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Bio-fortified horticultural crops: Combating hidden hunger and pathogen resistance

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Abstract

Biofortification is the enhancement of crops' micronutrient content via breeding, biotechnology or agronomy which offers a sustainable strategy to address widespread micronutrient deficiencies or "hidden hunger". In India, where anemia, vitamin A deficiency and other nutrient deficits affect large portions of the population, horticultural crops (fruits and vegetables) are especially promising vehicles for biofortification because of their natural richness in vitamins, minerals and antioxidants. This article reviews biofortification approaches for horticulture, including conventional breeding, genetic engineering, and agronomic methods, highlighting scientific details and examples. Indian case studies include "Madhuban Gajar" (a β -carotene-rich carrot), high-provitamin A banana efforts (e.g. NABI's CRISPR "golden banana" project), anthocyanin- and β -carotene-fortified sweet potatoes (varieties *Bhu-sona* and *Bhu-krishna*), and micronutrient-fortified vegetables. Biofortification in plants can confer dual benefits: enhancing human nutrition and often improving crop health and stress tolerance (for example, zinc-enriched seeds exhibit stronger seedling vigor and resistance to soil pathogens). We discuss the technical and adoption challenges in India (such as limited awareness, regulatory hurdles for GM crops, and consumer acceptance of novel varieties), and outline future prospects. These include integrating biofortified horticulture into national nutrition programs (e.g. Poshan Abhiyaan "Nutri-gardens"), incentivizing farmers (through seed subsidies or price supports), and advancing research (e.g. gene editing, nanofertilizers). Finally, we summarize international and Indian policy frameworks - HarvestPlus, ICAR and DBT initiatives, FAO/WHO guidance - and recommend stronger coordinated actions to mainstream biofortified fruits and vegetables in diets and agriculture.

Keywords: Biofortification, horticultural crops, hidden hunger, micronutrient deficiency, nutritional security, India, pathogen resistance, genetic engineering, agronomy, policy frameworks

Introduction

"Hidden hunger" refers to chronic micronutrient malnutrition - insufficient intake or absorption of vitamins and minerals - which quietly undermines health, cognition and economic productivity [12]. Globally, about one-third of people suffer from hidden hunger, and India bears a particularly heavy burden. National surveys report that 50-60% of preschool children and women are anemic, and substantial fractions of the population still lack adequate vitamin A and iodine [45]. India's monotonous, cereal-based diets explain much of this: nearly 60% of Indians are undernourished or stunted. Hidden hunger costs India an estimated 2.4% of GDP in lost productivity [28, 65].

Biofortification is a nutrition-sensitive agricultural strategy to combat hidden hunger by raising the nutrient density of food crops [66]. It seeks to increase vitamins and minerals in staple and vegetable varieties during plant growth, by breeding (traditional and modern), transgenic or genome editing, and agronomic practices. Unlike post-harvest fortification, biofortification builds nutrients into the crop itself. The World Health Organization recognizes biofortification as a cost-effective means to reduce vitamin and mineral deficiencies [67, 89].

In India's context, biofortification complements existing nutrition programs (ICDS, Mid-Day Meal, etc.) by improving the intrinsic quality of widely consumed crops [110].

It aligns with national goals: India's *National Nutrition Mission (Poshan Abhiyaan)* was launched in 2018 to make India "malnutrition-free" by 2022. The NITI Aayog's *National Nutrition Strategy (2017)* explicitly calls for food-based solutions to micronutrient deficiency^[90]. Agricultural research bodies (ICAR, NARS) have begun treating micronutrient enhancement as a mandatory breeding target alongside yield and stress tolerance^[46]. In this review, we focus on the role of horticultural crops in India's biofortification efforts: scientific techniques, illustrative cases (especially recent Indian examples), and their twin benefits for nutrition and plant health. We then discuss adoption barriers, policy frameworks, and future directions to harness horticultural biofortification against India's hidden hunger^[1, 13].

The Role of Horticultural Crops in Addressing Micronutrient Deficiencies

Fruits, vegetables and leafy greens are inherently rich in vitamins, minerals, fiber and phytonutrients. Integrating more horticulture into diets can significantly improve nutrient intake^[91, 111]. For example, leafy greens such as amaranth, Indian spinach and drumstick (moringa) leaves are excellent sources of iron, β -carotene (provitamin A) and folate, while fruits like mango, papaya, carrot, sweet potato and pumpkin provide high levels of provitamin A (β -carotene)^[68]. Citrus fruits, guava and other local fruits supply vitamin C, which enhances iron absorption. Thus, consuming a mix of fruits and vegetables can deliver daily requirements of vitamins A, C, iron, zinc and other micronutrients, as recommended by WHO/FAO (400 g of fruits/vegetables per day)^[29].

Unfortunately, Indian diets are deficient in these nutrient-dense foods. Studies show that less than 10% of Indian adolescents meet recommended fruit-and-vegetable intake. Lower-income and rural populations often subsist mainly on cereals, contributing to widespread micronutrient gaps. The Indian government's Poshan Abhiyaan is thus promoting "*Poshan Vatikas*" (nutri-gardens) around Anganwadi centers and households, planting local vegetables and fruits to improve access to micronutrients^[112].

Horticultural crops can serve as both carriers of naturally high nutrients and as platforms for biofortification. For instance, many Indian leafy greens are already good iron sources. Enhancing them further through breeding or nutrient management could yield leafy cultivars with even higher iron or zinc^[92]. Moreover, fruits with high β -carotene (orange-fleshed papaya, sweet potato) can be developed to combat vitamin A deficiency. In India, government initiatives emphasize dietary diversity and horticulture: e.g., the National Nutrition Mission's guidelines list high-iron and vitamin-rich vegetables (spinach, fenugreek, amaranth, drumstick, etc.) for kitchen gardens^[47]. Thus, bolstering horticultural production - especially varieties bred or managed for higher micronutrients - is a promising route to alleviate hidden hunger in India^[14, 69].

Biofortification Techniques in Horticultural Crops

Biofortification of plants can be achieved by three main strategies: conventional breeding, genetic engineering (transgenesis/ genome editing), and agronomic practices. Each has scientific nuances and differing timelines:

- **Conventional Breeding:** Traditional plant breeding uses natural genetic variation to select varieties with elevated nutrient content. This requires identifying or inducing nutrient-dense parent lines, crossing them, and screening progeny. For example, yellow/orange vegetables (carrot, maize, sweet potato) owe their color to higher β -carotene

^[30]. Breeders have introgressed high-provitamin A traits into local varieties (e.g., orange carrots and maize)^[70, 71, 132]. Marker-assisted selection and genomic selection now accelerate this process. Important breeding achievements in India include pearl millet with 30-70% higher iron and zinc, as well as nutritionally-enhanced sorghum and millet^[48]. For horticultural crops, breeders have developed β -carotene-rich *cauliflower* (>8 ppm vs. negligible baseline) and vitamin-C-enriched *pomegranate*. Leafy vegetables and tubers are also targets: ICAR has released sweet potato varieties rich in β -carotene (*Bhu-sona*, ~14 mg/100g dry) and anthocyanins (*Bhu-krishna*, ~40 mg/100g dry). These examples show how selection and crossing can yield nutritionally improved crops without transgenes^[2, 133].

- **Genetic Engineering and Genome Editing:** Biotechnology can accelerate nutrient enhancement by directly inserting or editing genes involved in nutrient pathways. A classic example is *golden rice* (transgenic rice expressing daffodil/maize *psy* and *crtI* genes to produce β -carotene). In horticulture, similar approaches have been applied: scientists have engineered a "Golden Banana" by transferring a high- β -carotene *psy* gene from an orange-fleshed banana into cooking bananas (resulting in provitamin A-rich fruits)^[72]. Research institutes such as India's NABI (National Agri-Food Biotech Institute) are now using CRISPR/Cas to edit banana genomes for enhanced provitamin A and stability. Other transgenic horticultural examples include "blue" tomatoes engineered to accumulate anthocyanins (using snapdragon transcription factors) and tomatoes modified to produce provitamin D3^[113]. Genetic engineering can also target mineral transporters: for instance, expressing enhanced zinc transporter genes has boosted grain Zn in cereals^[93]. In horticulture, overexpressing Fe- or Zn-transporter genes could increase these metals in fruits and tubers. However, regulatory constraints on GM crops in India mean that such transgenic or gene-edited varieties face hurdles before field use^[15].
- **Agronomic Practices (Fertilizer-based Biofortification):** Non-genetic methods involve managing soil and plant nutrition to raise crop micronutrient levels. This includes applying mineral fertilizers (e.g. ZnSO_4 , FeSO_4) to soil or foliage, using organic amendments, or employing biofertilizers/microbes that mobilize micronutrients^[49]. For example, foliar spraying of zinc or iron during plant growth can significantly increase those minerals in edible parts. Field trials have shown that applying Zn fertilizers to rice, wheat or vegetables can raise grain/fruit Zn content and help alleviate human Zn deficiency^[114, 142]. Agronomic biofortification is fast-acting but typically temporary (nutrients wash out yearly), requiring repeated application. Micronutrient-rich soils (e.g. through manure or manure + micronutrient) lead to higher nutrient uptake by plants and more nutritious produce^[94, 134]. Beneficial microbes (e.g. rhizobacteria or mycorrhizae) can also enhance nutrient availability and uptake. In summary, agronomic methods are practical and immediately applicable, but they complement rather than replace genetic approaches. As Bremer *et al.* note, "Application of micronutrients as fertilizers can help reduce human micronutrient deficiency"^[73].

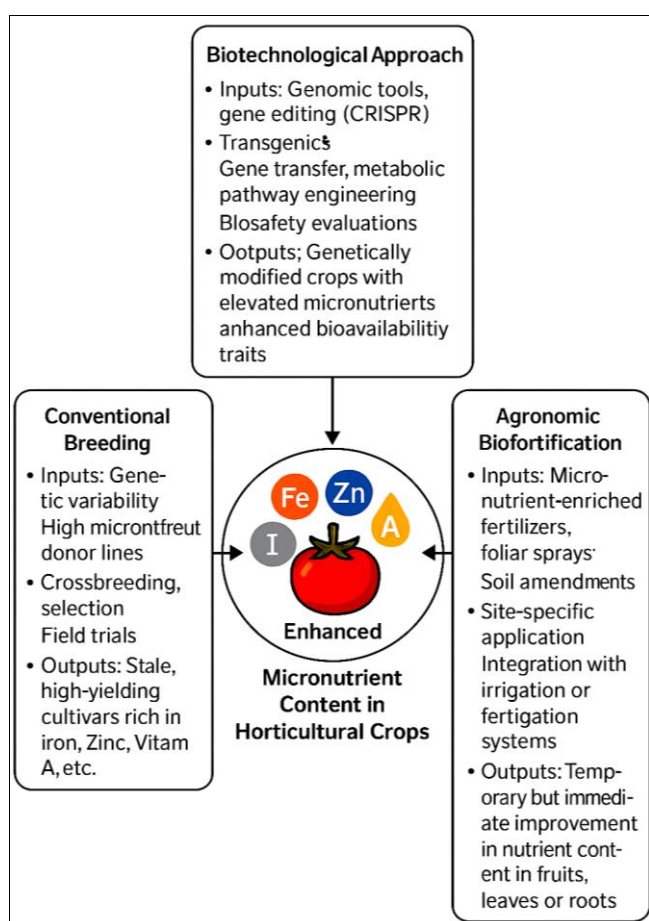
Each technique has pros and cons. Breeding is time-intensive but once done yields stable varieties; biotechnology can create leaps (stacking multiple traits) but is expensive and regulated;

agronomic methods are simple but not self-sustaining. In practice, integrated strategies are best ^[95, 115]. Horticultural biofortification efforts may combine approaches (e.g. a high- β -carotene carrot variety grown with Zn-rich fertilizer). The current trend is “stacking” multiple nutrients (e.g. developing crops with both high iron and zinc) and using modern tools like genome editing and nanotechnology to enhance efficiency ^[31].

Breeding

Cross high-micronutrient parents; select progeny with improved nutrient profiles. *E.g.*: β -carotene maize and sweet potato, high-iron beans; ICAR has developed high-Zn wheat and high-Fe pearl millet ^[3].

- **Biotechnology:** Transfer or edit genes to upregulate nutrient synthesis/transport. *E.g.*: Golden rice (β -carotene), transgenic banana with psy gene, gene-edited plant genomes ^[50].
- **Agronomic:** Fertilize soil or foliage with micronutrients; use biofortifying microbes. *E.g.*: Zinc foliar spray on tomatoes, biochar and zinc on rice, phosphate-solubilizing bacteria to increase iron uptake ^[96].



Case Studies of Biofortified Horticultural Crops in India

India has initiated or adopted several biofortified horticultural crops. Below are illustrative examples, including both indigenous varieties and research-stage innovations:

- **Madhuban Gajar (β -Carotene-Rich Carrot):** Developed by farmer-scientist Shri Vallabhbhai Marvaniya in Gujarat, *Madhuban Gajar* is a high-nutrient carrot. It contains very high β -carotene (~277.8 mg/kg, source of vitamin A) and iron (~276.7 mg/kg) - several-fold above conventional varieties ^[51]. This biofortified carrot yields about 40-50 tonnes/ha and is popular for its orange colour ^[74].

Cultivation has expanded to over 1,000 ha across Gujarat, Maharashtra, Rajasthan and other states. It serves both as fresh vegetable and as raw material for carrot chips, juices and pickles ^[16, 32]. The variety was tested and promoted by the National Innovation Foundation (NIF), recognizing its significant nutritional benefits. *Madhuban Gajar* exemplifies “hidden” biofortification - no genetic engineering, just traditional selection by a farmer. Its success underscores how local innovation can generate nutrient-rich vegetables that help combat vitamin A and iron deficiency in rural diets ^[5, 115].

- **Pro-Vitamin A (“Golden”) Banana:** Building on the global *golden rice* concept, researchers are creating provitamin A bananas. Banana is a staple fruit in many diets, so enhancing its β -carotene could deliver vitamin A on a large scale ^[52]. Internationally, scientists have engineered a “Super Banana” by inserting a high- β -carotene gene (*psy*) from an orange-fleshed banana variety (the Ugandan *Asupina banana*) into cooking banana cultivars. In India, the DBT-funded National Agri-Food Biotech Institute (NABI) project led by Dr. Siddharth Tiwari is using CRISPR/Cas to edit banana genes for high provitamin A content ^[34]. If successful, these *Golden Bananas* could help prevent Vitamin A deficiency. Besides nutrition, higher β -carotene may improve plant stress tolerance ^[75]. Note that these bananas are in development (not yet commercial). Regulatory approval is a major hurdle since India’s Genetic Engineering Appraisal Committee has approved only one GMO crop (Bt cotton) for field cultivation to date. Public acceptance is another issue - consumers must be willing to eat “golden” bananas ^[97, 135]. However, such biotech crops represent the potential for rapid improvement of diet with micronutrients ^[35].
- **Zinc-Enriched Tomato:** Tomatoes are widely consumed and can be a vehicle for micronutrients. While no specific commercial “zinc tomato” variety is released in India, research has shown that agronomic biofortification can work. For example, applying zinc-enriched fertilizer or nano-Zn formulations to tomato plants increases the fruit’s Zn concentration ^[53]. One study found that microbial consortia (plant-growth-promoting bacteria) applied to tomato raised its iron, zinc, and other nutrients significantly over controls. In horticultural breeding, lines with higher grain (or fruit) Zn could be selected ^[98]. The concept is that a “zinc-rich tomato” could supply dietary zinc, alleviating zinc deficiency. Although a marketed biofortified tomato is not yet noted in India, efforts are underway ^[116]. Improving growers’ access to Zn fertilizers and promoting Zn-treated tomato hybrids could yield “zinc-tomato” products in the future ^[6, 17].
- **Iron-Rich Leafy Vegetables:** Some leafies naturally have high iron and folate. For instance, Indian spinach (*Basella alba*) and amaranth are good iron sources. Biofortification efforts include breeding selections of these greens for even higher iron content ^[54]. Agronomic methods like soil or foliar Fe fertilizers can boost iron in leaves. For example, fortifying soil with iron chelates has been shown to increase Fe in spinach and fenugreek leaves (though exact Indian cases are sparse) ^[77, 143]. In policy, the *Poshan Vatikas* recommend planting iron-dense vegetables (spinach, methi, amaranth, drumstick leaves, etc.) to improve diets ^[99]. Future work could include naming and releasing high-iron cultivars of these vegetables, similar to *Madhuban Gajar* carrots. Even without novel varieties, simply promoting the

cultivation and consumption of high-iron veggies is a form of “home biofortification”^[18, 76].

- **β-Carotene Sweet Potato (*Bhu-sona*, *Bhu-krishna*):** The ICAR-Central Tuber Crops Research Institute (CTCRI) has released orange-fleshed sweet potato varieties^[117]. *Bhu-sona* is a white-fleshed variety enriched to have ~14 mg β-carotene per 100 g (dry weight), whereas *Bhu-krishna* is a purple-fleshed variety with very high anthocyanins (~40 mg/100 g dry)^[136]. These *nutri-tubers* can significantly raise vitamin A and antioxidant intake^[100]. These varieties have been disseminated among farmers; studies confirm that schoolchildren consuming *Bhu-sona* show increased serum retinol levels. The success of these sweet potato varieties demonstrates India’s commitment to biofortifying even minor staples for nutrient security^[55].
- **Other Examples:** Indian research has also explored nutrient-rich cauliflower (high β-carotene), pomegranate (high vitamin C and iron), and drumstick/moringa (already naturally rich in vitamins) through biofortification lenses^[118]. For instance, breeding has produced cauliflower hybrids with more than 8 ppm β-carotene. Similarly, biofortified orange-fleshed sweet potato (a global intervention) has been introduced to India^[101]. While not all such vegetables are on the market yet, they highlight the pipeline of biofortified horticulture. Overall, these case studies show that a combination of farmer-led breeding (carrot), institutional research (sweet potato, cauliflower), and biotech projects (banana) is generating a range of nutrient-dense fruits and vegetables for India^[78].

Dual Advantage: Nutrition and Pathogen Resistance

Biofortification can yield the “two-for-one” benefit of improved human nutrition and healthier crops. A key example is zinc. Zinc is vital for human immune function, but it also plays a crucial role in plant health^[19]. Studies show that seeds with higher zinc content produce more vigorous seedlings and better crop establishment^[56]. In fact, maintaining sufficient zinc in seeds “provides defence against soil-borne pathogens”. In other words, zinc-biofortified seeds germinate more strongly and are more resistant to seedling diseases. This improves overall yield and reduces the need for pesticides^[36, 137, 140].

More broadly, many micronutrients act in plant stress responses. For instance, sufficient zinc and iron are needed for enzymes that protect plants from oxidative stress and pathogens. Carotenoids and anthocyanins (targeted for vitamin A improvement) are antioxidants that also defend plants from UV or microbial attack^[79]. Thus, breeding fruits and vegetables for higher nutrient/antioxidant content often incidentally raises their pest and disease resilience. Indeed, agronomic zinc application is known to decrease disease incidence in many crops. A “dual advantage” emerges: by eating biofortified produce, humans get more nutrients and farmers benefit from stronger plants^[119]. It is important to emphasize that this synergy should guide breeding goals^[57]. Biofortified varieties should be at least as robust as conventional ones. For example, if tomato is bred for high zinc, breeders will ensure it still resists common blights. Conversely, pathogens exert less selection pressure when plants are well-nourished. In summary, enhancing micronutrients in horticultural crops not only fights human micronutrient deficiency, it also improves plant health - a win-win that boosts food security and reduces crop losses^[8].

Challenges and Limitations in India

Despite its promise, horticultural biofortification faces several hurdles in India:

- **Lack of Awareness and Demand:** Many farmers and consumers do not know about biofortified crops. A major constraint is “lack of awareness on the health benefits of biofortified crops”^[120]. If farmers don’t perceive demand, they hesitate to adopt new varieties. Consumers may not value extra iron or vitamins, so market pull is weak^[58].
- **Yield and Performance Concerns:** Farmers often worry that new varieties yield less than traditional ones. The perception that “biofortified varieties have low yielding potential” has slowed adoption^[121]. In reality, modern biofortified lines are typically bred for yield parity or advantage. WHO highlights those farmers will only plant varieties that match or exceed current cultivars in drought or disease resistance. Outreach must emphasize that nutrient-rich breeding does not compromise yield or agronomic traits^[20, 37].
- **Visual and Taste Differences:** Some biofortified crops have altered appearance (color or taste). For example, provitamin-A enrichment turns white maize or potatoes orange; anthocyanin-rich vegetables may become purple^[122]. Such changes can face consumer hesitation if not properly introduced. In India, farmers “generally hesitate in accepting the biofortified produce” when its colour differs (e.g. yellow vs. white maize)^[138]. Taste or cooking properties may also differ slightly. Educational campaigns and tastings are needed to overcome prejudice, as WHO notes for orange sweet potato and maize^[80].
- **Regulatory and Policy Barriers:** Genetically engineered crops face strict regulation. India currently allows only Bt cotton as a GMO crop (since 2002). Field trials of GM food crops are limited by the Genetic Engineering Approval Committee (GEAC) and public opposition (as seen with GM mustard)^[102, 143]. Hence, transgenic biofortified fruits/vegetables (golden banana, purple tomato) may take many years of bio safety review. Even non-GM biofortified crops lack formal labelling or incentives. The absence of clear policies (e.g. subsidies for biofortified seeds, mandatory inclusion in public programs) slows progress^[59].
- **Seed Systems and Infrastructure:** Releasing a new variety is one thing; getting seeds to millions of farmers is another. Seed production and distribution networks for biofortified horticulture are underdeveloped^[123]. Strengthening the “seed chain” and possibly using *seed villages* for farmer-produced seed are recommended. Without affordable, quality seeds, uptake will be low. Similarly, cold-chain, processing facilities and market linkages for novel crops need investment^[81].
- **Research and Measurement Gaps:** Many biofortified traits (iron, zinc, vitamins) are invisible to the naked eye or require lab tests. Farmers and consumers cannot verify nutrient levels on the spot^[124]. As the Indian review notes, we lack simple field tools (like Brix meters for sugar) to measure nutrient content. This makes quality assurance and marketing challenging^[38].

Overall, the combination of limited awareness, cultural preferences, policy hurdles and infrastructure gaps means that even proven biofortified horticultural varieties may struggle to reach the needy without concerted support. Education, demonstration projects, and supportive government programs are needed to overcome these barriers^[9, 21].

Future Prospects

The future of horticultural biofortification in India is promising if integrated into policy and practice:

- **Nutrition Program Integration:** India's national nutrition schemes provide ready platforms to distribute biofortified foods. For example, *Poshan Abhiyaan* encourages “Poshan Vatikas” of micronutrient-dense crops. Biofortified vegetables can be supplied to Anganwadis (childcare centers) and Mid-Day Meal programs^[60]. The NITI Aayog strategy explicitly calls for including biofortified staples and vegetables in government feeding programs^[103, 139]. If cauliflower, carrots or sweet potatoes with enhanced nutrients are grown in or near schools, children directly benefit. States like Bihar have even established entire “nutrition villages” growing only biofortified crops. Expanding such models will be key^[22].
- **Farmer Incentives:** Economic incentives can drive adoption. The review suggests subsidized seeds and guaranteed prices for biofortified crops. For instance, government procurement of zinc-fortified wheat already assures farmers a premium^[125]. Similar policies (minimum support prices or procurement) for fortified vegetables could motivate growers^[104]. Organic or cooperative models might also aid distribution. Linking farmers to processors and markets (e.g. for value-added products) will raise returns^[39].
- **Research and Innovation:** Continued R&D will create superior biofortified varieties. Genomic tools and CRISPR gene editing can speed breeding. Scientists can “stack” multiple micronutrients into a single variety (for example, a carrot high in both β -carotene and iron)^[126]. Exploring nanotechnology (nano-fertilizers), beneficial microbes and gene editing can further enhance efficacy^[105]. On the consumer side, food product innovation (e.g. juices or snacks from biofortified crops) can expand appeal^[82]. Investment in portable nutrient-assay kits would help certification and quality control.
- **Awareness and Education:** Educating farmers, nutritionists and the public is crucial. Mass-media, extension programs and cooking demonstrations can show that biofortified vegetables are as tasty and beneficial as traditional ones^[106]. Inclusion of nutrition curricula in agriculture and health training can build long-term support. Real-life success stories (like Madhuban Gajar) should be publicized via the media and government channels (as was done by NIF and PIB) to generate interest^[83].
- **Climate-Resilient Biofortification:** Climate change poses challenges to nutrition (e.g. higher CO₂ can reduce grain protein). Future programs should select biofortified cultivars that also resist heat, drought and new pests. Many micronutrients (Zn, Fe) can interact with stress tolerance. Thus, aligning biofortification with climate-smart horticulture can yield varieties that are both nutritious and hardy, further aiding adoption^[23, 40, 141].

With these prospects, India could mainstream micronutrient-rich fruits and vegetables into agriculture and diets^[107]. The success of staple-biofortification (wheat, rice, millet) provides a template. Extending these efforts to horticulture will require multisectoral collaboration - agriculture, health, education and industry working together^[10, 41].

Policy Frameworks and Recommendations

Effective biofortification requires enabling policies. Several global and Indian frameworks support this:

- **International Frameworks:** The UN's Sustainable Development Goal 2 (Zero Hunger) and WHO are nutrition

recommendations emphasize micronutrient security. The WHO/FAO eLENA guidelines explicitly define and promote biofortification. HarvestPlus (IFPRI-CGIAR) is a global partnership spearheading biofortified crop development^[61, 84]. It operates through alliances (CIMMYT, IRRI, ICRISAT, etc.) to breed and disseminate enriched varieties worldwide^[127]. HarvestPlus has worked in India since 2004, aiding the release of dozens of varieties and building evidence^[108]. Their reports highlight India as a model: by 2019, 10 iron-fortified pearl millet and 9 zinc-wheat varieties had been released under joint ICAR-CGIAR programs. The Prime Minister of India has publicly endorsed biofortification as cost-effective, aligning national policy with global advocacy^[24].

- **National Agriculture Research Policy:** The Indian Council of Agricultural Research (ICAR) and state institutions coordinate breeding programs (AICRPs) that now include biofortification as a mandate. ICAR's 2017 brochure “*Biofortified Varieties: A Sustainable Way to Alleviate Malnutrition*” prioritizes nutrient traits in crops^[128]. ICAR funds projects on micronutrient malnutrition and coordinates field trials^[85]. The Department of Biotechnology (DBT) supports biotech projects (e.g. the NABI banana CRISPR program) and provides biosafety oversight. The Department of Science & Technology funds fundamental research on plant nutrition. These ministries have begun to recognize biofortification in their schemes^[42].
- **Nutrition and Health Policies:** The National Nutrition Mission (Ministry of Women & Child Development) and POSHAN 2.0 scheme advocate diet diversity and nutrient-rich foods^[130]. Poshan Abhiyaan's support for kitchen gardens and *Fortified Ready-to-Eat* meals (millet-based) shows integration of agricultural biofortification into nutrition planning^[109, 129]. The Food Safety and Standards Authority of India (FSSAI) have rules for food fortification (e.g. adding vitamins to flours) and could extend labelling and standards to biofortified produce. The National Health Policy (2017) calls for food-based strategies to reduce deficiencies, implicitly supporting biofortified crops^[86].
- **State and Local Initiatives:** Some Indian states have taken the lead. Bihar's Agriculture Department committed to scaling up zinc-wheat seeds for farmers; Chhattisgarh and Odisha have distributed orange sweet potato varieties to tribal areas. Success at the state level often involves partnerships with NGOs and international agencies (e.g., HarvestPlus partnering with DRDA in Bihar)^[62].
- **Recommendations:** To advance horticultural biofortification, policy actions could include:

1. **Inclusion in Food Programs:** Mandate offering of biofortified fruits/vegetables in midday meals, ICDS supplementary nutrition and public procurement schemes^[25].
2. **Seed Subsidies and MSP:** Provide subsidized seed inputs and guarantee premium prices for biofortified crops^[63].
3. **Regulatory Streamlining:** Simplify approval for biofortified varieties (especially non-transgenic ones), and clear labelling guidelines to inform consumers^[43].
4. **Awareness Campaigns:** Government promotion (TV, radio, extension) about the health benefits of nutrient-rich crops, as suggested by experts^[26].
5. **Monitoring and Targets:** Set national targets for biofortified acreage and consumption, tracked by agencies

like NITI Aayog [87, 131].

6. **Research Support:** Increase funding for breeding and agronomic research on horticultural micronutrients, including public-private collaborations [109].

International bodies like FAO and WHO can assist by issuing guidelines on horticultural biofortification and supporting integration into the Zero Hunger agenda [27, 64]. HarvestPlus, UN agencies and NGOs can continue providing technical assistance and evidence. As of now, India's policy environment is generally favourable (see appended table of initiatives), but implementation and resource allocation must be strengthened [11, 44].

Conclusion

India's battle against hidden hunger must go beyond staple grains to embrace fruits, vegetables and other high-value foods. Biofortification of horticultural crops offers a sustainable, cost-effective way to enrich diets with essential vitamins and minerals. Scientific advances in breeding, genetics and agronomy have produced demonstrable successes (biofortified carrots, sweet potatoes, etc.), showing that even traditional agriculture can be nutrition-smart. Furthermore, nutrient-rich crops tend to be more resilient, bringing the dual benefit of better human health and stronger plants (for instance, zinc-biofortified seeds resist soil diseases). However, realizing this potential in India requires overcoming socio-economic and regulatory hurdles: farmers need to be convinced of the value and viability of new varieties, consumers need awareness and acceptance, and policies must actively promote biofortified crops in food systems. The government's nutrition programs and research institutions provide a strong platform, as do international partnerships (HarvestPlus, CGIAR, WHO/FAO). By integrating biofortified horticultural crops into national agendas - via kitchen gardens, public meals, incentives and education - India can make significant strides against malnutrition. In conclusion, biofortified horticulture can be a game-changer for India's nutrition security. The evidence shows it is scientifically feasible and beneficial; the policy frameworks are emerging. What remains is the will to scale up these innovations. With concerted effort from researchers (ICAR, DBT, ICMR, CSIR, etc.), farmers and policymakers, India can harvest a future where children and families enjoy healthier, fortified fruits and vegetables - a key step toward eliminating hidden hunger and boosting both public health and agricultural productivity.

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