

Integrated Use of Zinc and Nitrogen for Enhancing Grain Quality and Productivity of Wheat

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Abstract

Wheat (*Triticum aestivum* L.), a staple providing 20% of global calories and protein, faces challenges from micronutrient deficiencies like zinc (Zn), contributing to "hidden hunger" affecting over 2 billion people. This review examines the synergistic integration of nitrogen (N) and zinc fertilizers to enhance wheat productivity and grain quality. Nitrogen drives biomass accumulation, chlorophyll synthesis, and protein formation, while zinc acts as a cofactor for 300+ enzymes, stabilizing membranes and boosting antioxidant defenses against stresses. Combined application via soil incorporation (5–10 kg Zn/ha) and foliar sprays (0.5–2% ZnSO₄) improves photosynthetic efficiency, delays senescence, increases grain Zn concentration (20–50% biofortification), protein content (up to 15%), and yield (10–30%) under diverse conditions. Agronomic strategies address soil pH, organic matter interactions, and timing (e.g., booting stage foliar), mitigating deficiencies in alkaline calcareous soils. Environmental factors like drought amplify synergies, with integrated use reducing oxidative stress via enzymes like SOD and CAT. This approach offers a sustainable path for nutritional security, emphasizing balanced fertilization to optimize harvest index and resource efficiency in high-yielding systems.

Keywords: Wheat, Zinc, Nitrogen, Biofortification, Grain Quality, Productivity, Synergistic Effects, Foliar Application, Photosynthetic Efficiency, Antioxidant Defense, Harvest Index

1. Introduction

The intersection of global food security and human nutritional health presents one of the most significant challenges for contemporary agricultural science. Wheat (*Triticum aestivum* L.) stands as a cornerstone of the global food system, providing nearly 20% of all dietary calories and protein per capita (Hafeez et al., 2021). However, the drive for caloric sufficiency has historically prioritized absolute grain yield over nutritional density, leading to a widespread phenomenon known as "hidden hunger." This condition, characterized by micronutrient deficiencies, particularly of zinc (Zn) and iron (Fe), affects more than 2 billion people worldwide (Akram et al., 2017). Zinc deficiency, in particular, is a catastrophic public health concern linked to impaired physical growth, immune system dysfunction, DNA damage, and altered reproductive biology (Rogalski et al., 2025). Because wheat-based products are consumed as staples by over 1.2 billion people, the agronomic biofortification of wheat via the integrated use of nitrogen (N) and zinc offers a high-impact, sustainable intervention strategy (Bassi et al., 2021). Figure 1 show integrated

conceptual framework illustrating synergistic effects of nitrogen and zinc on physiological processes, grain quality, and productivity in wheat.

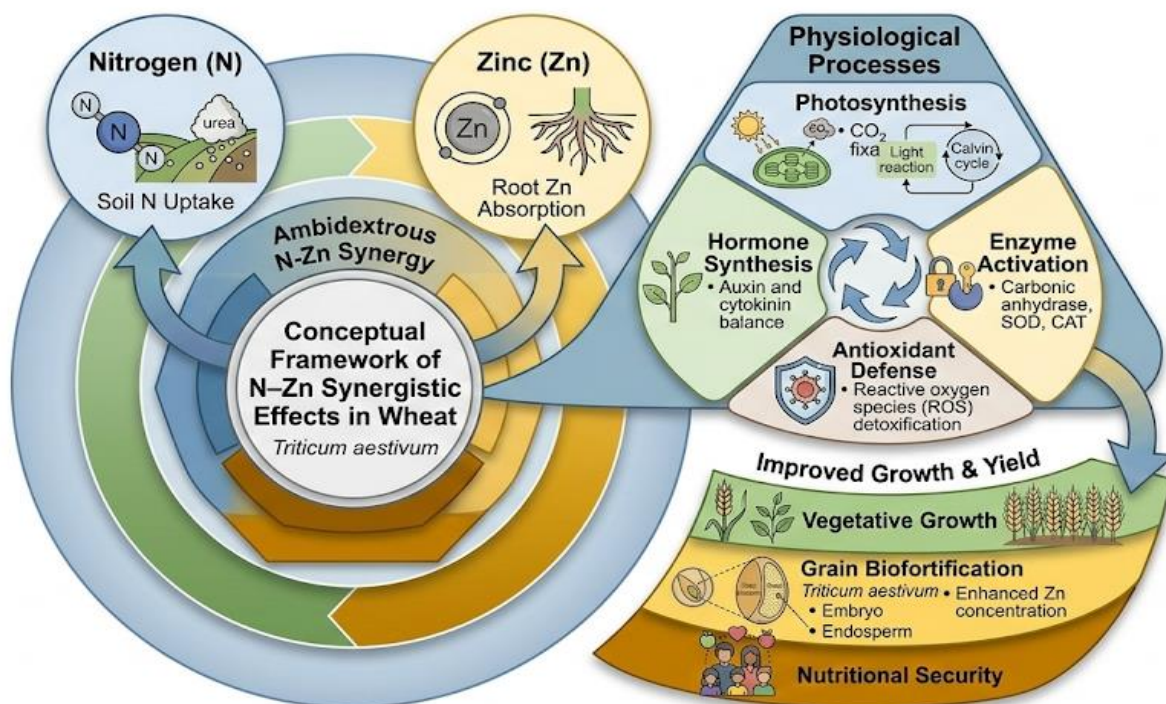


Figure 1. Integrated conceptual framework illustrating synergistic effects of nitrogen and zinc on physiological processes, grain quality, and productivity in wheat.

2. Physiological and Biochemical Synergy of Nitrogen and Zinc

The relationship between nitrogen and zinc in wheat is not merely additive but profoundly synergistic, rooted in the fundamental metabolic architecture of the plant (Zayed et al., 2023). Nitrogen, a primary macronutrient, is the principal constituent of amino acids, proteins, and chlorophyll, while zinc serves as an essential micronutrient and a structural or catalytic cofactor for over 300 enzymes (Shehzadi et al., 2025).

2.1 Coordination in Photosynthetic Metabolism

Zinc plays a critical structural role in the enzyme carbonic anhydrase, which facilitates the rapid conversion of bicarbonate (HCO_3^-) to carbon dioxide (CO_2) within the chloroplasts, thereby ensuring a constant supply of substrate for the Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) enzyme during the Calvin cycle (Jensen et al., 2020). This enzymatic function is directly enhanced by the nitrogen status of the plant, as nitrogen provides the necessary peptide framework for these enzymes. When nitrogen and zinc are applied together, there is a measurable increase in photosynthetic pigments, including chlorophyll a and b, which extends the green leaf area and delays senescence a process critical for the grain-filling period (Kamran et al., 2020).

In high-yielding wheat systems, the leaf area index (LAI) and radiation interception rate are primary determinants of biomass accumulation (Du et al., 2021). Adequate nitrogen fertilization increases leaf emergence and expansion, while zinc ensures that the expanded leaf surface remains physiologically active by stabilizing protein synthesis and protecting chlorophyll from oxidative degradation (Duan et al., 2018).

2.2 Phytohormone Synthesis and Growth Regulation

The growth-promoting effects of zinc are largely mediated through its role in the biosynthesis of

auxins, specifically indole-3-acetic acid (IAA). Zinc is required for the synthesis of tryptophan, a biochemical precursor to IAA, which regulates cell division, elongation, and the initiation of tillers (Kang et al., 2021). Nitrogen fertilization acts as a catalyst for this process, as it increases the overall metabolic demand for growth regulators. The integrated application of N and Zn has been shown to induce significant increases in plant height and tiller density, often recorded at concentrations of 150 kg N and 15 kg Zn ha⁻¹ (Jalal et al., 2024).

Table 1: Influence of Integrated Nitrogen and Zinc Application on Growth and Yield Components of Wheat

Growth Parameter	Control (N0, Zn0)	High Nitrogen (150 kg/ha)	Integrated (150 N + 15 Zn)
Plant Height (cm)	82.0 - 85.5	92.4 - 96.8	98.1 - 101.0
Tillers (m ⁻²)	296.0 - 304.0	319.8 - 321.9	335.5 - 348.0
Grain Yield (kg/ha)	2760 - 2850	3750 - 4040	4044 - 4250
Harvest Index (%)	38.1 - 42.0	48.5 - 51.0	54.0 - 55.3
<i>(Data adapted from Hafeez et al., 2021; Shehzadi et al., 2025)</i>			

2.3 Upregulation of Antioxidant Aptitude

The combined application of nitrogen and zinc serves as a defense mechanism against abiotic stressors, including drought, salinity, and high temperature. Zinc is a central component of Copper-Zinc Superoxide Dismutase (Cu-Zn SOD), which scavenges reactive oxygen species (ROS) such as the superoxide radical (O₂⁻) (Umair Hassan et al., 2020). Nitrogen further enhances the activities of other antioxidant enzymes like catalase (CAT) and ascorbate peroxidase (APX) to eliminate hydrogen peroxide (H₂O₂), thereby reducing lipid peroxidation and maintaining the integrity of biological membranes. This biochemical protection is essential under future climate scenarios where nutritional demand is high (Sattar et al., 2021).

3. Molecular Mechanisms of Uptake and Translocation

The enhancement of zinc concentrations in wheat grain through nitrogen management is underpinned by complex molecular and physiological pathways involving root absorption, xylem loading, and phloem-mediated remobilization (Mued et al., 2025).

3.1 Absorption Kinetics at the Root-Soil Interface

The efficiency of zinc uptake from the soil is significantly influenced by the nitrogen status of the plant. Nitrogen stimulates root development, increasing root length and surface area, which enhances the physical contact between the root system and zinc ions in the soil solution (Kutman et al., 2011). More importantly, nitrogen alters the absorption kinetics of zinc. In treatments receiving adequate nitrogen, the maximum influx rate (V_{max}) of zinc increases, indicating a higher affinity of root transporters for zinc ions (Erenoglu et al., 2011).

These changes are driven by the regulation of membrane transport proteins. Nitrogen supply upregulates the expression of TaZIP3 and TaZIP7, members of the Zinc-regulated Transporter/Iron-regulated Transporter-like Protein (ZIP) family (Nie et al., 2017).

3.2 Long-Distance Transport and Chelating Compounds

Once absorbed, zinc must be transported from the roots to the shoots and eventually to the developing grains. This process is highly dependent on nitrogen-containing ligands. Zinc ions are typically chelated by molecules such as nicotianamine (NA) and 2-deoxymugineic acid (DMA)

(Jagota et al., 2026). Nitrogen status governs the synthesis of these chelators, which are required for both xylem transport and phloem loading (Singh, 2024). Research using radiolabeled ^{65}Zn has demonstrated that nearly 80% of total shoot zinc can be remobilized to the grain under high nitrogen conditions, whereas under nitrogen deficiency, zinc remains sequestered in vegetative tissues (Nieder et al., 2018).

4. Agronomic Biofortification: Application Methods and Timing

To achieve the dual goals of high yield and grain biofortification, the method and timing of nitrogen and zinc application must be optimized (Ramzan et al., 2020).

4.1 Soil and Foliar Application Strategies

Applying zinc fertilizers to the soil before sowing is a common practice, but its impact on grain zinc concentration is often limited by soil pH and high CaCO_3 content. On average, soil zinc application improves grain Zn concentration by only 29.1%, which is frequently insufficient to meet the human nutritional target of 40 mg/kg (Rehman et al., 2018). Foliar application bypasses soil constraints by delivering zinc directly to the leaves, increasing grain zinc concentration by 55.2%. Combining soil and foliar applications can increase concentration by up to 62.3%, ensuring nutritional targets are met (Ramesh, 2024).

Table 2: Efficacy of Different Zinc Application Methods in Meeting Biofortification Targets

Application Method	Increase in Grain Zn (%)	achievement of 40 mg/kg Target
Soil Application Only	29.1%	Low Probability
Foliar Application Only	55.2%	Moderate to High
Soil + Foliar Combined	62.3%	High Probability
<i>(Data adapted from Akram et al., 2020; Akram et al., 2017)</i>		

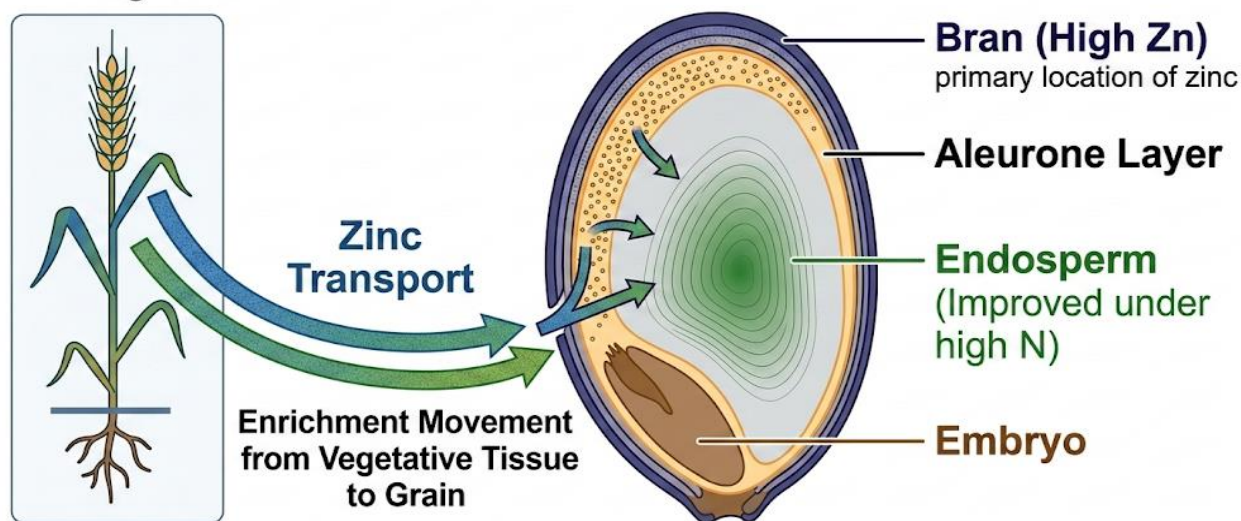
5. Enhancing Grain Quality and Nutritional Bioavailability

The nutritional quality of wheat is determined not only by the absolute concentration of minerals but by their localization within the grain and their bioavailability (Ramesh, 2024).

5.1 Endosperm Enrichment and GPC

High nitrogen supply has been shown to enhance whole-grain zinc concentrations and increase endosperm zinc by over 80%. This enrichment is positively correlated with grain protein concentration (GPC), as protein-rich grains provide a greater storage capacity for zinc and iron (Kutman et al., 2011). As showed in figure 2 distribution and nitrogen-enhanced enrichment of zinc within wheat grain tissues.

Figure 2. Distribution and nitrogen-enhanced enrichment of zinc within wheat grain tissues.



5.2 Managing Antinutrients: Phytic Acid

The bioavailability of zinc is limited by phytic acid, which chelates zinc into insoluble phytates. Integrated N and Zn management aims to minimize the phytic acid-to-zinc (PA:Zn) molar ratio. Optimized zinc application can reduce phytic acid by nearly 29%, substantially improving the nutritional efficacy of the wheat (Welch & Graham, 2004).

6. Impact on Processing and End-Use Quality

The technological quality of wheat is a function of its protein composition, specifically the balance of gluten proteins. Nitrogen fertilization increases GPC and enhances the concentrations of glutenins responsible for dough strength (Shewry & Halford, 2002). While zinc is required for enzymatic balance, some studies emphasize that combined application can slightly alter wet gluten contents depending on the cultivar (Cakmak et al., 2010).

7. Innovative Approaches: Seed Priming and Nanotechnology

Seed priming with zinc sulfate or urea solutions has been shown to improve seedling vigor and stand establishment. Optimal results are often achieved with a 10-hour priming duration using concentrations such as 75 to 100 ppm of zinc oxide (ZnO) (Akula Tejaswi et al., 2025). Furthermore, the use of nano-fertilizers like ZnO nanoparticles represents a frontier in precision agriculture, providing a controlled release of nutrients and enhancing plant resilience under moisture stress (Sharma et al., 2025).

8. Economic Feasibility and Environmental Sustainability

The integrated use of nitrogen and zinc is consistently more profitable than nitrogen alone. Highest net returns are obtained using 150 kg N/ha in combination with 5 kg Zn/ha plus a 0.5% ZnSO₄ spray (Beyer, 2025). From a sustainability perspective, replacing 20% to 40% of mineral nitrogen with organic alternatives like vermicompost can reduce greenhouse gas emissions and nutrient leaching while sustaining crop yields (Jensen et al., 2020). Modern mapping tools and climatic suitability models further aid in monitoring environmental risks and optimizing fertilizer placement (Barker et al., 2025).

Table 3: Economic Analysis of Integrated Nitrogen and Zinc Fertilization in Wheat

Economic Indicator	Nitrogen Only (150 kg/ha)	Integrated (150 N + Zn Soil + Foliar)
Gross Return (INR/ha)	88,400 - 90,500	100,747.61
Net Return (INR/ha)	56,200 - 58,000	68,346.86
Benefit-Cost Ratio	2.15 - 2.30	2.67
<i>(Data adapted from Hafeez et al., 2021; Shehzadi et al., 2025)</i>		

9. Conclusion

The integrated application of nitrogen and zinc emerges as a transformative strategy for elevating wheat grain quality and productivity, addressing both agronomic yield gaps and nutritional deficiencies in staple-dependent populations. By harnessing their biochemical synergies enhancing enzyme activity, protein synthesis, and stress resilience this approach can achieve 10–30% yield gains and 20–50% Zn enrichment without compromising environmental sustainability. Optimal practices, including soil testing, timed foliar sprays, and balanced N:Zn ratios, are essential to overcome soil constraints and maximize biofortification efficacy. As global demands intensify amid climate variability, future research should prioritize genotype-specific responses and precision agriculture tools to refine these interventions, ensuring wheat's role in combating hidden hunger and securing food systems for billions.

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