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REVIEW ARTICLE

Ways to address human nutritional deficiencies by increasing nutrient content in vegetable crops: a review

Hammadullah Al Mashuk[1] and Abu Hadi Md. Asadur Rahman[2*]

[1] Scientific Officer, Bangladesh Rice Research Institute (BRRI), Gazipur 1706
[2] Deputy Controller & PS to VC, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706

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ABSTRACT

A comprehensive review study has been conducted to address malnutrition problems prevailing over two billion global populations due to poor intake of daily diet especially vegetables. As a rich and easy source of essential nutrients like vitamins, minerals and other necessary phytochemicals, vegetables are considered as a sustainable dietary solution to this global problem, particularly for the vulnerable populations of developing countries. This study focuses on the deferent aspects of vegetables nutri-fortification conventional to molecular breeding, agronomic intervention to modern biotechnology and genetic engineering as well. The results of the research of different scientists revealed the efficacy of different conventional and molecular breeding to enrich concentration of iron, zinc, vitamin A *etc.*, in different vegetable species and cultivar. Conventional agronomic practices like foliar application or inoculation of micronutrients have been found to be effective for improving nutrient content in leafy vegetables. Modern biotechnological interventions, including genetic engineering and genome editing, enable targeted manipulation of nutrient pathways, although they face challenges in regulatory and public acceptance. Application of plant growth promoting rhizobacteria, mycorrhizal fungi or other beneficial microorganisms have also shown promising results to enhance nutrient uptake in vegetables as well as improving soil-plant interactions. Beyond the successes, several limitations also found such as limited bioavailability, complex nature of genetic-environmental interactions, socio-economic obstacles as well as technological scalabilities are pronounced to speed up these programs. The study revealed the necessities of integrated, interdisciplinary approaches that combine crop science, soil health management as well as policy framework to promote speedy adoption of biofortified vegetables addressing this malnutrition.

*Corresponding Author: Deputy Controller & PS to VC, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh. Email: asad@bsmrau.edu.bd

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1. Introduction

Micronutrient malnutrition popularly known as `hidden hunger' is of major concern of global health. Millions of people worldwide suffer from inadequate uptake of essential micronutrients like vitamins, iron, zinc, iodine *etc*. These nutritional deficiencies lead to a variety of serious health issues, such as stunted growth, weakened immune systems, impaired mental development and increased susceptibility to disease and mortality (WHO, 2021). Addressing micronutrient deficiencies is therefore crucial to ensuring global food and nutrition security, especially in regions with limited access to diverse and nutritious diets.

Vegetables are the main source of many essential nutrients for the human body. Therefore, increasing the nutritional value of edible vegetables is considered as a sustainable and food-based approach to address the hidden hunger prevailing worldwide. Due to the high content of micronutrients, dietary fiber and phytochemicals in vegetable crops, they are essential for a balanced diet and play an important role in addressing nutritional deficiencies. However, despite being nutritious, many widely consumed vegetable varieties still fail to provide adequate levels of some important nutrients required for optimal health. Improving the nutritional quality of vegetables through biofortification, and conventional breeding or genetic modification offers a cost-effective and long-term solution to increase micronutrient intake (Bouis & Saltzman, 2017). Unlike food fortification in supplements or processed foods, which rely on continuous external inputs and distribution networks, biofortified vegetables can ensure improved nutrient supply through regular dietary intake, which particularly benefits populations with limited access to a diverse food system.

Scientists have continuously strived to enhance nutritional quality of vegetable crops. They developed several technologies including genetic improvement through conventional as well as molecular breeding, advanced technologies like transgenic/GMO development, gene editing to enrich desirable micronutrients, agronomic practices like soil and/or foliar applications of nutrient-rich fertilizers etc are of prime importance (Garg *et al*., 2018; Marschner, 2012; White & Broadley, 2009).

Despite these momentous innovations, there are a few challenges remaining against the efforts of improving nutritional vegetable crops. The major constraints are limited bioavailability of certain nutrients in vegetable-based diets, the potential negative correlation between yield and nutrient density and socio-political barriers like consumer acceptance and regulatory approval of genetically modified crops those are particularly evident in developing countries (Saltzman *et al*., 2013). Beyond these constraints, it is hoped that integrating these scientific advances with public health strategies and appropriately applying them to address micronutrient deficiencies will open up a promising path to enhancing long-term human health and well-being.

The growing global concern about micronutrient malnutrition is encouraging extensive research into developing technologies to improve the nutritional quality of food crops - particularly in the case of vegetables, given their central role in the daily diet and their potential to provide essential micronutrients. Therefore, this review article is designed to explore the scientific basis and practical implications of innovative technologies to enhance the nutritional value of vegetable crops. It highlights the important roles of conventional as well as molecular genetics, agronomic practices, and soil-plant interactions in improving the nutritional value of vegetables. Moreover, it explores how these integrated technologies/packages can support global efforts to reduce malnutrition in a sustainable, scalable, and food-based manner.

2. Micronutrient Malnutrition and Its Global Impact

Micronutrient malnutrition, or hidden hunger, is a major obstacle to global public health and it remains a major challenge for the developing counties as well. This public health problem is mainly caused by inadequate intake of micronutrients. Unlike energy deficiency, its symptoms are not visible, but micronutrient deficiencies often go unnoticed and significantly impair health, development and productivity, especially in vulnerable populations (WHO, 2021).

The global prevalence of inadequate micronutrient intakes for 15 essential micronutrients in specific demographic groups and countries were estimated by Passarelli *et al.*, (2024). Their findings revealed that over 5 billion people i.e. about 68% of the global population -have insufficient intakes of iodine, vitamin E (67%), and calcium (66%). Additionally, more than 4 billion people fall short in consuming adequate levels of iron (65%), riboflavin (55%), folate (54%), and vitamin C (53%) (Fig. 1). These deficiencies are linked to a range of health consequences, such as impaired cognitive development, weakened immune function, maternal complications, and increased risk of morbidity and mortality, especially among children and women of reproductive age (Black *et al.*, 2013; Stevens *et al.,* 2015). Among the most prevalent micronutrient malnutrition, iron deficiency is a major cause of anemia, which negatively impacts on work performance, educational achievement, and maternal outcomes. However, vitamin A deficiency is a major cause of childhood blindness and immune dysfunction, while zinc deficiency increases the susceptibility of attacking infectious diseases (WHO, 2021). The prevalence of these type of malnutrition manifests underlying problems such as poor dietary diversity, limited access to nutritious foods, and inadequate public health interventions.

In addition to the health implications of micronutrient malnutrition, its economic importance cannot be ignored. According to the World Bank (2006), hidden hunger can reduce a country's gross domestic product (GDP) by up to 5%, due to reduced productivity, increased healthcare costs, and negative intergenerational effects. Considering all these consequences, it highlights the need for sustainable, long-term solutions beyond short-term supplementary or emergency food assistance.

Recognizing the importance of the problem, scientists have explored various solutions. Some common approaches, such as food fortification and micronutrient supplementation, have shown positive effects but often rely on sustained funding, infrastructure, and political commitment. Recently, biofortification has

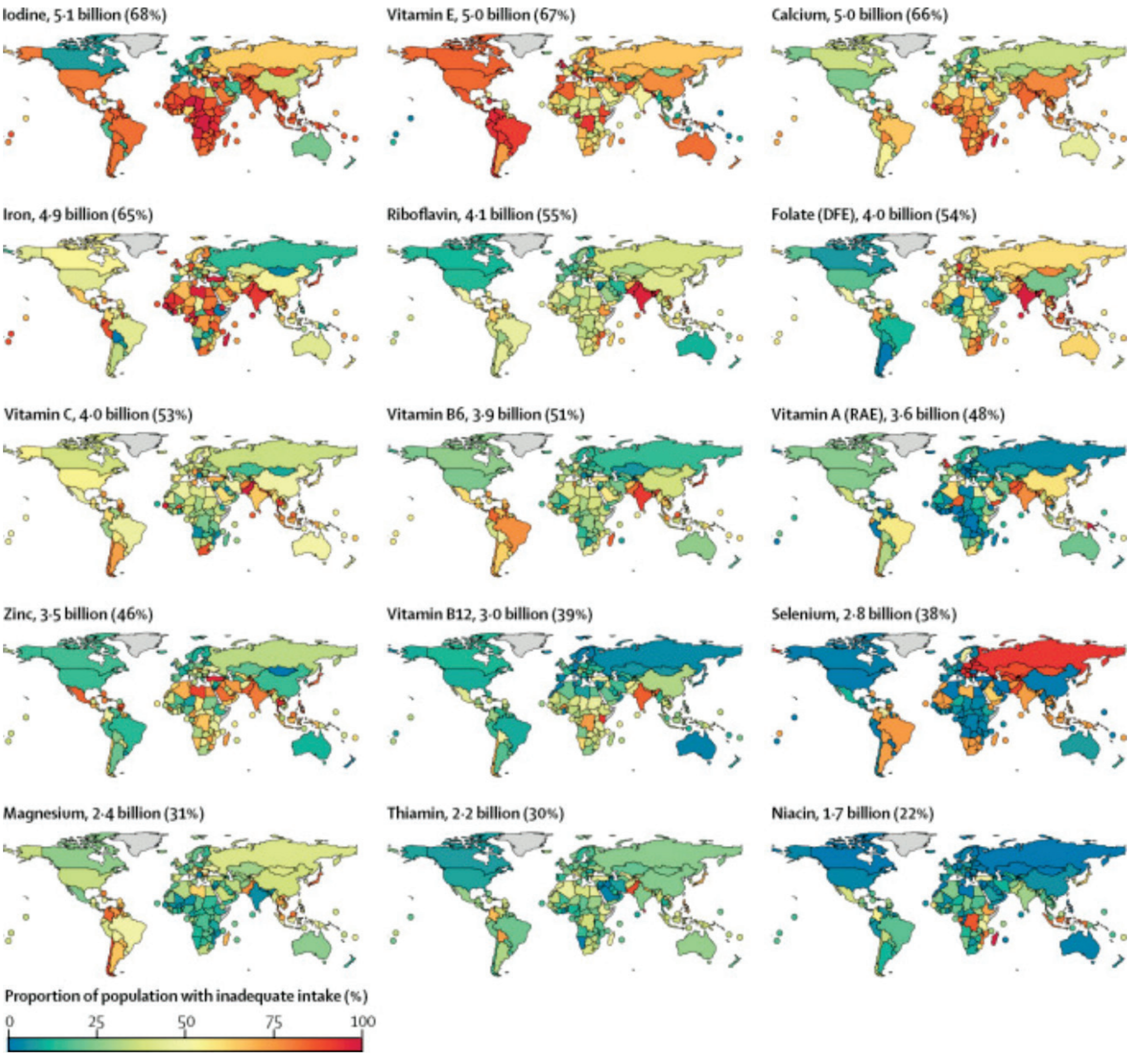

Fig. 1. Prevalence of nutrient deficiencies by country and nutrient in 2018. (Source: Passarelli *et al.*, 2024).

gained much attention, particularly because of its cost-effectiveness and sustainability. It is hoped that this will be of great benefit to rural populations with limited access to commercially fortified foods (Bouis *et al.*, 2011; Saltzman *et al*., 2013).

Despite these advancements, several challenges remain. These include the bioavailability of nutrients from plant-based sources, trade-offs between crop yield and nutrient density, and the sociopolitical complexities of adopting genetically modified crops, especially in developing regions (White & Broadley, 2009). Nevertheless, integrating agricultural innovation with public health and nutrition policies represents a promising pathway toward reducing global micronutrient deficiencies and achieving long-term health and development goals (UN, 2015).

2.1 Role of Vegetables in Human Nutrition

Vegetables are vital components of a healthy diet, providing a rich array of essential vitamins, minerals, dietary fiber, and bioactive phytochemicals. Their nutritional composition plays a key role in supporting immune function, preventing disease, and promoting overall well-being, making them indispensable to balanced diets. As primary dietary sources of micronutrients such as vitamin A, vitamin C, folate, potassium, calcium, iron, and magnesium -many of which are commonly deficient globally -vegetables are critical for addressing nutritional inadequacies (Slavin & Lloyd, 2012). Regular vegetable consumption is consistently associated with a reduced risk of chronic diseases, including cardiovascular disease, certain cancers, type 2 diabetes, and obesity (Boeing *et al*., 2012; Bazzano *et al*., 2002). These protective effects are due not only to their micronutrient content but also to the presence of phytochemicals such as flavonoids, carotenoids, and glucosinolates, which exhibit antioxidant, anti-inflammatory, and anticarcinogenic properties (Liu, 2013). Dietary fiber, abundantly present in vegetables, contributes significantly to digestive health, helps regulate blood glucose and cholesterol levels, and promotes satiety -factors essential for weight management and the prevention of obesity (Slavin, 2005). Additionally, the low energy density of most vegetables allows for better caloric control without sacrificing nutrient intake.

The nutrient profile of vegetables can vary due to genetic, environmental, and postharvest factors, influencing their overall dietary contribution (White & Broadley, 2009). Nonetheless, vegetables remain indispensable in the fight against malnutrition, particularly micronutrient deficiencies, or “hidden hunger,” which affect over two billion people worldwide (FAO, 2020). Increasing the intake of nutrient-dense vegetables -especially leafy greens, orange-fleshed varieties, legumes, and cruciferous crops -can substantially improve iron, zinc, iodine, and vitamin A status, especially in low-income populations with limited access to animal-source foods (WHO, 2021; Smith & Eyzaguirre, 2007).

Beyond nutrition, vegetables are often less resource-intensive to produce than animal-based foods and can be integrated into diverse farming systems. Their cultivation supports agrobiodiversity, improves soil health, and enhances dietary diversity (Frison *et al*., 2006). Despite these benefits, global vegetable consumption remains below recommended levels. Key barriers include limited availability, high post-harvest losses, perishability, cost, cultural preferences, and limited awareness of their health benefits (Herforth *et al*., 2019). Enhancing both the production and consumption of vegetables is essential to achieving global food and nutrition security, particularly in the face of climate change and resource scarcity.

3. Strategies to Increase Nutrient Content in Vegetables

Improving the nutritional quality of vegetables is a vital step toward addressing global micronutrient deficiencies and enhancing public health. As vegetables serve as important sources of essential vitamins, minerals, and bioactive compounds, enriching their nutrient profiles offers a food-based, sustainable approach to combat "hidden hunger" (Table 1).

A range of strategies has been developed to increase nutrient content in vegetables, including dietary modification, micronutrient supplementation, genetic approaches such as conventional breeding and modern biotechnology, agronomic intervention like micronutrient fertilization, and optimizing soil-plant interactions to enhance nutrient uptake and assimilation (Fig. 2). These strategies, when effectively integrated, can enhance the nutritional value of vegetables while supporting sustainable agriculture and food systems.

3.1 Genetic and Conventional Breeding Approaches

Traditional breeding methods have been used to enhance the nutrient profile of vegetables through selection of high-nutrient genotypes. Breeding programs have successfully

Table 1. Important micronutrients sources in vegetables

Nutrients	Vegetables
Vitamin A	Carrot, spinach and pumpkin
Vitamin B1	Tomato, chilli, garlic, leek and pea
Vitamin B5	Palak, amaranthus, bitter and pointed gourd
Vitamin C	Chilli, sweet pepper, cabbage and drumstick
Calcium	Hyacinth bean, amaranthus and palak
Iron	Amaranthus, palak, spinach, lettuce and bittergourd
Phosphorous	Pea, lima bean, taro and drumstick leaves
Iodine	Tomato, sweet pepper, carrot, garlic and okra
Sodium	Celery, green onion, Chinese cabbage and radish

Source: Gomathi *et al.* (2017).

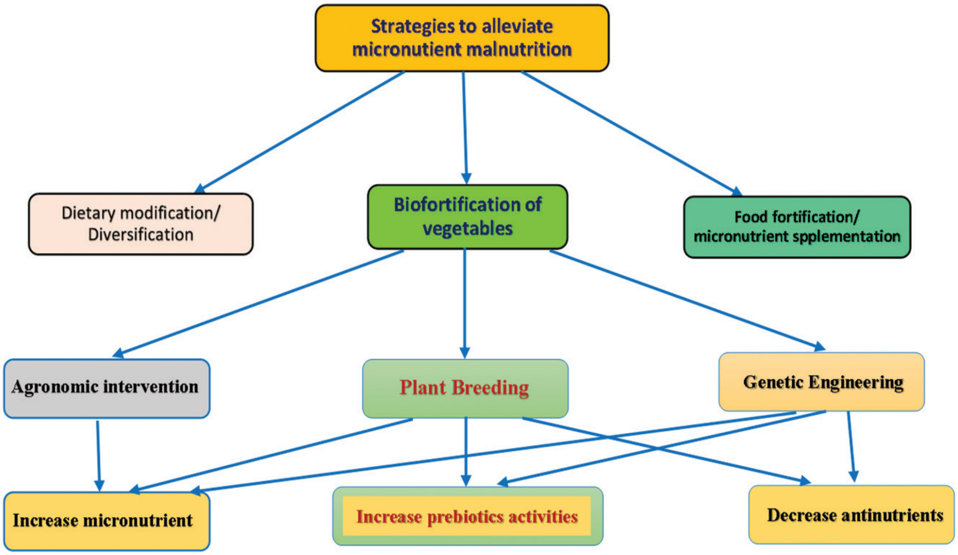

Fig. 2. Strategies to Increase Nutrient Content in Vegetables

increased beta-carotene in carrots and sweet potatoes, and iron content in spinach and amaranth (Nestel *et al.*, 2006). Similarly, increased levels of iron and zinc have been achieved in common vegetables like spinach and beans through recurrent selection and backcrossing with wild relatives (Welch & Graham, 2004). Bouis & Saltzman, (2017) proved that selective breeding of leafy vegetables resulted in increased iron and beta-carotene concentrations. The key advantage of conventional breeding is its wide acceptance among the general consumer and regulatory agencies, as it does not involve controversial technologies such as GMOs. However, its progress is often limited by the availability of genetic variant to obtain the desired trait and the long-term breeding program required to integrate stable traits in such processes (Saltzman *et al.*, 2013).

Recent advances in molecular breeding, like marker-assisted selection (MAS), genome-wide association studies (GWAS), and genetic engineering have rapidly led to the development of bio-fortified vegetables. MAS is effectively used for the selection of quantitative trait loci (QTL) responsible for nutrient related traits (Zhao *et al.*, 2020), whereas, GWAS is generally used to identify novel genetic loci that controls nutrient accumulation in complex genomes like tomato and pepper (Ganzali *et al.*, 2009). However, genetic engineering has enabled the breeders to directly insert nutrient biosynthesis genes which are limited in conventional breeding. For instance, the overexpression of the phytoene synthase gene is used to increase provitamin A content in tomatoes (D'Ambrosio *et al.*, 2004). Recently, CRISPR/Cas9-based genome editing techniques enabled specific and rapid modification of targeted gene for improving micronutrients contents in leafy vegetables and root crops (Chandrasekaran *et al.,* 2016).

However, the combination of conventional breeding with modern biotechnological tools or genetic engineering provides more promising results for the sustainable production of biofortified vegetables. Furthermore, prac-breeding efforts like use of wild relatives as well as landraces to broaden the genetic base of nutritional traits have also been proven successful by scientists (Khush *et al*., 2012). Direct involvement of farmer and ultimate user in such breeding programs ensure more success of innovation, adoption and acceptance of biofortified vegetable production.

3.2 Biofortification through Agronomic Practices

Agronomic biofortification means soil or foliar applications of micronutrients to the vegetable crops to enrich nutrient content like zinc (Zn), iron (Fe), selenium (Se), iodine etc. This method has proven to be successful especially for leafy vegetables which have high nutrient uptake capacity with low bioavailability barriers due to minimum interactions with soil elements (White and Broadley, 2009). Foliar application of zinc and iron enhance nutrient accumulation on leaves of spinach, lettuce and amaranth (Garg *et al*., 2018; Cakmak *et al*. (2010). D'Amato *et al*., 2020) demonstrated successful implementation of biofortification in garlic, onion and broccoli by spraying sodium selenite on leaves or soil which also enhance antioxidant and stress tolerance of those crops.

The efficacy of agronomic biofortification depends on nutrient status and physiochemical properties of soil, crop species and environmental conditions. Adverse soil conditions like highly acidic, alkaline/calcareous as well as saline soil can fixed essential micronutrients. Therefore, appropriate strategies have taken to overcome these problems, like chelated formulations or combined nutrient application etc. (Kumar *et al*., 2022). Cakmak (2008) revealed extensive variations in the ability of vegetable crops to absorb, transfer and accumulate micronutrients are observed among species or cultivars, which affects the results of agronomic interventions. Singh *et al*., (2021) also demonstrated the integration of compost with Zn and Fe fertilizers in okra and tomato cultivation improved micronutrient bioavailability without hampering the yield.

Moreover, it offers a commendable approach for addressing micronutrient deficiencies in vulnerable populations (Alloway, 2009). This method is cost-effective and compatible with existing farming systems. However, the success of this approach is dependent on soil characteristics, plant genotype, and the timing and method of application (Dimkpa & Bindraban, 2016). However, its limitations include the need for repeated applications, potential environmental concerns from overuse of fertilizers, and lower cost-effectiveness in rainfed or resource-poor areas. Furthermore, ensuring uniform distribution and uptake of micronutrients across fields remains a challenge in large-scale operations (Rietra *et al*., 2017).

3.3 Biotechnological Interventions

Modern biotechnological tools, including transgenic approaches and CRISPR-Cas9 genome editing, have opened new avenues for precise and targeted nutrient enhancement in crops. Likely to the development of the vitamin A-rich 'golden rice', efforts have been made in vegetables such as tomatoes and lettuce using genetic engineering tools (Giuliano, 2017). In the recent time, genetic engineering enables breeders to overcoming the limitations of conventional breeding. It enables breeders or scientists to insert targeted genes responsible for the biosynthesis or accumulation of micronutrients, bypassing the limitations of traditional breeding. We can see different transgenic vegetables with high content of vitamin A, iron, folate etc. An outstanding example is the biofortification of tomato (*Solanum lycopersicum*) by overexpression of phytoene synthase (PSY1) and carotene desaturase genes, which significantly increased β-carotene levels (D'Ambrosio *et al*., 2004). We also observed manipulation of the ethylene pathway and transcriptional regulation of carotenoid biosynthesis in tomatoes increased the accumulation of lycopene and other carotenoids (Giovannoni *et al*., 2004, Diaz de la Garza *et al.*, 2007). Iron biofortification has also been achieved in vegetables such as lettuce and potatoes, which induce genes involved in iron uptake and accumulation (Buniavs *et al*., 2017).

Moreover, scientists have also worked to redirect the flow of metabolic intermediates towards micronutrient synthesis in vegetable crops through metabolic engineering. Such as Clotault *et al*., (2008) used this technology in carrots where co-expression of multiple genes involved in the β-carotene pathway led to increased provitamin-A accumulation. In addition, transcription factors such as ORANGE (OR) and MYB families have been used through genetic engineering to increase carotenoid accumulation and anthocyanin production in crops such as cauliflower and tomato, contributing to improved nutritional value and antioxidant properties (Lu *et al*., 2006).

After the discovery of CRISPR/Cas9 genome editing, plant biofortification has been revolutionized, making it possible to make precise and/or, site-specific genetic changes without introducing foreign DNA. In vegetables, CRISPR/Cas9 is now being used to remove negative regulators or to increase the expression of local genes involved in micronutrient pathways. For example, in tomato, CRISPR-mediated editing of the SlMYB12 gene resulted in increased flavonoid biosynthesis (Li *et al*., 2016). Similarly, CRITISO gene editing increased the potential for lycopene accumulation (Yu *et al*., 2021). A major advantage of CRISPR technology is the potential to produce non-transgenic, genome-edited crops that may face fewer regulatory hurdles and enjoy greater consumer acceptance compared to traditional genetically modified organisms (GMOs) (Wang *et al*., 2019). However, continued research on gene discovery, nutrient transport mechanisms, and consumer-preference characteristics will be crucial to realize the full potential of this intervention.

4. Beneficial Microorganisms and Soil-Plant Interaction

Plant growth promoting rhizobacteria (PGPR) and mycorrhizal fungi help in increasing the availability and uptake of nutrients in vegetable crops. For example, the use of PGPR has been widely observed in increasing the availability and uptake of Zn and Fe in important crops such as spinach, carrot and tomato (Rana *et al*., 2012; Sarwar *et al*., 2018). Arbuscular Mycorrhizal Fungi (AMF) mostly establish symbiotic relationships with vegetable roots and enhance the uptake of phosphorus, Zn and Fe by the plant. Baslam *et al*. (2011) showed that mycorrhizal colonization in lettuce field significantly increased the concentration of Fe and Zn in edible tissues. Moreover. It also increased the levels of antioxidant compounds such as ascorbate and phenolics, which contribute to the functional food quality of the crop. In tomato, AMF inoculation increased Se and Zn concentrations and enhanced overall plant growth and stress tolerance (Roufael *et al*., 2015). Ramesh *et al*., (2014) showed how inoculation of vegetables with zinc-soluble endophytes significantly increased Zn content in leafy and fruiting vegetables. The use of multi-strain packages combining PGPR, AMF and endophytes has been shown to be more effective than single-strain inoculants. For example, combined inoculation of AMF and Azotobacter crococcum in broccoli fields increased Fe and Zn content in heads compared to individual treatments (Abohatem *et al*., 2020). Above all, understanding the physiological and molecular mechanisms of nutrient uptake, transfer and accumulation in vegetables is crucial for developing effective biofortification strategies. Soil conditions, rhizosphere microbiology, and root architecture all influence nutrient availability and assimilation (Marschner, 2012). Integrating soil management practices with crop genetic improvement offers additional benefits in nutrient enhancement.

5. Challenges and Future Perspectives

Despite these promising developments, several challenges remain, including nutrient bioavailability in humans, potential yield-nutrient inverse relationships, and scalability of interventions. One of these is the genetic complexity of micronutrient traits in vegetables. Most vegetables have higher heterozygosity and complex genome architecture than cereals, which makes breeding and genetic modification more difficult (Garg *et al*., 2018). In addition, the nutritional content of vegetables depends on environmental factors and post-harvest activities, which affect trait stability and nutrient retention (Saltzman *et al*., 2013). From a technological perspective, the limited availability of nutrient-rich parental lines, poor understanding of nutrient uptake pathways, and low transformation efficiency are major obstacles to the success of breeding and biotechnology-based strategies (Tiwari *et* *al*., 2022). For example, Bois and Saltzman (2017) have highlighted practical limitations for agronomic and microbial methods, including inconsistent field performance and variability in soil nutrient availability. Beyond this, various socio-economic factors also play an important role. Consumer awareness, market demand, and regulatory frameworks for bio-safe vegetables, especially genetically modified or bioengineered varieties, are often lacking, resulting in poor acceptance and commercialization (Finkelstein *et al*., 2017).

Looking ahead, advances in genomics, gene editing (e.g., CRISPR/Cas9), and synthetic biology offer exciting prospects for specific and efficient vegetable bio-safeguarding (Wang *et al*., 2019). Tiwari *et al*. (2022) reported that the integration of multi-omics approaches (genomics, transcriptomics, metabolomics) will help to better understand the molecular basis of micronutrient accumulation and regulation. Furthermore, adopting a holistic approach that combines breeding, agronomy, and microbial interventions can promote the success of biofortification. Strong public-private partnerships, consumer awareness, and supportive policies will be important to increase the production, distribution, and acceptance of biofortified vegetables (Saltzman *et al*., 2013). In the context of global climate change and food insecurity, climate-smart biofortification strategies, such as breeding for nutrient-dense and climate-resilient vegetable crops, will be important. Combining different strategies -such as integrated biofortification strategies with improved soil management -offers the most holistic and sustainable solution (Bouis & Welch, 2010). However, continued research, along with supportive policy frameworks and public awareness, is essential for the success of nutrient-enhanced vegetable production in addressing global malnutrition.

Based on the above discussion suggested way Forward for vegetable biofortification are provided below:

1. Harness advanced breeding tools
   - Leverage genomic selection, CRISPR/Cas9 gene editing, and marker-assisted breeding to overcome genetic complexity and accelerate the development of nutrient-dense, climate-resilient vegetable varieties.
   - Utilize multi-omics approaches (genomics, transcriptomics, metabolomics) to unravel nutrient uptake, transport, and accumulation mechanisms.
2. Develop and share nutrient-rich germplasm
   - Establish global and regional germplasm banks with high-micronutrient parental lines for breeding programs.
   - Promote international collaboration to facilitate germplasm exchange and access to elite genetic resources.
3. Integrate agronomic and microbial strategies
   - Combine genetic approaches with agronomic practices (e.g., soil amendments, micronutrient

fertilizers) and beneficial microbes (e.g., mycorrhizae, biofertilizers) to enhance nutrient bioavailability in soils and plants.
- Tailor interventions to specific agro-ecological zones to ensure consistent field performance.

4. Strengthen post-harvest and supply chain management
   - Develop technologies and best practices to minimize nutrient loss during harvesting, processing, and storage.
   - Encourage cold chain development and nutrient-retaining packaging solutions.
5. Promote consumer awareness and education
   - Launch nutrition education campaigns to improve public understanding of the benefits of biofortified vegetables.
   - Use community-based platforms and school feeding programs to promote acceptance and consumption.
6. Enable supportive policy and regulatory frameworks
   - Formulate clear, science-based regulations for genetically modified and bioengineered vegetables.
   - Provide incentives (e.g., subsidies, tax breaks) to encourage production and market entry of biofortified crops.
7. Foster public–private partnerships
   - Engage private seed companies, agri-tech startups, and food industries in scaling up biofortified varieties.
   - Promote collaborative research, co-funding mechanisms, and innovation platforms.
8. Monitor impact and ensure equity
   - Implement monitoring systems to evaluate nutritional outcomes, adoption rates, and social impacts.
   - Ensure inclusive access to biofortified vegetables, especially among low-income and nutritionally vulnerable populations.
9. Adapt to climate change
   - Prioritize breeding for resilience to heat, drought, and salinity alongside micronutrient enhancement.
   - Align biofortification strategies with climate-smart agriculture and sustainable food systems frameworks.

6. Conclusion

Enhancing the nutritional value of vegetable crops is an effective and promising way to address hidden hunger or micronutrient malnutrition worldwide. A multifaceted approach or technology package combining genetic improvement, agronomic practices, soil health management and supporting policies is crucial to ensure the development, widespread adoption and success of vegetable biofortification at the field level. Future efforts should also focus on increasing consumer acceptance, strengthening value chains and adapting strategies to local agro-ecological and socio-economic contexts to maximize impact and sustainability. Enhancing the nutritional value of vegetables has been identified as an effective and sustainable strategy to address global nutrient deficiencies. In particular, in the context of global climate change and food insecurity, climate-smart biofortification strategies, such as breeding nutrient-dense and climate-resilient vegetable crops, will be crucial. Continued research, policy support and consumer education are essential for the success of these initiatives.

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