Chapter-15
Improvement of Nutritional Values in Crops by Bionanofortification: A Solution to Combat Hidden Hunger

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Abstract:

Micronutrient malnutrition, commonly referred to as "hidden hunger," continues to pose a significant global health challenge, particularly in regions that rely heavily on nutritionally limited staple foods. Nanotechnology-assisted biofortification presents an advanced strategy for improving the micronutrient profile of crops by employing nanoscale materials to deliver essential trace elements such as zinc, iron, and silicon with greater precision and efficiency. Different categories of nanoparticles (NPs), including ZnO, Fe_2O_3, and Si-based NPs, enhance nutrient absorption and internal movement through mechanisms such as controlled release, improved solubility and stimulation of nutrient transport pathways. Nevertheless, concerns relating to potential toxicity, regulatory limitations and economic constraints are critically addressed. Prospective advancements emphasize the creation of smart, environmentally compatible nanocarriers and their integration into precision farming practices. Overall, nanotechnology-driven biofortification stands out as a promising solution for strengthening nutritional security and advancing sustainable agricultural systems.

Keywords: Hidden Hunger, Bionanofortification, Crops, Nutritional Value

Introduction

Nanotechnology, defined as the design and manipulation of materials at dimensions ranging from 1 to 100 nanometer has significantly expanded possibilities across numerous scientific fields, including modern agriculture. Among its emerging applications, nanotechnology-based biofortification represents a powerful method for enriching crops with essential nutrients using engineered nanomaterials. As micronutrient deficiencies continue to impact more than 2 billion individuals worldwide, especially within developing regions, improving the nutritional composition of staple food crops has become both a public health priority and an ongoing scientific challenge (Kapoor et al., 2022). Conventional fertilization approaches often exhibit low nutrient use efficiency, resulting in substantial nutrient losses to the surrounding environment and reduced availability to plants. Nanotechnology introduces a sustainable alternative by enhancing the efficiency of nutrient uptake, minimizing environmental dissipation and enabling controlled nutrient delivery to crops.

Methods of Crop Biofortification

1. Agronomic biofortification

Agronomic biofortification involves the application of mineral-based fertilizers to increase nutrient levels in crops. Major approaches include:

a. Micronutrient-rich fertilizers are incorporated into the soil. For example, zinc sulfate application in wheat fields has been demonstrated to notably elevate zinc accumulation in grains.
b. Nutrient-enriched sprays are applied directly to foliage. This method effectively improves micronutrient levels in crops such as mango and chickpea (Kharra et al., 2024).
c. Beneficial microorganisms, including Plant Growth-Promoting Rhizobacteria (PGPR), are used to enhance nutrient acquisition. Strains like *Pseudomonas fluorescens* have been shown to increase iron uptake in rice grains (Chaudhary et al. 2022).

2. Genetic biofortification:

Genetic biofortification aims to produce crop varieties with inherently elevated nutrient concentrations. Plants exhibiting naturally higher levels of nutrients are selected and crossbred. Numerous enriched varieties have been developed and released both in India and globally (Table 1). Specific genes are introduced to boost nutrient production in plants. A well-known example is "Golden Rice," engineered to synthesize beta-carotene to combat vitamin A deficiency.

Table 1: Bionanofortification of few varieties of crops (Kapoor et al., 2022)

Crop	Biofortified Characteristic	Micronutrient Improved	Varieties	Country/Region
Rice	Enhanced Zinc Levels	Zinc	DRR Dhan 45, DRR Dhan 49	India
Wheat	Elevated Zinc Content	Zinc	WB 02, HPBW 01	India
Maize	Provitamin A–rich (orange maize)	Vitamin A	HQPM 1, PVA 6, PVA 9	Nigeria, Zambia, India
Sweet Potato	Orange-fleshed (OFSP)	Vitamin A (beta-carotene)	Kabode, Ejumula	Uganda, Mozambique
Cassava	Yellow-fleshed	Vitamin A	IITA-TMS 07/0593, TMS 01/1368	Nigeria, DR Congo, Brazil
Pearl Millet	Increased Iron and Zinc	Iron, Zinc	ICTP-8203Fe, Dhanashakti	India, Africa
Beans	High Iron Content	Iron	MIB465, BIO101	Rwanda, DR Congo, Latin America
Lentils	Elevated Iron and Zinc	Iron, Zinc	IPL 220, L4076	India
Banana	High Provitamin A	Vitamin A	Matooke hybrids (such as NARITA varieties)	Uganda

Need for Nanotechnology-Based Biofortification

Agronomic biofortification techniques such as soil fertilization, foliar nutrient sprays, seed priming or immersing seedlings in nutrient solutions (Table 2) often require repeated applications, increased labor and significant resource input, which can also lead to secondary environmental impacts. Genetic engineering approaches, although beneficial, involve high costs and demand advanced technological infrastructure. In contrast, nanotechnology-based fertilizers address these limitations by enhancing nutrient use efficiency and achieving biofortification with improved accuracy and reduced resource wastage.

Table 2: Different methods of Bionanofortification of common crops and their applications

Crop	Bionanofortific-ation Method	Micronutrient Improved	Application Mode	Observed Effects	Reference
Wheat (*Triticum aestivum*)	ZnO nanoparticles	Zinc	Foliar spraying	Promoted plant growth, better yield and higher Zn accumulation in grains	Raliya et al., (2016)
Rice (*Oryza sativa*)	Chitosan–Zn nanoparticles	Zinc	Soil and foliar treatments	Increased Zn absorption and improved antioxidant response	Prajapati et al., (2022)
Maize (*Zea mays*)	Iron oxide (Fe_2O_3) nanoparticles	Iron	Foliar spraying	Elevated iron levels in leaves and seeds; stimulated chlorophyll formation	Dimkpa et al., (2017)
Tomato (*Solanum lycopersicum*)	Chitosan nanoparticles	Zinc	Soil application	Reduced nutrient leaching, enhanced uptake and increased biomass	Khot et al., (2012)
Wheat	Multi-walled carbon nanotubes	Mixed micronutrients	Seed priming	Improved seed emergence, nutrient transport and photosynthetic activity	Khodakovskaya et al., (2009)
Rice	SiO_2 nanoparticles	Silicon	Soil application	Better Fe/Zn assimilation due to modified root traits	Tripathi et al., (2017)
Mung bean (*Vigna radiata*)	Iron oxide nanoparticles	Iron	Seed priming	Enhanced Fe absorption, superior germination and biomass production	Nair et al., (2010)

Mechanisms of Nanotechnology in Biofortification (Nair et al., 2010)

Nanoparticles (NPs) are capable of interacting with plant systems. Nanoparticles interact with plant systems at both cellular and molecular scales. Due to their nanoscale dimensions, large reactive surface area and adjustable characteristics, they can enter plant cells, influence biochemical processes and enhance the assimilation of essential micronutrients. The principal mechanisms through which nanotechnology aids biofortification include:

a. Nanocarriers can be designed to discharge nutrients in response to environmental cues such as changes in pH or moisture, ensuring nutrient supply matches crop requirements.

b. Nanoparticles enhance the dissolution and movement of low-solubility nutrients like zinc and iron, promoting better uptake through roots and foliage.

c. Certain nanoparticles can upregulate genes responsible for transporter proteins, facilitating efficient movement of micronutrients from the roots to the aerial parts.

d. Some nanomaterials increase plant tolerance to drought, heat and salinity, thereby indirectly improving nutrient absorption and deposition.

Types of Nanoparticles Used in Biofortification

1. Zinc Oxide (ZnO) nanoparticles

Zinc plays a crucial role in enzyme activation, protein formation and overall defense responses in plants. However, zinc scarcity in many soils reduces Zn levels in edible crop tissues. ZnO nanoparticles are mainly used in foliar applications or mixed into soil. Research reports enhanced grain zinc accumulation, chlorophyll levels and antioxidant enzyme efficiency in crops such as wheat, rice and maize (Raliya et al., 2016).

2. Iron Oxide (Fe_2O_3) nanoparticles

Iron is indispensable for processes such as photosynthesis and cellular respiration. Iron deficiency in human populations results in anemia. Fe_2O_3 nanoparticles are commonly used in seed priming and foliar treatments. These iron nanomaterials have been shown to boost Fe uptake in crops including spinach, maize and mung bean, contributing to better chlorophyll formation and improved yield (Dimkpa et al., 2017).

3. Silicon nanoparticles (Si-NPs)

Although silicon is not categorized as an essential nutrient, it supports structural and defensive functions in plants. Si-NPs contribute to enhanced nutrient uptake indirectly by alleviating both biotic and abiotic stresses. Improved iron and zinc absorption has been documented in wheat and rice due to modifications in root architecture and stronger antioxidant systems (Tripathi et al., 2017).

5.4. Other emerging nanomaterials (Table 3)

a. Nano-hydroxyapatite used for supplying phosphorus.
b. Carbon-based nanomaterials, including graphene oxide, which assist in nutrient mobility and photosynthetic efficiency.
c. Chitosan-derived nanoparticles used for nutrient encapsulation along with plant protection.

Table 3: Varieties of Nanocarriers used for Bionanofortification and their applications

Type of Nanocarrier	Composition/ Material	Delivered Nutrients	Way of delivery	Applications for crops	Reference
Metals/ Oxide of Metals NPs	Fe2O3, ZnO, Fe3O4, Se, CuO, MnO2, NPs	Fe, Zn, Se, Cu, Mn	seed priming, soil, Foliar	rice, spinach, Wheat, tomato, maize	Raliya et al. (2016)
Silica NPs	SiO2	Silicon	Foliar, Soil	Maize, Rice, wheat	Tripathi et al. (2017)
Polymeric Nanocarriers	alginate, Chitosan, PLGA	Fe, Zn, Se, Cu	seed coating, soil, Foliar	-	Prajapati et al. (2022)
Carbon based Nanomaterials	Graphene, Multiwalled carbon nanotubes	Nutrient mixture	Foliar, Seed priming	Maize, Wheat, soy	Khodakovskaya et al. (2009)
Nano-Emulsions	Lipid based emulsions	Fe, Hydrophobic vitamins	Foliar	fruit crops, Leafy vegetables	Khot et al. (2012)
Nano chelates	nanoscale Chelated forms of the metals	Fe- EDTA, Zn-EDTA	Foliar	Wheat, Rice, vegetables	Dimkpa et al. (2017)

Advantages of Nano-biofortification

a. Nanoparticles provide controlled and prolonged nutrient dissolution because of their high surface area-to-volume ratio. This minimizes nutrient loss through leaching and ensures continuous supply during vital growth phases (Raliya et al., 2015).

b. Nano-formulations of Zn and Fe exhibit better solubility and higher uptake efficiency than conventional fertilizers due to improved nutrient persistence and enhanced bioavailability (Prajapati et al., 2022).

c. Improved absorption at the root level allows lower fertilizer dosages, increasing efficiency. Nano-Zn and nano-Fe formulations have demonstrated up to 35–40% greater uptake in maize compared with traditional sources.

d. Greater deposition of Fe and Zn in edible plant parts. Application of nano-$ZnSO_4$ and nano-$FeSO_4$ to sorghum resulted in 28% and 34% increases in Zn and Fe, respectively (Dimkpa et al., 2017).

e. Plants display stronger stress tolerance and better growth.

f. Helps combat hidden hunger and improves overall dietary quality.

g. Nanoparticles can be linked with smart tools and sensor-based delivery systems.

Challenges and Limitations

Even with its advantages, several obstacles restrict the large-scale implementation of nano-biofortification. The long-term impacts of nanoparticle buildup in ecosystems and food chains remain uncertain. Uniform guidelines for nanoparticle production, dosing and safety evaluation are not yet established. The manufacturing and designing nanomaterials involve high costs.

Moreover there are insufficient regulatory frameworks governing the safe agricultural application of nanotechnology.

Future Prospects

a. Advancement of nanoparticles that respond to environmental or biological signals to discharge nutrients precisely when required.
b. Utilizing genome-editing tools together with nanoparticle-assisted delivery of nutrients or regulatory molecules for enhanced fortification.
c. Adoption of green fabrication techniques to generate safer and more sustainable nanoparticles.
d. Conducting long-duration trials across varying agro-climatic conditions to confirm performance, stability and safety.

Conclusion

Nanotechnology-driven biofortification represents an emerging approach capable of addressing persistent micronutrient deficiencies by sustainably elevating the nutritional value of crops. By linking plant science with engineered materials, it enables the development of nutrient-rich, resilient cropping systems. Nonetheless, its widespread application will depend on collaborative research, coordinated public–private initiatives, supportive regulatory frameworks and increased awareness among stakeholders.

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