Field Crop 2024, Vol.7, No.5, 278-286
http://cropscipublisher.com/index.php/fc

Feature Review **Open Access**

Agronomic Biofortification: Addressing Micronutrient Deficiencies Through Maize Cultivation

Jin Zhou, Minli Xu
Hainan Provincial Key Laboratory of Crop Molecular Breeding, Sanya, 572025, Hainan, China
Corresponding email: minli.xu@hitar.org
Field Crop, 2024, Vol.7, No.5 doi: 10.5376/fc.2024.07.0028
Received: 13 Aug., 2024
Accepted: 25 Sep., 2024
Published: 18 Oct., 2024

Preferred citation for this article:
Zhou J., and Xu M.L., 2024, Agronomic biofortification: addressing micronutrient deficiencies through maize cultivation, Field Crop, 7(5): 278-286 (doi: 10.5376/fc.2024.07.0028)

Abstract Micronutrient deficiencies pose a significant global health challenge, particularly in regions with limited access to diverse diets. Agronomic biofortification, a promising approach to enhancing nutrient content in staple crops, holds great potential for addressing these deficiencies through maize cultivation. This study explores the concept and methods of agronomic biofortification, focusing on strategies such as soil amendment and foliar application to increase micronutrient uptake in maize. A comparative analysis with genetic biofortification is also provided. Case studies from regions where biofortified maize has been successfully implemented highlight the effectiveness of these interventions. Factors such as soil type, climate, and agricultural practices are discussed in relation to the efficacy of biofortification. The study further examines the positive impact of biofortified maize on human health and nutrition, providing evidence of improved micronutrient intake and health outcomes. The study concludes by discussing future opportunities for expanding biofortification programs, recommending integration with other nutritional interventions, and advocating for increased research and policy support to address global micronutrient deficiencies.
Keywords Agronomic biofortification; Maize; Micronutrient deficiencies; Soil amendment; Public health

1 Introduction

Micronutrient deficiencies, often referred to as "hidden hunger", affect over two billion people worldwide, predominantly in developing countries (Titcomb et Tanumihardjo, 2019; Avnee et al., 2023). These deficiencies, which include shortages of essential vitamins and minerals such as iron, zinc, iodine, and selenium, have severe health implications, including impaired cognitive and physical development, weakened immune systems, and increased morbidity and mortality rates (Jiang et al., 2020). Despite significant advancements in reducing undernutrition through improved crop yields, the issue of micronutrient deficiencies remains pervasive, particularly among populations that rely heavily on staple crops like maize, rice, and wheat, which are typically low in essential micronutrients (Kiran et al., 2022).

Agronomic biofortification is a promising strategy aimed at increasing the micronutrient content of food crops through the application of mineral fertilizers and other agronomic practices (Dhaliwal et al., 2022b). This approach is particularly significant for maize cultivation, as maize is a staple food for millions of people, especially in rural and resource-poor settings (Bouis and Saltzman, 2017). By enriching maize with essential micronutrients such as selenium, zinc, and iron, agronomic biofortification can help address the dietary deficiencies that contribute to hidden hunger (Garg et al., 2018). The process involves the application of micronutrient-enriched fertilizers to the soil or as foliar sprays, which are then absorbed by the plants, leading to increased concentrations of these nutrients in the edible parts of the crops (Teklu et al., 2023). This method has shown promising results in improving the nutritional status of populations, as evidenced by studies demonstrating significant increases in serum selenium levels among women and children consuming biofortified maize (Joy et al., 2022).

This study evaluates the effectiveness and potential of agronomic biofortification in addressing micronutrient deficiencies through maize cultivation, explores the current research status of agronomic biofortification, including its benefits, challenges, and factors influencing its success, and highlights case studies and evidence from various regions, with a particular focus on the impact of biofortified maize on improving micronutrient intake and overall health outcomes.

2 Micronutrient Deficiencies and Their Health Impacts

Micronutrient deficiencies, often referred to as “hidden hunger”, are a significant global health issue, particularly in developing regions. These deficiencies occur when the intake of essential vitamins and minerals is insufficient to meet the body's needs, leading to various health problems (Figure 1). The most common micronutrients lacking in human diets include zinc, iron, and vitamin A. Zinc deficiency can impair immune function and increase susceptibility to infections, iron deficiency can lead to anemia and reduced cognitive function, and vitamin A deficiency can cause vision problems and increase the risk of mortality in children and pregnant women (Goredema-Matongera et al., 2021; Dwivedi et al., 2023).

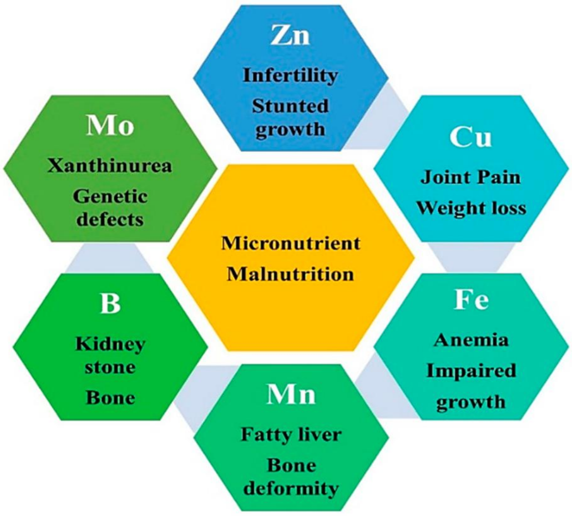

Figure 1 Effects of micronutrient malnutrition on human health (Adopted from Dhaliwal et al., 2022b)

2.1 Common micronutrients lacking in human diets

Zinc, iron, and vitamin A are among the most critical micronutrients often missing from diets, especially in developing countries. Zinc is essential for immune function, protein synthesis, and cell division. Iron is crucial for the formation of hemoglobin and oxygen transport in the blood, while vitamin A is vital for vision, immune function, and reproduction. Deficiencies in these nutrients can lead to severe health issues, including stunted growth, increased susceptibility to infections, and higher mortality rates (Galani et al., 2020).

2.2 The role of maize in addressing these deficiencies

Maize (*Zea mays* L.) is a staple food for a significant portion of the global population, particularly in Sub-Saharan Africa, Latin America, and parts of Asia. However, traditional maize varieties are often low in essential micronutrients. Biofortification, the process of increasing the nutrient content of crops through conventional breeding, genetic engineering, or agronomic practices, offers a promising solution to this problem (Li and Huang, 2024). Biofortified maize varieties enriched with zinc, iron, and provitamin A have been developed and are being promoted to address micronutrient deficiencies in regions where maize is a dietary staple (Garg et al., 2018; Ahmad et al., 2023).

2.3 Current global status of micronutrient deficiencies

Micronutrient deficiencies remain a pervasive issue worldwide, with significant impacts on public health and economic development. In Sub-Saharan Africa and South Asia, deficiencies in zinc, iron, and vitamin A are particularly prevalent, affecting millions of people. For instance, iron-deficient anemia affects 26 to 31% of women of reproductive age in Eastern and Southern Africa, while vitamin A deficiency affects up to 53% of the population in these regions. Efforts to combat these deficiencies through biofortification have shown promise, with biofortified crops like maize playing a crucial role in improving the nutritional status of vulnerable populations (Avnee et al., 2023).

3 Agronomic Biofortification: Concept and Approaches

Agronomic biofortification is a sustainable agricultural strategy aimed at increasing the concentration of essential micronutrients in crops through various agronomic practices. This approach is particularly significant in addressing micronutrient deficiencies, often referred to as "hidden hunger", which affect a large portion of the global population, especially in developing countries (Dhaliwal et al., 2022b).

3.1 Definition and principles of agronomic biofortification

Agronomic biofortification involves the application of mineral fertilizers to the soil or directly to the plant leaves (foliar application) to enhance the nutrient content of crops. The primary principle behind this approach is to increase the bioavailability of essential micronutrients such as zinc (Zn), iron (Fe), and selenium (Se) in the edible parts of the plant, thereby improving the nutritional quality of the food produced (Dhaliwal et al., 2022a). This method is considered a quick and cost-effective solution to improve crop nutrient content and is particularly useful in regions where soil nutrient deficiencies are prevalent.

3.2 Overview of strategies for biofortifying maize

Several strategies are employed to biofortify maize, a staple crop for many populations worldwide. These strategies include soil amendment, foliar application, and the use of advanced fertilizers such as chelated and nano-fertilizers. Soil amendment involves the addition of micronutrient-rich fertilizers to the soil, which enhances the nutrient uptake by maize plants. Foliar application, on the other hand, involves spraying nutrient solutions directly onto the leaves, allowing for quicker absorption and utilization by the plant (Bhardwaj et al., 2022). Additionally, the use of plant growth-promoting rhizobacteria (PGPR) has shown promise in enhancing the bioavailability of nutrients like Zn and Fe in maize, further improving its nutritional quality (Ahmad et al., 2023).

3.3 Genetic enhancement versus agronomic biofortification: comparative analysis

While both genetic enhancement and agronomic biofortification aim to increase the nutrient content of crops, they differ in their approaches and outcomes. Genetic enhancement involves the breeding of crop varieties with higher nutrient content through conventional breeding or transgenic techniques. This method provides a long-term solution but requires significant time and resources to develop and commercialize nutrient-rich varieties (Bouis and Welch, 2010; Garg et al., 2018). In contrast, agronomic biofortification offers a more immediate solution by directly supplying nutrients to the plants through soil and foliar applications. This method can be quickly implemented and adjusted based on the specific nutrient deficiencies of the soil and crop (Avnee et al., 2023).

However, genetic enhancement has the advantage of being a one-time investment that can provide sustained benefits over multiple growing seasons, whereas agronomic biofortification may require repeated applications of fertilizers. Additionally, genetically enhanced crops can be bred to possess multiple beneficial traits, such as increased resistance to pests and diseases, alongside improved nutrient content (Goredema-Matongera et al., 2021). Despite these differences, both approaches are complementary and can be integrated to achieve the best outcomes in combating micronutrient deficiencies and improving global nutritional security (Nuss and Tanumihardjo, 2010; Kiran et al., 2022).

4 Methods for Enhancing Micronutrient Content in Maize

4.1 Soil-based approaches (e.g., micronutrient fertilization, soil amendment)

Soil-based approaches for enhancing micronutrient content in maize primarily involve the application of micronutrient fertilizers and soil amendments. These methods are effective in addressing deficiencies in essential nutrients such as zinc (Zn), iron (Fe), and selenium (Se). For instance, the application of zinc sulfate to soil has been shown to increase Zn concentration in crops like cabbage and canola (Mao et al., 2014). Similarly, nitrogen fertilization can improve the uptake of Zn and Fe in maize, enhancing the overall nutritional quality of the crop (Grujcic et al., 2021). Soil amendments, including the use of chelated fertilizers and nanoparticles, have also been found to improve nutrient uptake efficiency and translocation to consumable parts of the plant (Figure 2).

The study of Bhardwaj et al. (2022) illustrates a holistic approach to agronomic biofortification, integrating crop improvement, soil management, fertilizer management, and agronomic practices. Strategies such as enhancing root characteristics, improving nutrient translocation, and using biofortified crop varieties work alongside optimizing soil quality and moisture. Fertilizer innovations, including foliar applications, chelated forms, and nanofertilizers, aim to boost nutrient uptake at critical growth stages. Agronomic practices like precision nutrient placement and seed treatment further enhance the efficiency of nutrient absorption, leading to better crop nutrition and higher yields. These interventions collectively target improved nutrient use efficiency and sustainable agricultural productivity.

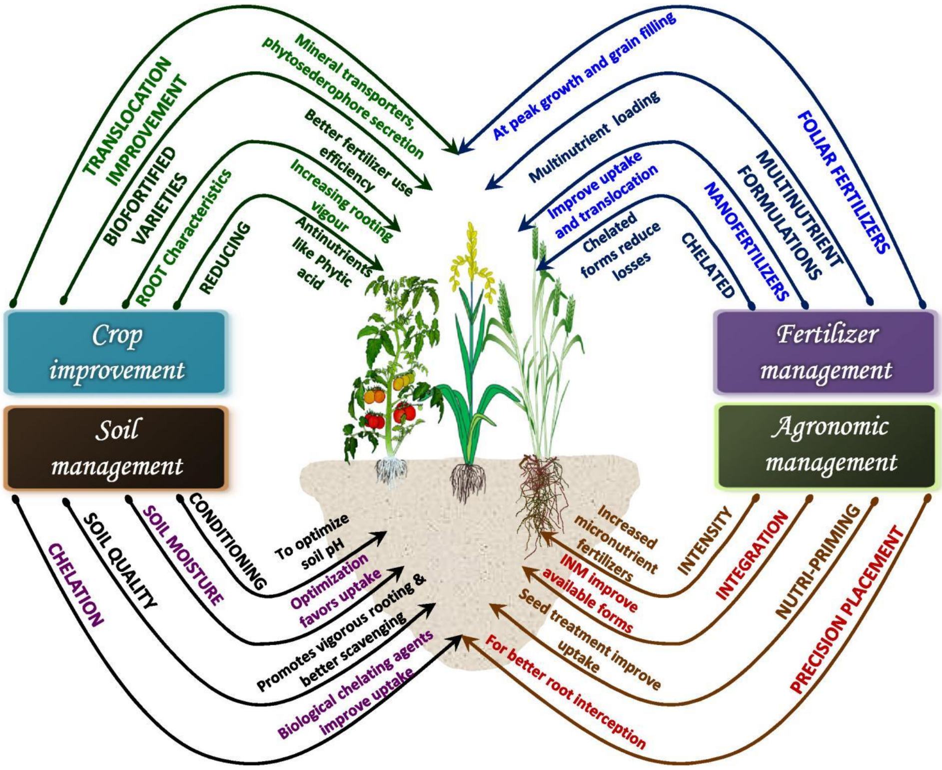

Figure 2 Agronomic, soil, fertilizer, and crop management based interventions to enhance the success of agronomic biofortification (Adopted from Bhardwaj et al., 2022)

4.2 Foliar applications for boosting micronutrient uptake

Foliar application is another effective method for biofortifying maize with essential micronutrients. This technique involves spraying nutrient solutions directly onto the leaves, allowing for rapid absorption and utilization by the plant. Studies have demonstrated that foliar application of micronutrients such as Zn, Fe, and Se can significantly increase their concentrations in crops. For example, foliar application of zinc sulfate has been effective in biofortifying winter wheat, increasing grain Zn content. Additionally, foliar feeding of a micronutrient mixture containing Zn, Fe, copper (Cu), manganese (Mn), and boron (B) has been shown to enhance the yield and nutritional quality of wheat (Aziz et al., 2019). The use of nano-Zn foliar sprays, in combination with plant growth-promoting bacteria, has also been identified as a sustainable approach to improve Zn biofortification in wheat (Jalal et al., 2023).

4.3 Integration of biofortification methods into existing agricultural practices

Integrating biofortification methods into existing agricultural practices involves combining soil-based and foliar applications with conventional farming techniques to enhance the micronutrient content of maize. This integrated approach ensures that biofortification efforts are sustainable and effective in the long term. For instance, the use of high-efficiency fertilizers, such as nano-fertilizers and chelated fertilizers, can be incorporated into regular fertilization schedules to improve nutrient uptake and translocation (Bhardwaj et al., 2022). Additionally, the selection of crop varieties with high nutrient use efficiency and the use of plant growth-promoting bacteria can further enhance the effectiveness of biofortification strategies. By adapting these methods to site-specific soil and management conditions, farmers can achieve better nutritional outcomes and contribute to addressing micronutrient deficiencies in human populations (Kihara et al., 2020).

5 Efficacy of Agronomic Biofortification in Maize Cultivation

5.1 Case studies highlighting successful biofortification programs

Agronomic biofortification is a promising strategy to address micronutrient deficiencies by increasing the concentration of essential minerals in food crops, such as maize. Several case studies have demonstrated the success of agronomic biofortification in increasing micronutrient concentrations in maize. For instance, a field experiment in Malawi showed that the application of zinc-enriched fertilizers significantly increased the zinc concentration in maize grains, which is crucial for addressing zinc deficiencies prevalent in the region (Botoman et al., 2020). Another study in Sub-Saharan Africa highlighted the effectiveness of micronutrient fertilization in improving the nutritional quality of staple crops, including maize, when combined with integrated soil fertility management practices (Valença et al., 2017). These case studies underscore the potential of agronomic biofortification to enhance the nutritional value of maize and contribute to food security.

5.2 Factors influencing the effectiveness of biofortification

The effectiveness of agronomic biofortification in maize cultivation is influenced by several factors, including soil type, climate, and crop management practices. Soil type plays a critical role, as different soils have varying capacities to retain and supply micronutrients to plants. For example, a study in Malawi found that the effectiveness of zinc biofortification varied between Lixisols and Vertisols, highlighting the importance of site-specific soil conditions. Climate also affects nutrient uptake and utilization by crops, with factors such as temperature and rainfall influencing the availability of micronutrients in the soil (Kihara et al., 2020). Additionally, crop management practices, including the type and method of fertilizer application, significantly impact the nutrient use efficiency and biofortification outcomes (Bhardwaj et al., 2022).

5.3 Challenges and limitations in implementing biofortification strategies

Despite its potential, agronomic biofortification faces several challenges and limitations. One major challenge is the variability in nutrient uptake and translocation efficiency among different maize genotypes, which can affect the consistency of biofortification outcomes (Teklu et al., 2023). Additionally, the cost and availability of micronutrient fertilizers can be a barrier for resource-poor farmers, limiting the widespread adoption of biofortification practices. Another limitation is the lack of direct evidence linking increased micronutrient concentrations in crops to improved human health outcomes, which is essential for justifying the investment in biofortification programs. Furthermore, socio-psychological factors, such as farmers' attitudes and beliefs, play a crucial role in the adoption of biofortification practices, as demonstrated in a study on iodine biofortification in Uganda (Aparo et al., 2023).

6 Case Study

6.1 Overview of a specific region where maize biofortification has been implemented

In the North-eastern region of Tamil Nadu, India, agronomic biofortification of maize has been actively implemented to address micronutrient deficiencies. This region, characterized by its reliance on maize as a staple crop, has seen significant efforts to enhance the nutritional quality of maize through biofortification practices.

6.2 Description of the biofortification approach used and the results achieved

The biofortification approach in Tamil Nadu involved the application of mineral fertilizers, specifically focusing on zinc (Zn) and iron (Fe). The study conducted in Chinnakandiankuppam village, Vriddhachalam Taluk, utilized integrated nutrient management practices. Two maize hybrids (biofortified and non-biofortified) were tested with six different treatments, combining recommended doses of fertilizers (RDF) through NPK and farmyard manure (FYM), along with foliar applications of Zn and Fe. The most effective treatment was found to be the application of 50% RDF through NPK and 50% through FYM, supplemented with foliar applications of Zn and Fe. This approach significantly improved growth attributes, yield, nutrient uptake, and quality parameters of maize (Augustine and Kalyanasundaram, 2021).

6.3 Lessons learned and best practices from the case study

The case study in Tamil Nadu highlighted several key lessons and best practices. Firstly, the integration of mineral fertilizers with organic amendments (FYM) proved to be highly effective in enhancing the bioavailability of micronutrients in maize. The combination of soil and foliar applications of Zn and Fe was particularly successful in increasing the micronutrient content in the edible parts of the crop. Additionally, the study underscored the importance of selecting appropriate hybrids that respond well to biofortification practices. The results demonstrated that agronomic biofortification is a viable and sustainable approach to combat micronutrient deficiencies in regions heavily dependent on maize. These findings suggest that similar integrated nutrient management practices could be adapted and applied in other regions facing similar nutritional challenges (Grujcic et al., 2021; Kiran et al., 2022).

7 Impact on Human Health and Nutrition

7.1 Evidence of improved micronutrient intake through maize consumption

Biofortified maize has shown significant potential in improving micronutrient intake among populations with limited access to diverse diets. For instance, a study conducted in Malawi demonstrated that the consumption of selenium-biofortified maize flour significantly increased serum selenium concentrations in women and children, indicating improved selenium intake through maize consumption (Joy et al., 2022). Additionally, research on biofortified fresh maize revealed that consuming 0.5 to 2 ears of fresh maize daily could supply substantial portions of the estimated average requirements for provitamin A, tryptophan, and zinc, further supporting the role of biofortified maize in enhancing micronutrient intake (Cabrera-Soto et al., 2018).

7.2 Assessment of the health outcomes from biofortified maize diets

The health outcomes from diets incorporating biofortified maize are promising. The addressing hidden hunger with agronomy (AHHA) trial in Malawi showed that selenium-biofortified maize significantly improved selenium status among women of reproductive age and school-aged children, with no adverse events reported. This improvement in selenium status is crucial as selenium is vital for immune function and antioxidant defense. Moreover, a systematic review of biofortified crops highlighted that biofortified maize, along with other crops, has been effective in improving micronutrient status in real-world settings, particularly in farmer households (Huey et al., 2022). These findings underscore the positive health impacts of biofortified maize diets.

7.3 Potential long-term benefits of biofortification on public health

The long-term benefits of biofortification on public health are substantial. Biofortification offers a sustainable and cost-effective strategy to address micronutrient deficiencies, which are prevalent in many developing regions (Kumar et al., 2022). By improving the nutritional quality of staple crops like maize, biofortification can help reduce the incidence of micronutrient deficiencies, thereby lowering the associated health risks such as impaired immune function, cognitive deficits, and increased morbidity and mortality (Dwivedi et al., 2023). Furthermore, the widespread adoption of biofortified crops has the potential to enhance overall public health outcomes by providing a consistent source of essential nutrients, contributing to better health and well-being on a population level.

8 Future Perspectives and Recommendations

8.1 Potential for expanding biofortification programs to other regions

The potential for expanding biofortification programs to other regions is significant, particularly in areas where micronutrient deficiencies are prevalent. For instance, Sub-Saharan Africa (SSA), Latin America, and South Asia are regions where maize biofortification could have a substantial impact due to the high prevalence of nutrient deficiencies (Goredema-Matongera et al., 2021). The success of biofortification in these regions can serve as a model for other areas facing similar challenges. Additionally, the variability in soil micronutrient deficiencies across different regions, such as the widespread zinc deficiency in SSA soils, suggests that tailored biofortification strategies could be developed to address specific regional needs (Kihara et al., 2020). Expanding these programs requires a comprehensive understanding of local soil conditions, crop varieties, and nutritional needs to ensure the effectiveness of biofortification efforts.

8.2 Opportunities for integrating agronomic biofortification with other nutritional interventions

Integrating agronomic biofortification with other nutritional interventions presents a holistic approach to combating micronutrient deficiencies. Combining biofortification with traditional methods such as supplementation and food fortification can enhance the overall nutritional status of populations. For example, the use of micronutrient fertilizers in conjunction with biofortified crops can further increase the nutrient content of staple foods (Kiran al., 2022). Additionally, integrating biofortification with community health programs and nutrition education can improve the acceptance and consumption of biofortified crops (Siwela et al., 2020). This multi-faceted approach ensures that the benefits of biofortification are maximized and that populations receive a balanced intake of essential nutrients.

8.3 Recommendations for policymakers, researchers, and farmers

Policymakers should prioritize the development and implementation of biofortification programs as part of national nutrition strategies. This includes providing funding for research and development, creating supportive policies for the adoption of biofortified crops, and ensuring that biofortified seeds are accessible to farmers. Researchers should focus on developing multi-nutrient biofortified crops that address multiple deficiencies simultaneously, as well as improving the efficiency of nutrient uptake and translocation in plants (Bhardwaj et al., 2022). Additionally, research should explore the integration of biofortification with other agricultural practices, such as the use of soil microorganisms and innovative fertilizer types, to enhance crop yield and nutritional quality (Feng, 2024). Farmers should be educated on the benefits of biofortified crops and trained in best practices for their cultivation. This includes understanding the importance of soil health, appropriate fertilizer application, and the selection of suitable crop varieties (Zuma et al., 2018). By working together, policymakers, researchers, and farmers can create a sustainable and effective system for addressing micronutrient deficiencies through agronomic biofortification.

9 Concluding Remarks

Agronomic biofortification has emerged as a promising strategy to address micronutrient deficiencies, particularly in regions like Sub-Saharan Africa (SSA) where soil and dietary deficiencies are prevalent. Studies have shown that the application of micronutrient fertilizers can significantly increase the concentrations of essential nutrients such as zinc (Zn), iron (Fe), and selenium (Se) in maize, thereby improving its nutritional quality. Additionally, biofortified maize varieties enriched with provitamin A have demonstrated potential in combating vitamin A deficiency (VAD), which affects millions of children in developing countries. The integration of biofortified crops into smallholder farming systems has been identified as a viable approach to reduce malnutrition and improve food security.

Agronomic biofortification is crucial for addressing micronutrient deficiencies, especially in developing regions where dietary diversity is limited, and staple crops form the bulk of the diet. By enhancing the micronutrient content of crops like maize, biofortification can directly improve the nutritional intake of vulnerable populations, including women and children. This approach not only addresses hidden hunger but also promotes sustainable agricultural practices by improving soil health and crop yields. The success of biofortified crops in various regions underscores the importance of continued investment in this strategy to achieve long-term nutritional security.

To fully realize the potential of agronomic biofortification, further research and implementation efforts are needed. Future studies should focus on optimizing fertilizer application methods, understanding the interactions between soil types and nutrient uptake, and developing multi-nutrient biofortified crop varieties that can thrive under diverse environmental conditions. Additionally, there is a need for comprehensive policy frameworks and community engagement to ensure the widespread adoption and acceptance of biofortified crops. Training programs and workshops for farmers, along with nutrition education for consumers, are essential to maximize the benefits of biofortification interventions. By prioritizing these efforts, we can make significant strides towards eradicating micronutrient deficiencies and improving global health outcomes.

Acknowledgments

The authors grateful to two anonymous reviewers for comments on previous drafts of this study.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Ahmad M., Hussain A., Dar A., Luqman M., Ditta A., Iqbal Z., Ahmad H., Nazli F., Soufan W., Almutairi K., and Sabagh A., 2023, Combating iron and zinc malnutrition through mineral biofortification in maize through plant growth promoting bacillus and paenibacillus species, Frontiers in Plant Science, 13: 1094551.
https://doi.org/10.3389/fpls.2022.1094551

Aparo N., Olum S., Atimango A., Odongo W., Aloka B., Ongeng D., Gellynck X., and Steur H., 2023, Farmers' intention to adopt agronomic biofortification: the case of iodine biofortified vegetables in Uganda, Horticulturae, 9(3): 401.
https://doi.org/10.3390/horticulturae9030401

Augustine R., and Kalyanasundaram D., 2021, Effect of agronomic biofortification on growth, yield, uptake and quality characters of maize (*Zea mays* .L) through integrated management practices under North-eastern region of Tamil Nadu, India, Journal of Applied and Natural Science, 13: 278-286.
https://doi.org/10.31018/JANS.V13I1.2539

Avnee, Sood S., Chaudhary D., Jhorar P., and Rana R., 2023, Biofortification: an approach to eradicate micronutrient deficiency, Frontiers in Nutrition, 10: 1233070.
https://doi.org/10.3389/fnut.2023.1233070

Aziz M., Yaseen M., Abbas T., Naveed M., Mustafa A., Hamid Y., Saeed Q., and Minggang X., 2019, Foliar application of micronutrients enhances crop stand, yield and the biofortification essential for human health of different wheat cultivars, Journal of Integrative Agriculture, 18(6): 1369-1378.
https://doi.org/10.1016/S2095-3119(18)62095-7

Bhardwaj A., Chejara S., Malik K., Kumar R., Kumar A., and Yadav R., 2022, Agronomic biofortification of food crops: An emerging opportunity for global food and nutritional security, Frontiers in Plant Science, 13: 1055278.
https://doi.org/10.3389/fpls.2022.1055278

Botoman L., Nalivata P., Chimungu J., Munthali M., Bailey E., Ander E., Lark R., Mossa A., Young S., and Broadley M., 2020, Increasing zinc concentration in maize grown under contrasting soil types in Malawi through agronomic biofortification: trial protocol for a field experiment to detect small effect sizes, Plant Direct, 4(10): e00277.
https://doi.org/10.1002/pld3.277

Bouis H., and Saltzman A., 2017, Improving nutrition through biofortification: a review of evidence from HarvestPlus, 2003 through 2016, Global Food Security, 12: 49-58.
https://doi.org/10.1016/j.gfs.2017.01.009

Bouis H., and Welch R., 2010, Biofortification - a sustainable agricultural strategy for reducing micronutrient malnutrition in the global south, Crop Science, 50: 20-32.
https://doi.org/10.2135/CROPSCI2009.09.0531

Cabrera-Soto L., Pixley K., Rosales-Nolasco A., Galicia-Flores L., and Palacios-Rojas N., 2018, Carotenoid and tocochromanol profiles during kernel development make consumption of biofortified "fresh" maize an option to improve micronutrient nutrition, Journal of Agricultural and Food Chemistry, 66(36): 9391-9398.
https://doi.org/10.1021/acs.jafc.8b01886

Dhaliwal S., Sharma V., Shukla A., Shivay Y., Hossain A., Verma V., Gill M., Singh J., Bhatti S., Verma G., Singh J., and Singh P., 2022a, Agronomic biofortification of forage crops with Zn and Cu for enhancing nutritive potential-a systematic review, Journal of the Science of Food and Agriculture, 103(4): 1631-1643.
https://doi.org/10.1002/jsfa.12353

Dhaliwal S., Sharma V., Shukla A., Verma V., Kaur M., Shivay Y., Nisar S., Gaber A., Brestič M., Bárek V., Skalický M., Ondrisik P., and Hossain A., 2022b, Biofortification-a frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security, Molecules, 27(4): 1340.
https://doi.org/10.3390/molecules27041340

Dwivedi S., Garcia-Oliveira A., Govindaraj M., and Ortiz R., 2023, Biofortification to avoid malnutrition in humans in a changing climate: enhancing micronutrient bioavailability in seed, tuber, and storage roots, Frontiers in Plant Science, 14: 1119148.
https://doi.org/10.3389/fpls.2023.1119148

Feng X.Z., 2024, Genetic and environmental factors influencing grain quality in maize, Maize Genomics and Genetics, 15(2): 93-101.
https://doi.org/10.5376/mgg.2024.15.0010

Galani Y., Orfila C., and Gong Y., 2020, A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa, Critical Reviews in Food Science and Nutrition, 62: 1568-1591.
https://doi.org/10.1080/10408398.2020.1844636

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

Goredema-Matongera N., Ndhlela T., Magorokosho C., Kamutando C., Biljon A., and Labuschagne M., 2021, Multinutrient biofortification of maize (*Zea mays* L.) in Africa: current status, opportunities and limitations, Nutrients, 13(3): 1039.
https://doi.org/10.3390/nu13031039

Grujcic D., Yazıcı A., Tutus Y., Cakmak I., and Singh B., 2021, Biofortification of silage maize with zinc, iron and selenium as affected by nitrogen fertilization, Plants, 10(2): 391.
https://doi.org/10.3390/plants10020391

Huey S., Krisher J., Bhargava A., Friesen V., Konieczynski E., Mbuya M., Mehta N., Monterrosa E., Nyangaresi A., and Meht S., 2022, Review of the impact pathways of biofortified foods and food products, Nutrients, 14(6): 1200.
https://doi.org/10.3390/nu14061200

Jalal A., Oliveira C., Fernandes G., Silva E., Costa K., Souza J., Leite G., Biagini A., Galindo F., and Filho M., 2023, Integrated use of plant growth-promoting bacteria and nano-zinc foliar spray is a sustainable approach for wheat biofortification, yield, and zinc use efficiency, Frontiers in Plant Science, 14: 1146808.
https://doi.org/10.3389/fpls.2023.1146808

Jiang L., Strobbe S., Straeten D., and Zhang C., 2020, Regulation of plant vitamin metabolism: backbone of biofortification for the alleviation of hidden hunger, Molecular Plant, 14(1): 40-60.
https://doi.org/10.1016/j.molp.2020.11.019

Joy E., Kalimbira A., Sturgess J., Banda L., Chiutsi-Phiri G., Manase H., Gondwe J., Ferguson E., Kalumikiza Z., Bailey E., Young S., Matandika L., Mfutso-Bengo J., Millar K., Nikšić M., Revilla L., Likoswe B., Phuka J., Phiri F., Lark R., Gashu D., Langley-Evans S., Ander E., Lowe N., Dangour A., Nalivata P., Broadley M., and Allen E., 2022, Biofortified maize improves selenium status of women and children in a rural community in malawi: results of the addressing hidden hunger with agronomy randomized controlled trial, Frontiers in Nutrition, 8: 788096.
https://doi.org/10.3389/fnut.2021.788096

Kihara J., Bolo P., Kinyua M., Rurinda J., Piikki K., and Piikki K., 2020, Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops, Environmental Geochemistry and Health, 42: 3015-3033.
https://doi.org/10.1007/s10653-019-00499-w

Kiran A., Wakeel A., Mahmood K., Mubaraka R.H., and Haefele S., 2022, Biofortification of staple crops to alleviate human malnutrition: contributions and potential in developing countries, Agronomy, 12(2): 452.
https://doi.org/10.3390/agronomy12020452

Kumar S., DePauw R., Kumar S., Kumar J., Kumar S., and Pandey M., 2022, Breeding and adoption of biofortified crops and their nutritional impact on human health, Annals of the New York Academy of Sciences, 1520: 5-19.
https://doi.org/10.1111/nyas.14936

Li L., and Huang W.Z., 2024, The genetic basis of nutritional quality traits in maize: insights from GWAS, Maize Genomics and Genetics, 15(1): 17-24.
https://doi.org/10.5376/mgg.2024.15.0003

Mao H., Wang J., Wang Z., Zan Y., Lyons G., and Zou C., 2014, Using agronomic biofortification to boost zinc, selenium, and iodine concentrations of food crops grown on the loess plateau in China, Journal of Soil Science and Plant Nutrition, 14: 459-470.
https://doi.org/10.4067/S0718-95162014005000036.

Nuss E., and Tanumihardjo S., 2010, Maize: a paramount staple crop in the context of global nutrition, Comprehensive Reviews in Food Science and Food Safety, 9(4): 417-436.
https://doi.org/10.1111/J.1541-4337.2010.00117.X

Siwela M., Pillay K., Govender L., Lottering S., Mudau F., Modi A., and Mabhaudhi T., 2020, Biofortified crops for combating hidden hunger in South Africa: availability, acceptability, micronutrient retention and bioavailability, Foods, 9(6): 815.
https://doi.org/10.3390/foods9060815

Teklu D., Gashu D., Joy E., Amede T., and Broadley M., 2023, Effectiveness of agronomic biofortification strategy in fighting against hidden hunger, Agronomy, 13(8): 2173.
https://doi.org/10.3390/agronomy13082173

Titcomb T., and Tanumihardjo S., 2019, Global concerns with b vitamin statuses: biofortification, fortification, hidden hunger, interactions, and toxicity, Comprehensive Reviews in Food Science and Food Safety, 18(6): 1968-1984.
https://doi.org/10.1111/1541-4337.12491

Valença A., Bake A., Brouwer I., and Giller K., 2017, Agronomic biofortification of crops to fight hidden hunger in Sub-Saharan Africa, Global Food Security, 12: 8-14.
https://doi.org/10.1016/J.GFS.2016.12.001

Zuma M., Kolanisi U., and Modi A., 2018, The potential of integrating provitamin a-biofortified maize in smallholder farming systems to reduce malnourishment in South Africa, International Journal of Environmental Research and Public Health, 15(4): 805.
https://doi.org/10.3390/ijerph15040805