***Review Article***

**“Bio-fortification- Strategy for Improved Nutritional Value in Fruit Crops”**

**Abstract**

Bio-fortification, or biological fortification, enhances the nutritional value and bioavailability of food crops through traditional breeding, modern biotechnology, and agronomic practices. With hunger and malnutrition posing significant socio-economic and health challenges, achieving the UN Sustainable Development Goal 2 (UN-SDG2) by 2030 remains a critical global objective. In fruit crops such as mango, banana, guava, citrus, papaya, apple, pear, and strawberry, bio-fortification efforts focus on increasing essential nutrients like beta-carotene, vitamin C, iron, and zinc. These biofortified fruits offer a cost-effective solution to improve nutrition, particularly for vulnerable populations, helping to mitigate the risks of hidden hunger and malnutrition.

While genetic modifications accelerate nutritional improvements, challenges such as regulatory approvals and public acceptance persist. Although food supplements and dietary diversification provide short-term relief, bio-fortification represents a sustainable, long-term strategy to combat malnutrition. Recent advancements in research have demonstrated the potential of bio-fortified crops to address micronutrient deficiencies effectively. Policy initiatives and global expansion efforts are further supporting the adoption of bio-fortification, emphasizing its role in improving food security and nutritional outcomes worldwide.

This review highlights the progress in bio-fortification research, the importance of policy frameworks, and the growing global momentum behind this approach. By integrating bio-fortification into agricultural systems, it is possible to create a resilient and nutritious food supply, contributing significantly to the fight against malnutrition and the achievement of global food security goals.

***Keywords***: Bio fortification, Fruit crops, Nutrients, Hidden hunger, Malnutrition.

**Introduction**

Global issues such as hunger, poor nutrition, and population growth present serious obstacles to the development of many nations. One of the major public health concerns associated with these challenges is the lack of essential vitamins and minerals, with Vitamin A Deficiency (VAD) being the most prevalent (Anonymous 2019). VAD is responsible for over 600,000 fatalities annually in developing countries, particularly affecting children under the age of five (WHO, 2021; Stevens *et al.,* 2015). Malnutrition remains a significant issue in India, where Uttar Pradesh has the highest stunting rate at 46.36%, followed closely by Lakshadweep at 46.31%. Other states with high stunting rates include Maharashtra (44.59%) and Madhya Pradesh (41.61%) (Women and Child Development Ministry, 2024). According to recent reports, approximately 17% of children aged 0-5 years are underweight, 36% are stunted and 6% are wasted leading to various health problems and physical impairments that exacerbate public health concerns (Global Nutrition Report, 2023; Black *et al.,* 2013).

To address this issue, bio fortification has emerged as a promising strategy. It involves the development and cultivation of nutritionally enriched food crops with increased bioavailability, achieved through conventional plant breeding, modern biotechnology techniques, and agronomic methods (Bouis & Saltzman, 2017). Currently, three primary approaches—plant breeding, transgenic techniques and agronomic bio fortification are being employed for enhancing the nutritional value of food crops (Garg*et al.,* 2018). These methods have been successfully applied to biofortify fruits, vegetables, legumes, oilseeds and cereals (Harvest Plus, 2020). Among these the transgenic approach stands out as a rapid, efficient and sustainable solution for bio fortification offering a viable means to combat micronutrient deficiencies and improve global nutrition (Qaim *et al.,* 2020).

**Methods of Biofortification**

**1. Agronomic Biofortification**

Agronomic bio fortification refers to the practice of adding mineral fertilizers to soil or crops to increase the concentration and bioavailability of specific nutrients in plants. Since vitamins are naturally synthesized in crops agronomic bio fortification primarily focuses on enhancing mineral content rather than vitamins (Çatmak & Kutman, 2018). Traditionally, mineral fertilizers have been used by farmers to improve plant health. However, this approach has certain limitations that must be considered. One major drawback is the high cost of fertilizers and their potential environmental impact due to excessive application (Dhotra *et al*., 2021).

To enhance nutrient absorption and improve fruit quality the use of advanced growing media creates optimal conditions for plant growth and development (Sharma et al., 2022). Another effective cultural intervention is the foliar application of plant growth regulators which significantly influence plants physiological and biochemical processes (Maanik & Sharma, 2022). While agronomic bio fortification provides rapid results in the short term it is highly dependent on farmers' consistent application of fertilizers. Since fertilizer use is a routine agricultural activity farmers may neglect it if they do not perceive financial benefits from the process (Umar *et al.,* 2019). Additionally, the high cost of mineral fertilizers increases the price of bio fortified crops, making them less accessible to economically disadvantaged populations. Therefore, while agronomic bio fortification is an effective approach for improving nutrient availability its economic and environmental challenges must be addressed to ensure widespread adoption.

**2. Breeding Method**

The process of breeding plants involves producing innovative or genetically unique crop types with higher micronutrient contents. The goal of bio fortification through plant breeding is to use genetic variations across closely related species to enhance the mineral content and bioavailability of crops.

Conventional breeding: The genetic variability of the target crop or wild varieties that can cross with the crop currently limits conventional breeding in bio fortification. In order to overcome these restrictions genetic engineering methods such as marker-assisted breeding or molecular breeding have become effective tools in contemporary biotechnology for transmitting desired traits (Dolkar *et al*. 2014). Another method that is widely used in bio fortification in both developed and developing nations is mutation breeding. It entails the use of chemical or physical mutagens to cause mutations in crops, increasing their genetic variability. This method has worked well for creating grain types that have better quality, increased yields and other desired characteristics. Unlike conventional breeding, genetic variations in crops are generated by inducing mutations through chemical treatments or physical techniques like irradiation. (Sheoran *et.al*., 2022).

Biofortification via molecular breeding involves locating the gene responsible for enhancing nutritional quality and identifying markers closely linked to that gene. Using these markers, the desired traits can be introduced into crops through conventional breeding methods. (Jha AB, 2020; Sheoran *et. al*., 2022). Molecular breeding allows for the identification of whether a desirable trait is present or absent in a crop during its developmental stages. As a result, it is a faster approach compared to other plant breeding methods. (Singh *et al*., 2016; Sheoran *et.al*., 2022).

**3. Genetic Engineering**

Unlike plant breeding, genetic engineering is not restricted to crops belonging to the same species. It has been demonstrated as an effective approach to enhancing crops that traditional plant breeding cannot improve including apples and bananas (Gómez-Galera *et al.,* 2010). Genetic engineering enables the introduction of new nutritional or agronomic traits into specific crop types by applying principles from plant breeding and biotechnology (Naqvi *et al.,* 2009). This approach allows scientists to identify and characterize genes that can be inserted into crops to enhance their nutritional value when bio fortification is used (Mayer *et al.,* 2008).

Genetic engineering incorporates genes from various organisms including fungi and bacteria to enhance crop traits (InabaandNishio). Increasing knowledge of these genetic pathways facilitates the development of strategies to improve the nutritional composition of fruits. Additionally, fruit ripening and growth regulation at the molecular level play a crucial role in biofortification efforts aimed at improving food quality (Osorio *et al.,* 2013). Genes involved in the production of growth hormones such as auxins, cytokinins and gibberellins significantly influence fruit size and quality making them essential targets for genetic enhancement (Tejpal *et al.,* 2018; Seyfferth *et al.,* 2020).

Genome editing, or gene editing, is a technology that enables the precise correction, insertion, or deletion of DNA sequences in a wide variety of cells and organisms. (Khalil *et.al*.,2020). Gene editing offers the potential to create genetically modified organisms (GMOs) without incorporating transgenes, thereby addressing regulatory concerns linked to transgenic crops. (Mir *et.al*., 2020; Kumar *et.al*., 2020). Techniques like Mega-nucleases, Zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR/Cas9) have been utilized in genome editing to develop β-carotene-enriched biofortified crop varieties. (Jaganathan *et al*., 2018). Despite being highly adaptable, cost-efficient, and accurate, CRISPR/Cas9 can occasionally result in unintended mutations when off-target regions of the genome are affected during the editing process. (Kumar *et al*., 2020). The transgenic approach has been shown to be sustainable and rapid when introducing desired traits into crops. (Singh *et al*., 2016)

|  |  |
| --- | --- |
| **Micronutrients** | **Macronutrients** |
| Micro-minerals | Vitamins | Amino acids (essential) | Fatty acids (essential) | Macro-minerals |
| Fe | A (Retinol) | Histidine | Linoleic acid | K |
| Zn | D (Calciferol) | Isoleucine | Linolenic acid | Ca |
| Cu | E (α-Tocopherol) | Leucine |  | Mg |
| Mn | K (Phylloquinone) | Lysine |  | S |
| I | C (Ascorbic acid) | Methionine |  | P |
| Se | B1 (Thiamin) | Phenylalanine |  | Na |
| Mo | B2 (Riboflavin) | Threonine |  | Cl |
| Co | B3 (Niacin) | Tryptophan |  |  |
| Ni | B5 (Pantothenic acid) | Valine |  |  |
|  | B6 (Pyridoxine) |  |  |  |
|  | B7 (Biotin) |  |  |  |

**Table 1: Essential micro- and macronutrients required for good human health.**

**Table 2. Recommended Dietary Allowances (RDAs) (day/mg) for Minerals / Vitamins according to different fruits**

|  |  |  |  |
| --- | --- | --- | --- |
| **Sr. No** | **Minerals****/Vitamins** | **Sources** | **Recommended Dietary Allowance (RDA) (day/mg)** |
| **Age group (Years)** | **1–8** | **9–13** | **14–18** | **19–50** | **51–80** |
| M | F | M | F | M | F | M | F | M | F |
| **1** | **Calcium** | Litchi, Kiwi, Orange, Papaya, Persimmon | 700 – 1000 | 1300 | 1300 | 1000 | 1000- 1200 |
| **2** | **Phosphorus** | Raisins, Passion Fruit, Avocado, Raspberries, Nectarine, Strawberries, Apricot, Kiwi, Peach | 460 – 500 | 1250 | 1250 | 700-800 | 700-800 |
| **3** | **Potassium** | Bananas, Papaya, Dates | 2000 - 2300 | 2300-2500 | 3000 | 2300 | 3400 | 2600 | 3400 | 2600 |
| **4** | **Sodium** | Apples, Guavas, Avocado, Papaya, Mango, Carambola, Pineapple, Banana, Melons, Pears | 500-600 |  |  |  | 2000 - 2300 | 2000 – 2300 |
| **5** | **Magnesium** | Bananas, Cherries, Peaches, Apricots, And Blackberries | 80 - 130 | 240 | 410 | 360 | 420 | 320 | 420 | 320 |
| **6** | **Iron** | Fig, Avocado, Strawberry, Dates, Prunes Dried Apricots, And Dried Peaches | 7 – 10 | 8 | 11 – 15 | 8 – 18 |
| **7** | **Zinc** | Pomegranate, Wild Blueberries, Avocado, Pomegranate, Guava, Kiwi | 3 – 5 | 8 | 9 - 11 | 8 – 11 |
| **8** | **Chromium****(mcg)** | Grapes, Apple, Oranges, Banana | 11 – 15 | 21- 25 | 24 - 35 | 35 | 25 | 30 | 20 |
| **9** | **Copper****(mcg)** | Pears, Mangoes and Dried Apricots | 340 - 440 | 700 | 890 | 900 |
| **10** | **Selenium** | Fresh Banana | 20 - 30 mcg | 40 mcg | 55 mcg | 55 mcg |
| **11** | **Iodine** | Strawberries, Pineapple | 90 mcg | 120 mcg | 150 mcg | 150 mcg |
| **12** | **Manganese** | Walnut, Bananas, Mango, Pineapple, Passion Fruit, Guava, Jackfruit | 1.2 - 1.5 | 1.6-1.9 | 1.6- 2.2 | 1.8-2.3 |
| **13** | **Vitamin A** | Mangos, Papaya, Nectarine, Grapefruit, Mandarin Orange | 300 – 400 mcgRAE | 600 mcgRAE | 700-900 mcgRAE | 600-900 mcgRAE |
| **14** | **Vitamin C** | Barbados Cherry, Aonla, Guava, Banana, Strawberry, Papaya, Mango | 15 -25 | 40-45 | 65-75 | 75 – 90 |
| **15** | **Vitamin B2** | Banana, Almond | 0.5 - 0.6 | 0.9 | 1.0-1.3 | 1.1-1.3 |
| **16** | **Protein (g)** | Cashewnut, Avocado Jackfruit, Kiwi, Apricot, | 13 - 19 | 34 | 46 - 52 | 46 – 56 |

**Table 3. Nutritional composition, mineral content, beta-carotene levels, and energy (Kcal) of selected fruits**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sr. no.** | **Fruit** | **Nutritional Value per 100 g** | **Minerals** | **Beta carotene****(μg)** | **Energy****(Kcal)** |
| **CH****(g)** | **Protein****(g)** | **Fats****(g)** | **Fiber****(g)** | **Vit C (mg)** | **Vit A****(IU)** | **Vit E (mg)** | **Vit K****(μg)** | **Riboflavin****(mg)** | **Thiamine****(mg)** | **K****(mg)** | **P (mg)** | **Ca****(mg)** | **Mg****(mg)** | **Na****(mg)** | **Cu****(mg)** | **Fe****(mg)** | **Zn****(mg)** | **Mn****(mg)** | **Se****(μg)** |  |  |
| **1** | **Mango** | 14.9 | 0.82 | 0.38 | 1.6 | 36.4 | 1080 | 0.9 | 4.2 | 0.038 | 0.028 | 168 | 14 | 11 | 10 | 1 | 0.11 | 0.16 | 0.09 | 0.06 | 0.6 | 640 | 60 |
| **2** | **Banana** | 22.8 | 1.09 | 0.33 | 2.6 | 8.7 | 64 | 0.1 | 0.5 | 0.073 | 0.031 | 358 | 22 | 5 | 27 | 1 | 0.07 | 0.26 | 0.15 | 0.27 | 1 | 26 | 89 |
| **3** | **Sapota** | 19.9 | 0.44 | 1.1 | 5.3 | 14.7 | 60 | - | - | 0.020 | - | 193 | 12 | 21 | 12 | 12 | 0.08 | 0.80 | 0.10 | - | 0.6 | - | 83 |
| **4** | **Papaya** | 10.8 | 0.47 | 0.26 | 1.7 | - | 950 | 0.3 | 2.6 | 0.027 | 0.023 | 182 | 10 | 20 | 21 | 8 | 0.04 | 0.25 | 0.08 | 0.04 | 0.6 | 274 | 43 |
| **5** | **Grape** | 18.1 | 0.72 | 0.16 | 0.9 | - | 66 | - | 14.6 | 0.07 | 0.069 | 191 | 20 | 10 | 7 | 2 | 0.12 | 0.36 | 0.07 | 0.07 | 0.1 | 39 | 69 |
| **6** | **Guava** | 14.3 | 2.55 | 0.95 | 5.4 | 228 | 624 | 0.73 | 2.6 | 0.04 | 0.067 | 417 | 40 | 18 | 220 | 2 | 0.23 | 0.26 | 0.23 | 0.15 | 0.6 | 374 | 68 |
| **7** | **Sweet orange** | 1.8 | 0.94 | 0.12 | 2.4 | - | 225 | 0.18 | - | 0.04 | 0.087 | 181 | 14 | 40 | 10 | - | 0.04 | 0.1 | 0.07 | 0.02 | 0.5 | 71 | 47 |
| **8** | **Mandarin**  | 13.3 | 0.81 | 0.31 | 1.8 | 26.7 | 681 | 0.2 | - | 0.036 | 0.058 | 166 | 20 | 37 | 12 | 2 | 0.04 | 0.15 | 0.07 | 0.03 | 0.1 | 155 | 53 |
| **9** | **Acid lime** | 10.5 | 0.7 | 0.2 | 2.8 | 29.1 | 50 | 0.22 | 0.6 | 0.02 | 0.03 | 102 | 18 | 33 | 6 | 2 | 0.06 | 0.6 | 0.11 | 0.00 | 0.4 | 30 | 30 |
| **10** | **C. Apple** | 25.2 | 1.7 | 0.6 | 2.4 | 19.2 | 33 | - | - | 0.1 | 0.08 | 382 | 21 | 30 | 18 | 4 | - | 0.71 | - | - | - | - | 101 |
| **11** | **Pomegranate** | 18.7 | 1.67 | 1.17 | 4 | 10.2 | - | 0.6 | 16.4 | 0.053 | 0.067 | 236 | 36 | 10 | 12 | 3 | 0.15 | 0.3 | 0.35 | 0.119 | 0.5 | - | 83 |
| **12** | **Pineapple** | 13.1 | 0.54 | 0.12 | 1.4 | -- | 58 | - | 0.7 | 0.032 | 0.079 | 109 | 8 | 13 | 12 | 1 | 0.11 | 0.29 | 0.12 | 0.92 | 0.1 | 35 | 50 |
| **13** | **Ber** | 20.2 | 1.2 | 0.2 | - | 69 | 40 | - | - | 0.04 | 0.02 | 250 | 23 | 21 | 10 | 3 | 0.07 | 0.48 | 0.05 | 0.08 | - | - | 79 |
| **14** | **Aonla** | 10.2 | 0.88 | 0.58 | 4.3 | 27.7 | 290 | 0.37 | - | 0.03 | 0.04 | 198 | 27 | 25 | 10 | 1 | 0.07 | 0.31 | 0.12 | 0.14 | 0.6 | - | 44 |
| **15** | **Jamun** | 15.6 | 0.72 | 0.23 | - | 14.3 | 3 | - | - | 0.012 | 0.006 | 79 | 17 | 19 | 15 | 14 | - | 0.19 | - | - | - | - | 60 |
| **16** | **Date palm** | 75 | 1.81 | 0.15 | 6.7 | - | 149 | - | 2.7 | 0.06 | 0.05 | 696 | 62 | 64 | 54 | 1 | 0.36 | 0.9 | 0.44 | 0.29 | - | 89 | 277 |
| **17** | **Carambola** | 6.73 | 1.04 | 0.33 | 2.8 | 34.4 | 61 | 0.15 | - | 0.016 | 0.014 | 133 | 12 | 3 | 10 | 2 | 0.13 | 0.08 | 0.12 | 0.03 | 0.6 | - | 31 |
| **18** | **Phalasa** | 21.1 | 1.57 | 0.1 | 5.53 | 4.38 | 300 | - | - | 0.264 | 0.02 | 372 | 24.2 | 136 | - | 17.3 | - | 1.08 | - | - | - | - | - |
| **19** | **Fig** | 19.2 | 0.75 | 0.3 | 2.9 | 2 | 142 | 0.11 | 4.7 | 0.05 | 0.06 | 232 | 14 | 35 | 17 | 1 | 0.07 | 0.37 | 0.15 | 0.12 | 0.2 | 85 | 74 |
| **20** | **Bael** | 32 | 1.8 | 0.3 | 2.9 | 8.7 | - | - | - | 1.19 | - | - | - | - | - | - | - | - | - | - | - | - | 20 |
| **21** | **Jackfruit** | 23.2 | 1.72 | 0.64 | 1.5 | 13.7 | 110 | 0.34 | - | 0.055 | 0.105 | 448 | 21 | 24 | 29 | 2 | 0.07 | 0.23 | 0.13 | 0.04 | - | 61 | 95 |
| **22** | **Avacado** | 8.53 | 2 | 14.7 | 6.7 | 10 | 146 | 2.07 | - | 0.13 | 0.067 | 485 | 52 | 12 | 29 | 7 | 7 | 0.55 | 0.64 | 0.14 | 0.4 | 62 | 160 |
| **23** | **Litchi** | 16.5 | 0.83 | 0.44 | 1.3 | 71.5 | - | 0.07 | 0.4 | 0.065 | 0.011 | 171 | 31 | 5 | 10 | 1 | 0.14 | 0.31 | 0.07 | 0.055 | 0.6 | - | 66 |
| **24** | **Dragon fruit** | 15.2 | 0.36 | 0.14 | 3.1 | 4.3 | - | 0.12 | 4.4 | 0.026 | 0.012 | 116 | 12 | 9 | 7 | 1 | 0.08 | 0.18 | 0.1 | - | 0.1 | 14 | 57 |
| **25** | **Cashewnut** | 30.2 | 18.2 | 43.8 | 3.3 | 0.5 | - | 0.9 | 34.1 | 0.058 | 0.423 | 660 | 593 | 37 | 292 | 12 | 2.2 | 6.68 | 5.78 | 1.66 | 19.9 | - | 553 |
| **26** | **Apple** | 13.8 | 0.26 | 0.17 | 2.4 | 4.6 | 54 | 0.18 | - | 0.026 | 0.017 | 107 | 11 | 6 | 5 | 1 | 0.027 | 0.12 | 0.04 | 0.03 | - | 27 | 52 |
| **27** | **Pear** | 15.2 | 0.36 | 0.14 | 3.1 | 4.3 | 25 | 0.12 | 4.4 | 0.026 | 0.012 | 116 | 12 | 9 | 7 | 1 | 0.08 | 0.18 | 0.1 | 0.04 | 0.1 | 14 | 57 |
| **28** | **Peach** | 9.54 | 0.91 | 0.25 | 1.5 | 6.6 | 326 | 0.73 | 2.6 | 0.031 | 0.024 | 190 | 20 | 6 | 9 | - | 0.06 | 0.25 | 0.17 | 0.06 | 0.1 | 162 | 165 |
| **29** | **Plum** | 11.4 | 0.7 | 0.28 | 1.4 | 9.5 | 345 | 0.26 | 6.4 | 0.026 | 0.028 | 157 | 16 | 6 | 7 | - | 0.05 | 0.17 | 0.1 | 0.05 | - | 190 | 46 |
| **30** | **Cherry** | 16 | 1.06 | 0.2 | 2.1 | 7 | 64 | 0.07 | 2.1 | 0.033 | 0.027 | 222 | 21 | 13 | 11 | - | 0.06 | 0.36 | 0.07 | 0.07 | - | 38 | 63 |
| **31** | **Strawberry** | 7.68 | 0.67 | 0.3 | 2 | 58.8 | 12 | 0.29 | 2.2 | 0.022 | 0.024 | 153 | 24 | 16 | 13 | 1 | 0.04 | 0.41 | 0.14 | 0.38 | 0.4 | 7 | 32 |
| **32** | **Loquat** | 12.1 | 0.43 | 0.2 | 1.7 | 1 | 1530 | - | - | 0.024 | 0.019 | 266 | 27 | 16 | 13 | 1 | 0.04 | 0.05 | 0.28 | 0.14 | 0.6 | - | 47 |
| **33** | **Apricot** | 11.1 | 1.4 | 0.39 | 2 | 10 | 1930 | 0.89 | 3.3 | 0.04 | 0.03 | 259 | 23 | 13 | 10 | 1 | 0.07 | 0.39 | 0.2 | 0.07 | 0.1 |  1090 | 48 |
| **34** | **Kiwi** | 14.7 | 1.14 | 0.52 | 3 | 92.7 | 87 | 1.5 | 40.3 | 0.025 | 0.027 | 312 | 24 | 34 | 17 | 3 | 0.1 | 0.31 | 0.14 | 0.1 | 0.2 | 52 | 61-63 |
| **35** | **Almond** | 21.6 | 21.2 | 49.9 | 12.5 | - | 2 | 25.6 | - | 1.14 | 0.205 | 733 | 481 | 269 | 270 | 1 | 1.03 | 3.71 | 3.12 | 2.18 | 4.1 | 1 | 579 |
| **36** | **Walnut** | 13.7 | 15.2 | 65.2 | 6.7 | 1.3 | 20 | 0.7 | 2.7 | 0.15 | 0.341 | 441 | 346 | 98 | 158 | 2 | 1.59 | 2.91 | 3.09 | 3.41 | 4.9 | 12 | 654 |
| **37** | **Quince** | 15.3 | 0.4 | 0.1 | 1.9 | 15 | 40 | - | - | 0.03 | 0.02 | 197 | 17 | 11 | 8 | 4 | 0.13 | 0.7 | 0.04 | - | 0.6 | - | 57 |

**Bio fortification in fruit crops**

**Mango (*Mangifera indica*):**

Biofortification in mango crops aims to enhance their nutritional value by increasing the concentrations of essential micronutrients and phytochemicals. Although research on mango biofortification is limited, both conventional breeding techniques and biotechnological approaches have been explored to improve the fruit's nutritional profile. In 2017, Saranya *et al*., conducted a study focusing on genetically modifying mangoes to elevate their pro-vitamin A carotenoid content, particularly beta-carotene, a precursor to vitamin A. The researchers successfully developed transgenic mango plants with higher beta-carotene levels by introducing a carotenoid biosynthetic gene from another plant species into mango embryogenic callus cells. Similarly, Padmesh *et al*., (2013) investigated the potential of traditional breeding methods to enhance the nutrient content of mango cultivars. Their study analyzed variations in mineral composition, including calcium, zinc, and iron, across different mango genotypes. The findings revealed significant differences in nutrient content, suggesting the possibility of selecting and breeding mango varieties with higher mineral concentrations. In addition to conventional breeding, biotechnological approaches such as genetic engineering have been explored to improve the nutritional composition of mangoes. For instance, Dhotra *et al*. (2021) studied the impact of foliar micronutrient sprays on the growth, yield, and quality of Dashehari mango fruits. Another study on the 'Kesar' mango variety demonstrated that foliar applications of zinc sulfate (ZnSO₄) and iron sulfate (FeSO₄) significantly increased micronutrient levels in both the pulp and peel. The highest nutrient concentrations were achieved with a combined application of 0.50% FeSO₄ and 0.50% ZnSO₄ (Mahida *et al*., 2023). While genetic engineering in mangoes shows promise, it remains an area of ongoing research and development. For example, efforts are being made to enhance beta-carotene levels in mangoes through genetic modifications (Sharma *et al*., 2023). These advancements highlight the potential of both traditional and modern techniques to improve the nutritional value of mangoes.

**Banana (*Musa spp*.):**

The development of biofortified banana cultivars has been achieved through conventional breeding techniques, focusing on selecting and crossbreeding varieties with enhanced nutritional profiles. A notable achievement in this area is the creation of biofortified Golden Bananas, enriched with pro-vitamin A carotenoids such as beta-carotene to combat vitamin A deficiency (Davey *et al.,* 2009; Arango *et al.,* 2010).

Genetic modification has further enhanced pro-Vitamin A Carotenoid (pVAC) levels in bananas. For instance, the introduction of a phytoene synthase gene from a Fe’i banana variety led to a substantial increase in beta-carotene content, with some lines reaching up to 55 µg/g dry weight (Paul *et al.,* 2017). Additionally, efforts have been made to reduce acrylamide, a potential carcinogen formed during cooking, improving the safety of bio fortified bananas.

Beyond nutritional enhancement, red bananas are recognized for their high dietary fiber, potassium, and antioxidant properties, including phenolic compounds (Joshi *et al.,* 2017). Another significant advancement in banana biotechnology is the use of RNA interference (RNAi) for viral resistance. RNA i-mediated suppression of viral components successfully eliminated symptoms of bunchy top virus disease six months after transgenic plants were developed (Shekhawat *et al.,* 2012). These advancements highlight the potential of both conventional breeding and genetic engineering in improving the nutritional quality, safety and disease resistance of bananas contributing to food security and public health.

**Guava (*Psidium guajava*):**

The primary objective of guava biofortification is to enhance the fruit’s levels of essential micronutrients and bioactive compounds, thereby improving its nutritional profile. Using conventional breeding techniques, researchers have developed guava varieties with superior nutritional composition. Selective breeding efforts have primarily focused on increasing the concentrations of key micronutrients such as vitamin C, beta-carotene, and essential minerals like iron and zinc (Navarro-Tarazaga *et al*., 2016). One notable guava cultivar, Paluma, originates from Brazil and is highly valued for its remarkable agronomic performance, delightful taste, high soluble solids content and vibrant red pulp. Biofortified guava varieties not only offer improved nutritional benefits but also exhibit enhanced antioxidant capacity.

In addition to genetic approaches, various cultural practices have been employed to further enrich guava’s nutritional content. Optimizing agricultural techniques including appropriate fertilization and irrigation strategies has been shown to enhance nutrient absorption and accumulation in guava plants (Sathya *et al*., 2019). Furthermore, research indicates that fermenting guava juice with specific pro biotic strains can significantly increase its vitamin B₁₂ content while also boosting its antioxidant properties and ensuring pro biotic viability. This value-added fermented guava juice presents a promising functional food product that could help address vitamin B₁₂ deficiency (Rastogi *et al*., 2024).

**Citrus (*Citrus spp*.):**

Traditional breeding techniques have been employed to enhance the nutritional value of citrus fruits by selecting and crossbreeding cultivars with naturally higher nutrient levels. Breeding programs have specifically targeted increasing the vitamin C content in citrus fruits (Salonia *et al.,*2020). Additionally, biofortification efforts aim to elevate essential micronutrients such as folate and pro-vitamin A carotenoids including beta-carotene. Genetic engineering has also been utilized to enhance the accumulation of pro-vitamin A carotenoids in citrus fruits improving their nutritional value (Pons *et al.,*2018). Beyond nutritional enhancement, various agronomic interventions have been explored to improve fruit quality. The application of calcium chloride and potassium sulfate (10%) has been shown to enhance the quality of Eureka lemons (Devi *et al.,* 2018). Furthermore, integrated nutrient management (INM) practices such as applying 100% nitrogen as urea in combination with Azotobacter, have been reported to maximize fruit nitrogen content (0.06%) in Kinnow mandarins (Bakshi *et al.,* 2017).

Biofortification strategies have also been investigated for micronutrient enhancement in citrus. A study comparing foliar and soil biofortification of zinc in Citrus reticulata (mandarin orange) demonstrated that both methods effectively increased zinc concentration in the fruit. However, the study emphasized the need to assess existing soil zinc levels before application as excessive zinc can have adverse effects (Bhantana *et al.,* 2022). These efforts collectively contribute to improving the nutritional quality of citrus fruits making them valuable in addressing dietary deficiencies particularly in regions where vitamin A and other micronutrient deficiencies are prevalent.

**Papaya (*Carica papaya*):**

One approach to bio fortifying papaya involves the use of genetic engineering to enhance the levels of pro-vitamin A carotenoids, such as beta-carotene. This has been achieved by introducing specific genes responsible for carotenoid biosynthesis, as reported by Shankar *et al.* (2010). In regions where papaya is a dietary staple, the development of biofortified varieties with elevated vitamin A content can play a crucial role in addressing vitamin A deficiency (Shankar *et al.*, 2010). Additionally, increasing the concentrations of essential minerals like zinc and iron is a significant aspect of papaya bio fortification. Genetic engineering techniques have been employed to boost the mineral content of papaya fruits, thereby improving their nutritional value (Maxwell *et al*., 2013). These efforts aim to enhance the dietary benefits of papaya, particularly in populations prone to micronutrient deficiencies.

**Graps (Vitis vinifera):**

Biofortified grape varieties have been developed using conventional breeding techniques to enhance the concentration of beneficial compounds such as polyphenols and anthocyanins. These compounds contribute to the antioxidant properties and overall health benefits of grapes (Di Lorenzo *et al*., 2019). Studies have shown that foliar application of zinc-based fertilizers, including zinc oxide (ZnO) and zinc sulfate (ZnSO₄), effectively increases zinc concentrations in grape tissues without negatively impacting their physicochemical properties (Daccak *et al*., 2022). Similarly, the foliar application of organic selenium fertilizers has been identified as a successful approach to enriching grape berries-particularly their skin-with selenium, without significantly affecting vine growth or fruit quality (Zhao *et al*., 2021).

Additionally, genetic engineering allows for precise regulation of metabolic pathways responsible for the production of desirable compounds, thereby enhancing the nutritional quality of grapes. Agricultural practices also play a crucial role in influencing grape composition. Factors such as irrigation strategies, canopy management techniques, and fertilization schedules can significantly impact the accumulation of phenolic compounds in grape berries (Cortell & Kennedy, 2006).

**Pomegranate (*Punica granatum*):**

The hybrid pomegranate variety *Solapur Lal* is recognized for its high nutritional value, containing significant amounts 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). This variety was introduced in 2017 for cultivation in semi-arid regions of the country. On average, fruit yields range between 23.0 and 27.0 t/ha. The ICAR-National Research Centre on Pomegranate, based in Pune, Maharashtra, was responsible for developing this bio fortified variety (Anonymous, 2017).Davarpanah *et al*. (2020) found that applying 2.6 mM FeSO₄ as a foliar fertilizer during the early season significantly improved pomegranate fruit yield and quality. The treatment resulted in a 20–31% increase in yield, enhanced the number of fruits per tree, and improved juice content, total soluble solids, and sugar levels. FeSO₄ also reduced juice acidity and increased the maturity index, although it slightly decreased antioxidant activity and phenolic compounds in the juice. This study demonstrates that FeSO₄ is an effective approach for enhancing pomegranate yield and fruit quality in high pH soils.

A study published in *Nature* examined the impact of postharvest zinc treatments on pomegranate fruit quality and nutrient content. The findings indicated that postharvest application of zinc not only increased the zinc concentration within the fruit but also enhanced its overall quality during storage. Notably, the treatment inhibited microbial growth, which helped preserve key sensory attributes such as sweetness, aroma, and sourness, ultimately extending the fruit’s shelf life (Aminzade *et al*., 2024).

**Aonla (*Phyllanthus emblica*)**

It is well known for its high vitamin C content and various health benefits. Traditional breeding methods, including cross-breeding and selection, can be employed to further enhance its nutritional profile (Singh *et al*., 2019). Additionally, genetic engineering offers the possibility of introducing specific genes to improve the fruit’s nutrient composition. However, the adoption of genetically modified crops faces potential challenges related to public acceptance and regulatory constraints (Chaurasia *et al*., 2009). Research has shown that using black polythene as a mulching material can enhance the quality characteristics of Aonla cv. NA-7, resulting in superior fruit quality (Iqbal *et al*., 2015). Furthermore, foliar application of micronutrients such as boron, zinc, and iron has been found to significantly enhance fruit retention, yield, and overall quality. The use of these micronutrients has been linked to reduced fruit drop and improved fruit attributes (Abhijith *et al*., 2018).

Moreover, the incorporation of bio fertilizers has demonstrated positive effects on seed germination rates and seedling vigor in aonla, leading to healthier plant growth. This improved development ultimately contributes to better nutrient content in the fruits (Reddy *et al*., 2021).

**Apple (*Malus domestica*)**

Researchers have discovered apple varieties that contain higher concentrations of antioxidants, including phenolic compounds, flavonoids, and anthocyanins. These compounds are linked to health benefits because of their antioxidant and anti-inflammatory properties. (Strand *et al*., 2018). Proper nutrient management, such as balanced fertilization, can enhance the nutritional quality of apples by positively affecting their nutrient composition. (Tagliavini *et al*., 2019). Genetic engineering is being investigated to improve apples through the introduction of specific genes. For instance, adding a stilbene synthase gene from grapevines can boost resveratrol levels, a powerful antioxidant, in apples. (Tian *et al*., 2017). This genetic modification seeks to enhance the antioxidant potential of apples. Researchers have also engineered apple plants to generate increased amounts of anthocyanins and flavan-3-ols, which are beneficial compounds that add to the apple's nutritional value. (Flachowsky *et al*., 2010). Additionally, Arctic® apples have been genetically modified to resist browning by suppressing polyphenol oxidases (PPOs), the enzymes that cause browning. Arctic varieties, such as Fuji, Granny Smith, and Golden Delicious, have been introduced in different types over the years. (Lobato-Gomez *et al*., 2021)

**Pear (*Pyrus communis*)**

Biofortification in pears focuses on enhancing their nutritional value and addressing nutrient deficiencies. While research on pears is not as advanced as in other crops, several strategies are being investigated. One approach is conventional breeding, where pear varieties are selectively crossed to elevate their content of vitamins, minerals, and antioxidants. Another approach is genetic modification, which involves introducing or enhancing specific genes to increase nutrient levels. For instance, researchers have explored enhancing genes associated with antioxidants, such as anthocyanins, to improve the antioxidant capacity of pears. (Han *et al*., 2016). Agronomic biofortification in the *Pyrus communis* L. variety Rocha has been effectively achieved through the foliar application of 0.6 kg Ca(NO₃)₂ ha⁻¹ or 1.6 kg CaCl₂ ha⁻¹, which enhances calcium biofortification in leaves without causing any symptoms of phytotoxicity. (Cardoso et al., 2018). Successful efforts for zinc fortification were carried out by (Liu *et al*., 2023) using both chelated and non-chelated zinc. It was noted that chelated ZnEDTA can be safely applied at a higher concentration of 1.5%, compared to 0.1%–0.4% for non-chelated zinc sources. Pear is a widely cultivated fruit crop globally, but its breeding process is time-intensive.

To support molecular breeding and gene identification, (Zhang *et al*., 2021) conducted genome-wide association studies (GWAS) on eleven fruit-related traits. They identified 37 loci linked to eight fruit quality traits and five loci associated with three fruit phenological traits. Over time, new beneficial mutations have reduced variation in neutral sites, suggesting that traits such as fruit stone cell content, organic acid levels, and sugar content may have undergone continuous selection during breeding improvements. One candidate gene, PbrSTONE, identified through GWAS, has been functionally validated to play a role in regulating stone cell formation, a key fruit quality trait in pears.

**Strawberry (*Fragaria × ananassa*)**

Efforts to enhance strawberries aim to increase their nutritional value and health benefits (Singh *et al*., 2022). Genetic engineering has been utilized to elevate vitamin C levels and improve the plants' resistance to diseases and environmental stresses (Borowski *et al*., 2016). For example, researchers modified strawberries to contain up to 47% less starch and 37% more soluble sugar by inhibiting a specific enzyme responsible for converting sugar into starch. (Park *et al*., 2006). Additionally, using a 900 ppm cycocel spray on strawberries has been found to improve their quality by boosting sweetness, vitamin C levels, juice yield, and reducing acidity (Kumar *et al*., 2012).

**Conclusion**

Malnutrition and hidden hunger are pervasive issues that affect both developed and developing countries and have catastrophic effects on the entire world. The pandemic's recent consequences emphasize how rapidly our food systems need to alter in order to address shortages in our food supply. The resolution of socio-political and economic challenges is crucial for the effective promotion, cultivation, and consumption of bio fortification. To effectively address hidden hunger through bio fortification, an integrated strategy including lawmakers, farmers, food developers, genetic engineers, dietitians, and educators is needed. Strategies for bio fortification should be adapted to address regional nutritional concerns while accounting for cultural differences in consumer acceptance. In order to sum up, bio fortification presents a variety of possible approaches to enhance global nutritional health, advancing our goal of reducing hunger and malnutrition. Continued research and development are essential to refine these strategies and ensure their widespread application, ultimately improving global fruit nutrition and health outcomes.

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