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Combating hidden hunger caused by wheat and soil-drived zinc deficiency

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Abstract. Essential vitamins, proteins, and microelements are provided by nutrition, but inadequate and nutrient-poor diets can lead to hidden hunger. Zinc deficiency is a significant hidden resource that affects multiple bodily functions, including immune system function, growth, and development. The primary reasons for the prevalence of zinc deficiency in humans are grain-based products with low concentrations and low zinc solubility in the soil. Intensifying plant production and the inability to replace nutrients absorbed in excess from the soil leads to zinc deficiency in the soil. Consequently, substantial reductions in crop yields are observed, along with decreased zinc concentrations in harvested grains. A number of unsustainable strategies, including expensive medical supplements and zinc-enriched flour-based products to address zinc deficiency, are temporary solutions. Additionally, one such strategy is agronomic biofortification, which recommends utilizing water-soluble zinc fertilizers to increase the concentration of zinc in the plant and soil. A more sustainable and cost-effective approach involves employing traditional plant breeding and molecular techniques to develop new zinc-biofortified cultivars. By enriching wheat with zinc, it absorbs 20-40% more zinc from the soil. Here, this paper will discuss the role of zinc deficiency in wheat and soil and its impact on both crop yield and human nutrition, with a particular emphasis on biofortified wheat.

1. Introduction

Wheat is one of the most widely cultivated staple crops, providing a significant source of calories and nutrients for nearly 40 countries, accounting for more than one-third of the world's population [1-2]. Insufficient vitamin, protein, and trace element content in food leads to malnutrition, a well-known hidden hunger. In this case, people can obtain sufficient food. However, the components that the body needs are not supplied. Today, 800 million people worldwide are unable to access enough food, and more than 3 billion people suffer from hidden hunger due to zinc deficiency [3]. Zinc deficiency in wheat is a pervasive issue that affects both crop yield and human nutrition. Socio-economic reasons, people's consumption of mainly grain-and legume-derived foods aggravates zinc deficiency in humans. Hidden hunger is not only a health problem but also an economic one. Economic losses due to undernutrition correspond to 1.9% ($3.7 billion) of the Egyptian national economy and 16.5% ($4.7 billion) of Ethiopia [4].

1.1. Impact of zinc deficiency on global health

Zinc deficiency adversely affects developmental functions, such as immunity, the brain, skin, bone, and reproduction, as well as the risk of many diseases, such as lung disease, neuropsychological changes, anemia, skin abnormalities, diarrhea, weakness, cancer, and pneumonia [5-6]. The major groups caused by hidden hunger are pregnant and children under the age of five, in terms of affecting their physical and mental development [7]. Zinc is a micronutrient that plays a crucial role in various physiological processes within plants, including enzyme activity and hormone regulation. The function of approximately 200 enzymes that affect the immune system and resistance to disease, and 3000 proteins involved in many other functions, is dependent on an adequate supply of zinc to the body [8-9-10]. Biofortified wheat offers several key benefits in combatting hidden hunger and improving global

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health. Firstly, by increasing the zinc content in wheat grains, biofortification ensures that individuals who rely on wheat as a staple food have access to a more nutrient-rich diet. This can have a significant impact on their overall health and well-being, particularly in vulnerable populations such as pregnant women and young children [11]. Due to the malnutrition and hidden hunger, every year nine million people worldwide die with 450,000 children [11]. Zinc deficiency is reported to be the fifth leading cause of death and major disease in developing countries and is one of the top 10 factors contributing to disease risk worldwide [12-13].

1.2. Facts for deficiency in wheat and the role of soil in plant zinc uptake

To understand the issue of zinc deficiency in wheat, it is important to first recognize the role of soil in plant nutrient uptake. Soil serves as the primary source of essential nutrients for plants, including zinc. However, not all soils are created equal, and many regions around the world have soils that are inherently low in zinc content. Similarly, zinc deficiencies have been observed in people living in areas with low available soil zinc [3-14]. (Welch and Graham, 2004; Çakmak, 2010). Soil is the most important source of zinc deficiency in grain-based food chains. Zinc availability in soil limits grain zinc concentrations. Approximately 50% of the soil in grain-growing regions of the world is deficient in plant-available zinc [15]. The reference [16] reported that Pakistan, Afganistan, India, Azerbaijan, and Türkiye were ranked as five countries among 128 countries necessary to enrich the zinc content of wheat. In Türkiye, 62% of soils were found to be deficient in available zinc, with the majority of these deficiencies concentrated in regions, including central Anatolia [17]. Inadequate zinc content in grains is therefore one of the major nutritional problems. Developing countries can ensure global food security simply by meeting people's caloric needs. Similar to food security, the nutritional fortification of foods is one of the main goals. Agriculture should therefore focus not only on production but also on nutrient-rich production.

The primary reason for the prevalence of zinc deficiency in plants is the low solubility of zinc in soil [18]. Zinc content in soil lies between 10 and 300 mg kg^{-1}, but an average of approximately 50 mg kg^{-1}, and plants can only take up 20% of zinc from the soil [19-20]. Low soil organic matter content, high pH (approximately 7.0), high carbonate content, and interactions between zinc and other elements (Mn^{+2}, $Cu^{+2,}$ Fe^{+2}, and $H_2PO_4^-$) can potentially influence the solubility and concentration of available zinc in plant roots [21-22-23]. Above soil pH 7.8, zinc adheres tightly to clay areas, making it difficult for zinc to penetrate the soil solution [24-25].

High water solubility of Zn fertilizers are the most efficient strategy to meet Zn deficiency [18-26]. Insoluble Zn accounts for more than 90% of soil Zn and is inaccessible to plants [27]. To address the Zn requirements for the current crop, zinc fertilizer water solubility levels of 50% of total Zn are required [28]. Plant tissue Zn concentrations have also been reported to decrease with decreasing fertilizer Zn water solubility [29].

Plants cannot synthesize micronutrients or obtain them from the soil environment. In zinc-deficient soils, grain yields and the zinc content in harvested grains were significantly reduced. Cereals are the main dietary source of zinc, and the amount of iron/zinc in cereals required for a healthy diet is 40-50 mg kg^{-1}. However, the zinc content of current Turkish grains is 20-30 mg kg^{-1} [30]. Grain zinc content in wheat was reported at 31.84 mg kg^{-1} worldwide, in which is lower than that recommended by the reference WHO, but varied across continents, e.g., 25.10 $mg \cdot kg^{-1}$ in Europe, 29 $mg \cdot kg^{-1}$ in Africa, 33.63 $mg \cdot kg^{-1}$ in Asia, and 33.91 $mg \cdot kg^{-1}$ in North America [31].

A remarkable increase in wheat yield has been observed since the Green Revolution in the 1960s. Breeding programs focus on increasing yields over trace element-rich varieties [32]. Despite a significant increase in yield, the zinc content in the grains decreased [33]. Another reason for zinc deficiency in wheat grains is the inability to enhance crop production to increase productivity and the inability to replace nutrients taken up in excess amounts from the soil, resulting in soil zinc deficiency.

1.3. Exploring the concept of biofortification and short-term solutions in addressing zinc deficiency

Expensive medical supplements and unsustainable methods using zinc-rich pills and syrups offer to meet daily zinc intake. Furthermore, zinc-fortified cereal products can provide daily zinc needs [34]. Zinc insufficiency has mostly been caused by inadequate consumption or poor absorption of zinc from the diet [34]. A solution to this problem might be to increase the zinc content of grains using supplemental zinc fertilizers, such as zinc, which are needed to feed the plants. However, looking at current global zinc fertilizer consumption rates, it is reported that zinc resources will be depleted in the next 60 years [35]. In this case, increasing the deficient zinc content in wheat grains can be achieved through breeding studies. From the perspective of sustainability and economy, the development of new cultivars with high grain zinc content seems to be the most appropriate method.

Biofortification is a promising strategy that aims to address nutrient deficiencies in crops by increasing their nutritional content through conventional breeding and molecular techniques. The concept of biofortification is particularly relevant in the context of zinc deficiency in wheat, as it offers a sustainable and cost-effective solution to combat hidden hunger. By enhancing the zinc content in wheat grains, biofortified varieties can improve both crop yield and the nutritional quality of the harvested grains.

In this context, zinc-rich wheat varieties have been developed as part of an international breeding program (HarvestPlus-Biofortification Challenge Program) that has been active for 15 years. Owing to this program, 50 million people have access to products developed using classical breeding methods enriched with vitamins and trace elements. The goal is to reach 1 billion people by 2030. The most cost-effective way to combat trace element malnutrition worldwide is to biofortify modern wheat with trace elements, which is known as biofortification [36]. Biofortification is the fortification of edible plant parts in terms of vitamins, minerals, and proteins, using classical molecular or genomic breeding methods [37-38].

There are two main approaches to biofortification: agronomic biofortification and genetic biofortification. Agronomic biofortification involves applying zinc-containing fertilizers to the soil or foliar spraying zinc solutions onto the plants, thereby increasing the availability of zinc for plant uptake. Genetic biofortification, on the other hand, focuses on breeding wheat varieties that naturally accumulate higher levels of zinc in their grains. Both approaches have shown promising results in increasing the zinc content of wheat, ultimately benefiting both farmers and consumers. Wheat products can be fortified with additional additives during processing, or agronomic biofortification involves applying zinc-containing fertilizers to the soil or foliar spraying zinc solutions onto plants, thereby increasing the availability of zinc for plant uptake. However, the most sustainable solution to increase the zinc content in grains is genetic biofortification, on the other hand, focusing on breeding wheat varieties that naturally accumulate higher levels of zinc in their grains [39]. There is a strong positive correlation between zinc and iron levels in wheat grains [3]. As the zinc content of the particles increased, the iron content also increased. Differences in zinc utilization efficiency between wheat genotypes, variations in zinc transport to crops, and genotype-associated relationships for zinc uptake and utilization influence zinc mobilization in plants [40]. A study by the International Center for Maize and Wheat Improvement (CIMMYT) analyzed iron and zinc content more than 3,000 wheat genotypes; however, there was little variation existed in modern adapted cultivars. Genetic resources carrying high levels of iron and zinc have been found in wheat progenitors, such as *Triticum dicoccoides*, *Aegilops tauschii*, *Triticum boeticum*, and landraces [41-42]. *Triticum dicoccon*, *Triticum monococcum*, and *Triticum spelta* have also been used as promising species to improve new zinc-enriched cultivars [43]. Recent breeding efforts have documented Zincol-2016 in Pakistan, Zinc Shakti (Chitra) in India, and WB02 and HPBW-01 as high-zinc wheat [43]. These wheat cultivars have higher zinc content than other wheat cultivars in soils with low available zinc content. The highest zinc content of wheat cultivars was reported to be 40% for Zinc Shakti, 20% for WB02 and HPBW-01, and 25% for Zincol-2016 [43]. The reference [15] showed that the zinc content in the stems and grains of Zincol 2016 was higher than that of the Jauhar-2016 cultivar in all zinc-enhanced applications and control applications containing zinc (0 mg kg^{-1}). Furthermore, CIMMYT has recently successfully incorporated a grain zinc content of 30-40% in high-yielding cultivars [44-45].

1.4. Molecular methods for zinc biofortification

Many molecular techniques, such as quantitative trait loci (QTL), marker-assisted selection, and genomic selection hold a great potential for enhancing grain zinc concentration in wheat. Several quantitative trait loci (QTL) associated with wheat zinc content have been recently identified [46-47-48]. A number of studies conducted in various locations have shown a significant and positive relationship between zinc and iron in wheat grains, implying that they are co-localized or pleiotropic or QTLs in regulating the concentrations of these elements [45]. Although there have been many successful attempts to increase the zinc content of cereals through classical breeding, studies on increasing the iron content in cereals have not been successful. However, it is possible to enhance the zinc and iron content of grains by marker-assisted backcrossing using QTL information [49]. Marker-assisted selection (MAS) can be used to introgress desired regions (alleles) into elite wheat cultivars [45]. In addition to MAS, a possible method could be to increase the amount of iron and zinc in the grains during genomic selection [50].

A previous study showed that advanced genomic prediction (GP) can select individuals with traits (alleles) of interest using only marker information [51]. The *Gpc-B1* gene has been shown to be closely associated with high zinc and iron loci in cereals and has been successfully transferred to tetraploid and hexaploid wheat in Argentina, Australia, Canada, India, Israel, Japan, and the United States [52]. An average increase of 11.6 mg kg^{-1} zinc/grain was observed in 93% of the lines transfected with the *Gpc-B1* gene [53]. Instead of cultivars harboring this gene, CIMMYT has successfully developed new cultivars with traditional breeding, which are rich in zinc (20–40%) and have high yields from adapted local cultivars [44]. The development of new cultivars with high yields and high iron and zinc contents can be achieved using materials with vast genetic diversity for relevant traits.

2. Conclusions

1. Hidden hunger is a silent crisis that affects millions of people worldwide, with severe consequences for both individual health and global development. Zinc deficiency in wheat is just one example of how nutrient deficiencies can impact crop yield and human nutrition.
2. Biofortification offers a promising sustainable and cost-effective solution to address hidden hunger, particularly in the context of wheat, by increasing the nutritional content of crops and ensuring long-term access to essential nutrients.
3. Unlike other interventions such as nutrient supplements or fortified foods, biofortification integrates nutrient enhancement directly into the crops themselves, ensuring long-term access to essential nutrients without the need for ongoing external interventions. This makes biofortification a scalable and sustainable strategy for combatting hidden hunger on a larger scale.
4. To fully harness the potential of biofortification, it is essential for governments, research institutions, and development organizations to continue investing in research, development, and implementation efforts.
5. The development of new biofortified varieties, strengthening seed systems and distribution networks, and establishing supportive policy frameworks should be supported by prioritizing the production and promotion of nutrient-rich crops.

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