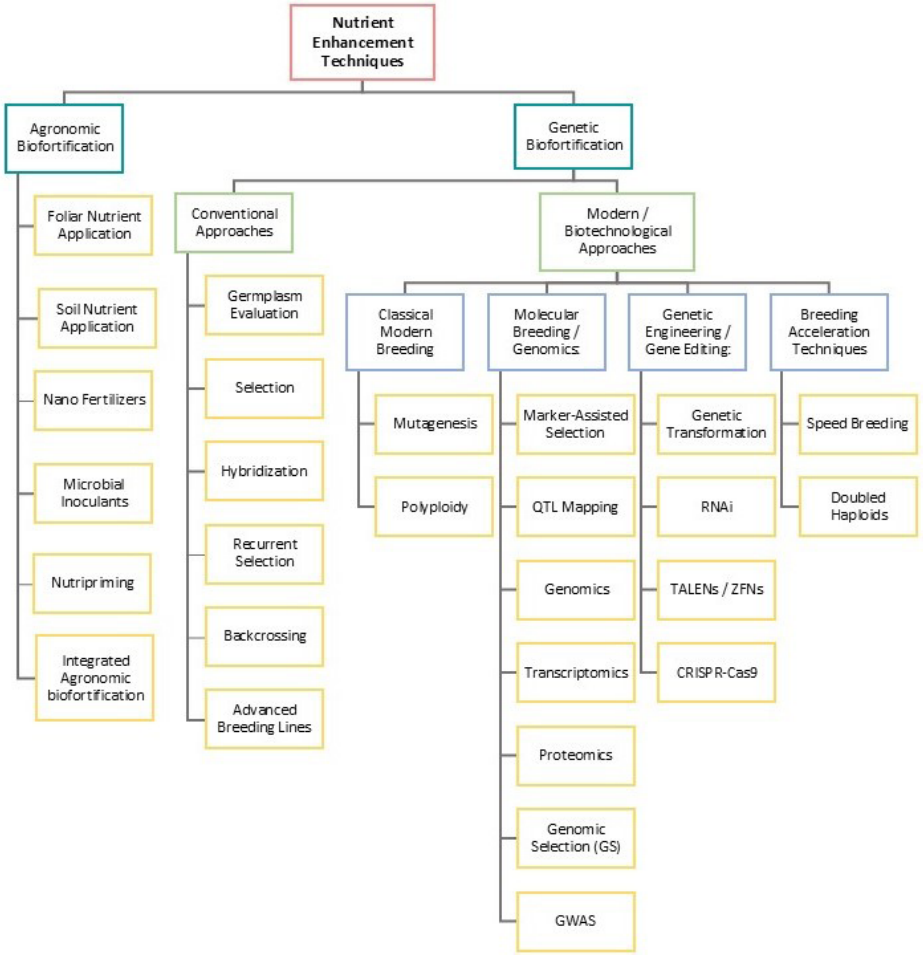


Figure 1. Nutrient enhancement techniques in vegetable crops.

Macronutrients in vegetables

Vegetables are a vital source of essential macronutrients, including carbohydrates, proteins, and lipids, although their composition varies significantly across different crops. A prominent example is tuber and starchy vegetables, such as yams (27.88 g/100 g carbohydrates), sweet corn (19.02 g/100 g), and potatoes (16.0 g/100 g), which provide a substantial amount of complex carbohydrates that support daily energy needs (Table 1). The macronutrient content of various vegetables is listed in Table 1. Vegetables are generally low in fat, with small amounts of healthy lipids that aid vitamin absorption.

Micronutrients in vegetables

Vegetables represent one of the most dependable natural sources of vitamins and minerals that sustain essential physiological and biochemical processes in the human body. Their regular intake is vital for preserving health and preventing micronutrient insufficiencies. Crops like carrot, pumpkin, sweet potato, spinach, and amaranth are rich in β-carotene, the primary precursor of vitamin A, which contributes to healthy vision, immune strength, and epithelial integrity (Beer *et al.* 2024). Similarly, vegetables abundant in vitamin C, such as broccoli, capsicum, and amaranth, are crucial for collagen production, tissue repair, and improved iron absorption (Aktaş & Satilmiş 2025) (Table 2). Cruciferous crops, including broccoli, cauliflower, and cabbage, provide compounds like glucosinolates, along with vitamin C and other antioxidants (Favela-González *et al.* 2020). Leafy greens, including kale and spinach, furnish vitamin K, indispensable for normal blood clotting and bone metabolism, while folate-rich vegetables like asparagus and beetroot reduce the risk of neural tube defects and maternal anaemia (Sarma *et al.* 2024). Leguminous and cruciferous crops are

Table 1. Mean concentrations of macronutrients (per 100 g of fresh vegetables)

Vegetable	Carbohydrates (g)	Protein (g)	Fat (g)	Dietary fibre (g)	Energy (kcal)
Amaranth	4.00	3.80	0.30	1.8	35
Artichoke	11.00	3.30	0.20	5.4	47
Asparagus	5.10	1.44	0.22	1.9	28
Bean, green (snap)	7.41	1.97	0.28	3.0	40
Beans, kidney	4.10	4.20	0.50	8.0	73
Beetroot	8.79	1.69	0.30	3.1	45
Bitter gourd	4.30	2.00	0.20	2.6	24
Brinjal	3.52	1.48	0.32	3.98	106
Broccoli	6.27	2.57	0.34	2.4	39
Brussels sprouts	9.62	3.98	0.56	4.8	59
Cabbage	6.38	0.96	0.23	2.5	31
Carrot	10.30	0.94	0.35	3.1	48
Cauliflower	4.72	1.64	0.24	1.9	28
Celery	3.32	0.49	0.16	1.6	17
Cucumber	2.95	0.62	0.18	0.5	16
Garlic	28.20	6.62	0.38	2.7	143
Kale	4.42	2.92	1.49	4.1	43
Knol khol	6.20	1.70	0.10	3.6	27
Leek	14.15	1.47	0.30	1.8	61
Lettuce	4.07	1.09	0.16	1.3	22
Okra	7.03	2.00	0.10	3.2	31
Onion	9.93	0.94	0.10	2.2	44
Peas	14.45	5.42	0.40	2.6	81
Capsicum	4.78	0.72	0.11	0.9	23
Potato	16.00	1.81	0.26	13.8	73
Pumpkin	6.50	1.00	0.10	0.5	26
Radish	3.40	0.68	0.10	1.6	16
Spinach	2.41	2.85	0.62	1.6	27
Sweet corn, yellow	19.02	3.22	1.18	2.0	86
Sweet potato	17.60	1.58	0.38	4.4	79
Tomato	3.84	0.70	0.42	1	22
Turnip	6.43	0.90	0.10	1.2	28
Yam	27.88	1.53	0.17	4.1	118

Source: IFCT (2017) and USDA (2025)

recognised for providing B-complex vitamins (B1, B2, B3, B6, B7), which assist in energy transformation and neurological health, whereas moderate levels of vitamin E in spinach, pumpkin, and tomato act as powerful antioxidants protecting cellular components (Abdelqader 2023).

Equally important, vegetables deliver a diverse range of minerals. Iron from spinach and amaranth supports haemoglobin synthesis; calcium from amaranth and kale strengthens bones; and zinc, magnesium, and potassium present in peas, spinach, and sweet potato regulate enzyme activity, nerve function, and

Table 2. Mean Concentrations of vitamins (per 100 g of fresh vegetables)

Vegetable	C (mg)	β-carotene (µg)	B1 (mg)	B2 (mg)	B3 (mg)	B7 (µg)	B6 (mg)	B9 (µg)	E (mg)	K (µg)
Amaranth	83.53	8553	0.01	0.19	0.71	2.46	0.21	70	0.44	280
Asparagus	9.15	-	0.07	-	1.08	-	0.11	183	-	-
Beans	15.81	388	0.06	0.12	0.73	4.71	0.12	45	0.06	44
Beetroot	4.60	10	0.01	0.01	0.21	2.56	0.07	103	0.09	3
Brinjal	0.80	146	0.06	0.11	0.53	1.76	0.07	20	0.07	14
Broccoli	91.30	93	0.08	0.11	0.64	-	0.19	65	0.15	102
Brussels sprouts	142.90	360	0.06	0.16	0.50	2.45	0.19	86	0.21	24
Cabbage	40.34	20	0.03	0.05	0.24	1.41	0.14	46	0.05	59
Capsicum	99.51	328	0.04	0.09	0.64	4.59	0.25	22	0.07	25
Carrots	6.22	1128	0.07	0.10	1.41	2.22	0.15	37	0.22	19
Cauliflower	67.10	1.59	0.04	0.07	0.3	2.47	0.13	97	0.02	14
Celery	12.30	465	0.03	0.04	0.48	2.09	0.05	22	0.03	26
Cucumbers	6.11	5.33	0.02	0.01	0.35	0.96	0.06	16	0.02	24
Garlic	10.00	-	0.20	0.25	0.38	2.55	0.56	86	0.07	280
Kale	93.40	-	0.11	0.35	1.18	-	0.15	62	0.66	390
Lettuce	15.15	1285	0.08	0.09	0.38	2.15	0.07	30	0.01	118
Okra	22.51	69	0.04	0.07	0.61	1.58	0.27	63	0.50	21
Onions	8.10	1	0.04	0.01	0.34	2.61	0.10	28	0.05	4
Peas	38.40	121	0.27	10.03	1.28	4.04	0.19	54	0.21	44
Potato	23.30	-	0.05	0.01	1.59	1.35	0.15	15	0.06	0.8
Pumpkins	10.07	363	0.03	0.02	0.44	1.41	0.05	31	0.87	81
Radishes	19.91	2	0.02	0.02	0.30	2.48	0.07	30	0.01	2
Spinach	26.52	2605	0.08	0.19	0.55	1.66	0.19	116	1.29	325
Sweet Potato	14.84	5376	0.05	0.04	0.43	5.19	0.12	16	0.01	0
Tomato	17.75	1513	0.06	-	0.53	0.47	0.08	10	0.22	24

Source: IFCT (2017) and USDA (2025)

blood pressure (Batool 2025). Trace nutrients like manganese, copper, and selenium further aid immune and metabolic performance (Table 3). The interplay among these compounds, such as vitamin C enhancing iron bioavailability and phytochemicals stabilising nutrients, highlights vegetables as a practical, affordable, and sustainable foundation for nutritional security, particularly in plant-based and low-resource diets.

Agronomic biofortification

The extensive use of NPK fertilisers has successfully elevated crop yields but failed to ensure a sufficient supply of essential micronutrients in the food chain. Agronomic biofortification addresses this limitation by using enriched fertilisers to increase the concentration of bioavailable minerals in edible plant parts. As a practical and immediately deployable strategy, it improves crop nutritional status and, subsequently, human health upon consumption (Cakmak & Kutman 2017). The successful implementation of this strategy across various crops relies on optimising fertiliser application methods, enhancing mineral solubilisation, and facilitating efficient nutrient translocation from source to sink tissues.

Conventional soil application of micronutrients serves as the foundation for replenishing soil nutrient pools. However, the effectiveness of this method is frequently compromised by nutrient fixation within the soil matrix. Alternatively, foliar application has gained

Table 3. Mean concentrations of minerals (per 100 g of fresh vegetables)

Vegetable	Ca	Fe	Mg	P	K	Na	Zn	Cu	Mn
Amaranth	330	4.64	194.00	73.22	572.00	16.80	0.86	0.21	1.24
Asparagus	20.58	0.44	13.78	53.90	277.50	2.46	0.60	0.13	0.15
Beans	40.05	0.65	28.21	41.15	290.40	-	0.35	0.10	0.33
Beet root	13.82	0.43	21.01	33.65	341.50	111.60	0.31	0.16	0.26
Bitter gourd	46.00	0.69	21.00	67.00	303.00	36.00	0.42	0.06	0.20
Brinjal	11.06	0.37	13.54	22.75	222.10	0.44	0.12	0.06	0.11
Broccoli	46.00	0.69	21.00	67.00	303.00	36.00	0.42	0.06	0.20
Brussels sprout	38.64	0.73	25.00	78.54	476.80	25.74	0.37	0.04	0.24
Cabbage	41.84	0.07	13.86	26.93	207.10	16.10	0.21	0.03	0.25
Capsicum	7.50	0.19	9.00	16.75	163.10	1.84	0.13	0.06	0.10
Carrots	30.48	0.15	12.45	39.81	279.60	86.65	0.24	0.06	0.13
Cauliflower	20.35	0.33	14.20	39.69	274.40	20.00	0.23	0.02	0.14
Celery	46.28	1.36	10.93	21.60	265.20	97.21	0.09	0.12	0.08
Chilli	18.45	1.20	29.51	50.91	341.00	2.50	0.27	0.15	0.28
Cucumbers	16.34	0.46	10.11	23.23	169.60	1.52	0.20	0.06	0.08
Garlic	0.001	1.05	27.08	119	430	9.42	0.89	0.19	0.34
Kale	254.00	1.60	32.70	55.00	348.00	53.00	0.39	0.05	0.92
Lettuce	39.84	0.32	12.77	26.55	277.10	28.88	0.31	0.04	0.16
Okra	86.12	0.84	66.10	57.48	263	7.37	0.45	0.13	0.30
Onions	17.00	0.24	11.40	41.00	197.00	1.00	0.17	0.06	0.12
Pea	28.24	1.58	40.11	55.95	249	3.66	1.09	0.22	0.46
Potatoes	5.94	0.37	22.30	56.95	445.80	2.24	0.37	0.13	0.16
Pumpkins	16.36	0.06	12.80	22.30	472.10	0.31	0.14	0.06	0.05
Radishes	30.20	0.36	16.07	30.10	288.00	28.20	0.22	0.03	0.10
Spinach	68.35	1.26	92.86	39.05	581.80	111.40	0.45	0.08	0.49
Sweet Potato	22.33	0.40	19.14	36.73	486.40	29.60	0.34	0.19	0.42
Tomato	9.96	0.10	8.09	19.09	192.80	11.86	0.08	0.03	0.09

Source: IFCT (2017) and USDA (2025)

prominence as a more efficient alternative, minimising nutrient losses through direct foliar absorption. This enables targeted nutrient delivery during critical growth stages, effectively bypassing the constraints inherent in soil-based methods. Nutripriming, or seed-priming are new technique which utilises pre-sowing seed treatment with nutrient solutions to improve germination, root development, and seedling establishment (Farooq *et al.* 2019).

Meanwhile, soilless cultivation systems, including hydroponics, aeroponics, and vertical farming, represent advanced platforms that employ controlled environments with precisely formulated nutrient solutions to optimise plant uptake and accumulation (Buturi *et al.* 2022). The technological evolution in this field continues with the emergence of nano-fertilisers, which leverage engineered nanoparticles possessing enhanced surface area and reactivity to improve nutrient uptake efficiency and bioavailability. Parallel to these developments, microbial inoculants utilising plant growth-promoting rhizobacteria and mycorrhizal fungi offer sustainable alternatives through biological mechanisms including soil acidification, siderophore production, and nutrient solubilisation (Sunderia *et al.* 2019).

These diverse approaches converge in the concept of integrated agronomic biofortification, which combines multiple intervention strategies to create synergistic effects that enhance micronutrient concentrations in edible crop parts beyond what individual methods can achieve. The agronomic biofortification has been successfully employed for various vegetable crops as listed in Table 4.

Conventional breeding approaches

Conventional breeding remains the cornerstone of efforts to enhance the nutritional quality of vegetables. It relies on the identification, evaluation, and utilisation of genetic variation present in cultivated varieties, landraces, and wild relatives. Through systematic selection and hybridisation, breeders have successfully improved levels of key micronutrients such as carotenoids, ascorbic acid, iron, zinc, and folates while maintaining desirable agronomic and consumer traits (Gaikwad 2020).

Table 4. Agronomic biofortification techniques utilized in vegetable crops

Application technique	Crop	Nutrient	Reference
Foliar application	Potato	Zn	White *et al.*, 2017
	Egg plant	Cu	Bana *et al.*, 2021
Soil application	Potato, carrot, and radish	Zn, Fe, and Mn	Mubarak *et al.*, 2022
Soil-less cultivation	Lettuce	Se, Zn, Fe	Giordano *et al.*, 2019; Sahin, 2020
	Cherry tomato	Fe	Buturi *et al.*, 2022
	Red cabbage	Zn	Di Gioia *et al.*, 2019
Nano fertilisers	okra	Zn, Fe, Cu	Bhardwaj *et al.*, 2022
	Garlic	Se	Bhardwaj *et al.*, 2022
Integrated soil and foliar application	Spinach	Cu	Obrador *et al.*, 2013
	Broccoli	Zn	Martín *et al.*, 2020
	Broccoli, carrot	Se	Bañuelos *et al.*, 2015
Seed priming and Nano fertilisers	Onion	Zn	Rico *et al.*, 2011
Microbial inoculation	Lettuce	Se	Marfetán *et al.*, 2023
	Beet root	Se	

Selection from diverse germplasm is often the first step toward nutritional improvement. Germplasm banks maintained by organisations such as the National Bureau of Plant Genetic Resources (NBPGR), ICAR institutes, and the World Vegetable Centre (AVRDC) provide extensive collections that serve as valuable sources of nutrient-dense accessions (Tyagi 2021). Screening and evaluation of these accessions enable the identification of naturally nutrient-rich donors for different traits such as high β-carotene carrot lines, folate-rich spinach landraces, and iron-dense amaranth varieties (Yoo *et al.* 2020). Significant genetic variation in micronutrient composition among thirty pumpkin and butternut genotypes indicated strong potential for nutritional enhancement through selection and breeding. The observed diversity and high heritability of key biochemical traits highlight pumpkin as a promising candidate for future biofortification programs (Singh 2022). Such selections can either be directly released as improved varieties or utilised as parental lines in breeding programs targeting enhanced nutritional traits.

Hybridisation remains one of the most effective strategies for combining high nutritional quality with desirable agronomic performance. Through the deliberate crossing of nutrient-rich parental lines with high-yielding or disease-resistant cultivars, breeders attempt to accumulate multiple beneficial traits within a single genotype (Mir *et al.* 2022). Such approaches have already produced promising outcomes, including tomato hybrids with elevated lycopene content and bottle gourd lines containing higher levels of ascorbic acid (Bhatt 2023).

Recurrent selection and pedigree breeding are particularly valuable for improving quantitative traits such as carotene and sugar content, which are controlled by multiple genes and strongly influenced by environmental factors (Yoo *et al.* 2020; Omar *et al.* 2022). Backcross breeding also plays a vital role,

allowing the transfer of specific nutrient-enhancing genes or alleles from wild relatives or exotic germplasm into elite cultivars, thereby improving both nutritional quality and adaptability.

Mutagenesis and polyploidy

Mutation breeding involves inducing genetic changes using physical mutagens such as gamma rays, X-rays, or chemical mutagens like Ethyl Methane Sulfonate (EMS). Several successful examples illustrate its potential. In carrots, EMS mutagenesis generated taproot colour variants (purple, red, yellow, *etc.*) that correspond to altered carotenoid and anthocyanin levels, pigments critical for human nutrition (Wu *et al.* 2020). Likewise, the well-known "Orange" (Or) mutant of cauliflower produces curds with exceptionally high β-carotene content (Welsch *et al.* 2020). In tomato, EMS-derived mutant lines were reported to have greatly elevated mineral and antioxidant levels (significantly higher Na, Mg, Ca, Fe, total phenolics, and antioxidant activity) compared to controls (Islam *et al.* 2024) These studies illustrate that classical mutagenesis can uncover alleles conferring improved vitamin and mineral profiles (*e.g.*, provitamin A carotenoids, folates, *etc.*) in many vegetables and provide novel germplasm for breeding.

Polyploidy breeding, through chromosome doubling induced by colchicine or oryzalin, offers another means of enhancing nutritional traits. Polyploidisation often leads to increased cell size, metabolic activity, and secondary metabolite accumulation, thereby improving both yield and nutrient density. Colchicine-induced tetraploid onion plants showed significantly higher antioxidant capacity (about 72.6% DPPH scavenging in bulbs) and greater sugar content than the diploid progenitor (Abubakar *et al.* 2025). Similarly, induced autotetraploid garlic plants produced far more healthful compounds – allicin and related sulphur metabolites (DADS, DATS) were roughly 44-50% higher than in the diploid, and total soluble proteins and sugars increased by over 150% (Wen *et al.* 2022). In fact, one study found garlic tetraploids with double the oil content of diploids and 15-25% higher levels of key sulphur phytonutrients, along with increased chlorophyll and mineral nutrients (N, P, K) (Yousef & Elsadek 2020).

Molecular breeding and genomic approaches

Marker-Assisted Selection (MAS) has now become a central part of nutritional improvement in vegetable crops. In tomato, for instance, SSR and SNP markers associated with β-carotene and lycopene content have been located near important genes such as *LCYB*, *CRTISO*, and *PSY1*, allowing breeders to select lines with higher carotenoid accumulation (Kinkade & Foolad 2013). Similarly, in sweet pepper (*Capsicum annuum*), molecular markers linked with genes for capsanthin and vitamin C biosynthesis (*GGP* and *GalUR*) have supported the development of high-ascorbate genotypes (Wang *et al.* 2023). In carrots, mapping of QTLs for provitamin A, α- and β-carotene has guided the selection of orange-rooted biofortified lines (Ellison *et al.* 2017). Comparable success has been achieved in *Brassica* species, where markers linked to glucosinolate and mineral accumulation (Zn, Ca, and Mg) are now routinely used for selecting nutritionally enhanced cultivars (Wu *et al.* 2008).

Genomic Selection (GS) has added another dimension by predicting the genetic merit of breeding lines using genome-wide marker data, an approach that works particularly well for polygenic traits like micronutrient levels or antioxidant activity. Its application in crops such as tomato, cabbage, and onion has demonstrated that combining phenotypic and genomic datasets can significantly increase selection accuracy even without pinpointing individual QTLs (Simko *et al.* 2021).

Recent advances in transcriptomics, metabolomics, and pangenomics have also deepened the understanding of nutritional trait regulation. Comparative transcriptome analyses in tomato and amaranths, for example, have identified differentially expressed genes within vitamin C and carotenoid pathways, offering promising targets for functional validation (Nyonje *et al.* 2025). In pumpkin, two highly conserved GGP gene homologs were identified, highlighting their key role in ascorbic acid biosynthesis and their potential for biotechnological enhancement of vitamin C content (Singh 2022). Interestingly, transcriptomic insights in onion and garlic have clarified the biosynthetic routes of flavonoids and sulphur compounds, both crucial for antioxidant and health-promoting effects (Jia *et al.* 2025).

Meanwhile, technologies like KASP (Kompetitive Allele-Specific PCR) and GBS (Genotyping-by-Sequencing) have made high-resolution genotyping more affordable and scalable, enabling large-scale genome-wide association studies (GWAS) to uncover loci controlling nutritional quality. For example, GWAS in tomato has revealed SNPs linked with ascorbic acid, lycopene, and tocopherol levels, while studies in cabbage and kale have mapped regions responsible for glucosinolate and carotenoid content (Sauvage *et al.* 2014). Integrating such genomic tools with classical breeding now allows pyramiding of multiple nutritional traits, such as combining genes for high iron and high vitamin C to enhance both nutrient density and bioavailability (Rana *et al.* 2019).

Genetic engineering and gene editing approaches

Genetic engineering and genome editing represent transformative tools for improving the nutritional quality of vegetables by allowing precise modification of metabolic pathways associated with the biosynthesis of vitamins, minerals, and bioactive compounds (Roychowdhury *et al.* 2025). In tomato, several metabolic engineering efforts have demonstrated the effectiveness of transgenic approaches for nutritional enhancement. For instance, overexpression of *phytoene synthase* (*PSY*) genes has produced "Golden Tomato" lines with elevated lycopene levels (Cao *et al.* 2024). Similarly, overexpression of *CsPSY1* has increased carotene content in carrot (Li *et al.* 2024). Manipulation of the *GDP-L-galactose phosphorylase* (*GGP*) gene, which is crucial in the ascorbate biosynthetic pathway that has substantially enhanced vitamin C accumulation in tomato and cucumber (Wang *et al.* 2023). In carrot and sweet pepper, transgenic introduction of key carotenoid biosynthesis genes has raised provitamin A levels, while overexpression of *StLCYb* in potato increased β-carotene in tubers (Song *et al.* 2016).

Recent breakthroughs in genome editing, particularly CRISPR-Cas9, have revolutionised biofortification by allowing targeted modification of endogenous genes without introducing foreign DNA, enhancing regulatory and consumer acceptance (Roy *et al.* 2022). In tomato, CRISPR-mediated knockout of *LYCOPENE ε-CYCLASE* (*LCY-E*) led to enhanced lycopene accumulation (Li *et al.* 2018). Similarly, editing of *Psy1* and *CrtR-b2* genes using CRISPR/Cas9 confirmed their efficiency in metabolic engineering and rapid improvement of carotenoid content (D'Ambrosio 2018). In *Brassica* species, targeted edits in *MYB28* and *AOP2* genes regulating glucosinolate biosynthesis successfully balanced beneficial and anti-nutritional compounds.

Metabolic engineering has been applied to improve mineral bioavailability by suppressing anti-nutritional factors. RNA interference (RNAi) has been used to silence *patatin* genes in potato, producing tubers suitable for developing therapeutic glycoproteins (Kim *et al.* 2008). Although the potential of transgenic and genome-edited vegetables is vast, regulatory restrictions, intellectual property issues, and consumer scepticism continue to hinder their large-scale deployment (Sabat & Tripathy 2024). Nevertheless, the successful commercialisation of genome-edited tomatoes with elevated γ-aminobutyric acid (GABA) and carotenoid content in Japan and the USA demonstrates growing acceptance of this technology (Ezura 2022).

Breeding acceleration techniques

The development of nutrient-enriched vegetable cultivars often encounters hurdles such as long breeding cycles, complex inheritance of nutritional traits, and strong environmental effects on their expression. To overcome these barriers, researchers have started using breeding acceleration approaches that can shorten generation time, hasten selection, and integrate genomic tools for faster varietal release (Pasala *et al.* 2024). Among these, speed breeding has gained particular importance. By carefully adjusting temperature, photoperiod, and light intensity, plants can be pushed to flower and set seed more quickly, allowing several generations in a single year (Samantara *et al.* 2022). This strategy has been tested successfully in tomato, lettuce, and cabbage, producing four to six generations annually in controlled environments. When combined with molecular marker-assisted selection, speed breeding not only saves time but also improves selection efficiency for nutritional and agronomic traits.

Another important approach is Doubled Haploid (DH) technology, which makes it possible to create completely homozygous lines within one generation. Though this method is better established in cereal crops,

recent work in vegetables such as broccoli, cabbage, and pepper shows that it can help lock in favourable alleles for nutrient content, resistance, and yield stability far more quickly (Najeeb *et al.* 2025). These DH lines often serve as excellent pre-breeding materials and parent lines for hybrid development. In addition, modern breeding programs are increasingly using automation, digital phenotyping, and AI to handle the vast amount of data generated during selection (Zhang *et al.* 2024). AI-based systems can predict inheritance patterns, suggest ideal parent combinations, and assess the consistency of nutritional traits across environments, allowing more confident and accurate decisions during selection. Taken together, these rapid-cycling and data-driven breeding tools mark a shift from slow, conventional approaches to precise and accelerated nutrition-oriented breeding. By compressing the breeding timeline from decades to just a few years, they make it more feasible to develop and deliver nutrient-rich vegetables that can strengthen global food and nutrition security sustainably.

Biofortified varieties available in vegetable crops

Vegetable breeding has dramatically enhanced nutritional security by developing biofortified varieties rich in diverse phytonutrients. Key achievements in enhancing the levels of specific bioactive compounds are summarised in the Table 5.

Challenges in vegetable-based breeding for nutrition security

Despite their enormous potential in combating malnutrition and hidden hunger, vegetables remain underutilised in mainstream nutrition security programs. Several scientific, economic, and social barriers hinder the success of breeding programs targeting nutritional enhancement in vegetables.

Unlike cereals such as rice, wheat, and maize that have undergone systematic and large-scale screening for micronutrient traits under global biofortification programs, vegetables still lag in this aspect (Ofori *et al.* 2022). The absence of standardised protocols for micronutrient screening, coupled with a lack of high-throughput phenotyping tools, slows progress in vegetable biofortification. As a result, identifying and mainstreaming nutritionally superior donors into breeding pipelines has been relatively limited compared to staple cereals.

One of the major challenges in breeding vegetables for nutritional traits is the strong influence of environmental factors on nutrient expression. Soil type, fertility status, irrigation, climatic conditions, and agronomic practices significantly affect the accumulation of vitamins and minerals in vegetables. This strong genotype × environment interaction reduces the heritability of micronutrient traits and complicates the selection process.

Research in vegetable biofortification has largely concentrated on a narrow set of nutrients, such as β-carotene (vitamin A), vitamin C, iron, and zinc, due to their global significance in addressing hidden hunger (Lowe 2021). However, several equally important vitamins and bioactive compounds remain underrepresented in breeding programs. For example, vitamin K, vitamin E, folate, and B-complex vitamins, which are abundant in certain vegetables, have received little attention in genetic studies. The lack of comprehensive nutritional profiling and limited funding for multi-trait analysis further contribute to these knowledge gaps.

Furthermore, the lack of strong interdisciplinary collaboration between plant breeders, nutritionists, food technologists, and policymakers restricts holistic progress (Lopes 2023). Without integration across disciplines, even nutritionally improved vegetable varieties may fail to reach vulnerable populations or to demonstrate measurable impact on public health.

Future Prospects and Way Forward

During the last few years, the issue of hidden hunger and micronutrient deficiency has drawn serious attention, reminding us how vital vegetables are for both global and national nutrition security. Considerable progress has been achieved in identifying nutrient-rich germplasm, but now the focus should be shifted towards mining nutrients from such germplasm. This phase of improvement will depend on blending classical breeding approaches with modern molecular techniques to develop nutrient-dense vegetables more efficiently. Traditional practices such as selection from diverse germplasm and hybridisation continue to play an important role, but when combined with tools like marker-assisted selection, genomic selection,

Table 5. Biofortified vegetables and their enhanced phytonutrients

S. No.	Crop	Varieties	Nutrient
1	Amaranthus	Pusa Lal Chaulai	Carotenoids
		Arka Arunima	Anthocyanin
2	Basella	Local Red, Local Green	Carotenoids
3	Bitter gourd	Pusa Aushadi	β-Carotene
		Pusa Vishesh, Pusa Hybrid-2	Iron
4	Brinjal	Punjab Sadabahar	Anthocyanin
		Pusa Safed Baigan 1	Phenols
5	Broccoli	Pusa Purple Broccoli-1, Palam Vichitra	Anthocyanin
6	Cabbage	Red Acre, Kinner Red	Anthocyanin
7	Carrot	Pusa Asita, Punjab Black Beauty, Kashi Krishna, Punjab Jamuni	Anthocyanin
		Pusa Rudhira	Total Carotenoids, Lycopene, β-Carotene
		Pusa Nayanjyoti, Pusa Vrishti, Pusa Yamdagni, Pusa Meghali, Solan Rachna	β-Carotene
		Pusa Kulfi, Punjab Roshni	Lutein
8	Cauliflower	Pusa Purple Cauliflower -1	Anthocyanin
		PC-1	Anthocyanin
9	French bean	Bio 101, Bio 107	Iron, Zinc
10	Okra	Kashi Lalima, Punjab Lalima	Anthocyanin
		Arka Nikita, Punjab Lalima	Iodine
11	Paprika	KTPL-19	Capsanthin
12	Potato	Kufri Neelkanth, Kufri Jamunia	Anthocyanin
13	Pumpkin	Pusa Vikas, Arka Chandan	Vitamin A
		PAU Magaz Kadoo-1	Omega-6
14	Radish	Pusa Jamuni, Pusa Hriday, Palam Hriday, Pusa Gulabi	Total Carotenoids and Anthocyanins
15	Sweet potato	Bhu Sona, Sree Kanaka, Sree Rethna, Sree Vardhini	β-Carotene
		Bhu Krishna	Anthocyanin
16	Tapioca	Sree Visakham	β-Carotene
17	Tomato	Pusa Upkar, Pusa Rohini	Vit C
		Punjab Sona Cherry	Carotene
18	Water melon	Arka Jyoti, Durgapura Lal, Durgapura Kesar	β-Carotene
19	Yam	Shri Neelima, DA 340	Anthocyanin

Source: Anonymous, 2025; Kumar *et al*., 2025 and Parulekar *et al.,* 2019

and genome-wide association studies, the process of transferring nutrition-related traits into elite varieties becomes faster and more precise. Genome editing tools, especially CRISPR/Cas9, now offer a focused and relatively simple way to enhance key nutrients without bringing in foreign DNA, making such improvements both accurate and publicly acceptable.

At the same time, there is a growing realisation of the importance of local and underutilised vegetables. These crops are often naturally rich in micronutrients and well adapted to local conditions, offering a way to diversify diets, preserve cultural preferences, and build resilience in food systems. To have a real impact, such crops need to reach households through kitchen

and community gardens, school meal programs, and nutrition-sensitive agricultural initiatives. Policy support, strong seed systems, and collaboration between public and private sectors are essential to scale up adoption. Linking these breeding and dissemination efforts with national missions like Poshan Abhiyaan, PM POSHAN, and international programs such as HarvestPlus and AVRDC can help ensure that vegetable biofortification contributes meaningfully to combating hidden hunger and improving public health outcomes.

REFERENCES

Abdelqader A, Obeidat MD, Al-Rawashdeh MS, and Alhaj AA 2023. The role of Vitamin E as an antioxidant and preventing damage caused by free radicals. Journal of Life Science and Applied Research **4(2):** 88-95. https://doi.org/10.59807/jlsar.v4i2.89

Abubakar MA, Gennadievna, NE, Mikhailovna SO, and Mikhailovna KE 2025. Effect of induced polyploidy on morphology, antioxidant activity, and dissolved sugars in *Allium cepa* L. Horticulturae **11(2):** 154. https://doi.org/10.3390/horticulturae11020154

Aktaş İ, and Satilmis M 2025. Foods containing Vitamin C and their health benefits. *Ejons* International Journal on Mathematic, Engineering and Natural Sciences **9(2):** 178-192.

Alcock TD, Lenka Havlickova, He Z, Bancroft I, White PJ, Broadley MR, and Graham NS 2017. Identification of candidate genes for calcium and magnesium accumulation in *Brassica napus* L. by association genetics. Frontiers in Plant Science **8**. https://doi.org/10.3389/fpls.2017.01968 PMid:29187860 PMCid:PMC5694822

Anonymous 2024. Hunger numbers stubbornly high for three consecutive years as global crises deepen: UN report. https://www.who.int/news/item/24-07-2024-hunger-numbers-stubbornly-high-for-three-consecutive-years-as-global-crises-deepen--un-report.

Ashraf SA 2025. Food fortification as a sustainable global strategy to mitigate micronutrient deficiencies and improve public health. Discover Food **5(1).** https://doi.org/10.1007/s44187-025-00512-5

Bana RS, Jat GS, Grover M, Bamboriya SD, Singh D, Bansal R, …, Singh T 2022. Foliar nutrient supplementation with micronutrient-embedded fertilizer increases biofortification, soil biological activity and productivity of eggplant. Scientific Reports **12(1).** https://doi.org/10.1038/s41598-022-09247-0 PMid:35338233 PMCid:PMC8956703

Bañuelos GS, Arroyo I, Pickering IJ, Yang SI, and Freeman JL 2015. Selenium biofortification of broccoli and carrots grown in soil amended with Se-enriched hyperaccumulator Stanleya pinnata. Food Chemistry **166**: 603-608. https://doi.org/10.1016/j.foodchem.2014.06.071 PMid:25053099

Batool Z, Hussain MB, Ahmad N, and Hassan W 2025. Mineral nutrition of vegetable crops. Sustainable and Innovative Vegetable Production in Times of Climate Change 245-268. https://doi.org/10.1007/978-981-96-6283-8_13 PMCid:PMC11939570

Beer K, Singh A, Ravi SC, Gupta AK, Kumar A, and Sharma MM. 2024. A comprehensive review on the role of Vitamin A on human health and nutrition. Journal of Environmental Biology **45(6):** 645-653. https://doi.org/10.22438/jeb/45/6/mrn-5339

Bhatt R, Raghav M, Bisht YS., Kumar V, Chauhan A, and Gaur, A 2023. Heterosis and combining ability for nutritional quality in bottle gourd (*Lagenaria siceraria*). The Indian Journal of Agricultural Sciences **93(11):** 1197-1201. https://doi.org/10.56093/ijas.v93i11.141969

Bouis HE, and Saltzman A. 2017. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Global Food Security **12:** 49-58. https://doi.org/10.1016/j.gfs.2017.01.009 PMid:28580239 PMCid:PMC5439484

Buturi CV, Machado R, Cannata C, Basile F, Giuffrida F, Leonardi C, and Rosario Paolo Mauro 2022. Iron biofortification of greenhouse cherry tomatoes grown in a soilless system. Horticulturae, **8(10):** 858-858. https://doi.org/10.3390/horticulturae8100858

Cakmak I, and Kutman UB 2017. Agronomic biofortification of cereals with zinc: A review. European Journal of Soil Science **69(1):** 172-180. https://doi.org/10.1111/ejss.12437

Cao X, Du R, Xu Y, Wu Y, Ye K, Ma J, …, Zhang J 2024. Phytoene synthases 1 modulates tomato fruit quality through influencing the metabolic flux between carotenoid and flavonoid pathways. Horticultural Plant Journal **10(6):** 1383-1397. https://doi.org/10.1016/j.hpj.2022.09.015

Chadha ML, Engle LM, Hughes Jd'A, Ledesma DR, and Weinberger KM 2010. AVRDC - The world vegetable center's approach to alleviate malnutrition. Combating micronutrient deficiencies: Food-based approaches. CABI EBooks (pp. 183-197). https://doi.org/10.1079/9781845937140.0183

D'Ambrosio C, Stigliani AL, and Giorio G. 2018. CRISPR/Cas9 editing of carotenoid genes in tomato. Transgenic Research **27(4):** 367-378. https://doi.org/10.1007/s11248-018-0079-9 PMid:29797189

Di Gioia F, Petropoulos SA, Ozores-Hampton M, Morgan K, and Rosskopf EN 2019. Zinc and iron agronomic biofortification of brassicaceae microgreens. Agronomy **9(11):** 677. https://doi.org/10.3390/agronomy9110677

Douthwaite B 2020. Mainstreaming of biofortification in the African Union: evaluation of CGIAR contributions to a policy outcome trajectory. CGIAR Research Programs on

Roots, Tubers and Bananas and Agriculture for Nutrition and Health: Lima, Peru. https://doi.org/10.4160/978929060-5522

Ebert AW 2020. The role of vegetable genetic resources in nutrition security and vegetable breeding. Plants **9(6):** 736. https://doi.org/10.3390/plants9060736 https://doi.org/10.3390/plants9060736 PMid:32545299 PMCid:PMC7357112

Ellison S, Senalik D, Bostan H, Iorizzo M, and Simon P 2017. Fine mapping, transcriptome analysis, and marker development for *Y2*, the gene that conditions β-carotene accumulation in carrot (*Daucus carota* L.). G3 Genes Genomes Genetics **7(8):** 2665-2675. https://doi.org/10.1534/g3.117.043067 PMid:28663343 PMCid:PMC5555471

Ezura H 2022. The world's first CRISPR tomato launched to a Japanese market: The social-economic impact of its implementation on crop genome editing. Plant and Cell Physiology **63(6):** 731-733. https://doi.org/10.1093/pcp/pcac048 PMid:35388425

Farooq M, Usman M, Nadeem F, Rehman Hur, Wahid A, Basra SMA, and Siddique KHM 2019. Seed priming in field crops: Potential benefits, adoption and challenges. Crop and Pasture Science **70(9):** 731. https://doi.org/10.1071/cp18604 https://doi.org/10.1071/CP18604

Favela-González KM, Hernández-Almanza AY, and De la Fuente-Salcido NM 2020. The value of bioactive compounds of cruciferous vegetables (Brassica) as antimicrobials and antioxidants: A review. Journal of Food Biochemistry **44(10).** https://doi.org/10.1111/jfbc.13414 PMid:32743821

Gaikwad KB, Rani S, Kumar M, Gupta V, Babu PH, Bainsla NK, and Yadav R 2020. Enhancing the nutritional quality of major food crops through conventional and genomics-assisted breeding. Frontiers in Nutrition **7:** 533453. https://doi.org/10.3389/fnut.2020.533453 PMid:33324668 PMCid:PMC7725794

Giordano M, El-Nakhel C, Pannico A, Kyriacou MC, Stazi SR, De Pascale S, and Rouphael Y 2019. Iron biofortification of red and green pigmented lettuce in closed soilless cultivation impacts crop performance and modulates mineral and bioactive composition. Agronomy **9(6):** 290. https://doi.org/10.3390/agronomy9060290

Grosso G, Mateo A, Rangelov N, Buzeti T, and Birt C. 2020. Nutrition in the context of the sustainable development goals. European Journal of Public Health, **30(Supplement_1):** i19-i23. https://doi.org/10.1093/eurpub/ckaa034 PMid: 32391903 PMCid:PMC7213573

Indian Council of Agricultural Research (ICAR). Biofortified varieties. https://icar.org.in/en/biofortified-varieties (Updated on 2025 Oct 29)

Islam MA, Tarannum F, Dina AH, Ahmed M, Haque MA, Ercişli S, Rasul MG, Simsek D, and Hasan M 2024. Phenotypic and biochemical trait improvement in husk tomatoes (*Physalis* sp.) through EMS-induced mutagenesis. Horticulturae **10(9):** 913. https://doi.org/10.3390/horticulturae10090913

Jia H, Song J, Zhang T, Tan Y, Wang M, Zang J, …, Wang H 2025. Comprehensive characterization of metabolites in multiplier onion bulbs and identification of regulatory genes for nutritional improvement. Foods **14(19):** 3290. https://doi.org/10.3390/foods14193290 PMid:41097465 PMCid:PMC12523680

Khura B, Mohanty P, Gandhi AP, Patnaik L, Mewara, A., Pradhan, K., & Padhi, B. K. (2023). Mapping concurrent wasting and stunting among children under five in india: a multilevel analysis. International Journal of Public Health **68:** 1605654. https://doi.org/10.3389/ijph.2023.1605654 PMid:37350797 PMCid:PMC10282129

Kiani AK, Dhuli K, Donato K, Aquilanti B, Velluti V, Matera G, Iaconelli A, Connelly ST, Bellinato F, Gisondi P and Bertelli M 2022. Main nutritional deficiencies. Journal of Preventive Medicine and Hygiene **63(3):** E93-E101. https://doi.org/10.15167/2421-4248/jpmh2022.63.2S3.2752

Kim Y-S, Lee Y-H, Kim, H-S, Kim M-S, Hahn K-W, Ko J-H, …, Jeon J-H 2008. Development of patatin knockdown potato tubers using RNA interference (RNAi) technology, for the production of human-therapeutic glycoproteins. BMC Biotechnology **8(1):** 36. https://doi.org/10.1186/1472-6750-8-36 PMid:18384693 PMCid:PMC2335101

Kinkade MP, and Foolad MR 2013. Validation and fine mapping of lyc12.1, a QTL for increased tomato fruit lycopene content. Theoretical and Applied Genetics **126(8):** 2163-2175. https://doi.org/10.1007/s00122-013-2126-5 PMid:23702514

Kumar A, Kumari A, Pareek V, Verma S, Shri Kant Bharty Dalang T, Jena SS, and Kumar S 2025. Biofortification strategies in horticultural crops: Addressing Micronutrient malnutrition through innovation. Journal of Advances in Biology and Biotechnology **28(6):** 819-849. https://doi.org/10.9734/jabb/2025/v28i62445

Samson A 2025. Strategies to address food insecurity and improve global nutrition among at-risk populations. International Journal of Science and Research Archive **14(2):** 1657-1680. https://doi.org/10.30574/ijsra.2025.14.2.0564

Lee YY, Saba E, Kim M, Rhee MH, and Kim H-K 2018. Antioxidant and anti-inflammatory properties of raw and processed fruits and vegetables. Biomedical Science Letters **24(3):** 196-205. https://doi.org/10.15616/bsl.2018.24.3.196

Li J-W, Zhou P, Deng Y-J, Hu Z-H, Li X-H, Chen X, Xiong A-S, and Zhuang J 2023. Overexpressing CsPSY1 gene of tea plant, encoding a phytoene synthase, improves α-carotene and β-carotene contents in carrot. Molecular Biotechnology **66(11):** 3311-3322. https://doi.org/10.1007/s12033-023-00942-5 PMid:37897587

Li X, Wang Y, Chen S, Tian H, Fu D, Zhu B, Luo Y, and Zhu H 2018. Lycopene is enriched in tomato fruit by CRISPR/Cas9-Mediated multiplex genome editing. Frontiers in Plant Science **9:** 559. https://doi.org/10.3389/fpls.2018.00559 PMid:29755497 PMCid:PMC5935052.

Lopes MA 2023. Rethinking plant breeding and seed systems in the era of exponential changes. Ciência e Agrotecnologia **47:** e0001R23. https://doi.org/10.1590/1413-70542023470001r23

Lowe NM 2021. The global challenge of hidden hunger: perspectives from the field. Proceedings of the Nutrition Society **80(3):** 283-289. https://doi.org/10.1017/S0029665121000902 PMid:33896431.

Marfetán JA, Gallo AL, Farias ME, Vélez ML, Pescuma M, and Ordoñez OF 2023. Exiguobacterium sp. as a bioinoculant for plant-growth promotion and Selenium biofortification strategies in horticultural plants. World Journal of Microbiology and Biotechnology **39(5).** https://doi.org/10.1007/s11274-023-03571-x PMid:36961610.

Rivera-Martin A, Broadley MR, and Poblaciones MJ 2020. Soil and foliar zinc application to biofortify broccoli (*Brassica oleracea* var. italica L.): effects on the zinc concentration and bioavailability Plant, Soil and Environment **66(3):** 113-118. https://doi.org/10.17221/14/2020-pse

Mir RR, Rustgi S, Zhang Y-M, and Xu C 2022. Multi-faceted approaches for breeding nutrient-dense, disease-resistant, and climate-resilient crop varieties for food and nutritional security. Heredity **128(6):** 387-390. https://doi.org/10.1038/s41437-022-00542-0 PMid:35606571 PMCid:PMC9177835.

Mishra N, Gupta PN, Khatri K, Goyal AK, and Vyas SP 2008. Edible vaccines: A new approach to oral immunization. Indian Journal of Biotechnology **7(3):** 283-294.

Mubarak MU, Kiran A, Shahzad AN, Qayyum MF, Ishfaq M, Mahmood K, and Wakeel A 2022. Mineral biofortification of vegetables through soil-applied poultry mortality compost. PLOS One **17(2):** e0262812. https://doi.org/10.1371/journal.pone.0262812 PMid:35113909 PMCid:PMC8812912.

Najeeb R, Uniyal A, Bondada R, and Maruthachalam R 2025. Doubled haploids: Accelerating the breeding of resilient crops for the future. Plant Breeding **2050:** 409-438. https://doi.org/10.1007/978-981-95-0583-8_12

Nyonje WA, Makokha A, Owino W, Lin C-Y, Yang R-Y, and Abukutsa-Onyango M 2024. Nutritional metabolite accumulation and transcription of selected biosynthesis genes in response to drought stress in leaf amaranth (*Amaranthus* sp.). Scientific African **27:** e02526–e02526. https://doi.org/10.1016/j.sciaf.2024.e02526

Obrador A, Gonzalez D, and Alvarez JM 2013. Effect of inorganic and organic copper fertilizers on copper nutrition in *Spinacia oleracea* and on Labile Copper in Soil. Journal of Agricultural and Food Chemistry **61(20):** 4692-4701. https://doi.org/10.1021/jf305473f PMid:23638953.

Ofori KF, Antoniello S, English MM, and Aryee ANA 2022. Improving nutrition through biofortification – A systematic review. Frontiers in Nutrition, **9:** 1043655. https://doi.org/10.3389/fnut.2022.1043655 PMid:36570169 PMCid:PMC9784929.

Omar N, Abdel-Aziz Khalaf-Allah, Abady M and Ragheb E 2022. Efficiency of simple recurrent selection and selfing with selection on improving growth, yield and quality of pumpkin (*Cucurbita Moschata*). Journal of the Advances in Agricultural Researches **27(1):** 1-17. https://doi.org/10.21608/jalexu.2022.113162.1033

Parulekar YR, Haldankar PM, Dalvi NV, Salvi BR and Bhattacharyya T 2019. Nutraceuticals and their biofortification in vegetable crops: A review. Advance Agriculture Research and Technology Journal **III(2):** 219-229.

Pasala R, Chennamsetti M, Patil B, Kadirvel P, Geethanjali S, Nagaram S, Sajja S, Vennapusa, AR, Prasad PV, and Mathur RK 2024. Revolutionizing crop production: The imperative of speed breeding technology in modern crop improvement. Crop Breeding Genetics and Genomics **6(2):** 1-23. https://doi.org/10.20900/cbgg20240003

Passarelli S, Free CM, Shepon A, Beal T, Batis C and Golden CD 2024. Global estimation of dietary micronutrient inadequacies: A modelling analysis. The Lancet Global Health **12(10):** E1590-E1599. https://doi.org/10.1016/s2214-109x(24)00276-6 PMid:39218000.

Peter K, Singh B and Sadhan Kumarm PG 2021. Zero hidden hunger: Role of vegetables. Vegetable Science **48(01):** 1-21. https://doi.org/10.61180/vegsci.2021.v48.i1.01

Pooja 2022. National nutrition mission or Poshan Abhiyaan fighting with undernutrition among children, lactating mothers, and pregnant women: An analysis. Journal of the Asiatic Society of Mumbai **96(10):** 107-117.

Rana M, Sood A, Hussain W, Kaldate R, Sharma TR, Gill RK, Kumar S and Singh S 2019. Gene pyramiding and multiple character breeding. Lentils 83-124. https://doi.org/10.1016/b978-0-12-813522-8.00006-6

Reddy GB, Shalini T, Ghosh S, Pullakhandam R, Kumar BN, Kulkarni B, …, Sachdev HS 2021. Prevalence of vitamin A deficiency and dietary inadequacy in Indian school-age children and adolescents. European Journal of Nutrition **61(1):** 197-209. https://doi.org/10.1007/s00394-021-02636-7 PMid:34251518.

Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR and Gardea-Torresdey JL 2011. Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry **59(8):** 3485-3498. https://doi.org/10.1021/jf104517j PMid:21405020 PMCid:PMC3086136.

Roy S, Kumar V, Behera BK and Parhi J, Mohapatra S, Chakraborty T and Das BK 2022. CRISPR/Cas genome

editing—Can it become a game changer in future fisheries sector? Frontiers in Marine Science 9: 924475. https://doi.org/10.3389/fmars.2022.924475

Roychowdhury R, Das SP, Das S, Biswas S, Patel MK, Kumar A, …, Gangurde SS 2025. Advancing vegetable genetics with gene editing: a pathway to food security and nutritional resilience in climate-shifted environments. Functional and Integrative Genomics **25:** 1. https://doi.org/10.1007/s10142-025-01533-0 PMid:39891757

Sabat M, and Tripathy A 2024. Genetically modified and gene-edited food crops: Recent status and future prospects. Advances in Science, Technology and Innovation (pp. 211-222). https://doi.org/10.1007/978-3-031-51647-4_18

Sahin O 2020. Combined biofortification of soilless grown lettuce with iodine, selenium and zinc and its effect on essential and non-essential elemental composition. Journal of Plant Nutrition **44(5):** 673-678. https://doi.org/10.1080/01904167.2020.1849300

Saiwal N, Dahiya M, and Dureja H 2019. Nutraceutical insight into vegetables and their potential for nutrition mediated healthcare. Current Nutrition and Food Science **15(5):** 441-453. https://doi.org/10.2174/1573401314666180115151107

Samantara K, Bohra A, Mohapatra SR, Prihatini R, Asibe F, Singh L, …, Varshney RK 2022. Breeding more crops in less time: A perspective on speed breeding. Biology **11(2):** 275. https://doi.org/10.3390/biology11020275 PMid:35205141 PMCid:PMC8869642.

Sarma U, and Bhavya TR 2024. Dietary phytonutrients in common green leafy vegetables and the significant role of processing techniques on spinach: A review. Food Production, Processing and Nutrition **6:** 10. https://doi.org/10.1186/s43014-023-00192-7

Sauvag C, Segura V, Bauchet G, Stevens R, Do, PT, Nikoloski Z, Fernie AR and Causse M 2014. Genome-wide association in tomato reveals 44 candidate loci for fruit metabolic traits. Plant Physiology **165(3):** 1120-1132. https://doi.org/10.1104/pp.114.241521 PMid:24894148 PMCid:PMC4081326.

Savarino G, Corsello A and Corsello G 2021. Macronutrient balance and micronutrient amounts through growth and development. Italian Journal of Pediatrics **47(1).** https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8106138/ PMid:33964956 PMCid:PMC8106138.

Selvarani K, and Subathra B 2024. Nutri-gardens: A way to manage malnutrition and ensure food security. International Journal of Environment and Climate Change **14(2):** 23-29. https://doi.org/10.9734/ijecc/2024/v14i23916

Simko I, Jia M, Venkatesh J, Kang B-C, Weng Y, Barcaccia G, Lanteri S, Bhattarai G and Foolad MR 2021. Genomics and marker-assisted improvement of vegetable crops. Critical Reviews in Plant Sciences **40(4):** 303-365. https://doi.org/10.1080/07352689.2021.1941605

Singh J 2022. Genetic variation for vitamins and minerals and characterization of GDP-L-galactose phosphorylase gene(s) in pumpkin (*Cucurbita moschata* Duch. ex Poir.) [Doctoral dissertation, Punjab Agricultural University, Ludhiana].

Singh S, Chandel A, Manjunath KS, Srivastava A, Varun MB, Kumar A, Srishti and Sharma A 2025. Status and perspective analysis of exotic vegetables for health, nutrition and entrepreneurship in India. Himachal Journal of Agricultural Research **51(1):** 14-27.

Song X, Zhu W, Tang R, Cai J, Chen M and Yang Q 2016. Over-expression of StLCYb increases β-carotene accumulation in potato tubers. Plant Biotechnology Reports **10(2):** 95-104. https://doi.org/10.1007/s11816-016-0390-y

Thakur V, Sharma A, Sharma P, Kumar P and Shilpa 2022. Biofortification of vegetable crops for vitamins, mineral and other quality traits. The Journal of Horticultural Science and Biotechnology **97(4):** 417-428. https://doi.org/10.1080/14620316.2022.2036254

Tyagi V, Brahmi P, Yadav S, Singh PS, Singh S and Singh K 2021. Germplasm access from ICAR-NBPGR and use within India. Indian Journal of Plant Genetic Resources **34(2):** 216-220. https://doi.org/10.5958/0976-1926.2021.00020.6

United States Department of Agriculture 2025. FoodData central - Foundation foods search page. FoodData Central. https://fdc.nal.usda.gov/food-search/?type=Foundation (Accessed 2025 Oct 10).

Vir SC 2023. National Programme of Mid-Day Meal Scheme (MDMS). Routledge EBooks (pp. 665-699). https://doi.org/10.4324/9781003459842-15

Wang Y, Wang Z, Geng S, Du H, Chen B, Sun L, …, Wang Q 2023. Identification of the GDP-L-galactose phosphorylase gene as a candidate for the regulation of ascorbic acid content in fruits of *Capsicum annuum* L. International Journal of Molecular Sciences **24(8):** 7529. https://doi.org/10.3390/ijms24087529 PMid:37108695 PMCid:PMC10145300.

Wang ZZ, Dong SY, Zhou Q, Miao H, Liu XP, Xu KP, Gu XF, and Zhang SP 2023. Cloning and analysis of key genes for vitamin C synthesis in cucumber fruit. Scientia Agricultura Sinica **56(3):** 508-518.

Welsch R, Zhou X, Koschmieder J, Schlossarek T, Yuan H, Sun T and Li L 2020. Characterization of cauliflower OR mutant variants. Frontiers in Plant Science **10**. https://doi.org/10.3389/fpls.2019.01716 PMid:32038686 PMCid:PMC6985574.

Wen Y, Liu H, Meng H, Qiao L, Zhang G, and Cheng Z 2022. *In vitro* induction and phenotypic variations of autotetraploid garlic (*Allium sativum* L.) with dwarfism. Frontiers in Plant Science **13,** 917910. https://doi.org/10.3389/fpls.2022.917910 PMid:35812906 PMCid:PMC9258943.

White PJ, Thompson JA, Wright G, and Rasmussen SK 2017. Biofortifying Scottish potatoes with zinc. Plant and Soil **411(1):** 151-165. https://doi.org/10.1007/s11104-016-2903-4

Wu J, Yuan Y-X, Zhang X-W, Zhao J, Song X, Li Y, …, Wang X-W 2008. Mapping QTLs for mineral accumulation and shoot dry biomass under different Zn nutritional conditions in Chinese cabbage (*Brassica rapa* L. ssp. pekinensis). Plant and Soil **310(1-2):** 25-40. https://doi.org/10.1007/s11104-008-9625-1

Wu Z, Liu Z, Chang S and Zhao Y 2020. An EMS mutant library for carrot and genetic analysis of some mutants. Breeding Science **70(5):** 540-546. https://doi.org/10.1270/jsbbs.20020 PMid:33603549 PMCid:PMC7878946.

Yilmaz H and Yilmaz A 2025. Hidden hunger in the age of abundance: The nutritional pitfalls of modern staple crops. Food Science and Nutrition. https://doi.org/10.1002/fsn3.4610 PMid:39901987 PMCid:PMC11788495.

Yoo KS, Bang H, Pike L, Patil BS and Lee EJ 2020. Comparing carotene, anthocyanins, and terpenoid concentrations in selected carrot lines of different colors. Horticulture, Environment, and Biotechnology **61(2):** 385-393. https://doi.org/10.1007/s13580-019-00225-6

Yoo KS, Pike LM, Patil BS and Lee EJ 2020. Developing sweet onions by recurrent selection in a short-day onion breeding program. Scientia Horticulturae **266:** 109269. https://doi.org/10.1016/j.scienta.2020.109269

Yousef EAA and Elsadek MA 2020. A comparative study of morphological and volatile oil composition characteristics in diploid and tetraploid garlic plants. Egyptian Journal of Horticulture **47(1):** 1-14.

Zhang Y, Huang G, Zhao Y, Lu X, Wang Y, Wang C, Guo X and Zhao C 2024. Revolutionizing crop breeding: next-generation artificial intelligence and big data-driven intelligent design. Engineering **44:** 245-255. https://doi.org/10.1016/j.eng.2024.11.034