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Agronomic Bio-Fortification of Cereals with Zinc to overcome the Malnutrition from Indian Population

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ABSTRACT

Zinc deficiency is a significant public health issue in India, contributing to malnutrition, impaired immune function, and stunted growth in children. Agronomic bio-fortification offers a sustainable and effective strategy to increase zinc concentrations in staple cereals like rice and wheat, which form the dietary backbone of the Indian population. This review highlights the role of agronomic practices such as soil and foliar zinc fertilization in enhancing zinc uptake, translocation, and accumulation in grains. Additionally, it addresses the impact of zinc bio-fortification on crop yield, nutritional quality, and human health outcomes. Special emphasis is placed on the challenges, potential strategies, and agronomic innovations to achieve large-scale implementation in Indian agricultural systems. The integration of zinc bio-fortification into conventional farming practices holds promise in combating widespread zinc deficiency and ensuring nutritional security for millions.

Keywords: *Agronomic bio-fortification, zinc deficiency, cereals, malnutrition, Indian population, zinc fertilization*

INTRODUCTION

Rapidly growing population jeopardizes worldwide food stability. Nutrition security, defined as "Universal access to nutritious food, promoting healthy living, and supported by proper healthcare, education, and a clean environment". This problem is significantly more serious in low-income countries like India, since farmers use extensive agricultural approaches to boost productivity and profitability. Imbalance diet is a lack of variety in food sources, eating foods with lesser nutritional value, and food insecurity all jeopardize human health. Nutritional is key to a healthy life for humans and animals. In recent years, micronutrient deficiency has become widespread across the world. Micronutrient deficiency is no longer exclusive to developing countries, as it's becoming increasingly common in regions where cereals are staple foods. The micronutrient insufficiency in soil restricts nutrient uptake in plants and, eventually, humans. Inadequate intake of these micronutrients has significant biological consequences because they are crucial for the overall health and functioning of the human body. For plants, 17 mineral elements are deemed important, whereas for humans, the number exceeds 22. The worldwide prevalence of Fe and Zn deficiencies affects more than 2 billion people, posing significant health risks deficiency of essential micronutrients such as Fe and Zn affects more than 2 billion individuals around the world. Globally, Zn- deficient soils are much more widespread than that of other micronutrient deficiencies. Zn is a crucial component of approximately 3000 proteins and multiple enzyme classes. Low Zn uptake poses a significant risk to approximately 60-70% of the population in Asia and Sub-Saharan Africa. Zn deficiency causes damage in DNA, resulting in weaker immune system, cancer, heart disease, issues during female germ cell pregnancy, and other issues in humans. Low-income countries in Asia and Africa rely heavily on cereals, which account for 55% of their dietary energy and offer a promising solution for micronutrient delivery. The high consumption and availability of cereal grains, coupled with their ability to absorb micronutrients, make them an attractive option for micronutrient fortification and malnutrition alleviation. Furthermore, wheat, rice, and maize are the three cereals that currently provide up to 60% of the daily energy intake of human populations. Low dietary intake, which is linked to high consumption of cereal-based meals, is a common cause of zinc deficiency [2].

Most stable food-like cereal crops serve as a primary food source for over half of the global population, meeting approximately 60% of human energy and protein requirements. Rice and wheat are the mainstay of the rural Indian diet, supplying around 75% of the daily calorie requirements [4]. Despite being a staple, a daily diet of 300-400g of cereals provides minimal zinc, with rice offering only 4-6mg and wheat providing 11-18mg. For optimal zinc nutrition, cereal grains should ideally contain 40-60 mg Zn/kg, but current levels range from 10-40 mg/kg.

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Cereal-based foods have significantly lower Zn contents. Adult men require 9-18 mg of zinc per day, a challenging target to achieve with a cereal-based diet that is inherently low in Zn. Biofortifying staple crops like wheat, rice, and maize with zinc can significantly mitigate nutritional insecurity due to their widespread consumption. Given these circumstances, it is imperative to improve zinc uptake and bioavailability in cereal crops to combat nutritional deficiencies and enhance food quality. Various strategies, including dietary diversification, food fortification, and medical supplementation, can improve nutritional security; hence, bio-fortification has emerged as a promising approach to combat malnutrition by narrowing the gap between nutrient supply and the limited availability of Zn in cereal grains.

Bio-fortification presents a novel approach to addressing human nutrition globally, particularly in impoverished and developing regions. The main objective is to decrease mortality rates caused by micronutrient deficiencies and improve food security in developing countries. By augmenting both the quality and quantity of micronutrients in staple crops, bio-fortification has significantly bolstered nutrient levels in humans. This strategy also aids in narrowing the gap in micronutrient absorption between humans and animals. The growing global population has led to a surge in micronutrient deficiencies, including iron and zinc, resulting in various health issues and compromising global well-being and economic growth. Malnutrition has severe and far-reaching consequences, including the onset of diseases, compromised global welfare, and hindered economic growth. The alarming prevalence of iron and zinc deficiencies, impacting approximately 3 billion people worldwide, demands urgent attention and action. WHO data reveals that anemia affects a significant proportion (25%) of the global population, with an additional 17.3% at risk of zinc deficiency worldwide. Worldwide, two billion people are struggling with 'hidden hunger', a silent epidemic of micronutrient deficiencies that can have devastating health consequences [9] caused by a shortfall in essential micronutrient intake through daily food consumption. India's malnutrition crisis is evident in the statistics: 50% of women and 46% of children under 3 are underweight, 38% of children are stunted, and a worrying 72% of infants suffer from anemia.

Malnutrition is a major contributor to child mortality in India, with 69% of deaths among children under five attributed to this cause. Furthermore, micronutrient deficiencies, including vitamin A, zinc, iron, and iodine, are responsible for around 20% of fatalities in this demographic. India was ranked 105th out of the 127 assessed countries on the 2024 Global Hunger Index. (GHI-2024). Consumers play a crucial role in the acceptance of bio-fortified food crops, ultimately determining the demand for these crops among farmers. For instance, the significant color contrast between standard crops and bio-fortified ones, which contain higher levels of β-carotene, poses a challenge in marketing efforts. In regions like Africa, white corn is traditionally consumed by humans and yellow corn is reserved for animals, persuading consumers to opt for yellow corn for human consumption requires concerted efforts. Even if both crops share the same color, consumers must still be able to differentiate between standard and nutrient-enriched varieties. Addressing these challenges necessitates effective information and communication channels among scientists, farmers, and consumers.

Bio-fortified foods are particularly vital in many developing countries, where diets primarily rely on local staple crops, often leading to nutritional imbalances. Enhancing the nutrient content of these crops can mitigate malnutrition, given their widespread daily consumption. Additionally, bio-fortification offers cost-effective solutions, propagates through seed-sharing practices, and potentially enhances plant growth, yielding various positive health benefits.

Micronutrient deficiency in Indian soil

Zinc deficiency is widespread in Indian soils, with approximately 49% of soils from key agricultural areas lacking sufficient zinc, which can impact crop yields and nutritional value [14]. Zinc deficiency in agricultural soils is a complex issue, influenced by various factors that have cumulatively led to the present situation. Several key soil factors contribute to zinc deficiency in staple crops like rice, including low total zinc content, high pH levels, high calcite and bicarbonate ion concentrations, high salt levels, and excessive available phosphorus [1]. The adoption of modern crop varieties, intensified farming practices, and increased zinc removal have all contributed to a rise in zinc deficiency [22]. Additionally, the practice of multiple cropping, combined with the use of high-analysis zinc-free fertilizers, has further depleted the soil's zinc reserves [16]. Iron, vitamin A, and iodine deficiencies are the most common micronutrient deficiencies globally, with children and pregnant women being the most vulnerable populations. This can lead to reduced educational outcomes, reduced work productivity, and increased risk from other diseases and health conditions. Micronutrient deficiencies are a common issue in Indian agriculture, with crops frequently experiencing deficiencies despite soils containing sufficient total micronutrient levels. These deficiencies vary in nature and extent based on factors like soil type, crop variety, management practices, and agroecological situations. The intensive cultivation of high-yielding rice and wheat varieties has resulted in micronutrient deficiencies, initially zinc, and subsequently iron and manganese. Although zinc fertilizer applications have reduced zinc deficiency, the issue of multi-micronutrient deficiencies is now gaining prominence. While the regular use of zinc fertilizers has led to a decline in zinc deficiency in recent years, a new challenge has emerged in the form of multi-micronutrient deficiencies. Soil and plant sample analysis reveals that nearly half of India's soils (49%) are potentially zinc-deficient, while 12% lack sufficient iron, and smaller percentages are deficient in manganese, copper, boron, and molybdenum.

Micronutrient malnutrition is a widespread issue, affecting over 2 billion people globally, which is roughly one-third of the world's population. More than 2 billion people worldwide experience deficiencies in multiple micronutrients, including iron and zinc, which can have far-reaching health consequences [24]. Approximately one-third of the global population, or one person in every three, suffers from micronutrient deficiency [25].

Table 1: Micronutrient status in the world

Deficiency	Extent in developing countries	Outcomes
Iron	1.6 billion people	Anemia maternal mortality
Zinc	1.3 billion people	Infectious disease, poor child growth, maternal mortality, reduced birth weigh

Source: Singh, M.V. 2008

Table 2: Micronutrient deficiency in Cereal grain

Cereals Plant food	Zn (mg/100g)
Rice	1.09
Wheat	3.33
Oats	3.97
Maize	2.21

Source: USDA Food Composition Databases, 2007

Table 3: Nutrient Requirement and Consumption per Capita per Day in India

Nutrients	Male		Female	
	Requirement	Consumption	Requirement	Consumption
Protein (g)	54	39	46	43
Zn (mg)	17	11	14.5	8
Thiamine (mg)	1.5	0.64	1.4	0.83
Riboflavin (mg)	2.1	0.69	2	0.64

Source: ICMR 2020

Why Bio-fortification

1) Poverty (poor people rarely have access to commercially fortified food.
2) Diversification of diet is not possible for all.
3) Among micronutrients iron and zinc remain significant problems in developing country populations.

What is Bio-fortification?

Biofortification involves breeding crops to enhance their nutritional content, making them more nutritious and beneficial for human consumption [2]. Biofortification refers to the process of enhancing the nutritional content of food crops, thereby increasing the bioavailability of essential micronutrients to the human population [15]. Micronutrient deficiency is a pressing global health concern, with far-reaching consequences for human health, economic productivity, and societal well-being. Biofortification is a cost-effective and sustainable approach to addressing micronutrient deficiencies, a widespread issue known as "hidden hunger." This innovative method involves:

1. Enhancing crop management practices

2. Improving crop genotypes

To increase the bioavailable concentrations of essential micronutrients in edible plant parts, thereby providing a long-term solution to micronutrient deficiencies and malnutrition. [24].

Bio-Fortification Approaches for Crops

1. Agronomic bio-fortification is the technique of boosting the level of the mineral in food grains and fruits by fertilization process at responsive growth stages of crop plants [19]. This practice enhances the density of minerals in crops through foliar application, soil application, seed treatment, and use of soil amendments. This is an inexpensive and easy method to enhance the micronutrient content of staple food crops, furthermore decrease dietary deficiency. Adding zinc and iron to cereal crops is a great way to reduce micronutrient deficiencies. For this purpose, it is very important to have knowledge about various forms of zinc fertilizer and their time of application. The recent introduction of nano fertilizers can also be included for agronomic bio-fortification [10].

2. Genetic bio-fortification is another approach to increase the mineral concentration in crops. In case of conventional breeding, breeding of crop is done for varieties with high micronutrient content. One of the most important tools in crop bio-fortification is to take advantage of the genetic variation in crops for micronutrient concentration. However, the transgenic/biotechnological approach is different from the plant breeding approach. Genetic engineering enables the transfer of desirable traits between unrelated species, overcoming traditional breeding limitations. This innovative approach has successfully introduced new traits into commercially valuable plants, resulting in novel combinations of characteristics that were previously unattainable.

3. Conventional Breeding- Conventional plant breeding involves the targeted improvement of crop cultivars through subtle modifications within their natural genetic parameters, resulting in enhanced essential nutrient content. Conventional plant breeding boasts a higher success rate, as evidenced by the greater proportion of released biofortified cultivars. Among the released biofortified cultivars, cereals account for the largest share (58.1%), followed by vegetables (19.8%), legumes (13.2%), and fruits (9%).

Methods of Agronomic Bio-fortification

1. Soil Application- The most common practices to increase the productivity in agricultural soils that are deficient in zinc is soil application of zinc fertilizer. The primary objective of zinc fertilizer application is to maintain optimal zinc concentrations in food crops, thereby increasing zinc levels in edible plant parts and enhancing zinc absorption in the human body. The effectiveness of soil-applied zinc fertilizer is significantly influenced by soil pH in the human body by increasing the concentration of zinc in the edible part of food crops. Soil pH determines the efficiency of soil-applied zinc fertilizer. The availability of zinc has been found to be higher in acidic soil. However, the application of lime to acidic soils can have an unintended consequence: reducing the bioavailability of zinc. Zinc availability is compromised in alkaline soils, rendering it less accessible to plants. As the transportation of zinc to the plant root takes place through diffusion, zinc availability to the plant will be reduced by moisture deficiency and low organic matter. The efficacy of soil-applied zinc fertilizer is significantly influenced by moisture conditions, with rainfed systems exhibiting greater variability in zinc fertilizer efficiency compared to irrigated systems. In addition to chemical properties, biological factors also significantly influence zinc availability to plants. Plant Growth-Promoting Rhizobacteria (PGPRs) are beneficial microorganisms that enhance nutrient uptake and mobility in plants. Furthermore, the source and dosage of zinc application have a profound impact on crop yield and grain quality. The source as well as the dose of zinc application affects the yield and grain quality. Therefore, to avoid zinc toxicity to plants, a dose of zinc application should be recommended carefully.

2. Foliar Application- Factors like type of fertilizer, characteristics of the crop, characteristics of leaf etc, determines the efficiency of foliar zinc application. Comparatively less requirement of fertilizer, reduction in zinc fixation etc are the several advantages provided by foliar application. Optimizing the timing of foliar zinc fertilizer application is crucial for achieving effective nutrient uptake and utilization by plants.

Applying zinc fertilizer at the heading and early milk stages proves more effective than foliar application at the stem elongation and booting stages. Furthermore, foliar zinc application can also improve grain productivity under drought conditions.

3. Seed Application- Seeds containing large amounts of zinc are capable of improving crop stand and seed vigor and in the field. If plants grow in an area that is deficient in a nutrient, then nutrient deficiency will also be observed in the produced seed and further use of such seed in a nutrient-deficient area will lead to a reduction in seedling vigor, growth and yield of the plant. As the transportation of zinc to the plant root takes place through diffusion, zinc availability to the plant will be affected by moisture deficiency. In the case of rainfed conditions where the soil moisture is totally dependent on rainfall, zinc nutrients is highly inconsistent. Therefore, to increase the yield and plant growth under rainfed conditions or zinc-deficient area zinc zinc-rich seed are required.

4. Organic Manure- In this approach, organic nutrient sources like plant residues and animal manure such as compost, FYM, oilcake, etc., are applied to the soil and evenly spread over the surface. The integration of organic and mineral fertilizers can sustain soil organic matter, leading to improved soil structure, cation exchange capacity, and water-holding capacity. Organic inputs provide a slow and steady release of nutrients, while mineral fertilizers offer flexibility in application timing, placement, and rate, allowing for synchronization with crop demand. Furthermore, fertilization with organic matter alone has the potential to enhance soil micronutrient content and availability.

Why Bio fortification for Zinc?

- More than 30% world's population is Zn deficient.
- Benefits of zinc supplementation on the growth rate of children.
- Impact on hormonal balance.
- Deficiency of zinc

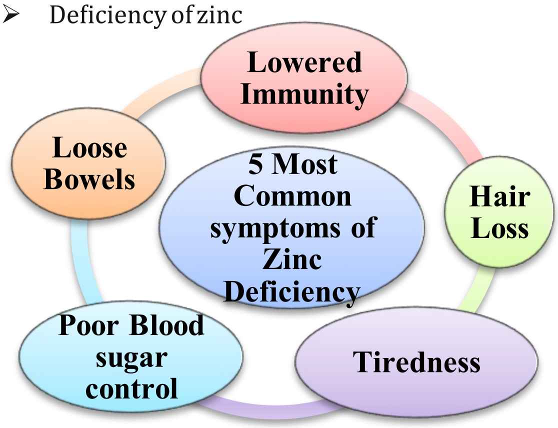

Fig: 1 deficiency in zinc

Reasons of low bioavailability Zinc

- Anti-nutrients (Zn:P ,Zn:Cu and Zn:Mn) balance.
- Low bioavailability of trace elements in soil.
- Several soil factors can impede the solubility and mobility of zinc, including:

- High pH levels
- High clay content
- Low organic matter (OM)
- Low soil moisture
- High concentrations of iron (Fe) and aluminum (Al) oxides.

Advantages and Limitations

Application Methods	Advantages	Limitations
Soil Application	Minimizes soil Zn deficiency the residual effect may benefit subsequent crops	High fertilizer requirement Availability to plant may decrease due to adverse soil properties
Foliar application	Lower fertilizer requirement Not affected by adverse soil characteristics	Crop requirement in the early seedling stage is not met Very high dose of nutrient cannot be applied using the foliar method
Seed priming	Lower fertilizer requirement Suitable for stressed environments	A higher amount of nutrient cannot be applied using this method as a high concentration of priming solution may negatively affect germination

Future Scopes

Though different research's have been carried out to improve nutrient in food through biofortification, some key points should be kept in mind for further improvement. They are highlighted below:

1. To boost zinc levels in crops, farmers can use the 4R approach: using the right type of zinc fertilizer, in the right place, at the right time, and in the right amount.

2. To enhance grain zinc concentration, it is essential to identify the primary physiological constraints limiting zinc accumulation in various crops under diverse conditions. Addressing these constraints through integrated agronomic and genetic approaches can help overcome the limitations and improve zinc levels in crops.

3. Biofortification must be studied under stressed condition and evaluation of the effect should be done. With change in climatic condition and more weather irregularities, a stress proof biofortification system should be developed.

4. Evaluation of the performance of zinc efficient genotype under the different availability of zinc in soil should be studied whether the combination of agronomic and genetic biofortification are beneficial or not.

5. Foliar application of zinc to the crop should be compared with other application method to increase the bioavailability of zinc under various agronomic management practices.

CONCLUSION

Bio-fortification aids in the treatment of malnutrition in humans as well as improvement of nutritional quality in regular diets. This technique is cost-effective, making it a viable choice for low-income countries. Agronomic bio-fortification through soil and foliar application of micronutrients fertilizer application presents a rapid and practical solution for enhancing mineral uptake in food crops, thereby improving their nutritional content. Agronomic bio-fortification not only enhances grain zinc content, which is beneficial to health, but can also help reduce the amount of zinc insufficiency, particularly in areas where intensive cropping systems and micronutrient treatment is neglected.

Application of Zn-containing fertilizers represents a quick and useful solution to bio-fortification of cereal grains with Zn. There is an urgent need for the adoptation of a new fertilizer policy to encourage and promote the production and application of Zn-enriched fertilizers in India. Application of Zn-fertilizers through an initiatives from government can be a push towards farmers for food enhancement. Fortification of fertilizers with Zn would be an excellent investment for humanity and for crop production in India. Thus, fortification can be highly appealing and useful a technique to efficiently addressing the global problem of zinc deficiency.

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