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Enhancing Nutritional Value Through Biofortification in Vegetable Crop: Strategies, Benefits and Challenges

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ABSTRACT
Biofortification enhances crop nutrient levels through agronomic practices, selective breeding, and genetic engineering, addressing malnutrition in resource-limited areas by providing nutrient-dense foods. Agronomic methods use fertilizers and microbes, while breeding improves yield and nutritional value. Genetic engineering introduces traits that boost nutrient bioavailability and crop quality. Notable biofortified crops include Pusa Betakesari-1 (cauliflower), Kufri Neelkanth (potato), and Pusa Meghali (carrot). Genetic advances like ferritin-enriched lettuce and anthocyanin-rich tomatoes further enhance food nutrition. Despite challenges such as consumer awareness and anti-nutritional factors, biofortification offers a sustainable way to improve public health and farmer livelihoods.

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INTRODUCTION
Biofortification—derived from the Greek word "*bios*"(meaning life) and the Latin "*fortificare*"(meaning to strengthen)—refers to the process of enhancing the levels of bioavailable micronutrients in crops. This can be achieved through agronomic methods, selective breeding, or genetic engineering, providing a cost-effective and sustainable way to improve the nutritional quality of food. Primarily intended for populations with limited access to fortified foods, biofortification increases nutrient intake and boosts crop resilience in nutrient-deficient soils (Borg et al., 2009). While biofortified foods generally contain lower nutrient levels than supplements, they help improve daily micronutrient intake. This approach is particularly valuable in low-income regions, aiding in the reduction of micronutrient deficiencies and supporting overall health (Waters and Sankaran, 2011).
Importance

- To improves the plant or crop quality.
- To increase the nutritional quality in daily diets.
- To overcome malnutrition in human beings.
- To promote food security.
- Application of biofortified crops would benefit farmers by increasing their income in the long term.

Methods of Biofortification:

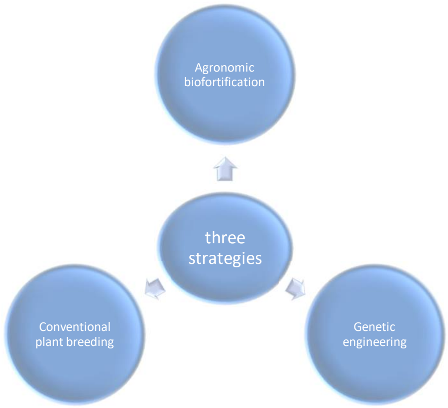

Fig1: Methods of Biofortification

Agronomic Biofortification

Fertilizers are often applied to enhance the micronutrient levels in the edible portions of crops. Key micronutrients suitable for agronomic biofortification include zinc (using foliar sprays of $ZnSO_4$), iodine (through soil applications of iodide or iodate), and selenium (as selenate). Foliar application is an efficient and straightforward technique for increasing plant concentrations of micronutrients such as iron (Fe), zinc (Zn), and copper (Cu). Research also shows that mycorrhizal associations boost Fe, Se, Zn, and Cu levels in plants, with arbuscular mycorrhizal (AM) fungi enhancing the uptake and utilization of essential micronutrients like Zn, Cu, and Fe. Additionally, sulfur-oxidizing bacteria can raise the sulfur content in crops such as onions.

Table 1: Nutritional trait improvements through agronomical biofortification

Crop	**Targeted micro nutrient**
Radish	Se
Carrot	I, Fe and Se
Broccoli	Zn, P, S, K, Fe, K, Cu, Mn
Cucumber	K and Ascorbic acid
Lettuce	Fe, P, K, I, Zn, Se
Tomato	Se
Potato	I

Biofortification of crops with Iron

Tomato plants are capable of tolerating elevated iodine levels, storing it within their tissues and fruits at concentrations that satisfy human dietary requirements, making them well-suited for iodine-biofortification efforts. In plants treated with 5 mM of iodide, the iodine content in the fruit exceeded the recommended daily intake of 150 µg. Furthermore, the application of *Spirulina platensis* as a microbial inoculant has demonstrated an ability to raise iron levels in *Amaranthus gangeticus*, thus enhancing its biofortification potential.

Biofortification of crops with Zinc

The concentration of zinc in tubers and its application as a foliar treatment follows a saturation curve, reaching a maximum of approximately 30 mg Zn per kg of dry matter (DM) with an application rate of 1.08 g Zn per plant. An application of 2.16 g Zn per plant resulted in a 40-fold increase in shoot zinc concentration compared to untreated controls. In the cultivation of sweet pepper, eggplant, and tomato, using the fertilizer "Riverm" enhanced zinc content by 6.60-8.59% compared to controls.

Conventional plant breeding

Over the past forty years, plant breeding has primarily focused on increasing yield and disease resistance, often neglecting nutritional quality, which has resulted in nutrient declines in some crop varieties. Recently, conventional breeding has shifted towards enhancing vitamins, antioxidants, and essential micronutrients in edible parts of plants. By selectively choosing breeding materials, these techniques have successfully raised levels of β-carotene, carotenoids, amino acids, amylase, carbohydrates, and minerals, thus improving the nutritional quality of crops (Gregorio et al., 2000). This strategy promotes ecologically and economically sustainable crop development with added nutraceutical benefits. Techniques such as selection, introduction, and hybridization have played a crucial role in enhancing the nutraceutical value of vegetables and tuber crops, allowing for the identification and transfer of resistant traits

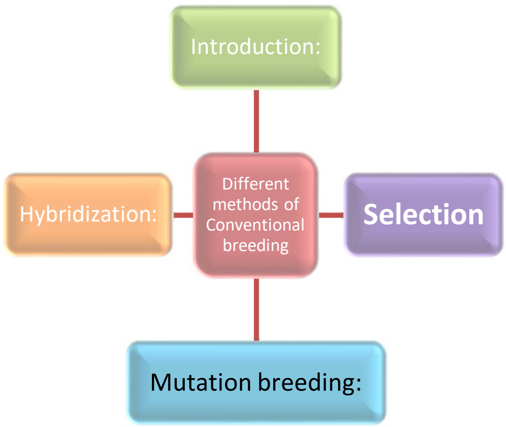

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Fig 2: Different methods of Conventional plant breeding

Cauliflower: The variety *Pusa Betakesari-1* was introduced in 2015–16 by the Indian Agricultural Research Institute (IARI), New Delhi, as the first biofortified cauliflower developed in India through marker-assisted backcrossing. This variety contains high levels of beta carotene (8–10 µg per gram) and is ready for harvest in December–January, classifying it within the mid-late maturity group of Indian cauliflower. Created to address beta carotene deficiency and related malnutrition issues in India (Parulekar et al., 2019), *Pusa Betakesari-1* has orange, compact curds that are visually appealing, with a semi self-blanching growth habit.
Potato: *Kufri Neelkanth* is a potato variety recognized for its attractive purple, ovoid tubers with shallow eyes and yellow flesh, featuring a medium dry matter content of 18%. It offers excellent flavor, good storability, and higher antioxidant levels than other indigenous red-skinned varieties. As a main-season table potato, it has medium maturity, high tuber yield, and field resistance to late blight, making it well-suited for cultivation in the North Indian plains. This variety was developed at CPRI, Shimla, through clonal selection from the cross of MS/89–1095 and CP3290 (Luthra et al., 2020).
Carrot: Pusa Meghali: This variety, developed at IARI, New Delhi, through selection by crossing *Pusa Kesar* and *Nantes*, has an exceptionally high beta carotene content of 11,571 IU per 100 grams. It belongs to the tropical group and features orange-colored flesh. With an average root yield of 25–30 tons per hectare, it is suitable for early sowing and reaches maturity within 100–120 days.
Brinjal: *Pusa Safed Baingan-1* is a nutritionally enhanced brinjal variety released by IARI in 2018. It has a total phenol content of 31.21 mg per 100 grams and antioxidant activity of 3.48 mg per 100 grams. Notably, it is the first white oval-fruited brinjal suitable for kharif season cultivation in the northern plains. This variety was developed through single plant selection from indigenous material gathered from farmers in West Garo Hills, Meghalaya, by the Division of Vegetable Science at ICAR-IARI, Pusa, New Delhi (Kumar et al., 2021).
Amaranthus: *Pusa Kiran* is a variety known for its high iron content, developed through the natural crossing of *Amaranthus tricolor* and *Amaranthus tristis*. It features glossy green leaves and stems, with an average yield of 55 tons per hectare.

Genetic engineering

Genetic engineering uses a broad gene pool to introduce desirable traits from one organism to another, creating elite cultivars and enhancing crop value. When sufficient trait variation is lacking within a species or conventional breeding is unsuitable, genetic engineering provides an effective alternative to increase micronutrient concentration and bioavailability in edible tissues (Prasad et al., 2015). Recent advancements enable trait incorporation unattainable through traditional breeding. Transgenic crops, with enhanced nutritional quality, also resist insects, viruses, and pathogens. Genetic modifications in vegetables improve flavor, nutrition, ripening, sweetness, and reduce anti-nutritional factors (Tripathy et al., 2020).

Crop	Gene	Content
Tomato	pGAntho	Anthocyanin
Potato	AmA1	Protein
Lettuce	Ferritin	Iron
Cauliflower	Or gene	Beta-Carotene
Sweet potato	IBOR-INS	Lutein and Carotene
Carrot	CAX1	Calcium

FUTURE CHALLENGES

- Consumer preference.

- Awareness generation.
- Research intervention.
- Decrease the level of anti-nutritional compounds.
- Enhancing the mineral uptake efficiency of the important crops.
- Promoting large-scale prospective studies on assessing the effects of nutrient enhancement in major staple crops to reduce malnutrition-related disorders in the future.
- Availability of choice of nutrient rich foods and vegetables in the market.

CONCLUSION

Hunger and malnutrition are major issues which need attention on priority. Biofortification provides a feasible means of reaching malnourished populations in relatively rural areas, delivering naturally fortified foods to people with limited access to commercially-marketed fortified foods, which are more readily available in urban areas. Development, production and consumption of biofortified vegetables need to be popularized for preventing various health issues. Thus, the suitable remedy to eliminate undernutrition as a public health problem is to provide higher consumption of a wide range of non-staple foods in developing countries

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