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Response of Wheat Crop to The Application of Different Micronutrients and Their Influence on Growth and Development

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ABSTRACT

Micronutrients are required in small quantities but play essential roles in wheat growth, physiological processes, yield formation, and grain nutritional quality. Deficiencies of zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B) can restrict plant development and reduce productivity, particularly in soils with limited nutrient availability. This study summarizes the roles of major micronutrients in wheat growth and development, with emphasis on their effects on germination, root development, tillering, biomass production, photosynthesis, nutrient uptake, enzyme activity, yield components, and grain quality. The study also evaluates major approaches for micronutrient management, including soil application, seed treatment, foliar application, and integrated fertilization. Particular attention is given to the influence of soil properties, environmental conditions, wheat genotype, fertilizer dose, application timing, and application method on micronutrient availability and utilization efficiency. Recent evidence indicates that balanced micronutrient management can improve wheat physiological performance, yield components, grain yield, and nutritional value, while agronomic biofortification offers an important strategy for increasing grain Zn and Fe concentrations. However, the effectiveness of micronutrient application varies considerably with soil conditions, climatic stresses, genotype, and management practices. Therefore, site-specific nutrient management, soil testing, genotype selection, and stage-specific application are essential for improving micronutrient-use efficiency. Integrating micronutrient management with wheat breeding and precision agriculture can contribute to sustainable productivity and improved grain nutritional quality. Future research should focus on genotype-specific micronutrient requirements, nutrient interactions, precision application technologies, and climate-resilient strategies for efficient wheat production and enhanced food and nutritional security.

Introduction and Importance of Micronutrients in Wheat

Importance of Wheat Production and Productivity

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally and plays a central role in food and nutritional security. It provides a substantial proportion of dietary energy and protein and is consumed as a staple food by billions of people, particularly in Asia, Africa and other developing regions (Gupta et al., 2024). The increasing global population, changing dietary requirements and pressure on agricultural resources have created a continuous need to improve wheat productivity through efficient crop management and sustainable production technologies. Consequently, increasing yield per unit area while maintaining grain quality has become an important objective of modern wheat production. Wheat productivity is influenced by genotype, soil fertility, water availability, temperature, disease pressure and agronomic management. Among these factors, balanced plant nutrition is particularly important because deficiencies of essential nutrients can restrict physiological processes and ultimately reduce yield. Although nitrogen (N), phosphorus (P) and potassium (K) are traditionally emphasized in wheat fertilization programs, micronutrients are equally important for maintaining optimum plant growth and productivity. Inadequate micronutrient availability may limit plant development even when macronutrients are supplied in sufficient quantities (Cakmak & Kutman, 2018). Micronutrient management is also important from a human nutrition perspective. Wheat grain is a major component of diets in many developing countries, and therefore its nutritional quality directly influences human micronutrient intake. Zinc (Zn) and iron (Fe), in particular, have received considerable attention because deficiencies of these elements are widespread among human populations. Wheat biofortification through breeding and agronomic management has consequently emerged as an important strategy for improving both crop nutritional quality and human nutrition (Gupta et al., 2024; Kumar et al., 2024). Thus, improving wheat productivity should not be limited to grain yield alone but should also consider the nutritional quality and micronutrient density of the harvested grain.

Role of Micronutrients in Plant Growth and Development

Micronutrients are essential elements required by plants in relatively small quantities but are indispensable for normal growth, development and reproduction. Important plant micronutrients include zinc, iron, manganese (Mn), copper (Cu), boron (B), molybdenum (Mo), nickel (Ni) and chlorine (Cl). These nutrients participate in numerous biochemical and physiological processes, including enzyme activation, photosynthesis, respiration, protein synthesis, electron transport, membrane stability and regulation of plant metabolism (Cakmak & Kutman, 2018).

Zinc is particularly important in wheat because it contributes to enzyme activity, protein synthesis, carbohydrate metabolism, membrane integrity and regulation of growth-related processes. Iron is essential for electron transport, chlorophyll formation and several redox reactions, while manganese participates in photosynthetic activity and enzyme functioning. Copper is associated with electron transport, lignification and reproductive development, whereas boron has important functions in cell-wall formation, membrane integrity, pollen development and reproductive processes. Consequently, adequate micronutrient availability can promote root growth, tillering, leaf development, photosynthetic efficiency and biomass accumulation in wheat. Micronutrients are also closely associated with the nutritional quality of wheat grain. Genetic variability for micronutrient accumulation exists among wheat genotypes and their wild relatives, providing opportunities for genetic biofortification (Kumar et al., 2024). Recent advances in molecular breeding, quantitative trait locus mapping, genome-wide association studies and genomic approaches have further increased opportunities for developing wheat genotypes with improved micronutrient concentrations (Kumar et al., 2025). Therefore, micronutrient management has significance at both the crop-production and human-nutrition levels.

Micronutrient Deficiency in Wheat Production Systems

Micronutrient deficiency is an important constraint to sustainable wheat production, particularly in soils where nutrient availability is restricted by unfavorable chemical or physical conditions. Zinc deficiency is of particular concern in wheat-growing areas because soil pH, calcareous conditions, low organic matter and interactions with other nutrients can reduce Zn availability to plants. Similarly, iron deficiency may occur where soil conditions restrict Fe solubility and uptake. The occurrence and severity of micronutrient deficiencies depend on soil characteristics, climatic conditions, genotype, crop management and nutrient interactions (Cakmak & Kutman, 2018). Micronutrient deficiency can adversely affect wheat growth by reducing root development, chlorophyll formation, photosynthetic activity, tillering and reproductive development. Severe or prolonged deficiencies may ultimately decrease grain number, grain weight and total grain yield. In addition, insufficient uptake of micronutrients can result in wheat grain with low concentrations of nutritionally important elements. This creates an important connection between soil micronutrient deficiency, agricultural productivity and human nutritional security (Gupta et al., 2024).

Among the micronutrients, Zn and Fe have received particular attention because wheat is an important dietary source of these elements in many countries. Reviews of wheat biofortification have demonstrated that genetic and agronomic approaches can increase grain Zn and Fe concentrations, although the effectiveness of these approaches varies with genotype, soil conditions, fertilizer source, application method and environmental conditions (Gupta et al., 2024; Kumar et al., 2024). Agronomic biofortification through soil, seed or foliar application can complement conventional breeding approaches and may provide a relatively rapid means of improving micronutrient accumulation in wheat grain. Therefore, an integrated approach involving balanced fertilization, efficient micronutrient application, selection of nutrient-efficient genotypes and genetic biofortification is necessary for sustainable wheat production. A better understanding of the individual and combined effects of micronutrients on wheat growth, physiology, yield and grain nutritional quality can contribute to the development of more efficient nutrient-management strategies and help address both food and nutritional security challenges.

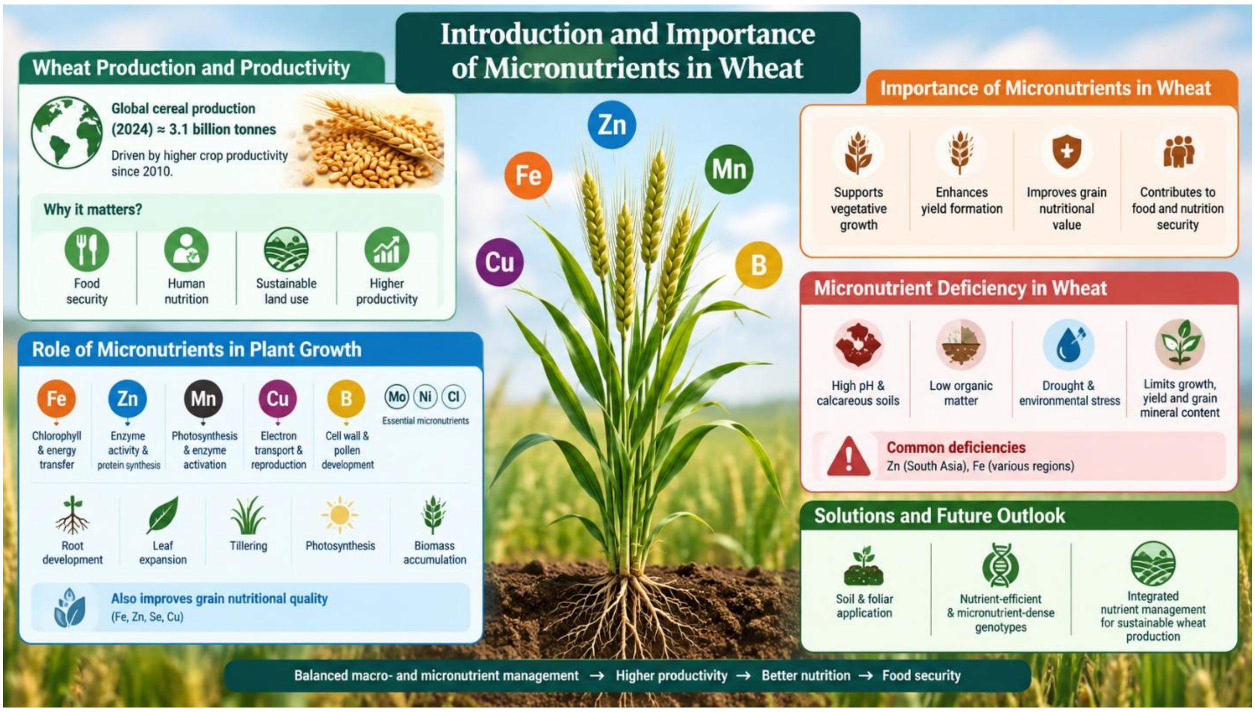

Figure 1: Importance and Role of Micronutrients in Wheat Growth and Productivity

Major Micronutrients Required for Wheat Growth

Micronutrients are required by wheat in relatively small quantities, but they are indispensable for maintaining normal physiological activity, growth and reproductive development. Among the essential micronutrients, zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) and boron (B) have received considerable attention because of their roles in enzyme activity, photosynthesis, cellular metabolism, reproductive development and grain nutritional quality. Adequate micronutrient nutrition is therefore essential for achieving high wheat productivity and improving the nutritional value of grain (Hänsch & Mendel, 2009; Nasim et al., 2025).

Zinc and Its Role in Wheat Growth

Zinc is one of the most important micronutrients for wheat production because it participates in numerous metabolic and physiological processes. It functions as a structural and catalytic component of several enzymes and contributes to protein synthesis, carbohydrate metabolism, membrane stability, gene regulation and antioxidant defense (Cakmak & Kutman, 2018). Adequate Zn availability promotes root development, leaf expansion, tillering and biomass accumulation, while Zn deficiency can restrict plant growth and reduce yield. Zinc is also particularly important for wheat grain nutritional quality. Wheat-based diets can provide a substantial proportion of dietary Zn, but the naturally low concentration and limited bioavailability of Zn in cereal grain can contribute to human Zn deficiency. Genetic and agronomic biofortification are therefore increasingly being used to improve Zn concentration in wheat grain (Gupta et al., 2024; Nasim et al., 2025). A recent global meta-analysis involving 139 studies demonstrated that soil Zn application increased grain Zn concentration by approximately 29%, whereas foliar and combined soil-plus-foliar applications produced substantially greater increases of approximately 55% and 62%, respectively (Hui et al., 2025). These findings emphasize the importance of application method and timing in achieving effective Zn nutrition.

Iron and Its Role in Physiological Processes

Iron is another essential micronutrient with a central role in wheat physiology. Although plants require Fe in relatively small quantities, it is indispensable for chlorophyll biosynthesis, electron transport, respiration and numerous redox reactions. Iron-containing proteins participate in photosynthetic and respiratory electron-transfer systems, making adequate Fe supply essential for maintaining photosynthetic efficiency and energy metabolism (Hänsch & Mendel, 2009). In wheat, Fe availability influences plant growth as well as grain nutritional quality. Genetic variation for Fe concentration exists among wheat genotypes, providing opportunities for breeding nutritionally improved cultivars. Recent advances in molecular breeding have identified quantitative trait loci, candidate genes and molecular mechanisms associated with Fe uptake, transport and accumulation in wheat grain (Nasim et al., 2025). Importantly, Fe accumulation is not uniform throughout plant development. Recent field research showed that Fe accumulation in wheat grain continued during grain filling, whereas Mn, Cu and Zn displayed different temporal accumulation patterns, demonstrating that micronutrient transport and remobilization are developmentally regulated (Li et al., 2026). Consequently, Fe management should consider both soil availability and the physiological stage of the crop.

Manganese, Copper and Boron in Wheat Development

Manganese, copper and boron also contribute significantly to wheat growth and development. Manganese is involved in photosynthetic processes, particularly the water-splitting reaction of photosystem II, and functions as an activator of several enzymes. Adequate Mn therefore supports photosynthesis, antioxidant metabolism and normal plant development. Copper participates in electron transport, redox metabolism, enzyme activity and reproductive development. Because Cu is involved in several cellular processes, both deficiency and excessive accumulation can adversely affect plant performance (Hänsch & Mendel, 2009; Ogo et al., 2021). Boron differs from many metallic micronutrients because of its important structural and developmental functions. It contributes to cell-wall formation, membrane integrity, carbohydrate transport and reproductive development. Adequate B availability is particularly important for pollen development and successful fertilization, while deficiency may impair reproductive growth and grain formation (Zeng et al., 2023). Recent research also indicates that B interacts with other nutrients, including Fe, Mn, Zn and Cu, suggesting that its effects should be considered within an integrated nutrient-management framework rather than independently (Zeng et al., 2023). Overall, Zn, Fe, Mn, Cu and B perform complementary functions in wheat growth, metabolism and reproduction. Their uptake, transport and accumulation are influenced by genotype, soil properties, environmental conditions and interactions with other nutrients. Therefore, balanced micronutrient management, combined with genetic improvement and agronomic biofortification, represents an important approach for improving wheat productivity and grain nutritional quality.

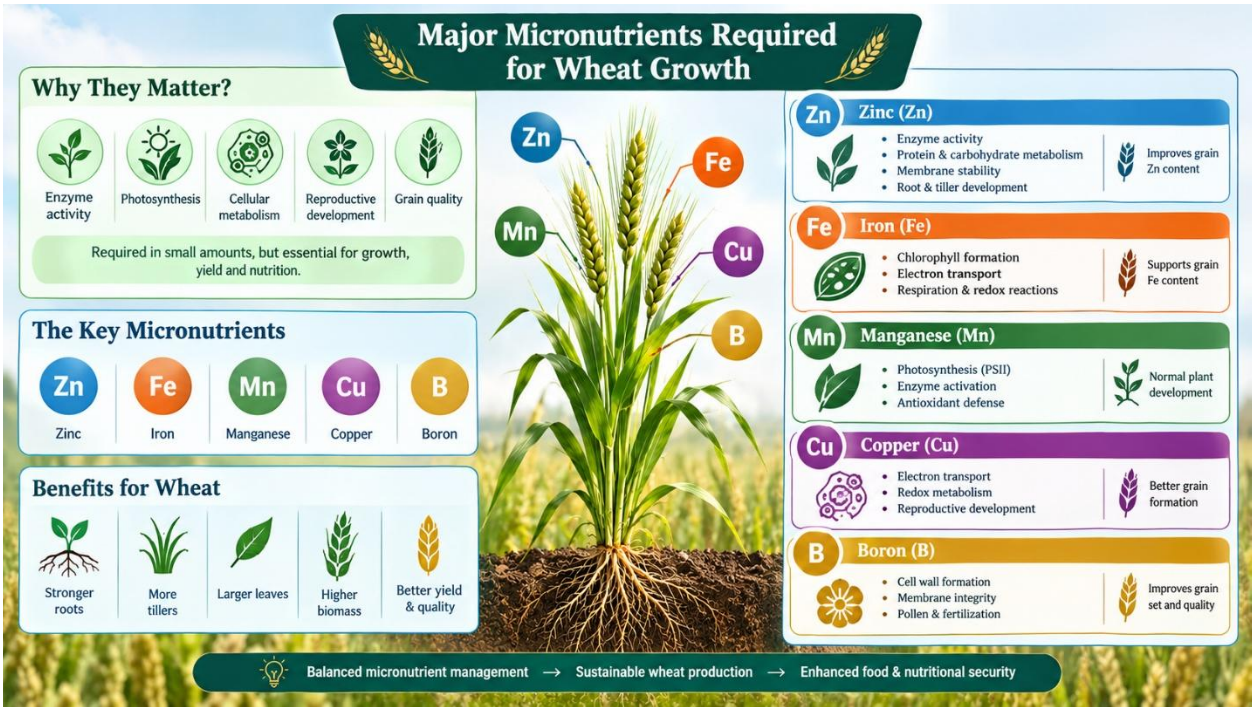

Figure 2: Major Micronutrients Required for Wheat Growth and Development

Effects of Micronutrients on Wheat Growth and Physiology

Micronutrients influence wheat growth through their involvement in cellular metabolism, root development, photosynthesis, nutrient acquisition and antioxidant defense. Although required in relatively small amounts, micronutrients can produce substantial changes in plant morphology and physiological performance when supplied to deficient soils. Their effects are particularly important during early vegetative development and under environmental stresses such as drought and salinity. Recent research has demonstrated that appropriate micronutrient supplementation can improve wheat growth by modifying root architecture, photosynthetic activity, water relations, nutrient uptake and antioxidant metabolism (Noor et al., 2024; Nawaz et al., 2024).

Effects on Germination, Root Development and Plant Height

Micronutrient availability can influence early seedling establishment by supporting cell division, enzyme activity, membrane stability and metabolic processes required for germination and subsequent root and shoot development. Zinc is particularly important during early wheat growth because it participates in DNA synthesis, protein metabolism and cellular development. Deficiency of Zn may restrict root elongation and seedling vigor, whereas adequate Zn supply can promote root growth and improve the plant's capacity to acquire nutrients from the soil. Root system architecture is particularly important for wheat because the roots determine the spatial exploration of soil and consequently influence water and nutrient acquisition. Noor et al. (2024) evaluated 100 wheat varieties and demonstrated considerable genetic variation in primary root length, lateral root development, total root length and lateral root density under Zn-sufficient and Zn-deficient conditions. Genotypes possessing vigorous root systems generally showed greater grain yield, indicating that root architectural traits can contribute to improved nutrient acquisition and overall crop performance. These findings suggest that micronutrient management should be considered together with root-system characteristics when developing nutrient-efficient wheat cultivars. Micronutrient application can also increase shoot development and plant height. For example, Nawaz et al. (2024) reported that balanced NPK plus Zn nutrition increased plant height and spike length compared with nutrient-deficient treatments. Similarly, Raza et al. (2025) demonstrated that ZnO nanoparticles improved several morphological characteristics of drought-stressed wheat, with responses depending on application rate and crop growth stage. These findings indicate that the beneficial effects of micronutrients on plant height and early development are strongly dependent on nutrient dose, genotype and environmental conditions.

Effects on Tillering, Leaf Development and Biomass Production

Tillering is an important determinant of wheat yield because the number of productive tillers contributes directly to the number of spikes per unit area. Adequate micronutrient nutrition can improve tiller formation by supporting meristematic activity, photosynthetic capacity and assimilate production. Zinc, in particular, has been associated with improved vegetative growth and biomass production because of its involvement in enzyme activity, protein metabolism and cellular development. Recent field evidence from Pakistan demonstrated that balanced NPK combined with Zn increased wheat growth, physiological performance and productivity compared with conventional nutrient management (Nawaz et al., 2024). Similarly, Raza et al. (2025) found that ZnO nanoparticle application improved plant biomass and morphological traits under drought conditions, although the response varied according to drought timing and ZnO nanoparticle concentration. These findings emphasize that micronutrients can contribute to maintaining vegetative growth under both favorable and stressful environments. Leaf development is closely linked with biomass accumulation because a larger and healthier leaf canopy provides greater photosynthetic surface area. Micronutrients can contribute to chlorophyll formation, enzyme activity and membrane stability, thereby supporting leaf expansion and delaying physiological deterioration under stress. Nazir et al. (2024) reported that foliar ZnO nanoparticles at appropriate concentrations increased biomass, leaf and root anatomical characteristics, chlorophyll and carotenoid contents in wheat. However, the study also demonstrated that excessive concentrations could produce inhibitory effects, highlighting the importance of optimizing micronutrient dose.

Effects on Photosynthesis, Nutrient Uptake and Enzyme Activity

Micronutrients have important roles in maintaining photosynthetic activity and nutrient-use efficiency. Zinc contributes to the structural and functional stability of photosynthetic tissues, while Fe and Mn are directly associated with electron transport and photosynthetic reactions. Copper also participates in electron-transfer processes and can influence chloroplast functioning. Consequently, inadequate micronutrient supply can reduce chlorophyll concentration, gas exchange and carbon assimilation. Field research in Pakistan showed that balanced NPK plus Zn increased photosynthetic rate, stomatal conductance, transpiration and water-use efficiency in wheat compared with nutrient-deficient treatments (Nawaz et al., 2024). Under drought conditions, ZnO nanoparticle application has also been shown to improve chlorophyll concentration, leaf gas exchange and water relations, indicating that Zn can help maintain photosynthetic performance during water limitation (Raza et al., 2025). Micronutrients also regulate antioxidant enzymes that protect plant cells from oxidative damage. Zinc supplementation can enhance antioxidant defense by increasing activities of enzymes such as superoxide dismutase, catalase and peroxidase. Nazir et al. (2024) observed increases in antioxidant enzyme activities following appropriate ZnO nanoparticle application in wheat. Copper has similarly demonstrated potential to improve physiological performance under drought stress. Raza et al. (2024) reported that Cu nanoparticles improved chlorophyll content, stomatal conductance, water-use efficiency and other physiological traits in drought-stressed wheat. Therefore, micronutrients can improve wheat performance not only through direct nutritional effects but also through enhanced antioxidant protection and regulation of physiological responses to environmental stress. Overall, the available evidence indicates that micronutrient nutrition influences wheat growth from seedling establishment through vegetative development and physiological functioning. Appropriate micronutrient management can promote root development, tillering, biomass accumulation, photosynthesis, nutrient uptake and antioxidant activity. However, responses are highly dependent on micronutrient source, dose, application method, genotype and environmental conditions. Future research should therefore focus on integrated nutrient-management strategies that optimize micronutrient availability while avoiding excessive application and potential phytotoxicity.

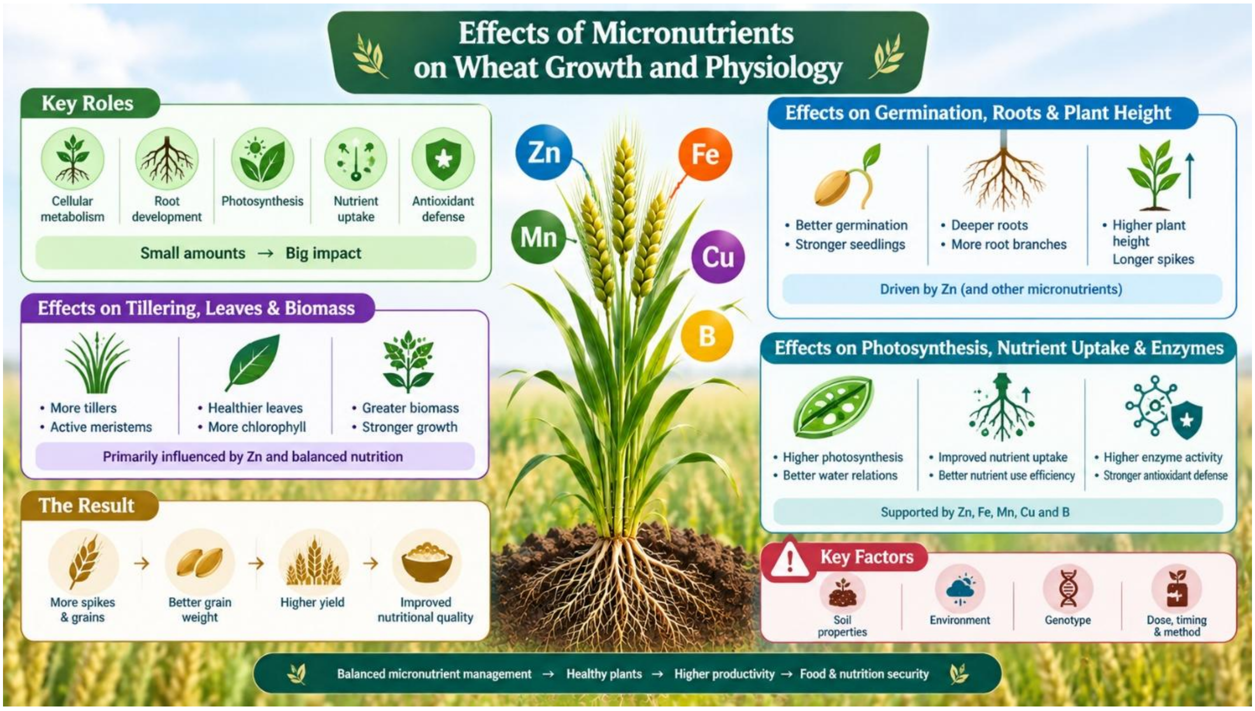

Figure 3: Effects of Micronutrients on Wheat Growth and Physiological Processes

Micronutrients and Wheat Yield Components

Micronutrient nutrition is an important component of wheat yield formation because reproductive development depends on adequate nutrient availability throughout the crop growth cycle. Micronutrients can influence spike initiation, spikelet development, grain setting, grain filling and assimilate partitioning. The magnitude of their effects depends on the nutrient source, application method, soil fertility, genotype and environmental conditions. Recent studies have demonstrated that appropriate micronutrient management, particularly zinc (Zn), can improve several yield components and, consequently, grain productivity in wheat (Singh & Singh, 2024; Khan et al., 2025).

Effects on Spike Formation and Spike Length

Spike development is a critical determinant of wheat yield because the number and size of spikes ultimately influence the potential number of grains produced per unit area. Micronutrients participate in the physiological processes associated with reproductive development and assimilate production. Zinc, iron (Fe), manganese (Mn), copper (Cu) and boron (B) can contribute to reproductive growth through their effects on enzyme activity, carbohydrate metabolism, hormonal regulation and nutrient translocation. Field experiments have demonstrated a positive response of wheat spike characteristics to Zn application. Singh and Singh (2024) reported that appropriate Zn management significantly improved spike length, productive tillers and other yield-related traits in zero-tillage wheat grown under Zn-deficient conditions. Similarly, a recent study evaluating different Zn fertilizer sources found that ZnO nanoparticles and conventional Zn fertilizers increased spikelet number and spike length, with integrated Zn treatments producing particularly favorable responses (Khan et al., 2025). These findings indicate that Zn availability during vegetative and reproductive stages can improve the development of reproductive structures. Boron may also be particularly important during reproductive development because of its involvement in pollen viability, pollen-tube growth and fertilization. Adequate B nutrition can therefore improve grain setting and reduce reproductive losses under nutrient-deficient conditions. However, micronutrient effects on spike development are not always consistent because responses depend on the initial nutrient status of the soil and the ability of individual genotypes to acquire and utilize nutrients.

Effects on Grain Number and Thousand-Grain Weight

Grain number per spike and thousand-grain weight (TGW) are major components determining wheat yield. Grain number is primarily established around anthesis, whereas final grain weight depends strongly on assimilate availability and the duration and rate of grain filling. Consequently, micronutrients supplied at appropriate developmental stages may influence both processes. Zinc has demonstrated considerable potential for improving grain number and grain weight. In a recent field experiment, low-dose ZnO nanoparticle application increased grains per spike and TGW substantially compared with an untreated control, while integrated $ZnSO_4$ and ZnO-nanoparticle treatments also improved spike length and other yield components (Khan et al., 2025). These responses can be attributed partly to improved photosynthetic activity, nutrient acquisition and assimilate translocation associated with adequate Zn nutrition. The interaction between grain number and grain weight should also be considered when evaluating micronutrient effects. Wheat plants may exhibit a physiological trade-off between the number of grains established and the resources available for filling individual grains. Vicentin et al. (2024) demonstrated that grain number and grain weight are determined during partially overlapping developmental phases, emphasizing that management practices affecting early reproductive growth can subsequently influence final grain weight. Therefore, micronutrient application should be appropriately synchronized with crop developmental stages rather than evaluated solely according to final grain yield.

Effects on Grain Yield and Harvest Index

Grain yield represents the integrated response of wheat to environmental conditions, genotype and agronomic management. Micronutrients can increase yield by improving several yield components simultaneously, including productive tillers, spike length, grains per spike and TGW. In Zn-deficient soils, correcting Zn deficiency can therefore produce substantial yield benefits. Singh and Singh (2024) reported approximately 25% greater grain yield when soil Zn application was combined with two foliar Zn sprays at heading compared with the untreated control in zero-tilled wheat. Similarly, Khan et al. (2025) observed a marked improvement in grain yield following ZnO-nanoparticle application, demonstrating the potential of alternative Zn fertilizer formulations for increasing wheat productivity. Nevertheless, micronutrient application does not invariably increase yield. Field experiments involving genetically biofortified wheat showed that foliar Zn, iodine and selenium treatments substantially increased grain micronutrient concentrations, whereas effects on grain yield varied among locations and genotypes (Cakmak et al., 2024). This finding highlights the importance of distinguishing agronomic yield improvement from nutritional biofortification. In some situations, micronutrient application may substantially improve grain nutritional quality without producing a statistically significant increase in grain yield.

Harvest index, which represents the proportion of total above-ground biomass partitioned into grain, can also be influenced by nutrient management. Improved micronutrient availability may enhance assimilate partitioning toward reproductive organs and grain, although the response is dependent on genotype and growing conditions. Overall, micronutrients should be regarded as an important component of integrated wheat nutrition rather than as substitutes for balanced macronutrient fertilization. Combining appropriate micronutrient sources with balanced N, P and K management, suitable application timing and nutrient-efficient genotypes offers greater potential for simultaneously improving wheat yield and grain nutritional quality.

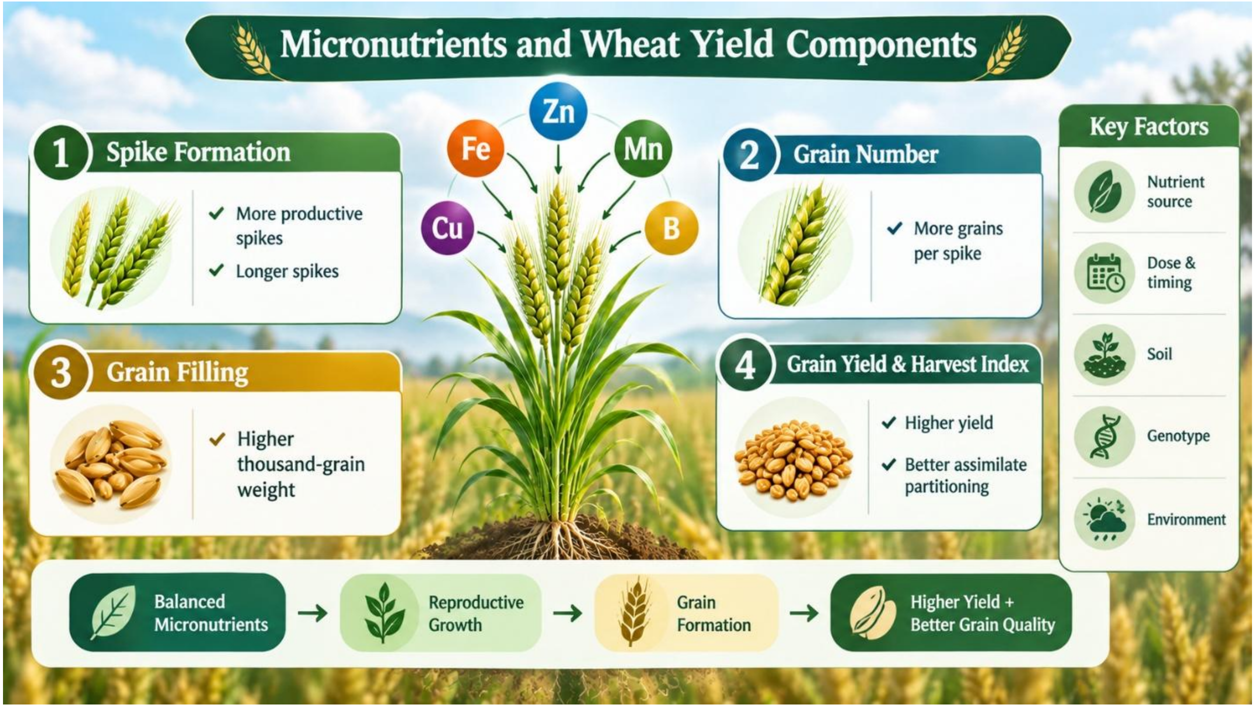

Figure 4: Influence of Micronutrients on Wheat Yield Components and Grain Production

Methods of Micronutrient Application in Wheat

The effectiveness of micronutrient management in wheat depends not only on the nutrient supplied but also on its source, dose, timing and method of application. Micronutrients can be supplied through soil application, seed treatment or priming, foliar spraying, or combinations of these approaches. Selection of an appropriate method depends on soil properties, existing nutrient status, crop growth stage, environmental conditions and the intended objective, whether improving crop productivity, correcting deficiency or increasing grain micronutrient concentration. Recent research indicates that integrated approaches can be particularly effective where soil constraints limit micronutrient availability (Kumar et al., 2024; Hui et al., 2025).

Soil Application and Seed Treatment

Soil application is one of the conventional approaches for supplying micronutrients to wheat. Zinc sulfate, zinc oxide, iron sulfate, manganese sulfate, copper sulfate and boron-containing fertilizers can be incorporated into the soil before or during sowing. Soil application provides nutrients to the developing root system and can support micronutrient acquisition throughout the growing season. However, its efficiency is strongly influenced by soil pH, organic matter, carbonate content, moisture and interactions with other nutrients. In alkaline and calcareous soils, for example, Zn may become less available because of adsorption and precipitation processes. Recent research under salt-affected alkaline-calcareous soil demonstrated that soil Zn application increased wheat grain and straw yield by up to 23%, while also increasing grain Zn concentration (Alam et al., 2024). The study further demonstrated that combining soil Zn application with seed Zn priming produced additional benefits, although the magnitude of the response depended on soil Zn status and salinity. These findings demonstrate the potential of soil application for correcting root-zone micronutrient deficiency. Seed treatment or seed priming represents another efficient method for delivering micronutrients during the earliest stages of crop establishment. Priming seeds with Zn, Fe or combined nutrient solutions can increase nutrient availability during germination and early seedling development. In rainfed wheat, combined seed priming and subsequent foliar nutrient application increased root development, chlorophyll concentration, antioxidant activity and grain yield (Saeed et al., 2023). Seed treatment may therefore be particularly useful where early root development and nutrient acquisition are restricted.

Foliar Application of Micronutrients

Foliar application involves spraying dilute solutions of micronutrients directly onto plant leaves. This approach can be advantageous when soil conditions restrict nutrient availability or when rapid correction of deficiency is required. Foliar application is especially important for micronutrient biofortification because nutrients applied during later developmental stages can be absorbed by leaves and subsequently transported to developing grains. Recent evidence strongly supports foliar Zn application for improving wheat grain Zn concentration. A global meta-analysis involving 139 studies found that foliar Zn application increased wheat grain Zn concentration by an average of 55.2%, compared with 29.1% for soil application (Hui et al., 2025). Combined soil-plus-foliar application produced an even greater average increase of 62.3%. The effectiveness of foliar application was strongly influenced by application rate, spray concentration and timing, with applications during flowering and grain filling generally being more effective for grain Zn enrichment.

Foliar application also permits relatively precise nutrient delivery and can reduce some of the soil-related losses associated with micronutrient fertilizers. However, excessive concentrations may cause leaf injury or phytotoxicity, while rainfall, temperature, humidity and leaf surface characteristics can affect nutrient absorption. Therefore, formulation, concentration, spraying time and environmental conditions must be carefully considered (Sánchez-Palacios et al., 2023).

Integrated Application of Micronutrients with Macronutrients

Integrated nutrient management combines micronutrients with essential macronutrients such as nitrogen (N), phosphorus (P) and potassium (K). This approach is based on the principle that plant nutrient requirements are interconnected and that micronutrients are most effective when overall plant nutrition is balanced. For example, adequate N can increase biomass production and nutrient demand, while micronutrients are required for the enzymes and physiological processes involved in efficient N and carbohydrate metabolism. Field studies have demonstrated beneficial effects from combining seed priming with foliar Zn and Fe applications. In rainfed wheat, integrated seed priming and foliar $ZnSO_4$ application improved chlorophyll concentration, antioxidant activity, thousand-grain weight and grain yield, while foliar $FeSO_4$ increased grain Fe concentration (Saeed et al., 2023). Similarly, recent evidence indicates that combining soil and foliar Zn application can provide greater grain Zn enrichment than either method alone (Hui et al., 2025). An integrated strategy is particularly relevant for micronutrient-deficient soils because soil application can provide a sustained nutrient supply to roots, whereas foliar application can address short-term requirements and improve nutrient accumulation during reproductive development. Therefore, combining soil, seed and foliar approaches with balanced NPK fertilization may provide a more reliable strategy for improving wheat growth, yield and grain nutritional quality. Nevertheless, fertilizer rates should be determined according to soil testing, crop requirements and environmental conditions to avoid unnecessary fertilizer use and potential micronutrient toxicity.

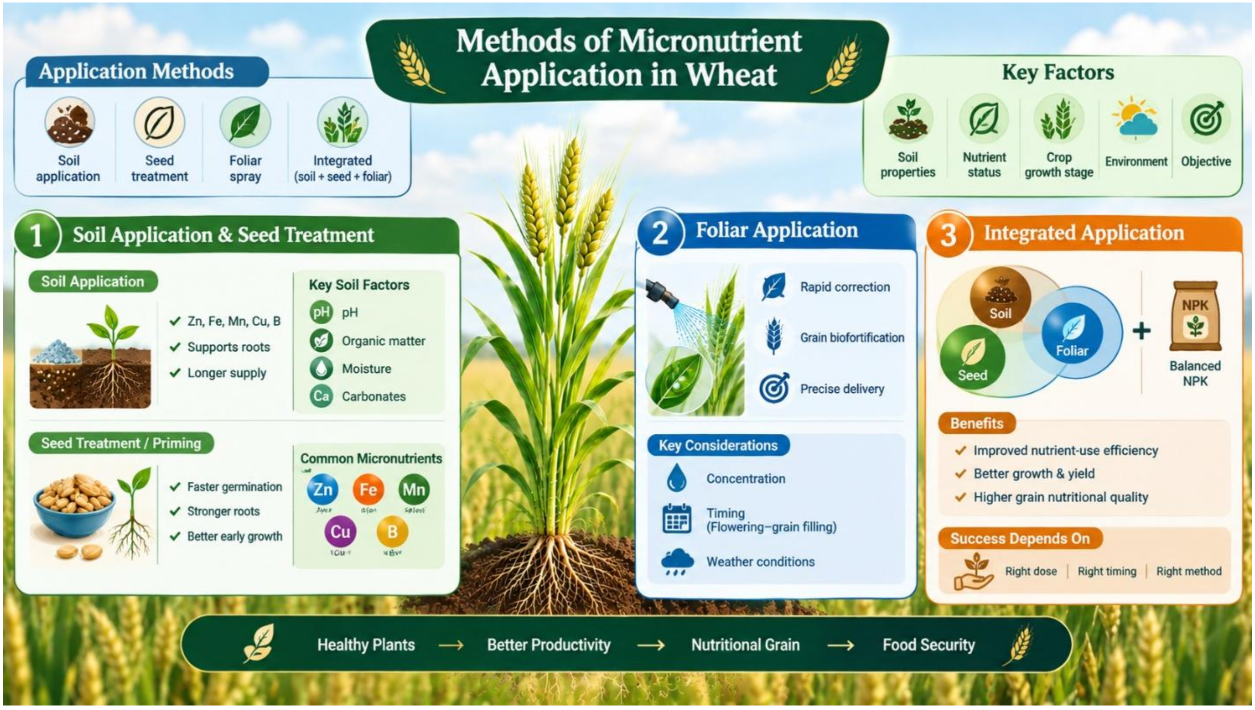

Figure 5: Methods of Micronutrient Application for Improving Wheat Performance

Factors Affecting Micronutrient Availability and Efficiency

The effectiveness of micronutrient management in wheat is determined by a complex interaction among soil characteristics, environmental conditions, genotype, fertilizer dose, application timing and method of application. The same micronutrient treatment may produce substantially different responses across locations or seasons because nutrient availability and plant uptake are dynamic processes. Recent studies have demonstrated considerable genotype × environment interactions for grain zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) and selenium (Se), emphasizing the importance of site-specific micronutrient management (Kumar et al., 2026). Moreover, the response to Zn fertilization is strongly influenced by initial soil and grain Zn concentrations, soil pH, application rate and spray timing (Hui et al., 2025).

Soil Properties and Micronutrient Availability

Soil characteristics are among the most important factors determining micronutrient availability to wheat. Soil pH strongly regulates the solubility, adsorption and mobility of micronutrients. In particular, increasing soil pH generally decreases the availability of Zn and Fe, making deficiencies more common in alkaline and calcareous soils. Soil organic matter can either increase micronutrient availability by forming soluble complexes or temporarily immobilize nutrients through adsorption and complexation. Soil texture, calcium carbonate concentration, cation exchange capacity, moisture status and available phosphorus also influence micronutrient behavior in the rhizosphere. A recent study across contrasting soil types demonstrated that soil properties, particularly pH and organic matter, significantly affected the concentrations of Zn, Fe and selenium in wheat grain and straw (Guwela et al., 2024). Similarly, field experiments in India and Pakistan showed substantial differences in soil pH, electrical conductivity, organic matter and available Zn among experimental locations, which contributed to variation in micronutrient responses (Ram et al., 2024). Soil nutrient interactions are also important. Excessive phosphorus application, for example, can influence Zn availability and uptake, while nitrogen nutrition can alter plant growth and consequently micronutrient demand. Therefore, soil testing before fertilizer application is essential for identifying deficient nutrients and selecting appropriate fertilizer rates. The effectiveness of soil-applied Zn is particularly dependent on initial soil Zn availability and pH; recent global evidence indicates that the response to Zn fertilization changes substantially with these soil properties (Hui et al., 2025).

Environmental Conditions and Wheat Genotype

Environmental conditions substantially influence micronutrient uptake, transport and accumulation in wheat. Temperature, rainfall, drought, salinity and irrigation regime can modify root activity, nutrient mobility and physiological demand. Water stress may restrict nutrient diffusion toward roots and reduce nutrient uptake, whereas excessive moisture can alter soil redox conditions and micronutrient solubility. Temperature also affects grain micronutrient accumulation through changes in plant development and nutrient remobilization. Recent multi-environment research demonstrated that production environment had a stronger effect on wheat grain mineral density than yield itself, while genotype and genotype × environment interactions also contributed substantially to mineral variation (McNelly et al., 2024). Similarly, Jagadeesha et al. (2024) found contrasting responses of grain Zn and Fe under terminal drought and heat stress, highlighting the complexity of micronutrient accumulation under changing climatic conditions. Genotype is another major determinant of micronutrient-use efficiency. Wheat cultivars differ in root architecture, nutrient uptake capacity, internal translocation and grain accumulation. Recent research comparing Zn-efficient and Zn-inefficient wheat varieties showed differential responses to Zn fertilizer sources and application methods, demonstrating that fertilizer recommendations cannot always be generalized across cultivars (Mousavi et al., 2024). Genetic studies have also identified numerous genomic regions associated with Zn and Fe accumulation, providing opportunities to develop nutrient-efficient and micronutrient-rich wheat genotypes (Leonova et al., 2024).

Micronutrient Dose, Timing and Method of Application

Micronutrient efficiency is strongly dependent on fertilizer dose, application timing and delivery method. Insufficient fertilizer may fail to correct deficiency, whereas excessive application can cause nutrient imbalance, toxicity and unnecessary economic costs. Consequently, fertilizer rates should be determined according to soil-test results, crop requirements, genotype and the intended objective of application. Application timing is particularly important for foliar fertilization. Micronutrients supplied during flowering and grain filling may be more effectively transferred to developing grains than applications made during early vegetative growth. A global meta-analysis demonstrated that foliar Zn application during later growth stages produced greater improvements in grain Zn concentration than earlier applications, with fertilizer rate and spray timing identified as major determinants of response (Hui et al., 2025). The application method also determines nutrient-use efficiency. Soil application is generally useful for correcting root-zone deficiencies and improving crop productivity, whereas foliar application can provide rapid nutrient delivery and is particularly effective for grain biofortification. Recent field experiments comparing soil and foliar Zn treatments confirmed that the response varies with cultivar and application strategy (Maqsood et al., 2025). Overall, efficient micronutrient management requires an integrated approach based on soil testing, environmental conditions, genotype selection, appropriate dose, growth-stage-specific application and suitable fertilizer formulation. Such site-specific strategies can improve nutrient-use efficiency while minimizing excessive fertilizer application and ensuring greater consistency in wheat productivity and grain nutritional quality.

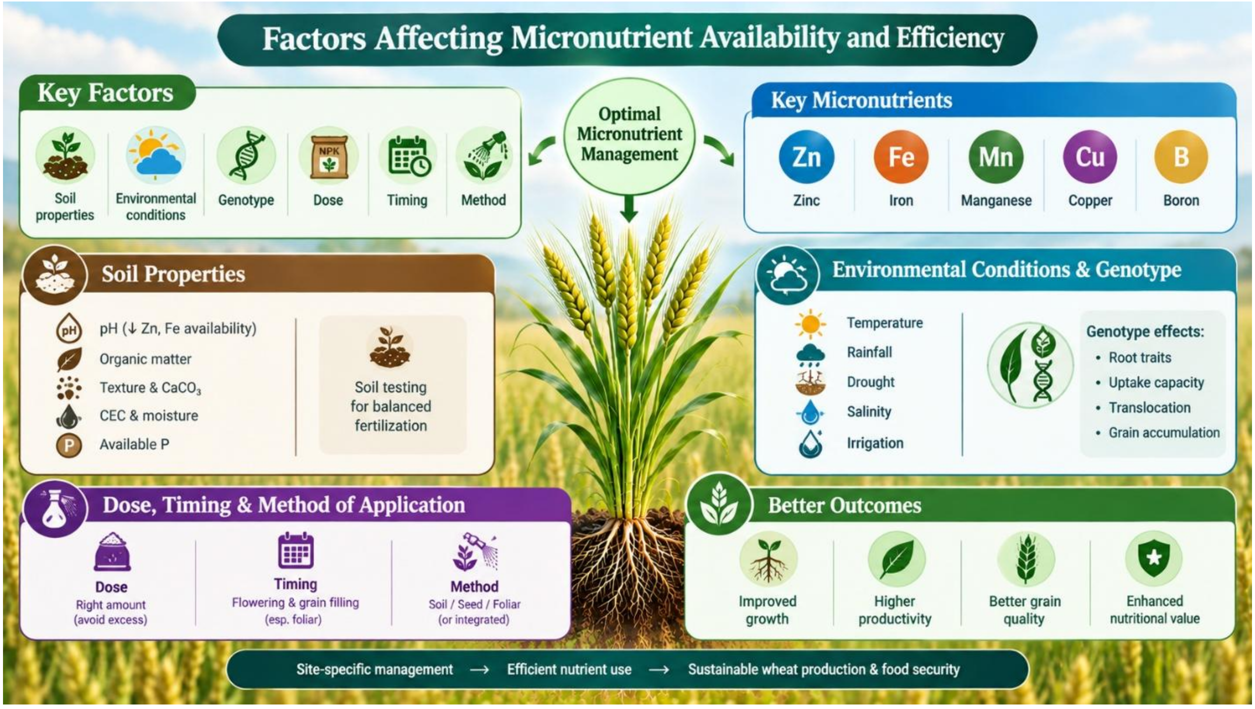

Figure 6: Factors Affecting Micronutrient Availability and Use Efficiency in Wheat

Conclusions, Research Gaps and Future Perspectives

Different micronutrients play complementary roles in wheat growth and productivity. Zinc and iron are particularly important for growth and grain nutritional quality, whereas manganese, copper and boron support photosynthesis, enzyme activity and reproductive development. Future research should focus on genotype-specific nutrient requirements, micronutrient interactions and site-specific fertilizer recommendations using soil testing, precision agriculture and advanced phenotyping approaches. Integrating micronutrient-efficient wheat genotypes with balanced fertilization, seed treatment, soil and foliar application can improve nutrient-use efficiency, grain yield and nutritional quality, contributing to sustainable wheat production and food security.

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