REVIEW ARTICLE

Zinc in Wheat Cultivation: Physiological Roles, Agronomic Impact, and Management Strategies—A Comprehensive Review

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Abstract

Zinc (Zn) is an essential micronutrient in wheat cultivation, playing a pivotal role in plant growth, yield optimization, and grain nutritional quality. Despite its significance, zinc deficiency remains widespread in cereal-growing regions, leading to reduced crop productivity and contributing to micronutrient malnutrition in human populations. This review provides a comprehensive analysis of zinc's physiological functions, uptake mechanisms, and interactions with other nutrients in wheat systems. It examines zinc's influence on key agronomic traits such as grain yield, biomass accumulation, and stress resilience. Furthermore, the review explores various zinc management approaches, including the development of zinc-efficient wheat genotypes, biofortification strategies, and both basal and foliar fertilization techniques. Regional challenges and context-specific solutions for mitigating zinc deficiency are also discussed. The review concludes by emphasizing the importance of integrated nutrient management and innovative agronomic practices to enhance zinc availability, improve wheat productivity, and contribute to global efforts in combating micronutrient malnutrition.

Keywords: Zinc deficiency, biofortification, wheat productivity, nutrient interactions, agronomic strategies, physiological roles.

Highlights

- Zinc is a vital micronutrient in wheat cultivation, directly influencing plant growth, grain yield, biomass accumulation, and overall stress tolerance.
- Zinc deficiency is widespread in cereal-growing regions, leading to reduced crop productivity and contributing to micronutrient malnutrition in human populations.
- The review emphasizes zinc's physiological functions and uptake mechanisms, including its complex interactions with other essential nutrients in soil-plant systems.
- Effective zinc management strategies, such as the use of zinc-efficient wheat varieties, biofortification, and both basal and foliar applications, are critically examined.
- The study underlines the need for integrated nutrient management and innovative agronomic practices to enhance zinc availability, improve wheat productivity, and combat global nutritional deficiencies.

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Introduction

Wheat (*Triticum aestivum*) is one of the most significant staple food crops globally, essential for both economic stability and food security. It serves as the main source of calories, protein, and vital nutrients for over 2.5 billion people worldwide. Due to its high productivity and adaptability to diverse agroclimatic conditions, wheat is crucial for meeting the rising food demands of a growing population (Acevedo *et al*., 2018). However, several challenges limit wheat production, with soil nutrient deficiencies, especially of micronutrients like zinc (Zn), being particularly critical. Zinc plays a key role in plant development, growth, and yield. It supports physiological functions such as membrane integrity, nitrogen metabolism, auxin synthesis, and photosynthesis (Tripathi *et al*., 2015). Its deficiency can lead to restricted growth, reduced tillering, yellowing of young leaves, and lower grain quality, significantly affecting crop output. Zinc is also vital in human nutrition, supporting immune health, tissue repair, and brain development (Ghimirey *et al*., 2024). Low zinc levels in soils often result in zinc-deficient grains, contributing to widespread micronutrient malnutrition, particularly in developing countries. This condition, known as "hidden hunger," impairs growth and weakens immunity, especially in pregnant women and children. Zinc deficiency in soils is common in calcareous, saline, and sandy regions due to high pH, low organic matter, and excessive phosphorus, which immobilizes zinc (Bolan *et al*., 2023). The prevalence of zinc deficiency has

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become a serious concern in major wheat-growing areas, resulting in reduced yields and poor grain quality. Addressing this issue requires effective zinc management strategies such as seed treatment, foliar sprays, and the application of zinc-based fertilizers like zinc sulfate and chelates, which have shown improvements in both productivity and grain quality (Montalvo *et al.*, 2016). Foliar application is effective for directly supplying zinc, while seed priming with zinc solutions enhances early growth. Recent innovations like nanotechnology offer promising solutions through controlled release and better absorption of zinc fertilizers (Singh *et al.*, 2023). Additionally, breeding and genetic engineering are being used to develop zinc-efficient wheat varieties that absorb and accumulate more zinc in grains. These strategies aim to address both soil and dietary zinc deficiencies sustainably (Maqbool & Beshir, 2019). The interactions of zinc with other soil nutrients and properties are also critical; for example, organic matter and microbes enhance zinc availability, while high phosphorus can reduce it (Prasad *et al.*, 2016). Integrated nutrient management plans are needed to balance these factors. Although zinc fertilizers are cost-effective and beneficial, improper use can harm the environment by contaminating soil and water. Thus, precision agriculture approaches that ensure site-specific fertilizer use are necessary for sustainable wheat production.

Bio-Physiological Functions of Zinc in Plants

An important micronutrient, zinc (Zn), is involved in numerous biochemical and physiological processes in plants. Although required in minute quantities, it is vital for normal growth, development, and reproduction. Its significance lies in its involvement in protein synthesis, enzyme function, and regulation of various metabolic activities (Nandal V, Solanki M, 2021). Zinc acts as a cofactor for over 300 enzymes that contribute to essential plant metabolic pathways. It influences a broad spectrum of biochemical mechanisms, including the metabolism of lipids, amino acids, and carbohydrates, all crucial for plant vitality and productivity. To generate energy and fix CO_2, zinc is crucial for the activation of enzymes associated with carbohydrate metabolism, including carbonic anhydrase and alcohol dehydrogenase (Hafeez *et al.*, 2013). It aids in protein synthesis by maintaining the structural integrity of ribosomes and supporting tissue formation. Furthermore, zinc supports lipid metabolism by activating enzymes involved in fatty acid biosynthesis, contributing to cell membrane construction and structural stability in plants. It is indispensable for the synthesis of genetic material and the translation process, facilitating DNA and RNA production that enables cell division and elongation, particularly during rapid growth phases (Bonaventura *et al.*, 2015). Zinc also plays a role in photosynthesis, aiding in chlorophyll biosynthesis, allowing plants to harness light energy. It stabilizes chloroplast structures and enhances carbon dioxide fixation through enzymes like carbonic anhydrase, promoting energy generation and productivity (Gupta *et al.*, 2016). In hormone regulation, zinc influences auxin activity, governing processes like apical dominance, cell expansion, and root growth. Sufficient zinc helps maintain the balance between vegetative and reproductive growth, ensuring optimal plant form. Additionally, zinc is fundamental to the stability of plant cell membranes. It protects against oxidative harm induced by stress by stabilizing membrane components like phospholipids and proteins (Hamzah *et al.*, 2022). Moreover, it contributes to intracellular signalling and modulates defence responses, enhancing plant adaptability. It enhances the activity of antioxidants like superoxide dismutase (SOD), which mitigate oxidative damage from salinity, drought, and temperature extremes. This protective capacity improves tolerance to adverse conditions and helps maintain productivity (Cruz *et al.*, 2015). Zinc is also vital during the reproductive phase, influencing pollen function, flower development, and seed production. Its deficiency can impair fertilization and reduce yield, emphasizing its necessity for producing high-quality seeds and fruits (Kandil *et al.*, 2022). Lastly, zinc contributes to nitrogen assimilation by activating enzymes like glutamate dehydrogenase and nitrate reductase. This enhances nitrogen use efficiency and protein biosynthesis, boosting both plant growth and the nutritional profile of crops like wheat.

Mechanisms of Zn Uptake, Translocation, and Assimilation in Wheat

A crucial micronutrient for wheat, zinc (Zn) affects a number of important physiological functions, such as protein synthesis, stress tolerance, enzyme activation, and reproductive development. Zinc uptake, translocation, and assimilation in wheat are intricate processes impacted by plant responses, root morphology, and soil characteristics. These processes are essential for increasing zinc efficiency, especially in zinc-deficient soils. Root membrane transporters like the ZIP (ZRT-IRT-like Protein) family facilitate zinc uptake in wheat, predominantly as Zn^{2+} ions from the soil solution (Ghosh *et al.*, 2024). Zinc absorption is influenced by soil characteristics such as pH, organic matter, and antagonistic ions like phosphorus. Compounds secreted by roots, including organic acids and phytosiderophores, enhance zinc solubility by chelating or mobilizing zinc from less available forms, thus improving its accessibility to roots (Chen *et al.*, 2017). After uptake, zinc is translocated to aboveground parts, including grains. It is loaded into xylem vessels by transport proteins like Heavy Metal ATPases (HMAs) and moved as free Zn^{2+} or in complex with ligands to ensure solubility. Distribution via the phloem ensures delivery to active sites like seeds, enhancing grain nutritional quality (Swamy *et al.*, 2023). Inside plant tissues, zinc is incorporated into enzymes such as superoxide dismutase (SOD) and carbonic anhydrase, essential for physiological functions including defense and metabolism. Excess zinc is compartmentalized in vacuoles or bound by proteins like metallothioneins and phytochelatins, ensuring detoxification and storage (Andresen *et al.*, 2018). During reproduction, zinc is directed to grains, improving their micronutrient profile. Zinc balance is maintained through nutrient interactions, internal recycling, and transport regulation. Under zinc-limiting conditions, wheat shows upregulated ZIP and HMA expression and increased exudation of metal-chelating molecules like deoxymugineic acid (DMA). Zinc is also remobilized from senescing tissues (Kambe *et al.*, 2015). Since zinc uptake and use are influenced by other nutrients such as phosphorus and nitrogen, maintaining nutrient balance is vital for plant performance and zinc accumulation (Nath *et* *al*., 2015). Despite these mechanisms, soil zinc deficiency is still widespread. Strategies to improve zinc nutrition include developing genotypes with enhanced uptake, seed priming, and proper fertilization. Distending zinc pathways supports biofortification efforts to increase grain zinc and combat human deficiency (Sharma *et al*., 2020).

Symptoms of Zinc Deficiency and Toxicity in Wheat

Zinc (Zn) is a critical micronutrient for wheat growth and development. Both its deficiency and toxicity can negatively impact plant health, resulting in characteristic symptoms that can be identified through visual assessment and physiological changes.

Symptoms of Zinc Deficiency in Wheat

A common micronutrient limitation in cereal crops, especially in calcareous or alkaline soils, is zinc deficiency, which affects a number of physiological functions such as growth, reproduction, and enzymatic activity. Decreased tillering with small, narrow leaves, delayed flowering and maturity, distinct white or yellow bands along leaf margins, interveinal chlorosis on older leaves due to its immobility, and stunted growth from impaired cell division and auxin production are all visual signs of zinc deficiency (Al-Hashimi *et al*., 2023). Other symptoms can include shortened internodes, poor root development, and a general decline in plant Vigor, especially under high pH conditions. Physiologically, a zinc deficiency results in decreased pollen viability, which ha seed formation and grain yield; poor chlorophyll production, which restricts photosynthesis and energy generation; and impaired protein synthesis because of decreased enzymatic activity (Roosta *et al*., 2018). Grain yield, size, and zinc content are all decreased as a result of these deficiencies, which lowers nutritional quality. Zinc deficiency in wheat is made worse by elements like high soil pH, low OM, and high P levels, which further impair crop growth and productivity (Murphy, 2015).

Symptoms of Zinc Toxicity in Wheat

Though less frequent than deficiency, zinc toxicity can happen in soils that have too much zinc applied to them or in contaminated areas like mining sites and industrial zones, where it causes oxidative stress and interferes with nutrient uptake (Garg and Kaur, 2021). Stunted growth because of toxic levels that prevent root and shoot elongation, thicker, shorter, or darker roots, and dark green or purplish pigmentation in leaves are all visual signs of zinc toxicity, as represented in Table. 1 (Suganya *et al*., 2018). In addition, excessive zinc accumulation may damage cell membranes and disturb water uptake, further aggravating stress responses in plants. Excess zinc interferes with normal enzyme function by inhibiting key enzymes such as superoxide dismutase (SOD), leading to elevated oxidative stress, and it also restricts the absorption and internal movement of essential nutrients like iron and manganese, causing secondary nutrient imbalances. These physiological disruptions significantly affect crop performance, resulting in stunted grain formation, reduced yield, and alterations in grain nutrient composition due to disrupted mineral homeostasis (Noulas *et al*., 2018).

Prevalence of Zinc Deficiency in Agricultural Soils Worldwide

Zinc (Zn) deficiency is a widespread issue in agricultural soils, adversely affecting crop quality, yields, and food security. This problem is particularly severe in countries relying heavily on staple cereals such as rice and wheat, where Zn-deficient soils are commonly reported. Globally, approximately 50% of cereal-cultivated soils are Zn-deficient (Alloway, 2008; Cakmak, 2008). In India alone, over 50% of cultivated soils are deficient in zinc, especially in regions with alkaline pH and high phosphorus content (Singh, 2007). Similar patterns are observed in countries like Bangladesh, China, and Pakistan. Zn deficiency often results from multiple soil-related factors, including high pH, low organic matter, and nutrient imbalance. High soil pH leads to the precipitation of Zn as insoluble hydroxides and carbonates, reducing its availability to plants (Alloway, 2009). Moreover, excessive use of phosphate fertilizers can suppress Zn uptake due to antagonistic interactions. Low organic carbon content, typical in intensively cropped or degraded soils, further diminishes Zn solubility (Shivay *et al*., 2008). These conditions are common in tropical and subtropical regions, where high temperatures and intense weathering further deplete micronutrient reserves. The implications of Zn deficiency extend beyond crop health. In crops such as wheat, Zn scarcity leads to poor seed development, stunted growth, and lower grain Zn concentration, thereby reducing both yield and nutritional quality. This contributes to human Zn deficiency, particularly in populations relying on cereals as a major dietary component. Efforts to mitigate this problem include Zn fertilization through soil and foliar applications, seed priming, and the adoption of Zn-efficient crop varieties. Soil application of zinc sulfate and foliar sprays have been shown to effectively enhance Zn uptake and grain content in wheat and rice (Zou *et al*., 2012).

Furthermore, integrated nutrient management combining organic matter amendments with micronutrient fertilizers improves Zn bioavailability and crop response (Rattan *et al*., 2009). Biofortification strategies, both agronomic and genetic, are being promoted to sustainably address Zn malnutrition in humans. For example, the Harvest Plus program supports breeding of Zn-rich cereal varieties to alleviate hidden hunger.

Table 1: Comparison of Deficiency and Toxicity Symptoms

Aspect	*Zinc deficiency*	*Zinc toxicity*
Leaves	Yellowing, interveinal chlorosis, white bands	Dark green/purplish leaves, necrosis
Growth	Stunted growth, reduced tillering	Stunted growth, thickened roots
Root Development	Sparse and weak root systems	Short, thickened, and discoloured roots
Grain Yield	Decreased yield, poor grain quality	Reduced yield due to nutrient imbalances

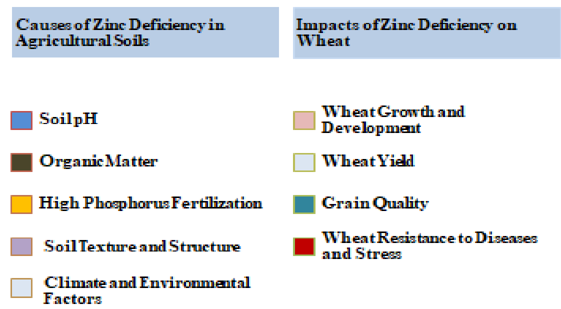

Fig 1: Causes of Zn deficiency and its impact on wheat crop

Causes of Zinc Deficiency in Soils and its impact on wheat crop

In agricultural soils, zinc deficiency is a common problem that significantly influences crop quality and yield. Zinc (Zn) is an important micronutrient required for many plants' physiological functions, as shown in Fig. 1. However, several factors limit its availability for plant uptake (Alloway, 2009). These include soil properties, agricultural methods, and environmental conditions. High pH (alkaline) soils above 7.5 reduce zinc solubility, forming zinc hydroxides and zinc phosphates, which are poorly available to plants (Riaz *et al.*, 2020). This is worse in calcareous soils rich in calcium carbonate, common in dry and semi-dry areas. Soils low in organic matter, such as sandy soils, lack sufficient chelation, which helps keep zinc in a plant-accessible form (Zaman *et al.*, 2018). In intensive systems with minimal organic input, microbial activity declines, further reducing availability. Overuse of phosphorus fertilizers also restricts zinc uptake by creating stable compounds. Continuous monocropping and tillage degrade zinc-rich topsoil. Soil texture influences availability; clay may bind zinc, while sandy soils have higher leaching rates (Montalvo *et al.*, 2016). Environmental factors like drought reduce root activity, hindering uptake. Heavy rainfall or irrigation promotes leaching, especially in sandy soils. Excessive dependence on NPK fertilizers without micronutrients causes nutrient imbalance and worsens zinc deficiency.

Impacts of Zn Deficiency on Wheat Growth, Yield, and Quality of Grain

The activation of enzymes involved in metabolic pathways, protein synthesis, and growth hormone regulation is just a few of the vital biochemical processes in wheat that depend on zinc. In addition to impairing essential physiological processes, its absence has serious agronomic repercussions (Rehman *et al.*, 2018). Due to decreased photosynthetic activity and impaired chlorophyll synthesis, zinc-deficient wheat exhibits stunted growth, reduced leaf area index, and chlorosis, especially in new leaves. In nutrient-poor or dry soils, these plants' shallow, underdeveloped roots impede their ability to absorb water and nutrients, making stress worse (Abbas *et al.*, 2021) that demonstrated in Table. 2 as well as Fig. 2. A major drop in yield results from the inability to produce enough tillers, which lowers the total number of productive stems, and from disruptions in cell division, which result in decreased grain number and weight. Furthermore, zinc deficiency impairs the quality of wheat grains by producing lighter, smaller grains with lower protein and starch contents, which reduces the grains' nutritional value and milling capabilities (Suganya *et al.*, 2020). Additionally, a zinc deficiency weakens wheat's resistance to disease, making it more susceptible to bacterial infections and fungal diseases like powdery mildew and rust, which decrease yield and quality. The deficiency not only affects above-ground plant parts but also compromises root architecture, leading to reduced soil exploration. Lack of zinc reduces a plant's capacity to withstand abiotic stressors like drought, salinity, and high temperatures, which lowers water use efficiency and overall plant health. A persistent zinc shortage in soil throws off nutrient cycles, causing deficiencies in other vital elements like potassium, phosphorus, and nitrogen, which lowers soil fertility overall (Khan *et al.*, 2022). Without appropriate supplementation or soil management techniques, the ongoing loss of zinc from agricultural soils can result in a persistent nutrient imbalance that further jeopardizes crop sustainability and productivity (Montalvo *et al.*, 2016). This can lead to economic instability and food insecurity in areas where wheat is the main food source, underscoring the pressing need for efficient zinc management techniques to preserve soil health, crop productivity, and long-term agricultural sustainability (Dimkpa *et al.*, 2023).

Application methods

Direct Soil Application of Zn in Wheat Cultivation

Applying zinc to the soil is a very common and successful method for preventing zinc deficiency in wheat, especially in soils with low zinc availability, high pH, or low organic matter. Zinc chelates, which are especially helpful in alkaline soils, ($ZnSO_4$), and zinc oxide (ZnO) are common zinc fertilizers applied to soil. There are several ways to optimize zinc availability for wheat plants, including localized application, banding, and broadcasting (Rehman *et al.*, 2018). Several variables, like soil pH, texture, OM content, and microbial activity, affect how well zinc is absorbed by the soil; zinc uptake is more effective in acidic or high-organic matter soils. Long-term advantages of soil application include increased zinc availability during the growing season, which promotes healthy wheat growth, enhanced photosynthesis, and improved grain quality, all of which increase yields and improve nutritional value (Noulas *et al.*, 2018). The efficiency of this approach, however, may be constrained by issues like the slower release of zinc in less active soils, the decreased availability of zinc in alkaline soils, and possible leaching in specific soil types (Prasad *et al.*, 2016). As long as the right fertilizers and application methods are chosen to fit particular soil conditions, soil application is still a financially sensible and widely adopted way to treat zinc deficiency in spite of these obstacles, supporting both sustainable crop production and soil health.

Foliar Sprays of Zinc in Wheat Cultivation

Zinc deficiency in wheat can be effectively treated by foliar application, especially during crucial growth stages when zinc demand is high. Because of its high-water solubility and ease of absorption by plant leaves, $ZnSO_4$, zinc chelates, and, less frequently, zinc oxide (ZnO) are common sources of zinc for foliar sprays (Xu *et al.*, 2022). Zinc concentrations in foliar sprays typically range from 0.5% to 1%, and they are usually applied

Table 2: Sources of Zinc for Wheat Cultivation

Source Type	*Zinc Fertilizer/Product*	*Form of Zinc*	*Application Method*	*Remarks*
Inorganic Sources	($ZnSO_47H_2O$)	Zn^{2+} ion (21% Zn)	Soil application, Foliar spray	Most commonly used: water-soluble
	Zinc Oxide (ZnO)	Zn (78–80% Zn)	Soil application	Less soluble; slow-release
	Zinc Chloride ($ZnCl_2$)	Zn^{2+} ion (48–50% Zn)	Soil or foliar	High solubility, but may be phytotoxic
	Zinc Nitrate ($Zn(NO_3)_2$)	Zn^{2+} ion	Foliar spray	Rapid uptake; used in low doses
Organic Sources	Zinc-EDTA (Chelated Zinc)	Zn^{2+} in chelated form	Foliar spray, Soil application	High efficiency; less reactive with soil minerals
	Zinc-Lignosulfonate	Zn in organic complex	Foliar spray	Less risk of toxicity; eco-friendly
Natural Sources	Zinc-enriched compost or FYM	Organic-bound Zn	Soil application	Improves soil health along with Zn supply
	Poultry manure	Organic-bound Zn	Soil amendment	Slow-release; contributes micronutrients
	Rock phosphate fortified with Zn	Zn compound	Soil application	Long-term benefit; slow nutrient release
Biofertilizers	Zinc-solubilizing bacteria (ZSB)	Converts insoluble Zn to Zn^{2+}	Soil inoculation	Enhances Zn availability naturally

when plants are actively growing, ideally in the early morning or late afternoon. To maximize absorption, the application should make sure that the upper and lower leaf surfaces are completely covered. Since zinc is not retained in plant tissues for extended periods of time, foliar sprays offer a quick fix by giving the plant zinc directly, but their effects are usually transient (Ahmad *et al*., 2021). Problems like the possibility of phytotoxicity from high concentrations, the requirement for several applications in cases of severe deficiency, and the effect of weather on spray efficacy must also be taken into account. Notwithstanding these drawbacks, foliar spraying provides a focused approach that gets around soil-related restrictions and is especially helpful when soil conditions prevent zinc uptake. Foliar spraying can improve wheat yield, quality, and overall plant health when combined with soil application or other zinc management techniques. This ensures that there is a sufficient supply of zinc for metabolic processes that are vital for growth, development, and stress resistance throughout the plant lifecycle (Ramzan *et al*., 2020).

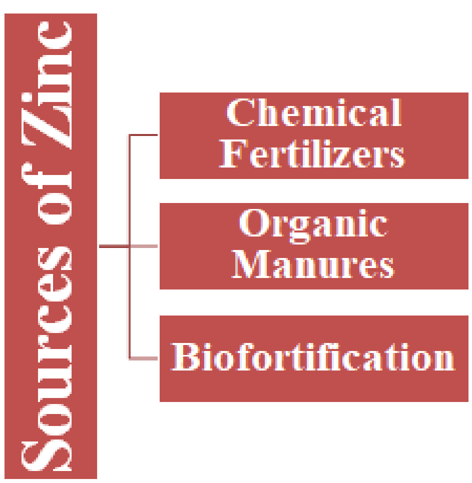

Fig. 2: Sources of zinc

Seed Priming with Zn in Wheat Cultivation

To promote early growth and development, especially in soils lacking zinc, seed priming is a pre-sowing method that entails soaking wheat seeds in a zinc solution. $ZnSO_4$, zinc chelates, and zinc oxide (ZnO) are common zinc sources for priming; sulfate is most frequently utilized because of its high solubility (Janmohammadi *et al*., 2023). To avoid premature germination, the priming procedure usually entails soaking seeds in a zinc solution with concentrations ranging from 0.5% to 2% for 6 to 12 hours, then drying the seeds to their initial moisture content (Zhao *et al*., 2020). Better yield and grain quality result from zinc priming, which enhances seed germination, root and shoot growth, nutrient uptake efficiency, stress tolerance, and general plant health (Muhammad *et al*., 2015). Zinc concentration, seed quality, soaking time, and drying conditions are some of the variables that affect the technique's efficacy; incorrect application may result in toxicity or seed damage. The effectiveness of seed priming is also greatly influenced by environmental factors and soil zinc levels; for long-term plant growth and maximum crop productivity, it may need to be combined with other zinc management techniques, such as soil or foliar applications, to ensure sustained zinc availability throughout the crop cycle (Carbone & Donia, 2023).

Optimal Rates and Timing of Zinc Application in Wheat Cultivation

Wheat needs zinc as a micronutrient because it plays a vital role in numerous physiological and biochemical processes, including protein synthesis, enzyme function, chlorophyll production, and cell division, all of which are essential for healthy growth, development, and optimal yield as seen in Fig. 3. To ensure

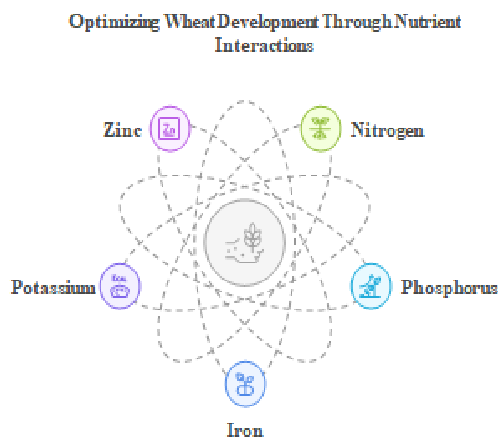

Fig. 3: Optimizing wheat development through nutrient interaction

wheat plants obtain adequate zinc during key growth phases while minimizing the chances of toxicity or nutrient imbalance, determining the appropriate zinc application rates and timing is crucial (Rehman *et al*., 2018). Both soil and foliar methods can be used to apply zinc; foliar sprays, which are typically applied as a 0.5% to 1% zinc solution, are frequently used to correct deficiencies during critical growth phases, while soil applications typically range from 1 to 10 kg per hectare, depending on the soil's zinc levels and the severity of the deficiency (Khan *et al*., 2022). When deficiency symptoms start to show during the growing season, topdressing and pre-sowing or pre-planting are the usual times to apply soil. When zinc demand is at its highest, foliar application works best during the vegetative stages (tillering and early jointing) and reproductive stages (flowering and grain filling). The pH of the soil, the amount of organic matter, the availability of water, and the particular symptoms of zinc deficiency in the plant all affect how effective zinc application is (Umair *et al*., 2020). While acidic soils increase zinc solubility and require lower application rates, alkaline soils with high pH tend to limit zinc availability and require higher application rates. Because of their higher cation exchange capacity (CEC), organic matter-rich soils retain zinc better, requiring fewer applications over time. Since dry conditions impede absorption and transport within the plant, adequate soil moisture is also essential for optimal zinc uptake. Zinc is available when the plant needs it most, when it is applied at critical growth stages. This improves enzymatic functions, fosters better root and shoot development, increases stress tolerance, and eventually boosts yield and grain quality (Rudani *et al*., 2018). Zinc application must be adjusted to meet the unique needs of wheat through regular soil testing, careful crop growth stage monitoring, and environmental considerations. This approach ensures that the nutrient is applied effectively and economically, ultimately supporting high-yielding and sustainable wheat cultivation while minimizing environmental impact.

Synergistic Effects of Zinc with Other Nutrients

Since these nutrients often exhibit cooperative interactions that enhance plant growth and nutrient use efficiency, the relationships among nitrogen (N), phosphorus (P), iron (Fe), potassium (K), and zinc (Zn) are crucial for optimizing wheat development. Nitrogen, an important macronutrient, promotes root growth by expanding the surface area for nutrient uptake, which supports vegetative growth and boosts zinc absorption (Pandey *et al*., 2020). Sufficient nitrogen levels improve zinc's role in key metabolic functions such as photosynthesis and protein formation. When both phosphorus and zinc are adequately available, they interact to enhance phosphorus absorption and energy transfer within plant cells through the activation of enzymes involved in phosphorus metabolism. This synergy supports robust root growth, stronger seedling development, better flowering, and higher yields. Furthermore, zinc and iron have a mutually beneficial association, particularly concerning iron metabolism and chlorophyll production (Li *et al*., 2021). Zinc aids in the uptake and utilization of iron, which stimulates chlorophyll synthesis, thereby improving photosynthesis and plant vitality. Potassium also plays a role by aiding nutrient transport within the plant and maintaining cellular water balance, which facilitates zinc uptake (Roosta *et al*., 2018). Applying potassium and zinc together promotes overall wheat growth and enhances tolerance to stresses like drought and heat. Besides supporting wheat development, maintaining balanced levels and application of these nutrients improves yield, plant Vigor, and adaptability to environmental changes (Zhang *et al*., 2020). Moreover, understanding these nutrient interactions is vital for developing integrated fertilization strategies that optimize nutrient availability, minimize antagonistic effects, and promote sustainable wheat production under diverse soil and climatic conditions.

Antagonistic Effects of Zinc with Other Nutrients

Zinc accessibility and absorption by wheat plants can be influenced by opposing interactions with phosphorus (P), iron (Fe), calcium (Ca), and magnesium (Mg). Elevated phosphorus concentrations can cause zinc precipitation, reduce its availability, and lead to zinc deficiency, which adversely affects wheat growth, particularly in alkaline soils with elevated phosphate levels (Rietra *et al*., 2017). In these types of soils, overfertilization with phosphorus can intensify this effect, necessitating cautious management to preserve balanced nutrient levels. Since both iron and zinc are divalent cations with comparable uptake mechanisms, high iron concentrations may also compete with zinc for absorption sites in plant roots. Due to this competition, wheat plants may experience zinc deficiency, which would show up as chlorosis and stunted growth (Gupta *et al*., 2016). Although it is necessary for plant growth, calcium can also limit the availability of zinc in soils with high calcium levels, especially calcareous soils, by forming insoluble complexes with zinc. Zinc deficiency symptoms in wheat can result from excessive calcium locking up zinc. Furthermore, because of competition at the absorption sites in plant roots, high magnesium levels can hinder zinc uptake, especially in soils that are high in magnesium or where magnesium fertilizers have been overapplied (Xie *et al*., 2021). This may result in less zinc being available, which would further hinder wheat yield and growth. These antagonistic relationships emphasize how crucial balanced nutrient management is to maximizing wheat performance and zinc availability. Therefore, understanding these nutrient interactions is essential for designing effective fertilization programs that maintain nutrient equilibrium, avoid negative interactions, and enhance zinc use efficiency for improved crop health and productivity.

Soil Properties Affecting Zinc Availability

The amount of organic matter, soil texture, and pH all have a big impact on how readily available zinc (Zn) is to plants. Acidic soils (pH 5.5 to 6.5) have higher zinc availability because they are still soluble and available for plant uptake. Zinc precipitates as insoluble compounds in alkaline soils (pH > 7), which lowers its bioavailability (Hou *et al.*, 2019). This can be reduced by applying zinc in chelated forms or using acidifying agents, and enhancing zinc availability in soil can be achieved by modifying pH with sulphur or organic materials. Besides aiding microbial activities that release zinc from soil minerals, organic matter boosts the cation exchange capacity (CEC) of soils, which helps hold onto zinc and other nutrients. Zinc availability can be improved by incorporating organic materials, such as compost or manure, particularly in soils deficient in organic content. Another key aspect is soil texture; soils with finer particles, like clay or loam, possess higher CEC and retain zinc more effectively (Sarwar *et al.*, 2020). To ensure adequate zinc availability for plant growth, sandy soils with low CEC, on the other hand, need higher or more frequent zinc applications to make up for nutrient leaching and poor retention. These elements highlight how crucial it is to take soil characteristics into account when controlling zinc fertilization techniques. Moreover, ongoing soil testing and monitoring can guide precise zinc management, ensuring that applications are optimized according to changing soil conditions, thus improving nutrient use efficiency and reducing environmental risks.

Influence of Soil Properties (e.g., pH, Organic Matter) on Zinc Availability

An essential micronutrient for wheat growth, zinc participates in several physiological roles, such as protein synthesis, enzyme activity, and chlorophyll formation. However, soil properties greatly influence its accessibility to plants, either enhancing or restricting zinc absorption. Soil pH and organic matter levels are among the most important factors controlling zinc availability (Sarwar *et al.*, 2020). To optimize zinc nutrition in wheat and prevent deficiencies that could hinder growth and yield, understanding these factors is vital. Both soil pH and organic matter strongly affect zinc's solubility and uptake in wheat. Zinc remains soluble as Zn^{2+} in acidic soils (pH < 6), ensuring good availability for plant uptake and supporting optimal wheat development. In neutral soils (pH 6–7), zinc availability is generally adequate, although slight management adjustments may be necessary to prevent deficiency (Rajamuthuramalingam *et al.*, 2024). On the other hand, alkaline soils (pH > 7) cause zinc to precipitate, which lowers its bioavailability and causes symptoms of zinc deficiency in wheat, including chlorosis and stunted growth. In alkaline soils, this can be lessened by increasing availability through the use of organic amendments and chelated zinc. Through processes like enhanced cation exchange capacity (CEC), which retains zinc and decreases leaching, and the creation of zinc-organic complexes, which improve solubility, organic matter increases zinc availability. Moreover, soil microbes that aid in zinc mineralization are supported by organic matter, guaranteeing a consistent supply of nutrients (Antoniadis & Golia, 2015). Because organic matter can buffer pH extremes and increase zinc availability, the relationship between pH and organic matter is also crucial. Thus, maintaining ideal zinc levels in the soil, encouraging wheat growth, and avoiding zinc deficiency all depend on controlling pH and organic matter (Yadav *et al.*, 2023). Furthermore, adopting integrated nutrient management practices that combine soil amendments, zinc fertilization, and regular soil testing can ensure sustained zinc availability, helping to maximize wheat productivity and maintain soil health over time.

Strategies for Wheat Biofortification and Its Implications for Public Health

Hidden hunger, an important strategy to combat widespread micronutrient shortages, particularly zinc, which significantly impacts public health by causing stunted growth, weakened immune responses, and cognitive impairments, is wheat biofortification, which targets the enhancement of essential nutrients such as zinc, iron, and folate (Wani *et al.*, 2022). Wheat biofortification can be achieved through conventional breeding, genetic modification, and agronomic methods like zinc fertilization and foliar sprays. The objective is to boost levels of important micronutrients, including iron, zinc, and folate. While genetic engineering employs transgenic approaches and marker-assisted selection for precise trait improvement, breeding focuses on crossbreeding and selecting high-zinc cultivars to raise nutrient content. Agronomic practices such as soil amendments and zinc fertilizer application further improve zinc availability (Kumar *et al.*, 2019). Using zinc-biofortified wheat offers a cost-effective and sustainable solution to reduce "hidden hunger," especially in regions where zinc deficiency is prevalent. This approach can help decrease zinc deficiency-related health issues by supporting immune function, growth, cognitive development, and maternal well-being (Ibrahim *et al.*, 2021). Compared to supplementation programs, biofortification provides a scalable and long-term strategy benefiting vulnerable populations, especially in areas where wheat is a dietary staple. Successful dissemination and cultivation of biofortified wheat varieties require strong policy frameworks, collaboration between public and private sectors, and farmer awareness programs to ultimately enhance public health outcomes (Garcia-Casal *et al.*, 2017). Additionally, integrating educational outreach and ensuring accessibility to improved seed varieties are vital steps to promote adoption and maximize the nutritional benefits across diverse agro-ecological zones.

Conclusion

Zinc deficiency is a widespread form of micronutrient malnutrition, affecting millions of people worldwide. In wheat, zinc deficiency leads to reduced growth, lower yields, and poor grain quality, as zinc is vital for key plant functions such as enzyme activation, protein synthesis, and cell division. The problem is aggravated by the prevalence of zinc-deficient soils, often influenced by factors like intensive cropping practices, high soil pH, and low organic matter content. To address this challenge, zinc biofortification in wheat has emerged as a promising and sustainable approach. Strategies include genetic engineering, conventional breeding for high-zinc varieties, and agronomic interventions such as soil zinc fertilization, foliar sprays, and seed priming. These methods have been shown to enhance zinc uptake and translocation, resulting in wheat grains with improved nutritional value. Biofortified wheat not only improves dietary zinc intake for populations that rely on wheat as a staple food but also supports agricultural productivity. This approach offers a practical and affordable way to combat "hidden hunger," particularly in regions most vulnerable to micronutrient deficiencies. Successful implementation requires coordinated efforts. Policymakers must prioritize biofortified wheat in national food security programs, researchers should refine techniques to maximize zinc accumulation in grains, and farmers need to adopt effective zinc application practices. Through such collaboration, zinc biofortification in wheat can significantly improve public health and contribute to global food and nutrition security

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Authors Contribution

*1. *Conceptualization* – [Mohd Mued]*

developed the research idea and designed the conceptual framework of the study.

*2. *Methodology* – [A.S. Yadav]*

designed the experimental methodology, including sample collection and analysis procedures.

*3. *Data Curation* – [Saba Siddiqui]*

organized and managed the data, ensuring accuracy and consistency for analysis.

*4. *Formal Analysis* – [P. Smriti Rao]*

performed the statistical analysis and interpreted the results.

*5. *Writing – Original Draft* – [Nadeem Khan]*

wrote the initial draft of the manuscript.

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Conflict of interest

No conflict of interest

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