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Nano-biofortification for Improving Nutrient Status of Crop Plants

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Abstract

Micronutrient malnutrition, often termed "hidden hunger," remains a major global health concern, particularly in developing nations dependent on staple crops with limited nutritional diversity. Nanotechnology-enabled biofortification offers a revolutionary approach to enhancing the nutritional content of crops by using nanoscale materials for the precise and efficient delivery of essential micronutrients like zinc, iron, and silicon. Various types of Nanoparticles (NPs) such as (ZnO, Fe_2O_3 and Si-NPs) enhance nutrient uptake and translocation, including controlled release, increased solubility and activation of nutrient transporters. However, challenges such as potential toxicity, regulatory gaps and high costs are critically examined. Future directions focus on the development of smart, eco-friendly nanocarriers and integration with precision agriculture. Overall, nanotechnology-enabled biofortification emerges as a promising strategy to address nutritional security and promote sustainable agriculture.

1. Introduction

Nanotechnology, the manipulation and application of materials at the atomic or molecular scale (1 to 100 nanometers), has opened new frontiers across many disciplines, including agriculture. One of the most promising applications in the agri-food sector is nanotechnology-enabled biofortification, a process of increasing the nutrient content of crops using nanomaterials. With micronutrient deficiencies (hidden hunger) affecting over 2 billion people globally, especially in developing countries, enhancing the nutritional quality of staple crops is both a public health necessity and a technological challenge (Kapoor et al, 2022). Traditional fertilization techniques often suffer from low nutrient use efficiency, resulting in the loss of nutrients to the environment and limited bioavailability to the plants. Nanotechnology offers an innovative and sustainable

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pathway by enhancing nutrient uptake efficiency, reducing environmental losses and delivering nutrients in a controlled manner.

2. Methods of Crop Biofortification

2.1. Agronomic biofortification

Agronomic biofortification involves the application of mineral fertilizers to enhance the nutrient content of crops. The key techniques include:

• **Soil application**: Incorporating micronutrient-rich fertilizers into the soil. For instance, applying zinc sulfate to wheat fields has been shown to increase grain zinc concentration significantly.

• **Foliar application**: Spraying nutrient solutions directly onto the plant leaves. This method has proven effective in increasing micronutrient content in crops like chickpea and mango (Kharra et al., 2024).

• **Use of biofertilizers**: Employing beneficial microorganisms, such as Plant Growth-Promoting Rhizobacteria (PGPR), to enhance nutrient uptake. The PGPR strains like *Pseudomonas fluorescens* have been shown to increase iron concentration in rice grains (Chaudhary et al., 2022).

2.2. Genetic biofortification

Genetic biofortification focuses on developing crop varieties with inherently higher nutrient content.

• **Conventional breeding**: Selecting and cross-breeding plants with naturally higher nutrient levels. Many varieties have been developed and released in India and across the world (Table 1).

• **Genetic engineering**: Introducing specific genes to enhance nutrient synthesis. A notable example is "Golden Rice," engineered to produce beta-carotene, addressing vitamin A deficiencies.

3. Need for Nanotech based Biofortification

The main drawback from the agronomic biofortification involving fertilization of food crops with through physical application either directly to the soil, as foliar spray, by seed priming or by immersing seedlings into fertilizer solutions (Table 2). It needs a repeated amendment, more labour and resource intensive, leading to potential secondary environmental damage. Whereas for genetic engineering, it costs more and needs more and more technological advancements. Above all the current scenario where nanotech based fertilizers clear out the drawbacks and provide improve nutrient use efficiency and impart biofortification with near precision.

4. Mechanisms of nanotechnology in biofortification

Nanoparticles (NPs) can interact with plant systems

Table 1: Some biofortified varieties developed across the globe

Crop	Biofortified trait	Micronutrient enhanced	Varieties	Country/Region
Rice	High Zinc	Zinc	DRR Dhan 45, DRR Dhan 49	India
Wheat	High Zinc	Zinc	WB 02, HPBW 01	India
Maize	Provitamin A (Orange maize)	Vitamin A	HQPM 1, PVA 6, PVA 9	Nigeria, Zambia, India
Sweet Potato	Orange-fleshed (OFSP)	Vitamin A (be-ta-carotene)	Kabode, Ejumula	Uganda, Mozam-bique
Cassava	Yellow-fleshed	Vitamin A	IITA-TMS 07/0593, TMS 01/1368	Nigeria, DR Congo, Brazil
Pearl Mil-let	High Iron and Zinc	Iron, Zinc	ICTP-8203Fe, Dhanashakti	India, Africa
Beans	High Iron	Iron	MIB465, BIO101	Rwanda, DR Con-go, Latin America
Lentils	High Iron and Zinc	Iron, Zinc	IPL 220, L4076	India
Banana	High Provitamin A	Vitamin A	Matooke hybrids (e.g., NARITA va-rieties)	Uganda

Table 2: Details of different nano-biofortification

Crop	Biofortified trait	Micronutrient enhanced	Varieties	Country/Region	
Wheat (*Triticum aestivum*)	ZnO nanopar-ticles	Zinc	Foliar Spray	Improved growth, yield and grain Zn content	Raliya et al. (2016)
Rice (*Oryza sativa*)	Chitosan-Zn nanoparticles	Zinc	Soil and Foli-ar	Enhanced Zn uptake and antioxidant ac-tivity	Prajapati et al. (2022)
Maize (*Zea mays*)	Iron oxide (Fe_2O_3) NPs	Iron	Foliar Spray	Increased iron con-tent in leaves and seeds; better chloro-phyll synthesis	Dimkpa et al. (2017)
Tomato (*Solanum lycopersicum*)	Chitosan na-noparticles	Zinc	Soil	Delayed leaching, higher uptake and improved biomass	Khot et al. (2012)
Wheat	Carbon nano-tubes (MWCNTs)	Micronu-trient Mix	Seed Priming	Enhanced germina-tion, nutrient translo-cation, and photosyn-thesis	Khoda-kovskaya et al. (2009)
Rice	SiO_2 nano-particles	Silicon	Soil	Improved Fe/Zn up-take by altering root morphology	Tripathi et al. (2017)
Mung bean (*Vigna radiata*)	Iron oxide NPs	Iron	Seed Priming	Enhanced Fe uptake, improved germina-tion and biomass	Nair et al. (2010)

at the cellular and molecular level. Their small size, high surface area, and tunable properties allow them to penetrate plant cells, influence metabolic pathways, and improve the assimilation of micronutrients. The following are key mechanisms through which nanotechnology supports biofortification:

• **Controlled and targeted release**: Nanocarriers can be engineered to release nutrients in response to environmental stimuli (e.g., pH, moisture), aligning nutrient availability with crop demand.

• **Enhanced nutrient solubility and uptake**: Nanoparticles improve the solubility and transport of poorly soluble nutrients like iron and zinc, enhancing their absorption through root and foliar pathways.

• **Activation of nutrient transporters**: Nanoparticles can activate genes encoding specific nutrient transporters, improving translocation of micronutrients from root to shoot.

• **Mitigation of abiotic stress**: Certain nanomaterials provide tolerance against drought, salinity, and heat stress, indirectly supporting nutrient uptake and accumulation.

5. Types of Nanoparticles Used in Biofortification

5.1. *Zinc Oxide (ZnO) nanoparticles*

Zinc is essential for enzyme activation, protein synthesis, and immune function. However, zinc deficiency in soils limits crop zinc content. The ZnO nanoparticles are commonly applied through foliar sprays or soil amendments. Studies show increased grain Zn concentration, chlorophyll content, and antioxidant enzyme activity in wheat, rice, and maize (Raliya *et al.*, 2016).

5.2. *Iron Oxide (Fe_2O_3) nanoparticles*

Iron is vital for photosynthesis and respiration in plants. Iron deficiency in humans leads to anemia. Fe_2O_3 NPs are used for seed priming and foliar application. Iron NPs improved Fe uptake in mung beans, maize, and spinach, leading to enhanced chlorophyll synthesis and yield (Dimkpa *et al.*, 2017; Nair *et al.*, 2010).

5.3. *Silicon nanoparticles (Si-NPs)*

Silicon, though not classified as an essential element, contributes to mechanical strength and stress resistance in plants. The Si-NPs are applied to improve nutrient uptake indirectly by mitigating biotic and abiotic stresses. Enhanced iron and zinc uptake in rice and wheat due to improved root architecture and antioxidant defense (Tripathi *et al.*, 2017).

5.4. Other emerging nanomaterials (Table 3)

• Nano-hydroxyapatite ($Ca_{10}(PO_4)6(OH)_2$) for phosphorus delivery.

• Carbon-based nanomaterials (e.g., graphene oxide) for their role in enhancing nutrient transport and photosynthetic activity.

• Chitosan-based nanoparticles for nutrient encapsulation and disease resistance.

6. Advantages of Nano-biofortification

• **Slow and controlled nutrient release:** Nanoparticles exhibit high surface area-to-volume ratios, allowing for controlled and gradual nutrient dissolution in the soil. This significantly reduces leaching losses and ensures nutrient availability during critical crop growth stages. (Raliya et al., 2015)

• **Sustained nutrient availability**: Nano-sized Fe and Zn fertilizers improved micronutrient solubility and root uptake efficiency, compared to conventional bulk fertilizers due to increased residence time of nutrients and their bioavailability (Prajapati et al., 2022).

• **Improved nutrient uptake efficiency**: Better root absorption leads to reduced fertilizer doses and enhanced use efficiency. Nano-formulations of iron and zinc improved uptake efficiency by up to 35-40% in maize compared to conventional fertilizers.

• **Enhanced nutrient status of crops**: Increased accumulation of micronutrients (like Zn, Fe) in edible parts of plants. Nano $ZnSO_4$ and $FeSO_4$ formulations applied to sorghum increased 28%, 34% of Zn, Fe respectively (Dimkpa et al., 2017).

• **Better plant health and yield**: Stronger resistance to stress and improved growth performance.

• **Biofortified food with high nutrient density**: Contributes to combating hidden hunger and improving human nutrition.

• **Precision agriculture integration**: Nanoparticles can be integrated with sensors and smart delivery systems.

7. Challenges and Limitations

Despite its promise, several limitations hinder the widespread adoption of nano-biofortification:

• **Toxicological risks**: The long-term effects of nanoparticle accumulation in soil, water, and food chains are not fully understood.

• **Standardization issues**: Lack of standard protocols for nanoparticle synthesis, application rates, and safety assessments.

• **High costs**: Production and formulation of nanomaterials are cost-intensive.

• **Regulatory gaps**: Absence of comprehensive policies for the safe use of nanotechnology in agriculture.

Table 3: Different Nanocarriers used in Nano-Biofortification

Nanocarrier type	Material/Composition	Nutrient delivered	Mode of delivery	Applications in crops	Reference
Metal/Metal Oxide NPs	ZnO, Fe_2O_3, Fe_3O_4, CuO, MnO_2, Se NPs	Zn, Fe, Cu, Se, Mn	Foliar, soil, seed priming	Wheat, rice, maize, spinach, tomato	Raliya et al. (2016)
Silica Nanoparticles	SiO_2	Silicon (indirect Fe/Zn aid)	Soil, foliar	Rice, wheat, maize	Tripathi et al. (2017)
Polymeric Nanocarriers	Chitosan, alginate, PLGA	Zn, Fe, Cu, Se	Foliar, soil, seed coating	-	Prajapati et al. (2022)
Carbon-Based Nanomaterials	Multi-walled carbon nanotubes (MWCNTs), graphene	Nutrient mix	Seed priming, foliar	Wheat, maize, soy	Khodakovskaya et al. (2009)
Nano emulsions	Lipid-based emulsions (lecithin, Tween)	Hydrophobic vitamins, Fe	Foliar	Leafy vegetables, fruit crops	Khot et al. (2012)
Nano-chelates	Chelated forms of metals at nano-scale	Zn-EDTA, Fe-EDTA	Foliar	Rice, wheat, vegetables	Dimkpa et al. (2017)

8. Future Prospects

• **Smart nanocarriers**: Development of stimuli-responsive nanoparticles that release nutrients in response to specific triggers.

• **CRISPR and nanotech synergy**: Combining gene editing with nanoparticle-mediated delivery of nutrients or regulatory molecules.

• **Eco-friendly green synthesis** to produce safer nanoparticles.

• **Field-based validation**: Long-term field trials across diverse agro-climatic zones to evaluate efficacy and safety.

9. Conclusion

Nanotechnology-enabled biofortification is a frontier technology offering solutions to persistent nutritional challenges by improving the nutrient profile of crops sustainably. By bridging the gap between plant biology and materials science, it opens the door to smarter, more resilient and nutritionally enriched agriculture. However, its full-scale implementation requires interdisciplinary research, public-private partnerships, effective policies and societal awareness.

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