AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 02, Issue: 04 (April, 2025)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

Zinc Biofortification in Maize

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Micronutrient deficiencies, mainly zinc (Zn), iron (Fe), and selenium (Se), often lead to malnutrition (also known as hidden hunger), causing a significant global health issue and affecting almost one-third of the world's population. Zinc plays an essential role in both human and plant health. In humans, it causes weak immune systems, stunted growth and development, impaired brain function, poor mental development, weakness in babies, anemia, and increased vulnerability to diseases. In plants, Zn supports photosynthesis, seed development, and resistance to environmental stresses like drought and pests. Thus, in the absence of sufficient Zn, the world's overall food security is impacted due to the decrease in plant growth, low crop yield, and poor food quality (Gallego-Castillo et al. 2021, Maqbool and Beshir, 2018).

This problem is especially severe in developing countries, where diets mainly consist of staple cereals with low nutrient content. Maize, a key food source, contributes significantly to global protein (15%) and calorie (20%) intake, making its nutritional quality vital for human and animal health. In regions like South Asia, declining soil fertility and high crop demand for minerals have led to widespread zinc depletion, further exacerbating the deficiency. As a result, people relying on low-zinc cereals face serious health risks, worsening the global burden of malnutrition, which costs an estimated $3.5 trillion annually (Nugent et al. 2020). In low-income and rural areas, mostly women, children, and elderly people are affected, as they do not fulfill their diet's daily recommended allowance (DRA) of zinc (Table 1).

The main causes of Zn deficiency include diets based on low-Zn cereals, lack of dietary diversity, and limited access to animal-based foods rich in zinc, such as fish, meat, eggs, and dairy. Strategies like supplementation and dietary diversification have been suggested, but affordability and accessibility remain major challenges, especially in rural areas. A more sustainable and cost-effective solution is biofortification—enhancing Zn levels in crops through genetic improvement, fertilizer application, or biotechnology.

Maize (*Zea mays* L.), as a widely consumed staple, is a prime target for Zn biofortification. Scientists are improving its Zn content using breeding programs, fertilizer applications, and genetic modifications. Agronomic biofortification, such as foliar sprays of Zn, has proven effective, especially when combined with nitrogen, which enhances zinc absorption and bioavailability.

This article provides a brief understanding of the strategies for improving Zn levels in maize through various biofortification approaches, their needs and challenges in adopting the improved crop varieties, soil management, and optimized fertilization practices, which can significantly enhance food security, nutrition, and public health.

Table 1. Daily Recommended Allowance (DRA) of Zinc for different age groups and genders (Source NIH, 2022)

Variable age	Male (mg/day)	Female (mg/day)
0-6 months	2	2
7-12 months	3	3
1-3 years	3	3
4-8 years	5	5
9–13 years	8	8
14-18 years	11	9
19+ years	11	8
Pregnancy	-	11-12
Lactation	-	12-13

Zinc Biofortification—What does it mean?

Zinc biofortification is a process that enhances the zinc content in maize through selective breeding, genetic modification, or fertilizer-based agronomic practices. This method ensures that crops such as maize, wheat, and rice naturally contain higher zinc levels as they grow, unlike traditional fortification methods that require adding nutrients after the harvesting of crops. It also facilitates the increase in nutrient levels in the crops throughout their growth and development.

This approach aims to improve the nutritional value of staple crops, making them more resilient, productive, and beneficial to human health, especially in rural and low-income communities. Once a biofortified crop is successfully developed and grown in a region, its higher nutrient levels remain consistent without the need for repeated genetic modifications.

Methods of Zinc Biofortification in Maize

There are three primary approaches to biofortify zinc in maize: agronomic biofortification, conventional breeding, and genetic engineering approaches.

1. **Agronomic Biofortification:** In the agronomic biofortification approach, essential micronutrient-enriched fertilizers are used to enhance the crop's nutritional value. It is a simple, quick, but efficient method to increase a plant's nutrient absorption, especially in nutrient-deficient soils. It can be done via soil application (addition of minerals externally to improve soil's nutrient availability), foliar spraying (direct spray on leaves for faster absorption), seed treatment (coating seeds with zinc before sowing), or soil management (crop rotation and addition of biofertilizer to improve soil quality).
2. **Conventional Breeding:** Conventional breeding methods, such as marker-assisted selection (MAS), QTL mapping, and genomic selection, are also essential methods to biofortify Zn in maize. QTL mapping has identified chromosomal regions linked to Zn and Fe accumulation, allowing simultaneous improvement of both minerals. Genome-wide association studies (GWAS) additionally identify important SNPs for targeted breeding, whereas genomic selection combines the molecular and phenotypic data to overcome environmental challenges. Due to yield dilution effects, landraces usually have higher Zn levels than modern varieties, and MAS accelerates Zn biofortification. Organizations like HarvestPlus and CIMMYT lead global efforts, which show that selective breeding elevates Zn levels via natural genetic variation. Heritability estimation for kernel Zn concentration (0.60–0.69) reflects strong genetic control, despite environmental effects. Quality protein maize (QPM) varieties naturally contain higher Zn levels, promoting multi-nutrient enhancement (Maqbool and Beshir, 2018). Conventional breeding remains the most affordable biofortification strategy to cure micronutrient deficiencies and improve food security in vulnerable populations globally.
3. **Genetic Engineering:** Genetic engineering and advanced breeding techniques play a vital role in maize biofortification to increase zinc content and improve its accumulation in maize. By allowing the regulation of Zn and Fe, the overexpression of NAS genes like

AtNAS1 and OsNAS1 can increase their accumulation. And by reducing an anti-nutrient, phytic acid (PA), bioavailability of Zn and Fe can be enhanced. CRISPR/Cas9 and other genome editing technologies offer a promising solution by targeting the IPK1 gene, which controls PA biosynthesis. There are also some examples of transgenic maize varieties with increased levels of provitamin A, vitamin C, vitamin E, and essential amino acids like lysine via genetic modification. Even with a high initial cost, the genetic engineering approach is still a cost-effective and sustainable way to enhance nutrition globally.

Zinc Biofortification— The Need

Zinc biofortification in maize is a major strategy to overcome widespread zinc deficiency that affects billions of people globally, primarily children and pregnant women. Recent studies show that consuming biofortified maize can provide up to 29% more zinc than conventional maize, significantly improving immune function, cognitive development, and overall health (Gallego-Castillo et al. 2021). Unlike supplements that require continuous distribution, biofortified maize provides a sustainable and cost-effective solution, improving food security while benefiting both consumers and farmers. Furthermore, cultivating zinc-rich maize increases crop yields and resilience to environmental stresses, ensuring better profitability for farmers in regions where zinc deficiency is common. Moreover, zinc biofortification can improve nitrogen (N) and potassium (K) absorption, strengthening the grain quality and having no adverse impact on the plant's Fe levels. For livestock farmers, fodder with a rich zinc level can enhance crude protein content, resulting in healthier animals and increased production of milk and eggs (Obaid et al., 2022).

Zinc Biofortification— Its Challenges and Future

Globally, Zn biofortification in maize faces several challenges in its adoption at the production level. The foremost concern is that the biofortified maize varieties may have lower yields, making the switch to these varieties hard for farmers. Even so, the researchers have suggested that yield and nutritional values can be improved simultaneously. Another problem is the biofortified maize's limited genetic diversity, which requires considerable breeding efforts to diversify its parental lines. Also, the need to prevent biofortified lines from getting contaminated with non-biofortified lines is a huge task. Additionally, inductively coupled plasma spectrometry (ICP) and X-ray fluorescence (XRF) methods provide precise and accurate mineral quantification but are expensive and thus inaccessible to small-scale farmers. Acceptance from consumers and the market is also another challenge, as it is difficult to promote Zn-enriched varieties that lack visible traits.

For zinc biofortification in maize to succeed, economic viability, policy support, and public awareness are essential. Subsidies, market incentives, and education can drive acceptance. Genome editing offers precise improvements without foreign DNA, making it more acceptable. Combined with advanced breeding and better post-harvest management, biofortification can effectively combat malnutrition globally.

Conclusion

To tackle global malnutrition, zinc biofortification in maize is an essential tactic, particularly in developing countries with limited dietary diversity. By enhancing zinc levels through genetic modification, agronomic approach, and biotechnology, biofortified maize enhances nutrition, strengthens immunity, and improves overall health. HarvestPlus initiatives have successfully introduced biofortified crops across the world; however, they require policy support, sustained funding, and collaboration between researchers, policymakers, and farmers for widespread adoption (HarvestPlus). Advancements in agronomic biofortification, such as nano-fertilizers, foliar sprays, and hydroponics, and genome editing, like CRISPR, show promising solutions to increase zinc levels in maize, ensuring long-term nutritional security.

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