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Golden Greens: Bringing Micronutrient Richness to Vegetable Varieties

Anubha Kaushal[1], Mitali Sharma[2], Sherup Otzer[1] and Ramesh Kumar Bhardwaj[1]

[1]Department of Vegetable Science, Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni-Solan (HP)-173 230, India

[2]Department of Vegetable Science and Floriculture, CSK HPKV, Palampur, (HP)- 176062, India

***Correspondence Author Email :** *sharma2000mitali@gmail.com*

ABSTRACT

Rapid increases in population, ongoing issues of hunger, and pervasive deficiencies in micronutrients-frequently referred to as "hidden hunger" which impacts over two billion individuals worldwide, thereby compromising their health, productivity, and overall economic welfare. Vegetables, being full of vitamins, minerals, fibers, and phytochemicals, play a crucial role in a balanced diet, but nutrient-depleted soils frequently reduce their nutrient content. Historically, prevention of micronutrient deficiency has involved dietary diversification (typically not feasible in low-income settings) or supplements (demanding complicated distribution), yet biofortification means increasing the nutrient value of crops through conventional breeding, agronomic practices like enriched fertilizers, or genetic modification provides a cost-saving, environmentally friendly option. As the Green Revolution concentrated on crop yields at the expense of nutrient density, deficiencies ensued; now, incorporating biofortification into sustainable agriculture is designed to increase levels of vitamins, minerals, and phytochemicals in vegetables, both addressing food safety and dietary quality. The COVID-19 pandemic has also further highlighted the value of nutrient-dense produce and immune-protective phytochemicals, and biofortified vegetables form a critical part of sustainable, health-improving food systems.Through this review, we aim to bridge the gap between AI innovations and practical agricultural applications, fostering sustainable and adaptive

Keywords: *Biofortification, COVID-19, Green revolution, Micronutrients, Vegetables.*

1. Introduction

The rapid increase in the global population is significantly straining nutritional security, with over two billion individuals suffering from micronutrient deficiencies, particularly iron and zinc, which are crucial for various physiological functions such as immune defence and cognitive development (Rai et al. 2024). The deficiency has been exacerbated by soil micronutrient depletion, constricting plant uptake and food intake (Hussain et al. 2025). Biofortification is a cost-effective, promising intervention to boost the nutritional content of staple foods, consequently filling these gaps sustainably (Raut et al. 2024). Experiments have proven that biofortified crops like iron-biofortified pearl millet and zinc-biofortified wheat have been effective in enhancing micronutrient consumption as well as health status, suppressing conditions like anemia and stunting. Nonetheless, attainment of the UN Sustainable Development Goal 2 by 2030 will require concerted efforts to expand biofortification and resolve systemic food system inequalities, especially in low- and middle-income countries (Acharya et al. 2014).

Vegetables play a key role in dietary variety and nutritional value, containing vitamins, minerals, dietary fibres, and bioactive phytochemicals like polyphenols and carotenoids, which are associated with decreased chronic disease risks of cardiovascular disorders,

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diabetes, and cancer (Ülger et al. 2018). The World Health Organization suggests a daily consumption of 400-600 grams of fruits and vegetables to counter health problems related to nutrient deficiencies (Mirza 2023). Yet, current agricultural methods have decreased the nutrient content of most vegetable varieties, mainly because of yield targeting and land degradation. The occurrence highlights the necessity for new approaches in agriculture to improve the nutritional value of vegetables, thus bridging the twofold challenge of increasing nutritional requirements and declining nutrient levels, critical to public well-being and health prevention (Dias 2023).

2. Scientific Rationale for Nutrient-Enriched Vegetables

Vegetables are essential in addressing "hidden hunger," a condition affecting over two billion people globally due to micronutrient deficiencies, particularly in low- and middle-income countries. Dark leafy greens like spinach and kale are rich in vital nutrients such as provitamin A, vitamin C, iron, and calcium, while pulses provide B vitamins and protein (Mirza, 2023). These foods not only enhance nutrient intake but also improve the absorption of non-heme iron, crucial for combating iron deficiency anemia, especially in vulnerable populations like pregnant women and children (Nair et al. 2016). Epidemiological studies indicate that higher vegetable consumption correlates with reduced risks of chronic diseases, including cardiovascular issues and certain cancers, benefits that are amplified by dietary diversity. However, many populations fall short of the WHO/FAO recommended intake of at least 400 grams per day, necessitating food-based strategies to increase both the quantity and diversity of vegetable consumption to effectively combat malnutrition and chronic disease.

3. Nutraceutical and Phytonutrient Power of Vegetables

Vegetables are powerful functional foods, providing necessary vitamins, minerals, and a wide range of nutraceuticals—bioactive nutrients that provide health benefits beyond minimum nutrition. Originally coined by Dr. Stephen DeFelice in 1989, nutraceuticals are food-derived substances in particular, isolatable and consumer-palatable in pill or powder form that are demonstrated to promote physiological well-being or avoid chronic illness.

Phytonutrients, including carotenoids, anthocyanins, betalains, flavonoids, and polyphenols, are vital for health promotion and disease prevention, exhibiting antioxidant and anti-inflammatory properties. Lycopene, abundant in tomatoes and watermelon, is linked to reduced risks of cancer and heart disease, while β-carotene from orange vegetables supports vision and immune health. Lutein and zeaxanthin, found in green leafy vegetables like spinach, kale, and broccoli, are crucial for eye health, particularly in preventing age-related macular degeneration (Sharma et al. 2021). Anthocyanins, present in purple-hued vegetables, purple carrots, eggplants, red cabbage, beets, and purple sweet potatoes offer anti-aging benefits and enhance overall health (Tahir 2024). These low-calorie, safe nutraceuticals can be easily integrated into diets, prompting ongoing research into optimizing their health benefits through improved cultivars and breeding techniques (Sharma et al. 2021).

Vegetables provide essential health benefits in vitamins, minerals, fibres, and health-enhancing phytochemicals, but they are also rich in anti-nutritional factors called natural defence chemicals such as phytates, tannins, oxalates, lectins, protease inhibitors, cyanogenic glycosides, and glycoalkaloids. These may chelate essential minerals (e.g., Fe, Zn, Ca), inhibit digestion enzymes, or be toxic at high concentrations, thus lowering nutrient bioavailability and possibly inducing health problems such as kidney stones, hypothyroidism, or gastrointestinal distress (Sinha and Khare 2017). However, increasing vegetable intake is still crucial in the prevention of chronic diseases because of their nutraceutical content. The older processing techniques such as soaking and fermentation reduce antinutrient content. Recent strategies for improving nutrient supplementation, biofortification means by adding crops with beneficial substances during cultivation proves to be the most sustainable by outshining fortification and supplementation by providing improved nutrition directly through the food chain.

4. Biofortification and its significance

Biofortification is a strategic agricultural approach aimed at enhancing the nutritional quality of staple crops by integrating essential vitamins and minerals through breeding, genetic engineering, or agronomic practices, thereby addressing micronutrient deficiencies affecting over 2 billion people globally (Paul et al. 2024). This method is particularly beneficial for rural populations with limited access to processed fortified foods, as it embeds nutrients directly into crops, ensuring sustained dietary benefits across harvest cycles. Notably, biofortification counters the "carbon nutrient penalty," where elevated CO_2 levels diminish protein, iron, and zinc concentrations in C_3 cereals by 3–17% (Raut et al. 2024). Successful examples, such as the orange-fleshed sweet potato, demonstrate biofortification's potential to improve health outcomes and food security, although challenges like genetic diversity, environmental factors, and consumer acceptance remain (Paul et al. 2024). Continued research and policy support are essential to maximize biofortification's impact on global nutrition security (Raza et al. 2024).

4.1 Biofortification Strategies

4.1.1 Agronomic biofortification - It involves applying micronutrient-rich mineral fertilizers to the soil, foliage, or seeds to boost essential nutrient levels in edible crop parts. This rapid, cost-effective strategy is especially valuable in regions with micronutrient-poor soils, where access to fortified foods is limited.

- Soil application: Micronutrient-enriched fertilizers (e.g., Zn, B, Fe) are incorporated into the soil, facilitating plant uptake and enhancing yield stability. The efficacy of this approach is contingent upon soil characteristics—such as pH, texture, and organic matter—that regulate micronutrient bioavailability (Jan et al. 2020). Soil-applied zinc, for instance, has been shown to improve both productivity and nutritional quality in legume crops.
- Foliar feeding: Nutrient solutions are sprayed directly on leaves, circumventing soil interactions that often immobilize elements like iron. Through stomatal and epidermal absorption, this method can elevate micronutrient levels more effectively than soil application, addressing deficiencies promptly and with minimal soil alteration.
- Seed coating: Seeds are coated with micronutrient powders (e.g., Zn, B, Mn) using adhesives like gum arabic, which improves micronutrient availability during germination and early growth. Coating seeds with micronutrient powders, such as ZnO, improves germination rates, seedling vigor, and chlorophyll content, as demonstrated in bell pepper and onion (Singh et al. 2024).
- Seed priming: Seeds are pre-soaked in nutrient-rich solutions (e.g., Fe, Zn, B, or microbial inoculants) to trigger early metabolic activation without radicle emergence. In vegetables, onion seeds primed with ZnO, CuO, TiO_2, or Ag nanoparticles showed substantial improvements in germination percentage, seedling growth, and vigor index.
- Nano-priming: Vegetable crops such as watermelon and pepper benefit from nanoparticle seed priming with ZnO or MnO_2 nanoparticles stimulate phytohormonal activity, increase photosynthetic pigment levels, augment antioxidant enzyme responses, and enhance abiotic and biotic stress resilience. Promoting stress resilience and efficient nutrient absorption due to the high surface-area-to-volume ratio of nanoparticles (Sarmah et al. 2024). However, careful dosage control is crucial, as excessive concentrations can induce phytotoxic effects, underscoring the need for optimized formulations in agricultural practices (Prajapati et al. 2024).

4.1.2 Conventional breeding:

Traditional breeding strategies for enhancing the nutritional quality of vegetable crops focus on leveraging intra-species genetic variability to incorporate micronutrient-rich traits into high-yielding cultivars. This approach, which includes systematic crossing and selection, aims to address yield and disease resistance, often resulting in diminished nutrient content in modern varieties (Singh et al. 2020). Current methodologies involve screening germplasm collections for nutrient-dense accessions and utilizing marker-assisted selection (MAS) to expedite the introgression of these traits into elite lines (Kumar et al. 2015). While this breeding for biofortification is promising, it necessitates careful management of the yield-nutrient trade-off and extensive phenotypic validation to ensure that enhanced micronutrient levels do not compromise agronomic performance (Karmakar et al. 2016). Moreover, the success of these programs hinges on the availability of genetic variation and the ability to combine high yield with improved nutritional traits, which is essential for farmer adoption and consumer acceptance.

4.1.3 Genetic engineering:

The direct manipulation of an organism's genome through biotechnological tools, such as genetic engineering, has emerged as a pivotal strategy for enhancing the nutritional quality of crops. This approach facilitates the introduction of beneficial traits from one species to another, resulting in elite cultivars with improved micronutrient concentrations and bioavailability. For instance, transgenic lettuce engineered to express soybean ferritin has demonstrated a remarkable 70% increase in leaf iron concentration, while the overexpression of the Arabidopsis CAX1 calcium transporter in carrots has successfully elevated bioavailable calcium levels without adverse phenotypic effects (Banerjee et al. 2023).

5. Biofortification in vegetable crops

Plant breeders are increasingly utilizing both conventional and genomic methods to enhance the mineral content of staple crops, significantly impacting global nutrition. Initiatives like HarvestPlus aim to reach one billion consumers by 2030, having already introduced over 150 biofortified varieties, such as iron-rich beans and zinc-enriched pearl millet, which have demonstrated measurable health benefits in various populations (Bouis 2018). For instance, orange-fleshed sweet potatoes have reduced vitamin A deficiency by 24% among children in Mozambique. The advent of transgenic biofortification, exemplified by "Golden lettuce," showcases a 30-fold increase in bioaccessible vitamin A, addressing critical deficiencies that lead to blindness and immune issues in children (Saltzman et al. 2017). Furthermore, biofortification with micronutrients like boron and molybdenum has shown potential in enhancing calcium absorption and glucose metabolism, respectively, indicating a broad scope for improving public health through targeted crop enrichment (Kumar et al. 2022). Likewise, selenium-fortified basil and lettuce developed in hydroponics offer enhanced shelf life, antioxidant content, and detoxification benefits.

India has made remarkable progress in enriching its vegetable crops through breeding and biofortification: Pusa Beta Kesari 1 cauliflower, released in 2015–16, delivers 800–1,000 µg β-carotene per 100 g (8–10 ppm), boosting provitamin A intake with strong yield and farmer appeal; innovative carrot lines like Pusa Asita, Pusa Rudhira, and Punjab Black Beauty offer exceptionally high antioxidant levels, with anthocyanins up to 520 mg/100 g alongside elevated carotenoids, lycopene, and phenolics ; radish varieties such as Pusa Gulabi and Pusa Jamuni are rich in carotenoids, anthocyanins, and vitamin C ; disease-resistant tomato varieties like Pusa Shakti (6 mg lycopene/100 g, heat tolerant, and with thick, transport-friendly fruit) and Pusa Tomato Hybrid-6 (29 mg vitamin C /100 ml juice, resistant to four major diseases) have been officially released ; and in the onion category, Pusa Riddhi, released in 2013, contains 107 mg quercetin per 100 g, offering both strong antioxidant benefits and good storage quality . Over 591 advanced vegetable varieties and hybrids developed under ICAR's AICRP-VC—many with enhanced nutritional profiles—have been released, underscoring a robust national shift toward health-centric vegetable agriculture.

6. Challenges

6.1 Restricted Genetic Diversity in Target Crops

The process of biofortification is limited by the narrow genetic base of target staple foods such as rice, wheat, and maize mainly due to years of yield- and agronomic trait-based breeding. This limited diversity impedes the discovery and deployment of varieties with inborn potential for high micronutrient uptake and accumulation. In order to meet this, the programs need to leverage wide germplasm pools (e.g., landraces, wild relatives) and utilize new breeding and genetic techniques to combine nutrient-dense traits into locally adapted and diverse cultivars

Table1: Nutrient-Enriched Vegetable Varieties Across Breeding Strategies (Reddy et al. 2024)

Crop	Variety / Trait	Approach	Enhanced Nutrient (Content)
Watermelon	Arka Jyoti, Durgapur Lal (hybrids)	Hybridization	β-Carotene, lycopene
Brinjal	Punjab Sadabhar	Hybridization	Anthocyanin
Okra	Khasi Lalima	Hybridization	Anthocyanin (3 mg/100 g)
Bitter gourd	DRAR-1, DVBTH-5 hybrids	Hybridization	β-Carotene, ascorbic acid
Carrot	Kashi Arun, Pusa Nayanjyoti, Pusa Meghali	Hybridization & Selection	Lycopene 7.5 mg; β-carotene 38 mg; anthocyanins
Radish	Kashi Lohit	Hybridization	Anthocyanin (39.9 µg/100 g)
Tomato	Pusa Rohini; Punjab Red Cherry	Hybridization & Selection	Vitamin C 31.2 mg; lycopene; polyphenols, flavonoids
Potato	Kufri Neelkanth; Kufri Jamunia	Hybrid & Selection	Anthocyanin >100 µg/100 g; purple flesh
Sweet potato	Sree Kanaka; Sree Rethna; Bhu Krishna/Bhu Sona	Hybridization & Selection	β-Carotene 2–3 mg; anthocyanins 90 mg; carotene 14 mg
Pumpkin	Arka Chandan	Selection	β-Carotene (3333 IU/100 g)
Cauliflower	Pusa Beta Kesari 1	Selection & Genetic engineering	β-Carotene 8–10 ppm
Cassava	Sree Visakham	Hybridization	β-Carotene (466 IU)
Cowpea	Pant Lobia-1/2	Selection	Iron (82–100 ppm), Zinc (37–40 ppm)

Table2: Transgenic Vegetable Crops Engineered for Enhanced Nutritional Traits (Behera et al. 2024)

Transgenic (GM) Crops	Gene / Trait	Enhanced Nutrient
Tomato	*pGAnth0* (anthocyanin gene)	Anthocyanin content increased
Potato	PSY, LCYb, Or gene constructs	Provitamin A (β-carotene, lutein, zeaxanthin)—e.g., "Golden" tubers
Lettuce	Soybean ferritin	Enhanced iron storage
Cauliflower	*Or* gene insertion	β-Carotene enrichment
Sweet potato	*IbOr-Ins, IbMYB1*	Lutein, β-carotene, anthocyanins
Cassava	PSY; bioCassava Plus gene stack	Provitamin A, iron, zinc
Carrot	*CAX1* transporter	Calcium accumulation

6.2 Balancing Nutrient Enhancement with Agronomic Performance

Attaining target levels of nutrient enrichment without compromising vital traits like yield potential, stress tolerance, and disease resistance is still a major challenge. Raising micronutrient concentration by conventional or transgenic approaches may inadvertently influence plant physiology and productivity. Success demands understanding the genetic determinants of nutrient deposition, followed by accurate breeding strategies and broad field validation across environments to ascertain that gains in nutrients do not negatively influence agronomic viability.

6.3 Consumer Acceptance and Awareness

Adoption of biofortified crops is thwarted by low consumer awareness, food culture, and sensory issues especially when biofortified characteristics change color, taste, or texture. Research in countries such as South Africa and Nigeria finds that, no matter their nutritional value, consumers will shun biofortified varieties based on unfamiliar appearance or taste unless enlightened through education and community outreach. Successful marketing, promotion by local opinion leaders, and culturally sensitive marketing are necessary to develop trust and enhance consumer acceptance.

7. Drivers of Adoption for Nutrition-Enhanced Vegetable Varieties

7.1 Farmer Awareness, Attitudes & Behavioural Intent

Farmers who understand clearly the concept of hidden hunger and the advantages of nutrient-rich produce are much more likely to embrace biofortified vegetables. For instance, iodine-biofortified cabbage and cowpea experiments in Uganda revealed 75 per cent of farmers were ready to adopt when properly informed. Farmers' positive attitudes, control belief (self-efficacy in using fertilizers), and risk perception as the major determinants for their adoption willingness.

7.2 Economic Incentives & Risk Perception

A strong economic benefit drives farmer interest in nutrient-rich crop systems. In China, for example, wheat farmers who adopted biofortification achieved returns on investment up to 42%, especially among cooperative members and those with higher risk tolerance. However, the cost of conventional fertilizers required for agronomic biofortification can exclude resource-poor farmers. Likewise, biofortified seeds often carry premium prices due to high research and development expenses, restricting access in areas with limited subsidies or underdeveloped distribution networks.

7.3 Seeds, Inputs & Extension Service Access

Local seed multiplication systems are often inadequate especially in remote areas due to low production capacity and poor logistical infrastructure, which severely restricts farmers' access to biofortified vegetable seeds and related inputs. To build farmer confidence and awareness, extension services such as on-farm demonstration trials, field days, radio broadcasts, and television programs have proven invaluable. Additionally, ICT-driven tools including mobile advisory apps, SMS services, and decision-support platforms have shown strong potential in rural India by enhancing farmers' decision-making capabilities and ability to adapt to new practices.

7.4 Market Demand & Consumer Acceptance

A rising preference for nutrient-enriched vegetables is creating real market incentives for farmers. In Uganda, consumers demonstrated a willingness to pay premium prices for iodine-rich cabbage and cowpea enough to cover extra production costs and boost farmer profitability. While sensory attributes like taste, color, and appearance may differ slightly from conventional varieties, acceptance increases significantly when health benefits are communicated. Furthermore, integrating these vegetables into institutions—through processors, retailers, and programs such as school meals enhances visibility and normalizes consumption, further strengthening market demand.

7.5 Policies, Subsidies & Institutional Support

Government support via seed subsidies and minimum support prices (MSP) provides farmers with strong incentives to cultivate nutrient-rich crop varieties. By reducing input costs and guaranteeing a remunerative price for biofortified produce, these policies enhance profitability and reduce financial risk. Furthermore, integrating biofortified crops into public nutrition programs—such as school feeding initiatives and child development services ensures stable demand and promotes broader consumption, creating a positive feedback loop that supports both production and public health goals.

7.6 Social & Demographic Influences

Educated farmers with larger households are more likely to embrace nutrient-enriched crop varieties, drawing on their broader knowledge base and greater need for diverse, high-quality produce. Being part of cooperatives further boosts adoption rates by facilitating information sharing, peer support, and improved market access. Additionally, demographic factors such as age, willingness to take risks, and gender play a role: younger or more risk-tolerant farmers are generally more open to innovation, and in China, female farmers growing biofortified wheat achieved approximately 12 % higher ROI than their male counterparts.

8. Future Directions

Realizing the full potential of biofortified vegetables requires intertwining advanced breeding approaches, precision agronomic practices, and emerging technological platforms that address both nutritional deficiencies and environmental resilience. Integrating genomic tools such as marker-assisted selection, speed breeding, and even genome editing with drought- and stress-tolerant traits can accelerate the development of high-yielding, nutrient-dense vegetables. Complementarily, nanotechnology-based innovations (like nano-fertilizers, nano-encapsulation, and nutritionally targeted nanoparticles) offer efficient micronutrient delivery systems, reducing losses and enhancing uptake; these technologies also enable smart packaging and nano-sensors for real-time monitoring although comprehensive assessments of environmental safety are still needed. Simultaneously, highthroughput phenotyping, IoT, and AI-driven analytics can enable dynamic tracking of nutrient accumulation and plant responses, fostering informed decision-making in varied production system. Expanding efforts to co-biofortify multiple micronutrients (like iron, zinc, vitamin A, selenium) in a single crop is on the horizon, though multigenic interventions pose regulatory, technical, and public-acceptance hurdles. Equally crucial is the establishment of responsible innovation frameworks grounded in public engagement, equity, ethics, and environmental stewardship to ensure these emergent technologies translate equitably to farmers and consumers. As these advanced approaches are scaled, cross-sector collaboration and sustained investment will be pivotal in monitoring long-term agronomic performance, ecological impact, cost-effectiveness, and health outcomes. In essence, forging a future-ready biofortification strategy demands not just technical breakthroughs, but also holistic systems thinking, policy foresight, and inclusive partnerships.

9. Conclusion

Biofortification is a tremendous promise as a cost-efficient, sustainable means of fighting micronutrient deficiencies in vegetable-producing areas. Through the enrichment of staple vegetables with vital vitamins and minerals through agronomy, breeding, or biotechnology this process transcends conventional fortification to meet the needs of far-flung communities where processed foods are unavailable. Field programs such as *HarvestPlus* and their partners have already put dozens of biofortified crop varieties on farm in dozens of countries, showing quantifiable gains in iron and vitamin A status for women and children. Though promising, biofortification is confronted with challenges ranging from regulatory barriers to seed delivery bottlenecks, market and consumer acceptance challenges, the possibility of reducing crop diversity. Future actions must thus embrace holistic, multi-micronutrient strategies underpinned by strong digital platforms, nanotechnology, policy sets, and active community collaboration. When integrated into sustainable food systems, biofortified vegetables can be instrumental in the realization of global nutrition and health goals, particularly among vulnerable and rural populations.

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