SAARC J. Agric., 24(1): 287-300 (2026) DOI: https://doi.org/10.3329/sja.v24i1.90744

SAARC Journal of Agriculture
Journal Homage: https://www.banglajol.info/index.php/SJA

Advances and Prospects in Fruit Biofortification for Nutritional Security

H. A. Mashuk[1*] and A. H. M. A. Rahman[2]

[1]Plant Breeding Division, Bangladesh Rice Research Institute (BRRI), Gazipur
[2]Gazipur Agriculture University, Bangladesh

Abstract

Micronutrient malnutrition commonly referred to as "hidden hunger" which continues to affect more than two billion people worldwide, particularly in low and middle-income countries. Traditional interventions such as supplementation and industrial food fortification have had limited reach and sustainability. Biofortification, the process of increasing the nutrient content of crops through agronomy, conventional breeding, or modern biotechnology, offers a cost-effective and sustainable solution. While staple crops have been the primary focus, fruit biofortification is emerging as a powerful strategy due to fruits' inherent richness in vitamins, antioxidants, and phytochemicals, and their widespread raw consumption. This review synthesizes the latest advances in biofortification including agronomic practices, marker-assisted selection, genomic tools, and genome editing (e.g., CRISPR/Cas9) of different fruit crops. Successful case studies involving provitamin A-enriched bananas in Uganda, vitamin C-rich apples in China, carotenoid-rich citrus fruits in Brazil and Spain, anthocyanin-enhanced berries in the USA and Chile, and iron-fortified mangoes in India demonstrate the potential of biofortified fruits to improve human nutrition and food security. Challenges related to regulation, public acceptance, and technical capacity are critically analyzed. The paper concludes that fruit biofortification, if mainstreamed into agriculture and nutrition policies, could play a transformative role in global food and nutrition security. With evolving biotechnology and supportive policies, fruit biofortification is poised to bridge the gap between agricultural innovation and public health nutrition.

Keywords: Agronomic practices, Conventional breeding, CRISPR/Cas9, Genetic engineering, Micronutrient deficiency

* Corresponding author: al.mashuk2917@gmail.com

Received:11.06.2026 *Accepted: 30.06.2026*

Introduction

Micronutrient malnutrition commonly known as "hidden hunger" is a persistent global health challenge, affecting over two billion people worldwide, particularly in low- and middle-income countries (Rai et al., 2024; WHO, 2021). This condition arises from insufficient intake of essential micronutrients such as iron, vitamin A, zinc, and iodine, which are required in minute quantities yet play crucial roles in human growth, immune defense, cognitive function, and general well-being (Bailey et al., 2015; Avnee et al., 2023). The burden is especially heavy among vulnerable populations, especially children and pregnant women, are disproportionately affected, with the highest burden observed in regions such as Southeast Asia and sub-Saharan Africa (Harika et al., 2017; Chitekwe et al., 2021). Although interventions such as micronutrient supplementation, food fortification, and dietary diversification, micronutrient deficiencies remain widespread due to infrastructural, economic, and behavioral barriers (Rawat et al., 2013). While industrial-scale food fortification programs have shown success in high-income countries but often fall short in developing contexts due to limited processing capabilities and distribution challenges (Bois & Saltzman, 2017). This has prompted the search for more sustainable and context-appropriate solutions.

Biofortification has emerged as a promising intervention for addressing micronutrient deficiencies in resource-poor settings (Blancquaert et al., 2016). While significant attention has been given to staple crops-such as vitamin A-rich golden rice, zinc-enhanced wheat, and orange-fleshed sweet potatoes-there is growing recognition of the untapped potential of fruit biofortification (Jha & Warkentin, 2020; Sen et al., 2024). Fruits are inherently rich in vitamins, antioxidants, and phytochemicals, making them ideal candidates for nutrient enhancement. Moreover, their frequent consumption in raw form reduces nutrient losses associated with cooking or processing, thereby increasing the effectiveness of biofortification (Garg et al., 2018). Beyond enhancing nutritional quality, biofortified fruits contribute to dietary diversity, promote healthier eating habits, and align with sustainable agricultural practices.

In light of these benefits, integrating fruit biofortification into national nutrition and agricultural strategies offers a holistic pathway to combat hidden hunger. This review explores the global burden of micronutrient malnutrition, evaluates the mechanisms and outcomes of fruit biofortification strategies-including agronomic approaches, breeding, and genetic modification and assesses case studies, challenges, and future prospects. By doing so, it highlights the potential of fruit biofortification as a scalable, nutrition-sensitive innovation in addressing micronutrient deficiencies and strengthening food systems worldwide.

Global Burden of Micronutrient Malnutrition

Micronutrient malnutrition remains a persistent public health challenge, especially in low- and middle-income countries. Deficiencies of essential nutrients such as iron, vitamin A, zinc, and folate adversely affect growth, cognitive development, immune function, and overall health, especially among children and pregnant women (WHO, 2021).

Iron deficiency anemia is the most common nutritional disorder worldwide, affecting nearly 30% of the global population and reducing cognitive performance, productivity, and educational outcomes (Pasricha et al., 2021). Vitamin A deficiency, which affects over 190 million preschool-aged children worldwide, is a leading cause of preventable childhood blindness and significantly increases the risk of infectious diseases (UNICEF, 2020; Stevens et al., 2015). Zinc deficiency is another widespread concern, contributing to compromised immune function, increased morbidity, and heightened child mortality rates (Wessells & Brown, 2012). Folate deficiency, especially during early pregnancy, is strongly associated with neural tube defects in newborns, highlighting its importance in maternal health (Crider et al., 2014).

Beyond its health impacts, micronutrient malnutrition imposes significant economic costs through lost productivity and increased healthcare expenditures (FAO, 2019). Although supplementation and food fortification programs have improved nutritional status in many regions, challenges related to coverage and sustainability persist. Consequently, biofortification has emerged as a promising long-term strategy, enhancing the micronutrient content of staple crops to provide sustainable and accessible nutrition for vulnerable populations.

Fruit Biofortification: A Sustainable Strategy to Combat Micronutrient Deficiencies

Fruit biofortification is an emerging strategy that employs scientific approaches to enrich the micronutrient content of fruits, aiming to improve nutritional intake without requiring changes in dietary habits. By boosting essential nutrients, biofortified fruits can serve as effective tools for addressing micronutrient malnutrition. Unlike cereals and legumes, fruit biofortification has received less attention despite its nutritional importance. Nevertheless, the favorable perception of fruits and their widespread consumption make them promising targets for long-term, sustainable nutritional improvement.

Approaches to Fruit Biofortification

Three principal strategies are used in fruit biofortification: agronomic practices, conventional breeding, and genetic engineering. Each method varies in terms of cost, time requirements, societal acceptance, and types of nutrients enhanced (Table 1).

Table 1. Comparative Analysis of Biofortification Strategies

Strategy	Timeframe	Cost	Acceptance	Nutrients Enhanced
Agronomic	1–2 seasons	Low-Medium	High	Zn, Fe, Se, I
Conventional Breeding	5–15 years	Medium	High	Provitamin A, Fe, Zn
Genetic Engineering	3–8 years	High	Low-Medium*	All (customizable)

*Varies by region; higher acceptance in North America, lower in Europe.

Agronomic Biofortification

Agronomic biofortification improves the nutritional quality of fruits through the application of micronutrient fertilizers to soil or foliage, enhancing the uptake of nutrients such as zinc, iron, and selenium. Successful examples include zinc fertilization in banana and iron foliar sprays in apple and grape, which significantly increased fruit micronutrient concentrations (Aciksoz et al., 2011). Prasad et al. (2014) reported enhanced zinc uptake in citrus and banana using zinc sulfate. Zinc sulfate application has also enhanced zinc accumulation in citrus and banana crops (Prasad et al., 2014). Additionally, nutrient-enriched culture media, targeted root-zone fertilization, and the use of plant growth regulators can further improve nutrient assimilation (Sharma et al., 2022). Agronomic biofortification is a cost-effective, non-GMO, and farmer-friendly approach with minimal regulatory barriers. However, its effectiveness depends on soil characteristics, often requires repeated applications, and may have limited impact on some micronutrients.

Conventional Breeding

Conventional breeding is a widely used strategy for fruit biofortification that exploits natural genetic variation to enhance micronutrient content. By selecting and crossing nutrient-rich parental lines, breeders have developed fruit varieties with increased levels of vitamin C, carotenoids, and flavonoids in crops such as banana, apple, citrus, and papaya (Bouis & Saltzman, 2017; Lobato-Gómez et al., 2021). This approach is compatible with organic agriculture and contributes to the conservation of genetic diversity through the use of landraces and wild relatives (Perić *et al*., 2024)

Despite its advantages, conventional breeding is a slow process, often requiring 5-15 years to develop improved varieties, and is constrained by limited genetic diversity and trait trade-offs (Biselli et al., 2022). To enhance efficiency, marker-assisted selection (MAS) has been incorporated into breeding programs, enabling rapid identification of desirable genes and quantitative trait loci (QTLs) (Collard et al., 2008). MAS has successfully improved fruit quality, disease resistance, and micronutrient content in crops such as apple (Kumar et al., 2024). The integration of conventional breeding with modern genomic tools offers significant potential for accelerating the development of nutrient-rich fruit varieties and addressing global micronutrient deficiencies sustainably (Sen et al., 2024).

Genetic Engineering and Biotechnology

Genetic engineering and biotechnology are powerful tools for biofortification, enabling the identification and manipulation of genes controlling micronutrient accumulation in edible plant tissues. Molecular techniques such as QTL mapping and marker-assisted selection (MAS) accelerate the development of nutrient-rich fruit varieties by facilitating the selection of desirable traits (Yu et al., 2021). Advanced approaches, including intragenesis and cisgenesis, enhance nutritional quality and stress tolerance while addressing some biosafety concerns associated with conventional transgenic methods (Schaart *et al*., 2016).

The transport of nutrients from source to sink organs like fruits is mediated by the phloem and xylem systems, which are regulated by specific genes and transport proteins (Reid et al., 2011). Biological agents like plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal (AM) fungi enhance micronutrient uptake in fruits. PGPR improve nutrient availability by solubilizing minerals, fixing nitrogen, and releasing siderophores and phytohormones (Compant et al., 2019). AM fungi form root symbioses, extending hyphal networks that boost uptake of phosphorus, zinc, and copper while improving soil structure and stress resistance (Schweiger et al., 2020). These agents offer eco-friendly, cost-effective solutions suitable for organic farming. Although their success depends on plant and soil factors, they remain a promising strategy for sustainable fruit biofortification and improved nutritional quality.

Modern biotechnological interventions have successfully increased micronutrient levels in fruits, including provitamin A-enriched bananas and folate-rich strawberries and tomatoes (Dale et al., 2017; Paul *et al*., 2017; Blancquaert et al., 2017). Genome-editing tools such as CRISPR-Cas9 provide precise and efficient modification of nutrient biosynthesis pathways, enabling rapid development of biofortified crops.

Biological approaches also contribute to fruit biofortification. Plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal (AM) fungi enhance nutrient uptake, improve soil health, and increase the availability of essential minerals such as phosphorus, zinc, and copper (Compant *et al*., 2019; Schweiger et al., 2020). These eco-friendly technologies are particularly suitable for sustainable and organic production systems.

Despite their advantages, including targeted nutrient enhancement and faster breeding cycles, biotechnological approaches face challenges related to regulatory restrictions, public acceptance of genetically modified organisms (GMOs), high development costs, and intellectual property concerns, which may limit their widespread adoption.

Success Stories of Fruit Biofortification

Fruit biofortification has demonstrated significant potential in addressing micronutrient malnutrition through various approaches. Some significant case studies implementing fruit biofortification successfully are highlighted below.

Golden Banana Initiative in Africa

A notable success in fruit biofortification is the development of provitamin A-enriched bananas in Uganda by the National Agricultural Research Organization (NARO) and Queensland University of Technology (Fig. 1). The project aims to combat vitamin A deficiency through bananas with enhanced β-carotene content. Study has shown that early activation of carotenoid biosynthesis enzymes and prolonged fruit maturation are key factors in increasing provitamin-A accumulation (Paul et al., 2017). To enhance β-carotene content, genetic engineering techniques were employed, incorporating the phytoene synthase gene from maize (Dale et al., 2017).

Cultivars such as 'Nakitembe' can provide up to 50% of the daily vitamin A requirement for children (Mbabazi et al., 2019). However, adoption has been limited by stringent GMO regulations in several African countries. To address this challenge, public awareness campaigns have been launched to improve understanding and acceptance of biofortified crops, highlighting the importance of supportive regulations and community engagement for successful implementation.

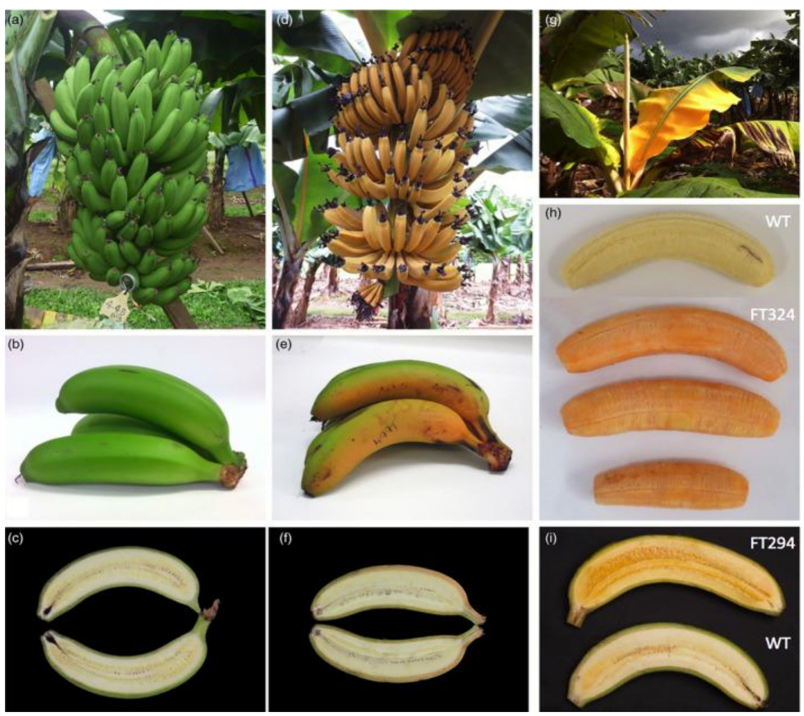

Fig. 1. Characteristic phenotypes observed transgenic Cavendish banana lines (g-h) compared to wild-types (a-f)

Apple Biofortification in China

China has made notable advancements in apple biofortification by combining conventional breeding with molecular tools such as genomics and marker-assisted selection (MAS). Key genes involved in vitamin C biosynthesis, including MdGGP and MdDHAR, have been identified to develop high-ascorbate apple cultivars (Wang *et al*., 2019). Agronomic practices, such as foliar application of zinc and selenium and optimized fertilization, have further enhanced the mineral content and antioxidant capacity of apples (Zhang et al., 2021). These integrated strategies have improved the nutritional quality of apples and hold promise for enhancing food security and public health.

Citrus Biofortification in Spain and Brazil

Spain and Brazil have achieved significant progress in citrus biofortification through breeding, genetic, and metabolic engineering approaches (Table 2). In Spain, a high-vitamin C mandarin hybrid was developed through conventional breeding (Rodríguez et al., 2020), while CRISPR-Cas9 technology has been used to enhance vitamin C biosynthesis in lemons (Perez et al., 2022). In Brazil, high-carotenoid orange cultivars such as 'Pera Rio' and 'Valencia' have been selected (Silva et al., 2021), and QTLs associated with elevated folate content have been identified (Oliveira et al., 2021). Metabolic engineering has increased folate levels in citrus fruits up to tenfold, supporting public health initiatives aimed at improving maternal nutrition (Strobbe & Van Der Straeten, 2018)

Table 2. Biofortified varieties of citrus fruits

Citrus cultivar	Biofortification traits	Reference
Ruby blood red citrus	Deep red colour due to anthocyanins	Butelli *et al.* (2012).
Malta (Maltase) citrus	Sweet taste and high vitamin C content	Medina-Remon *et al.* (2011)
Star ruby grapefruit	Pink-red flesh rich in lycopene	Strother and Lila (2016)
Rio red grapefruit	Red-fleshed with high lycopene content	Dorado *et al.* (2021)

Despite existing challenges, sustained innovation and supportive policy frameworks have the potential to significantly improve the nutritional quality of citrus fruits, thereby advancing global health and contributing to food security.

Berries Biofortification in USA/Chile

The USA and Chile have made notable advances in blueberry biofortification to enhance antioxidant intake and reduce oxidative stress-related diseases. Conventional breeding combined with marker-assisted selection (MAS) has produced high-anthocyanin cultivars containing 30–50% more anthocyanins than conventional varieties (Bassil et al., 2022). These `superberries' have gained popularity in the functional food market due to their proven cardiovascular and cognitive health benefits (Kalt *et al*., 2020). Growing consumer awareness of the role of nutrition in disease prevention has further increased demand for these nutrient-enriched berries (Granato et al., 2023)

Mangoes Biofortification in India

In India, mango biofortification has emerged as a promising strategy to address iron-deficiency anemia, particularly among women. Agronomic biofortification using iron-EDTA fertilizers has increased iron content in mango pulp from 0.5 to 2.8 mg/100 g (Singh et al., 2020). Combined with mango's naturally high vitamin C content, which enhances non-heme iron absorption, this approach provides significant nutritional benefits (Saunders et al., 2022). Field trials have demonstrated that biofortified mangoes maintain improved nutrient levels and acceptable fruit quality after harvest (Patil et al., 2021), making them a practical and scalable solution for combating micronutrient malnutrition in South Asia.

Challenges and Limitations

Despite its potential, fruit biofortification faces several challenges. Stringent and evolving GMO regulations often delay commercialization and adoption of biofortified fruits. Limited genomic resources and breeding tools for many fruit species also constrain research and development. In addition, high investment costs and long breeding cycles make biofortification a resource-intensive process. Consumer skepticism and misinformation regarding biotechnology and genetically modified crops further hinder public acceptance and market penetration

Future Prospects of Fruit Biofortification

Fruit biofortification presents a promising frontier in the global effort to reduce micronutrient deficiencies through sustainable agricultural practices. Future progress will rely on integrating conventional breeding with advanced technologies such as marker-assisted selection (MAS), genomic selection, and genome editing. MAS and whole-genome sequencing will accelerate the identification and incorporation of nutrient-enhancing traits, while CRISPR/Cas9 will enable precise genetic modifications for improving nutrient content, shelf life, flavor, and stress tolerance (Mathiazhagan et al., 2021; Roy & Sandhu, 2024). Recent successes in β-carotene-enriched bananas and nutritionally enhanced tomatoes highlight the potential of these approaches (Tripathi et al., 2024). As research advances and regulatory frameworks become more supportive, biofortified fruits are expected to contribute significantly to reducing hidden hunger and strengthening global food and nutritional security (Chen et al., 2024; Sen et al., 2024).

Expected Impacts on Human Nutrition

Fruit biofortification can substantially improve human health by reducing deficiencies of iron, vitamin A, folate, and zinc. Vulnerable groups, including children, pregnant women, and low-income populations, are likely to benefit through enhanced immunity, cognitive development, and maternal health. Biofortified fruits also promote dietary diversity and overall nutritional quality while providing a sustainable, food-based alternative to supplementation programs. In the long term, improved nutrition can increase productivity, reduce healthcare costs, enhance educational outcomes, and strengthen food system resilience, making fruit biofortification an important strategy for achieving global nutrition goals.

Conclusions and way forward

Fruit biofortification represents a transformative frontier in addressing global micronutrient malnutrition through sustainable agriculture. With the integration of agronomic practices, conventional breeding, and cutting-edge biotechnological tools such as marker-assisted selection, genomic prediction, and CRISPR/Cas9 gene editing, significant strides have been made in enhancing the nutritional profile of fruits. Successful implementation across diverse geographies for instance, β-carotene-rich bananas in Uganda, iron-fortified mangoes in India, and high-vitamin C apples in China demonstrates both the feasibility and global relevance of fruit biofortification initiatives.

Despite progress, challenges related to regulatory constraints, high development costs, and limited consumer awareness continue to hinder large-scale adoption. Addressing these barriers through supportive policies, transparent regulatory frameworks, public engagement, and international collaboration will be essential. Fruit biofortification not only addresses nutrient gaps in vulnerable populations but also aligns with global efforts toward sustainable food systems, climate resilience, and the United Nations Sustainable Development Goals.

Future efforts should focus on integrating fruit biofortification into national nutrition and agricultural policies, strengthening research and breeding programs, promoting consumer awareness, ensuring equitable access to planting materials, and fostering partnerships among governments, research institutions, and the private sector. With continued innovation and coordinated action, fruit biofortification can evolve into a widely accepted strategy for improving diets, enhancing public health, and strengthening resilient and sustainable food systems. By pursuing these actions, fruit biofortification can transition from a scientific innovation to a scalable, socially accepted solution that enriches diets, improves health outcomes, and enhances the resilience of food systems.

Acknowledgement

The authors are grateful to Professor Dr. Md. Mizanur Rahman, faculty member of the Department of Soil Science, for his valuable suggestions and constructive guidance during the preparation of the manuscript.

References

Aciksoz, S. B., Yazici, A., Ozturk, L. and Cakmak, I. (2011). Biofortification of wheat with iron through soil and foliar application of nitrogen and iron fertilizers. *Plant and Soil*, 349(1-2): 215–225. https://doi.org/10.1007/s11104-011-0863-2.

Avnee, T., Hossain, M. and Rahman, M. (2023). Micronutrient deficiency in South Asia: Challenges and nutritional approaches. *Asian Journal of Clinical Nutrition, 15*(1): 12–24. https://doi.org/10.3923/ajcn.2023.12.24

Bailey, R. L., West Jr, K. P. and Black, R. E. (2015). The epidemiology of global micronutrient deficiencies. *Annals of Nutrition and Metabolism*, 66(Suppl. 2): 22-33. https://doi.org/10.1159/000371618.

Bassil, N., Bidani, A. and Hummer, K. (2022). Genetic markers for anthocyanin accumulation in *Vaccinium corymbosum*. *Journal of Agricultural and Food Chemistry*, 70(12): 3891–3902.

Blancquaert, D., De Steur, H., Gellynck, X. and Van Der Straeten, D. (2017). Metabolic engineering of micronutrients in crop plants. *Annals of the New York Academy of Sciences*, 1390(1): 59–73. https://doi.org/10.1111/nyas.13274.

Blancquaert, D., Van Daele, J., Strobbe, S., Kiekens, F. and Van Der Straeten, D. (2016). Improving folate (vitamin B9) stability in biofortified rice through metabolic engineering. *Nature Biotechnology, 34*(8): 976–981. https://doi.org/10.1038/nbt.3628.

Bouis H. E., Saltzman A. (2017). Improving nutrition through biofortification: a review of evidence from HarvestPlus through 2016. *Global Food Security*, 12: 49–58. doi: 10.1016/j.gfs.2017.01.009.

Chen, X., and Yu, G. (2024). The Impact of Urban–Rural Integration on Food Security: Evidence from Provincial Panel Data in China. *Sustainability*, 16(9): 3815.

Chitekwe, S., Torlesse, H., Hoddy, A., and Wight, D. (2021). Progress in tackling micronutrient malnutrition: Evidence from 10 countries. *Maternal and Child Nutrition,* 17(1): e13072. https://doi.org/10.1111/mcn.13072.

Collard BC and Mackill DJ. (2008). Marker-assisted selection: an approach for precision plant breeding in the twenty-first century. *Philosophical Transactions of the Royal Society*, 363(1491):557-72. doi: 10.1098/rstb.2007.2170.

Compant, S., Samad, A., Faist, H. and Sessitsch, A. (2019). A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. *Journal of Advanced Research*, 19, 29–37. https://doi.org/10.1016/j.jare.2019.03.004.

Dale, J., James, A., Paul, J. Y., Khanna, H. and Harding, R. (2017). Transgenic biofortification of bananas. *CAB Reviews*, 12(020): 1-10. https://doi.org/10.1079/PAVSNNR201712020.

Davey, M. W., Van den Bergh, I., Markham, R., Swennen, R. and Keulemans, J. (2009). Genetic variability in Musa fruit provitamin A carotenoids, lutein and mineral micronutrient contents. *Food Chemistry*, 115(3): 806–813. https://doi.org/10.1016/j.foodchem. 2008.12.088.

Dolkar D., Bakshi P. and Wali., V.K. (2014). Genetic engineering in fruit crops. *The Journal of Genetics. Photon*, 115:146-163.

FAO. (2019). The state of food security and nutrition in the world 2019. Food and Agriculture Organization of the United Nations.

Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V. and Arora, P. (2018). Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. *Frontiers in Nutrition,* 5: 12. https://doi.org/10.3389/fnut.2018.00012

Garg, N., Singh, S. and Singh, R. (2018). Fruits and vegetables and its nutritional benefits. *International Journal of Current Microbiology and Applied Sciences*, 7(8): 2430–2435.

Granato, D., Mocan, A. and Câmara, J. S. (2023). Functional foods: Consumer awareness, marketing trends, and policy implications. *Comprehensive Reviews in Food Science and Food Safety*, 22(1): 367–402.

Harika, R., Faber, M., Samuel, F., Kimiywe, J., Mulugeta, A. and Eilander, A. (2017). Micronutrient status and dietary intake of iron, vitamin A, iodine, folate and zinc in women of reproductive age and pregnant women in Ethiopia, Kenya, Nigeria and South Africa: A systematic review of data from 2005 to 2015. *Nutrients,* 9(10): 1096. https://doi.org/10.3390/nu9101096

Harsh Kumar, Shivani Guleria, Neetika Kimta, Eugenie Nepovimova, Rajni Dhalaria, Daljeet Singh Dhanjal, Nidhi Sethi, Suliman Y. Alomar, Kamil Kuca, (2024). Selected fruit pomaces: Nutritional profile, health benefits, and applications in functional foods and feeds, *Current Research in Food Science*, 9:100791, doi.org/10.1016/j.crfs.2024. 100791.

Jha, A. B. and Warkentin, T. D. (2020). Biofortification of pulse crops: Status and future perspectives. *Plants,* 9(1): 73. https://doi.org/10.3390/plants9010073.

Kalt, W., Cassidy, A., Howard, L. R., Krikorian, R., Stull, A. J., Tremblay, F. and Zamora-Ros, R. (2020). Recent research on the health benefits of blueberries and their anthocyanins. *Advances in Nutrition*, 11(2): 224–236. https://doi.org/10.1093/advances/nmz065.

Kumar, S., Volz, R. K., Alspach, P. A. and Bus, V. G. M. (2015). Development of a recurrent apple breeding programme in New Zealand: A synthesis of results, and a proposed revised breeding strategy. *Euphytica*, 204(3): 505-522. https://doi.org/10.1007/s10681-014-1349-0.

Lobato-Gomez M., Hewitt S., Capell T., Christou P., Dhingra A. and Giron-Calva P. S. (2021). Transgenic and genome-edited fruits: background, constraints, benefits, and commercial opportunities. *Horticulture Research*, 8 (1): 1–3. doi: 10.1038/s41438-021-00601-3.

Mathiazhagan, M., Chidambara, B., Hunashikatti, L. R. and Ravishankar, K. V. (2021). Genomic Approaches for Improvement of Tropical Fruits: Fruit Quality, Shelf Life and Nutrient Content. *Genes*, 12(12): 1881. https://doi.org/10.3390/genes12121881.

Mbabazi, R., Harding, R., Khanna, H., Namanya, P., Arinaitwe, G., Tushemereirwe, W., Dale, J. and Paul, J.-Y. (2019). Pro-vitamin A carotenoids in East African highland banana and other Musa cultivars grown in Uganda. *Food Science and Nutrition*, 8(1): 311–321.

Oh, J., Zang, H., Lee, Y., and Kwon, D. (2021). Future directions of food fortification: Fermentation and microbiome approaches. *Trends in Food Science and Technology,* 112: 267–278. https://doi.org/10.1016/j.tifs.2021.03.030.

Olanbiwoninu, A. A., Yusuf, A. O. and Ayinde, K. E. (2023). Enhancing micronutrient availability in fermented foods: Microbial strategies and implications. *Journal of Food Biochemistry,* 47(3): e13575. https://doi.org/10.1111/jfbc.13575.

Oliveira, T. S., Moura, M. S. B., Bastianel, M. and Novelli, V. M. (2021). Identification of QTLs associated with high folate content in sweet oranges (*Citrus sinensis*). *Theoretical and Applied Genetics*, 134(8): 2733-2745. https://doi.org/10.1007/s00122-021-03854-7.

Patil, S., Singh, A. K. and Dwivedi, P. (2021). Post-harvest stability of micronutrients in biofortified mango cultivars. *Journal of Food Composition and Analysis*, 104: 104175. https://doi.org/10.1016/j.jfca.2021.104175.

Paul, J. Y., Khanna, H., Kleidon, J., Hoang, P., Geijskes, J., Daniells, J., Zaplin, E., Rosenberg, Y., James, A., Mlalazi, B., Deo, P., Arinaitwe, G., Namanya, P., Becker, D., Tindamanyire, J., Tushemereirwe, W., Harding, R., Dale and J. (2017). Golden bananas in the field: elevated fruit pro-vitamin A from the expression of a single banana transgene. *Plant Biotechnology Journal*, 15(4):520-532. doi: 10.1111/pbi.12650. Epub 2016 Dec 20. PMID: 27734628; PMCID: PMC5362681.

Perez, R., Guirado, S., Alquézar, B. and Peña, L. (2022). CRISPR-Cas9-mediated editing of vitamin C biosynthesis genes (GGP, GalUR) in Spanish lemons. *Plant Biotechnology Journal*, 20(3): 512-525. https://doi.org/10.1111/pbi.13735.

Perić, K., Čupić, T., Krizmanić, G., Tokić, B., Andrić, L., Ravlić, M., Meglič, V. and Tucak, M. (2024). The Role of Crop Wild Relatives and Landraces of Forage Legumes in Pre-Breeding as a Response to Climate Change. *Agronomy*, 14(7): 1385. https://doi.org/10.3390/agronomy14071385.

Prasad, R., Shivay, Y. S., and Kumar, D. (2014). Agronomic biofortification of cereal grains with iron and zinc. *Advances in Agronomy*, 125: 55-91. https://doi.org/10.1016/B978-0-12-800137-0.00002-9.

Rai, N., Prasad, V. and Singh, M. (2024). The burden of micronutrient deficiencies and the role of sustainable food systems. *Journal of Nutritional Health and Food Engineering,* 18(1): 23–30. https://doi.org/10.15406/jnhfe.2024.18.555933.

Rawat, R., Nguyen, P. H. and Menon, P. (2013). Livelihoods, food and nutrition security in Bangladesh: Nutritional outcomes of integrated interventions. *Maternal and Child Nutrition,* 9(4): 67–79. https://doi.org/10.1111/mcn.12068.

Reid, M. S., Kalaitzis, P. and Solomos, T. (2011). The role of the vascular system in determining the composition and quality of fruits. *Postharvest Biology and Technology*, 62(3): 207-212. https://doi.org/10.1016/j.postharvbio.2011.05.006.

Rodríguez, A., Pérez, J., Cervera, M. and Navarro, L. (2020). Development of a high-vitamin C mandarin hybrid through conventional breeding in Spain. *Scientia Horticulturae*, 265: 109234. https://doi.org/10.1016/j.scienta.2020.109234.

Roy, A., and Sandhu, R. (2024). Advancements in genetic enhancement: CRISPR/cas-mediated genome editing in leguminous crops. *Journal of Advances in Biology and Biotechnology*, 27(6): 670-681.

Saunders, C., Smith, L. and Kiely, M. (2022). Ascorbic acid enhances iron absorption from mangoes: A randomized crossover study. *Nutrients*, 14(3): 512. https://doi.org/10.3390/nu14030512.

Schaart, J. G., van de Wiel, C. C. M., Lotz, L. A. P. and Smulders, M. J. M. (2016). Opportunities for products of new plant breeding techniques. *Trends in Plant Science*, 21(5): 438–449. https://doi.org/10.1016/j.tplants.2015.11.006.

Schweiger, P., Robson, A. D. and Barrow, N. J. (2001). Phosphorus uptake by hyphae of arbuscular mycorrhizal fungi into field-grown peas. *Soil Biology and Biochemistry*, 33(4–5): 763–769. https://doi.org/10.1016/S0038-0717(00)00223-2.

Sen, K., Kruse, S., Mileski, M. and Ramamonjiarivelo, Z. (2025). The need for interventions to alleviate social isolation and food insecurity to improve the health-related quality of life in older adults. A Systematic Review Author Information. *Frontiers in Nutrition*, 12: 1607057.

Sen, S., Roy, M., and Das, K. (2024). Fruit biofortification as a sustainable approach to mitigate micronutrient deficiency. *Current Nutrition and Food Science,* 20(2): 165–174. https://doi.org/10.2174/1573401320666221201103746.

Sharma, S., Kaur, N. and Pati, P. K. (2022). Optimizing culture media for enhanced nutrient uptake and fruit quality: A review. *Scientia Horticulturae*, 295: 110842. https://doi.org/10.1016/j.scienta.2021.110842.

Silva, L. F. O., Soares, M. S., Gesteira, A. S. and Passos, O. S. (2021). Selection of carotenoid-rich orange varieties (Pera Rio, Valencia) in Brazil. *Journal of Agricultural and Food Chemistry*, 69(15): 4501-4510. https://doi.org/10.1021/acs.jafc.1c01234.

Stevens, G. A., Bennett, J. E., Hennocq, Q., Lu, Y., De-Regil, L. M., Rogers, L., XDanaei, M.G., Li, G. White, R.A., Flaxman, R.S., Oehrle, S.P., Finucane, M.M., Guerrero, R. Bhutta, Z.A., Paulino, A.T. Fawzi, W., Black, R.E. and Ezzati, M. (2015). Trends and mortality effects of vitamin A deficiency in children in 138 low-income and middle-income countries between 1991 and 2013: A pooled analysis of population-based surveys. *The Lancet Global Health*, 3(9): e528–e536. https://doi.org/10.1016/S2214-109X(15)00039-X.

Tripathi, L., Ntui, V. O., and Tripathi, J. N. (2024). Application of CRISPR/Cas-based gene-editing for developing better banana. *Frontiers in Bioengineering and Biotechnology*, 12: 1395772.

UNICEF. (2020). State of the World's Children 2020: Children, food and nutrition. United Nations Children's Fund.

Wang, H., Cao, G., Qi, X., Liu, Q., Wang, Q. and Chen, W. (2019). Breeding of new apple varieties with high vitamin C content. *Horticultural Plant Journal*, 5(3): 105–114. https://doi.org/10.1016/j.hpj.2019.05.004.

Wessells, K. R. and Brown, K. H. (2012). Estimating the global prevalence of zinc deficiency: Results based on zinc availability in national food supplies and the prevalence of stunting. *PLOS ONE*, 7(11): e50568. https://doi.org/10.1371/journal.pone.0050568.

WHO. (2021). Micronutrient deficiencies. World Health Organization. https://www.who.int/health-topics/micronutrients.

Yu, Y., Wang, Y., Zhang, Y., Chen, Y. and Li, X. (2021). The sequencing-based mapping method for effectively cloning plant genes. *International Journal of Molecular Sciences*, 22(12): 6224. https://doi.org/10.3390/ijms22126224.

Zhang, J., Wang, L., Chen, R. and Zhao, M. (2021). Agronomic biofortification of selenium in apples. *Frontiers in Plant Science*, 12, 671234.

Zhao, F. J., McGrath, S. P. and Meharg, A. A. (2020). Biofortification strategies for improving micronutrient density in edible parts of crops. *Advances in Agronomy*, 170 1–74. https://doi.org/10.1016/bs.agron.2020.06.001.