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Biofortified fruits for a nutritionally secure future

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Abstract

As the world marks World Food Day 2025, themed *"Hand in Hand for Better Foods and a Better Future,"* the spotlight turns toward nourishing communities through innovation and sustainability. In India, where fruits account for nearly a third of horticultural output, biofortification offers a promising route to combat *hidden hunger*. It bridges the gap between agriculture and nutritional security by enriching fruits with vital nutrients like vitamin A, iron, zinc, and antioxidants. Across the world, researchers are combining agronomic innovations, smart breeding methods, beneficial microbes, and modern genomic tools like CRISPR to create fruit varieties that are richer in nutrients, hardier in the field, and more appealing in the market. Fruits like *Solapur Lal* pomegranate, golden banana and Ataulfo mango showcase fruit-based nutritional innovation. Biofortified fruits embody the spirit of this year's World Food Day — working *hand in hand* across science, farming, and nutrition to create better foods for a healthier, more sustainable future.

Introduction

Fruits are essential components of human diets due to their high content of vitamins, minerals, antioxidants, and dietary fibre, nutrients often lacking in staple cereals. Regular consumption of fruits contributes to the prevention of micronutrient deficiencies, supports immune function, and reduces the risk of chronic diseases. India is a global horticultural powerhouse, with horticulture production reaching 355.48 million tonnes in 2022–23, cultivated over 13.1% of the gross cropped area (MoA&FW, 2024). Fruits and vegetables together account for nearly 90% of India's total horticulture output, and the sector contributes approximately 33% to agriculture's Gross Value Added (GVA). Among fruits, India ranks first in the world in banana, mango, and papaya production, producing over 107 million tonnes of fruits annually, including 44% of global mango output. These numbers underscore both the scale and the nutritional potential of India's orchards.

Despite this abundance, per capita fruit consumption in India remains low — around 15 grams per day in rural areas and 29 grams in urban areas, far below the levels recommended for optimal health. This gap contributes to *hidden hunger*, a form of malnutrition caused by insufficient intake of essential micronutrients, which affects nearly two billion people globally and contributes to almost half of all deaths among children under five in low- and middle-income countries. Addressing hidden hunger requires not only increasing food availability but also enhancing the nutrient profile of the fruits.

Biofortification

Biofortification is a plant-breeding strategy aimed at increasing the nutrient content of edible portions of crops through natural or scientific methods, thereby improving their nutritional quality. This approach not only addresses micronutrient deficiencies but also enhances the resilience of fruits to environmental stressors such as drought, pests, and diseases, while improving their nutraceutical value to meet the growing global demand for functional foods (Garg et al., 2018).

In India, ongoing research focuses on developing fruit crops such as mango, guava, and banana with enhanced concentrations of vital micronutrients, including vitamin A, iron, zinc, and antioxidants. For example, biofortified mango varieties rich in beta-carotene are being bred to help address widespread vitamin A deficiency prevalent in several parts of the country. By integrating biofortification into fruit cultivation, India can not only enhance the nutritional quality of its widely consumed fruits but also contribute to global efforts in combating malnutrition and promoting health

Approaches towards biofortification

Agronomic approach

Agronomic biofortification involves enhancing the nutrient content of commercially grown fruit varieties through cultivation practices such as fertigation, foliar sprays, or conventional fertilizer application, without exceeding safe limits for other nutrients. This approach has been successfully applied to several fruits. For instance, pomegranate has been enriched with higher levels of iron, zinc, and vitamin C using targeted agronomic methods, grapes have been improved to increase polyphenols, anthocyanins, resveratrol, and vitamins C and K, while watermelon has been biofortified for elevated lycopene, protein, and essential amino acids. By optimizing nutrient management in the field, agronomic biofortification offers a practical, cost-effective way to improve the nutritional quality of fruits.

Conventional breeding approach

Conventional breeding improves the nutrient content of fruits by selecting and crossing plants with naturally higher levels of vitamins, minerals, and bioactive compounds.

Methods include mass and pure line selection, pedigree crosses, and induced mutations to enhance traits like antioxidants, polyphenols, and anthocyanins. Backcross breeding transfers desirable genes into commercial varieties without affecting yield, though use of wild relatives is limited due to gene interactions and linkage drag. Successful examples include India's Solapur lal pomegranate, mango varieties like Amrapali, Pusa Arunima, Pusa Surya, and the antioxidant-rich Pusa Navrang grape. Globally, vitamin A-rich bananas like Apantu, Bira, Pelipita, Lai, and To'o in Uganda and the beta-carotene-rich Ataulfo mango from Mexico demonstrate the effectiveness of conventional breeding in enhancing fruit nutrition (Amah et al., 2019).

Microbe-mediated approach

Microbe-mediated biofortification enhances the nutritional quality of fruits by leveraging beneficial microorganisms such as Plant Growth-Promoting Rhizobacteria (PGPR), Arbuscular Mycorrhizal Fungi (AMF), and other plant growth-promoting microbes (PGPM). These microbes improve crop nutrition through mechanisms like nitrogen fixation, phosphate solubilization, zinc mobilization, siderophore production, and bioaccumulation of micronutrients, vitamins, and fatty acids. For example, inoculation of *Pseudomonas fluorescens* in blackberry plants increased flavonoid content, while strains such as *Phyllobacterium endophyticum*, *Paenibacillus polymyxa*, and *Bacillus simplex* enhanced vitamin C levels and fruit yields in strawberries.Microbial biofortification offers a sustainable, eco-friendly approach by naturally boosting both nutrient content and crop productivity to improve the nutritional value of fruits.

Biotechnological approach

Biotechnological approaches offer precise and innovative strategies to enhance the nutritional quality of fruit crops. Marker-assisted breeding (MAB) uses molecular markers to identify and select traits that improve nutrient content, and it works synergistically with genetic engineering and genome editing. Tools like CRISPR/Cas9 enable targeted modifications to enhance traits such as vitamin and mineral content, anthocyanin accumulation, shelf life, and oleic acid levels. RNA interference (RNAi), Site-Directed Nucleases (SDNs), cisgenesis, intragenesis, and Oligonucleotide-Directed Mutagenesis (ODM) allow the introduction or modification of beneficial genes within the same or closely related species, improving nutrient uptake, disease resistance, and health-promoting compounds without introducing foreign DNA. For example, genes involved in beta-carotene synthesis or iron accumulation can be precisely edited to produce biofortified mangoes, guavas, and bananas with enhanced nutritional profiles. Overall, these biotechnological tools provide a fast, accurate, and sustainable way to develop nutrient-rich fruit varieties, complementing conventional and agronomic biofortification strategies in combating micronutrient deficiencies.

Biofortified fruits: case studies

Several fruit varieties have been successfully biofortified to enhance their nutritional and health-promoting properties. In India, The Pomegranate 'Solapur Lal', developed by ICAR-NRC on Pomegranate, contains significantly higher levels of iron (5.6–6.1 mg/100 g), zinc (0.64–0.69 mg/100 g), and vitamin C (19.4–19.8 mg/100 g) compared to conventional varieties (Raigond et al., 2025). Red bananas such as "Red Dacca" and "Red Cavendish" are richer in vitamin C, potassium, dietary fiber, and anthocyanins, providing antioxidant and anti-inflammatory benefits. The Paluma guava cultivar from Brazil, with crimson pulp and high soluble solids, offers improved antioxidant and nutritional properties. In papaya, the isolation of the *lcy-β2* gene, correlated with fruit color and carotenoid content, enables marker-assisted breeding and metabolic engineering to enhance both color and nutritional value.

Conclusions

Biofortified fruits represent the next frontier in combining nutrition, technology, and horticulture. India's diverse orchards — from mangoes and guavas to bananas and pomegranates — are being transformed into natural powerhouses of vitamins, minerals, and antioxidants. Through agronomic practices, conventional breeding, microbial interventions, and cutting-edge biotechnological tools like CRISPR, marker-assisted breeding, and metabolic engineering, scientists can precisely enhance nutrient content while improving resilience, shelf life, and consumer appeal. Looking ahead, integrating these innovations with smart farming, genomic insights, and consumer-driven design can make nutrient-rich fruits widely accessible, turning everyday diets into a tool for public health. India has the expertise, biodiversity, and scientific momentum to lead a fruit-based nutritional revolution, where each bite delivers not just flavor, but measurable health impact for generations to come.

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