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Evaluation of Micronutrient Application for Improving Growth, Development, Yield Components, Grain Yield, and Overall Productivity of Maize Crop

Muhammad Adnan Rafique

Pesticide Quality Control Laboratory, Kala Shah Kaku

Annum Sattar

Pesticide Quality Control Laboratory, Kala Shah Kaku

Asifa Naz

Soil and Water Testing Laboratory, Sargodha

Rabia Abdur Rehman

Department of Soil Science, Bahaudin Zakaria University, Multan

Hafiz Imran Iqbal

National Agricultural Research Centre, Islamabad

Asia Shaheen

Soil and Water Testing Laboratory, Khanewal

Muhammad Ibrar Ahmad

Fodder Research Institute, Sargodha

Email: ibrar.agrarian1982@gmail.com

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Corresponding Author:

Muhammad Ibrar Ahmad

Email:

ibrar.agrarian1982@gmail.com

Maize (*Zea mays* L.) is an important cereal crop widely cultivated for food, feed, industrial raw materials, and bioenergy. Achieving higher and sustainable maize productivity requires balanced plant nutrition, including an adequate supply of essential micronutrients. Micronutrients such as zinc, iron, manganese, boron, copper, and molybdenum are required in small quantities but play critical roles in enzymatic activity, photosynthesis, chlorophyll formation, nutrient metabolism, reproductive development, and grain formation. Their deficiencies can adversely affect plant growth, physiological processes, yield components, grain yield, and grain nutritional quality. This review evaluates the role of micronutrient application in improving maize growth, development, yield components, grain yield, and overall productivity. Particular emphasis is given to the physiological functions of major micronutrients, their uptake and utilization, and their effects on seedling establishment, root development, plant height, leaf area, biomass accumulation, photosynthetic activity, cob development, grain number, kernel weight, and harvest index. Different application strategies, including soil application, foliar feeding, seed priming, fertilizer-based supplementation, and integrated nutrient management, are also discussed. The review highlights that micronutrient responses are influenced by soil characteristics, nutrient availability, environmental conditions, application method, dosage, genotype, and interactions with macronutrients. In addition, agronomic biofortification and genetic approaches provide opportunities to enhance the micronutrient concentration and nutritional quality of maize grain. Sustainable and site-specific micronutrient management can therefore contribute to improved crop productivity while addressing hidden micronutrient deficiencies in human diets. Future research should focus on precision nutrient management, efficient micronutrient formulations, genotype-specific responses, biofortification, and environmentally sustainable application technologies to develop productive and nutritionally superior maize production systems.

Introduction

Maize (*Zea mays* L.) is one of the world's most important cereal crops and plays a central role in food, feed, industrial production, and agricultural livelihoods. Along with wheat and rice, maize contributes substantially to global food-energy supply and is particularly important in developing countries, where it supports the food and income security of millions of smallholder farmers (Shiferaw et al., 2011). Maize is cultivated across a wide range of climatic and edaphic conditions and is used directly as human food, livestock and poultry feed, and as a raw material for starch, sweeteners, biofuels, and other industrial products (Shiferaw et al., 2011). The continued expansion of livestock production, industrial processing, and bioenergy has further increased global demand for maize. FAO statistics also indicate continued growth in global cereal production, with productivity improvements remaining important for meeting increasing demand under changing climatic conditions (FAO, 2025). In South Asia, maize has considerable importance for food, feed, and industrial purposes. In Pakistan, it is an important kharif crop and is increasingly cultivated as a commercial crop because of its demand from the poultry, livestock, and feed industries. However, achieving the genetic yield potential of modern maize hybrids requires balanced plant nutrition, including adequate supplies of micronutrients (Tariq et al., 2002).

Micronutrients are required by plants in relatively small quantities compared with macronutrients, but their physiological importance is fundamental. The essential plant micronutrients include boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). These elements participate in enzyme activation, electron transport, photosynthesis, protein synthesis, membrane stability, hormone metabolism, and other essential biochemical processes (Hänsch & Mendel, 2009; Cakmak et al., 2023). Zinc is particularly important in maize because it contributes to enzyme activity, protein synthesis, carbohydrate metabolism, photosynthesis, auxin metabolism, pollen formation, and membrane integrity (Alloway, 2008; Cakmak et al., 2020). Iron is essential for electron-transfer reactions and chlorophyll-associated physiological processes, whereas manganese and copper participate in photosynthesis and antioxidant defense. Boron contributes to cell-wall structure and membrane functions, while molybdenum has important roles in nitrogen metabolism (Cakmak et al., 2023). Thus, although micronutrients are needed in small amounts, inadequate availability can substantially disrupt plant metabolism and ultimately reduce crop productivity.

Micronutrient deficiency is an important limitation to crop productivity worldwide. The occurrence and severity of deficiency depend on soil properties, pH, organic matter, moisture conditions, nutrient interactions, crop genotype, and agricultural management (Alloway, 2008). Among micronutrients, zinc deficiency is particularly widespread and maize is considered relatively sensitive to inadequate Zn availability (Mutambu et al., 2023). In Pakistan, Zn and B deficiency have been identified as important soil constraints to maize production, particularly where soils have limited micronutrient availability (Anjum et al., 2017). Field research in Pakistan has demonstrated that Zn application can improve maize growth and yield, while seed priming with zinc sulfate has also increased grain yield under Zn-deficient conditions (Harris et al., 2007). Similarly, studies conducted in calcareous soils have reported improvements in maize grain yield and grain Zn concentration following different Zn application methods (Khan et al., 2017). Evidence from a global meta-analysis indicates that Zn fertilization can increase maize grain yield and grain Zn concentration, although the magnitude of response varies considerably among environments and management systems (Mutambu et al., 2023). More recent evidence also indicates that combined Zn and Fe management can improve maize grain micronutrient concentrations, highlighting the importance of integrated micronutrient management for both crop productivity and nutritional quality (Devkota et al., 2024). Therefore, identifying micronutrient limitations and selecting appropriate application strategies are essential components of sustainable maize production.

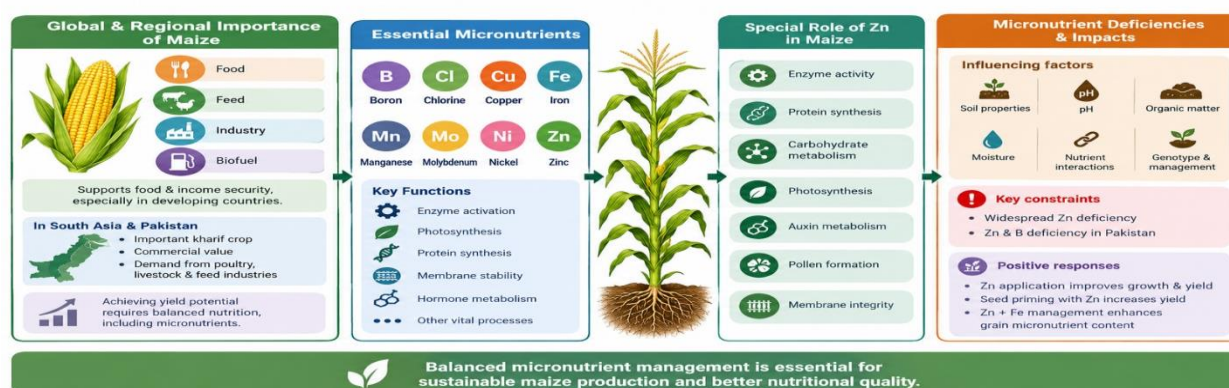


Figure 1: Importance of Micronutrients in Maize Production, Their Key Functions, and the Impact of Micronutrient Deficiencies.

Essential Micronutrients and Their Physiological Roles in Maize

Role of Zinc, Iron, and Manganese in Maize Growth and Development

Zinc (Zn), iron (Fe), and manganese (Mn) are essential micronutrients that participate in numerous biochemical and physiological processes governing maize growth. Zinc is involved in enzyme activation, protein synthesis, gene expression, membrane stability, carbohydrate metabolism, photosynthesis, and auxin metabolism. Adequate Zn supply is particularly important for maintaining photosynthetic activity and chlorophyll development in maize, while Zn deficiency can impair carbonic anhydrase activity, protein synthesis, and antioxidant defense (Hafeez et al., 2013; Rana et al., 2021). In maize, genetic regulation of Zn homeostasis involves several transporter families, including ZIP, YSL, NRAMP, HMA, and CDF proteins, which collectively regulate Zn uptake, cellular distribution, sequestration, and grain accumulation (Mondal et al., 2010; Li et al., 2019). Iron is indispensable for chlorophyll formation, photosynthetic electron transport, respiration, and numerous redox reactions. Because maize is a graminaceous species, it primarily employs a Strategy II mechanism for Fe acquisition. Under Fe deficiency, maize roots release phytosiderophores that chelate Fe(III), followed by uptake of Fe-phytosiderophore complexes through Yellow Stripe1 (YS1) transporters (Curie et al., 2001; von Wirén et al., 1994). The importance of this mechanism is demonstrated by the *ys1* maize mutant, which exhibits impaired Fe-phytosiderophore uptake and characteristic interveinal chlorosis (von Wirén et al., 1994). Manganese is essential for photosynthesis because it forms the catalytic core of the oxygen-evolving complex of photosystem II and contributes to antioxidant protection through Mn-superoxide dismutase. Consequently, Mn deficiency can reduce photosynthetic efficiency even before pronounced visual symptoms appear (Schmidt et al., 2016; Alejandro et al., 2020).

Functions of Boron, Copper, and Molybdenum in Maize Physiology

Boron (B) has an important structural role in plant cell walls, particularly through cross-linking of rhamnogalacturonan II, thereby contributing to cell-wall stability, tissue development, and reproductive growth (Funakawa & Miwa, 2015). Boron also affects membrane integrity, cell expansion, root development, and pollen formation. Because B has limited mobility in many plant species, continuous supply is important for actively growing tissues (Miwa & Takano, 2013). Copper (Cu) functions as a redox-active cofactor in proteins involved in photosynthesis, respiration, antioxidant defense, ethylene perception, and cell-wall metabolism. Copper is incorporated into proteins such as plastocyanin and Cu/Zn-superoxide dismutase and therefore contributes to electron transport and protection against oxidative stress (Burkhead et al., 2009; Pilon et al., 2009). However, the narrow range between adequate and excessive Cu concentrations makes regulated uptake and intracellular distribution essential. Molybdenum (Mo) is required in extremely small quantities but has a major role in nitrogen metabolism. It forms part of the molybdenum cofactor of nitrate reductase, which catalyzes the first major step in nitrate assimilation. Mo is also associated with other enzymes involved in sulfur metabolism and phytohormone biosynthesis (Kaiser et al., 2005; Anke & Seifert, 2007).

Mechanisms of Micronutrient Uptake, Transport, and Utilization in Maize

Micronutrient acquisition in maize involves coordinated processes of rhizosphere mobilization, root uptake, xylem loading, long-distance transport, cellular sequestration, and remobilization to developing tissues. Transport proteins belonging to ZIP, YSL, NRAMP, HMA, CDF, and related families regulate the movement of metal ions across cellular membranes (Sinclair & Krämer, 2012). Maize contains multiple ZIP transporters capable of contributing to Zn and Fe homeostasis, while YS1/YSL proteins transport metal-phytosiderophore or nicotianamine complexes (Li et al., 2013; Schaaf et al., 2004). Iron acquisition illustrates the complexity of micronutrient transport particularly well. Maize synthesizes and secretes phytosiderophores under Fe limitation, and YS1 subsequently transports Fe(III)-phytosiderophore complexes into root cells. ZmYS1 functions as a proton-coupled symporter and can recognize several metal-chelate complexes, demonstrating that micronutrient transport systems can have overlapping substrate specificities (Schaaf et al., 2004). Once absorbed, micronutrients are transported through the xylem toward shoots and can subsequently be redistributed through the phloem, particularly toward metabolically active and developing organs. Cellular chelators such as nicotianamine, citrate, and deoxymugineic acid help maintain micronutrient solubility and prevent uncontrolled accumulation.

Boron provides another example of tightly regulated nutrient transport. NIP-type proteins facilitate boric-acid movement across membranes, whereas BOR proteins mediate borate export and contribute to xylem loading and whole-plant distribution (Miwa et al., 2010). Thus, efficient maize nutrition depends not simply on the presence of micronutrients in soil, but on the coordinated regulation of their availability, uptake, transport, cellular utilization, and homeostasis.

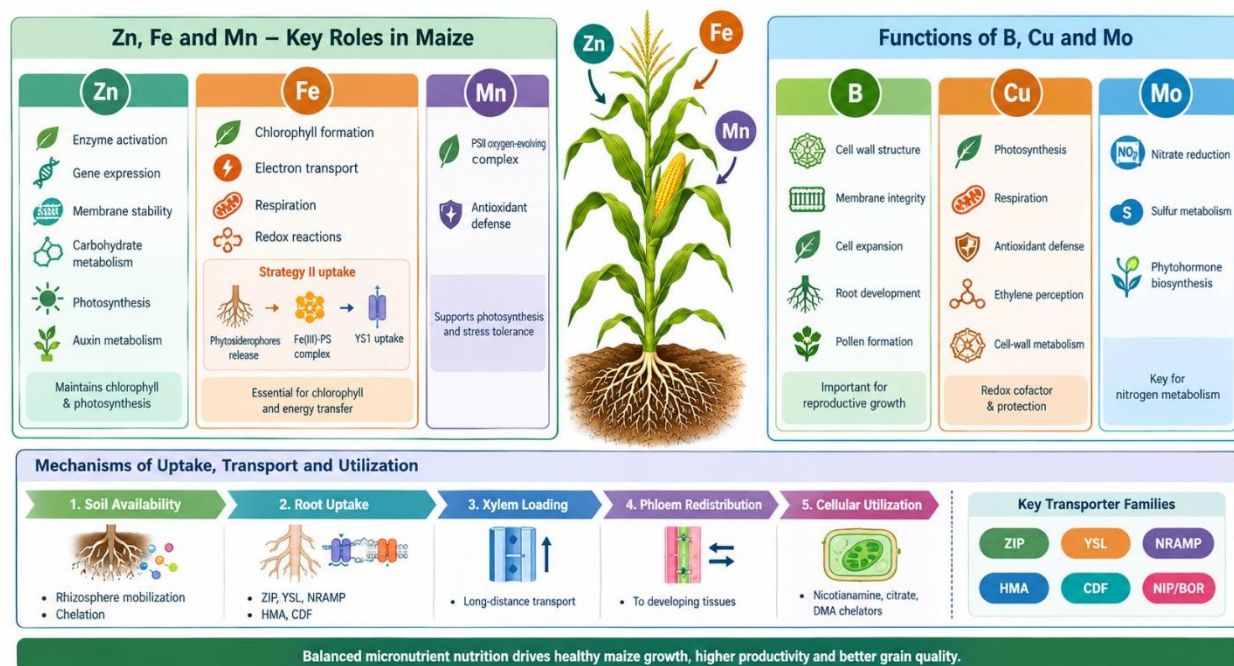


Figure 2: Essential Micronutrients in Maize: Physiological Roles, Uptake, Transport, and Cellular Utilization

Effects of Micronutrient Application on Maize Growth and Development

Influence on Seed Germination, Root Development, and Plant Establishment

Micronutrient availability during the early stages of maize development is important for rapid germination, root establishment, and uniform crop stand. Seed priming and coating can provide nutrients directly to the developing embryo and emerging seedling, potentially overcoming limitations associated with low nutrient availability in the rhizosphere. Muhammad et al. (2015) reported that seed priming with Zn and Mn substantially improved maize seedling growth under nutrient-deficient conditions, while the primed nutrients were efficiently transferred to developing shoots. Under field conditions, Zn + Mn seed priming increased grain yield by 15%. Micronutrient seed coating has also demonstrated potential for improving establishment. Chen et al. (2023) found that coating maize seeds with B, Fe, Mn, Mo, and Zn significantly improved emergence, seedling vigor, root length, root number, and shoot and root biomass across different soil types. Similarly, Olatunji et al. (2020) demonstrated that Zn, B, and Mo seed priming could accelerate maize emergence and improve early seedling biomass and chlorophyll status in micronutrient-deficient soils. These responses may be associated with improved enzyme activity, membrane function, nutrient availability, and early root metabolic activity. Micronutrient treatments can therefore contribute to stronger root systems capable of exploring a larger soil volume and acquiring water and nutrients more efficiently.

Effects on Vegetative Growth, Plant Height, Leaf Area, and Biomass Production

Adequate micronutrient nutrition supports vegetative development by facilitating cell division, cell expansion, enzymatic reactions, photosynthesis, and carbohydrate production. Consequently, improvements in plant height, leaf development, leaf area index, and biomass accumulation have frequently been reported following appropriate micronutrient application. Under rainfed conditions in the Pothwar plateau of Pakistan, combined foliar application of Zn and B improved relative water content, SPAD chlorophyll values, leaf area index, and crop growth rate compared with untreated plants (Wasaya et al., 2017). Similarly, Singh et al. (2021) reported that foliar Zn and B application significantly influenced maize plant height and several growth and yield-related characteristics. Recent field evidence also indicates that combined micronutrient application can produce stronger vegetative responses than individual nutrient treatments. For example, Fe + Zn + B application substantially increased plant height and biological yield compared with the untreated control in maize (Khan et al., 2025). These effects demonstrate that balanced micronutrient nutrition can improve canopy development and dry-matter accumulation, although responses depend on soil fertility, genotype, environmental conditions, nutrient dose, and application method.

Influence on Photosynthesis, Chlorophyll Content, and Physiological Processes

Micronutrients influence maize productivity partly through their effects on photosynthesis and associated physiological processes. Zinc contributes to enzyme activity and chlorophyll formation, while iron is closely associated with electron transport and chloroplast function. Manganese is particularly important for photosystem II and the oxygen-evolving complex. Experimental evidence shows that Mn deficiency in maize can reduce chlorophyll a, electron transport, oxygen evolution, photophosphorylation, and activities of Rubisco and Rubisco activase (Gong et al., 2010). Field studies further demonstrate that micronutrient application can improve physiological indicators. Wasaya et al. (2017) observed increases in SPAD chlorophyll values and leaf area index following combined Zn and B foliar application under rainfed conditions. Iron application has likewise been associated with improvements in chlorophyll and antioxidant-related responses in maize cultivated on Fe-deficient soil (Kavita & Kumar, 2020). Nevertheless, micronutrient application does not invariably improve physiological performance; benefits are generally greatest where a genuine deficiency exists. Multi-location research has shown that foliar responses vary considerably according to nutrient, application rate, growth stage, and initial plant nutritional status (Fernández et al., 2021). Thus, micronutrient management should be based on deficiency diagnosis and appropriate nutrient doses rather than indiscriminate application.

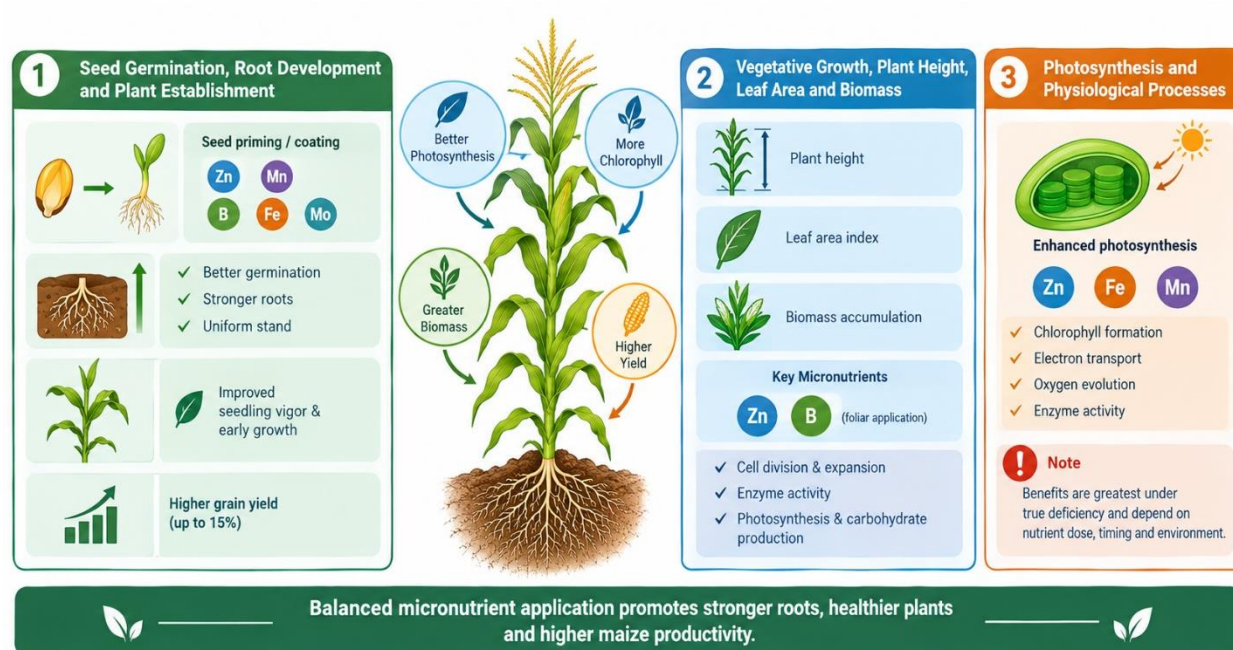


Figure 3: Effects of Micronutrient Application on Maize Germination, Growth, Photosynthesis, and Productivity

Effects of Micronutrients on Yield Components and Grain Yield of Maize

Influence on Cob Development, Cob Length, and Number of Grains per Cob

Micronutrient nutrition has an important role in reproductive development and consequently influences major yield components of maize. Adequate availability of zinc (Zn), boron (B), iron (Fe), and manganese (Mn) during the reproductive phase supports pollen development, fertilization, assimilate production, and kernel establishment. Boron is particularly important for reproductive growth because it contributes to pollen viability, pollen-tube growth, cell-wall formation, and translocation of assimilates toward developing reproductive organs. A field experiment reported that repeated foliar application of boron significantly improved cob length, cob diameter, cob weight, and grains per cob, with three sprays of 0.5% borax producing 481 grains per cob compared with lower values under untreated conditions. Similarly, foliar Zn and B application has been associated with improvements in cob characteristics. Singh et al. (2021) reported that Zn and B application significantly affected cob length, cob girth, grain rows, grains per row, and seed index. Such responses may result from improved photosynthetic activity and nutrient availability during tasseling and grain-setting stages. Recent research involving Fe, Zn, and B combinations also demonstrated substantial improvements in maize reproductive performance, indicating that simultaneous micronutrient supply can be beneficial where multiple deficiencies occur.

Effects on Kernel Weight, Thousand-Grain Weight, and Grain Number

Kernel number and kernel weight are major determinants of maize grain yield. Micronutrients can influence these characteristics by improving pollination, photosynthesis, carbohydrate accumulation, enzyme activity, and assimilate transfer to developing kernels. Zinc, for example, contributes to carbohydrate metabolism and enzyme function, while boron facilitates reproductive development and translocation processes. Consequently, micronutrient supplementation during critical growth stages can improve both kernel formation and filling. Experimental evidence demonstrates considerable variation among maize genotypes and environments. Foliar Zn application increased grain number per cob in some cultivars, whereas its effect on 1000-grain weight was not consistently significant across all genotypes (Zhang et al., 2024). This indicates that genotype, initial soil fertility, and the severity of micronutrient deficiency influence crop response. In contrast, a recent field study found that Fe, Zn, and B applied individually or in combinations significantly increased 1000-grain weight, with Fe + Zn + B producing the largest increase relative to the control. Boron application has likewise been reported to improve 1000-grain weight alongside increases in grains per cob and cob dimensions. Micronutrient management may therefore influence yield through both source and sink effects. Improved canopy function increases assimilate production, while better reproductive development enhances the capacity of the maize ear to establish and fill kernels. However, excessive micronutrient application may not produce additional benefits when nutrient concentrations are already adequate.

Impact on Grain Yield, Stover Yield, and Harvest Index

Grain yield represents the combined outcome of plant growth, reproductive success, kernel number, and grain filling. Numerous studies demonstrate that micronutrient application can increase maize grain yield when nutrient availability limits productivity. A meta-analysis of maize responses to Zn fertilization found an overall positive effect of Zn application on grain yield, although the magnitude of response differed substantially among experimental conditions (Mutambu et al., 2023). Similarly, a global meta-analysis showed that combining Zn and/or Fe with NPK fertilizer can increase maize grain Zn and Fe concentrations while frequently maintaining or increasing grain yield. The response of maize to foliar micronutrients, however, is not universally positive. Fernández et al. (2021) evaluated B, Mn, Fe, and Zn across multiple locations and found that most foliar treatments did not significantly increase grain yield, although an Mn treatment at one deficient site produced a 19% yield increase. This demonstrates that micronutrient fertilization is most effective when it corrects a genuine nutritional limitation. Micronutrients can also influence stover and total biological yield by promoting vegetative biomass production. Recent research reported increases in biological yield, grain yield, straw yield, and harvest index following Fe, Zn, and B application, with combined treatments producing stronger responses than individual nutrients. Harvest index is particularly useful for assessing whether additional biomass is efficiently partitioned into grain. In maize, grain yield is closely associated with total dry-matter accumulation, while improvements in kernel setting and reduction of unnecessary vegetative biomass can contribute to greater harvest index (Echarte et al., 2017). Therefore, effective micronutrient management should aim not only to increase total biomass but also to promote efficient partitioning of assimilates toward grain production.

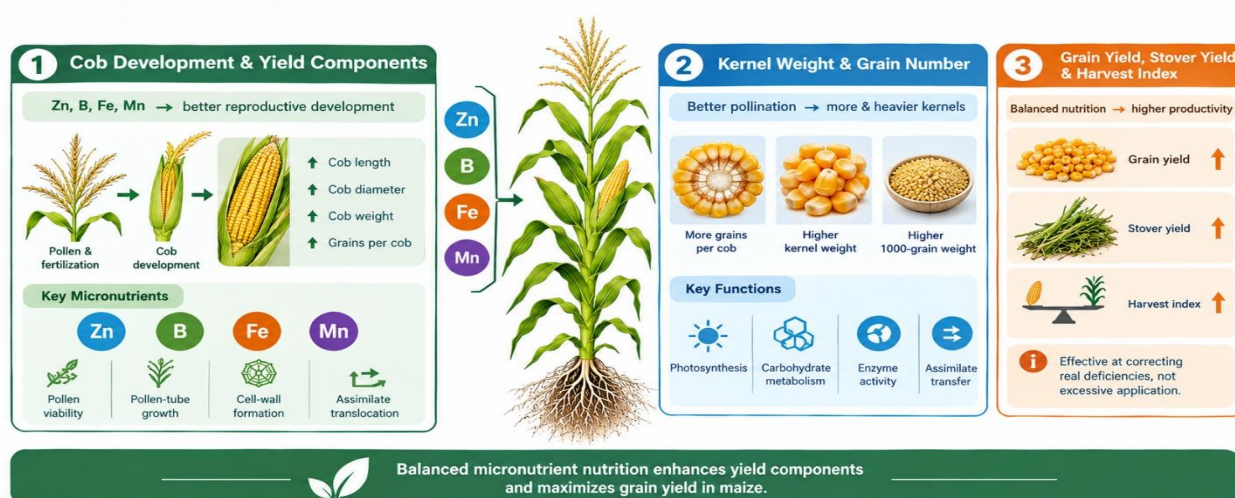


Figure 4: Effects of Micronutrient Nutrition on Maize Yield Components, Grain Yield, Stover Yield, and Harvest Index

Micronutrient Application Strategies for Improving Maize Productivity

Soil Application and Its Effectiveness in Maize Production

Soil application is one of the most widely used approaches for correcting micronutrient deficiencies in maize because nutrients are incorporated into the root-zone and remain available for uptake over an extended period. Zinc (Zn), iron (Fe), boron (B), and other micronutrients can be supplied through inorganic salts, fortified fertilizers, chelated formulations, or micronutrient-enriched organic amendments. The effectiveness of soil application depends strongly on soil pH, texture, organic matter, moisture, nutrient concentration, and interactions with other nutrients. In particular, Zn availability is often restricted in alkaline and calcareous soils because of adsorption and precipitation processes. A field study in Zn-deficient soils of Pakistan demonstrated that soil application of 2.75 kg Zn ha⁻¹ increased maize grain yield by approximately 25%, whereas increasing the rate to 5.5 kg Zn ha⁻¹ did not provide additional yield benefits (Harris et al., 2007). Placement method can also determine fertilizer efficiency. Recent evidence indicates that localized Zn application can outperform conventional broadcasting, particularly in alkaline soils, because placing fertilizer near developing roots reduces spatial losses and improves nutrient availability (Gao et al., 2026). Therefore, soil testing and site-specific fertilizer placement are important for improving the agronomic and economic efficiency of micronutrient fertilization.

Foliar Application, Seed Priming, and Fertilizer-Based Micronutrient Management

Foliar application provides micronutrients directly to plant tissues and is particularly useful when soil conditions restrict nutrient availability or when a rapid correction of deficiency is required. Foliar Zn has demonstrated considerable potential for increasing grain Zn concentration, although effects on grain yield may vary among environments. In maize grown on the Loess Plateau of China, foliar Zn substantially increased grain Zn concentration and produced much greater apparent grain-Zn recovery than soil application (Zhang et al., 2012). Foliar B can also improve reproductive development and yield; however, excessive B may reduce productivity, emphasizing the importance of appropriate concentration and timing (Tahir et al., 2012). Seed priming is another efficient technique because only a small quantity of nutrient is required and the nutrient becomes available during germination and early seedling establishment. Farooq et al. (2012) identified micronutrient seed treatment as a cost-effective approach capable of improving crop establishment, yield, and grain micronutrient concentration. In maize, Zn priming has produced substantial improvements in productivity and grain Zn concentration, with 0.5% ZnSO₄ priming for 24 h increasing silage maize yield by 47% in one study (El-Sabagh et al., 2022). Thus, soil fertilization, foliar feeding, and seed priming should be regarded as complementary rather than mutually exclusive strategies.

Integrated Micronutrient Management and Interaction with Macronutrients

Integrated micronutrient management combines micronutrients with appropriate N, P, and K fertilization to address multiple nutritional limitations simultaneously. Such integration is important because plant response to micronutrients is influenced by the overall nutritional status of the crop. Research has shown that Zn fertilization can interact positively with nitrogen and phosphorus, particularly during early maize development. A recent field study found that localized NP fertilization combined with Zn seed treatment improved maize development compared with Zn treatment alone (García et al., 2024). Meta-analytical evidence further supports integrated nutrient management. Combining NPK with micronutrients and organic inputs increased maize grain yield, grain Zn, and grain Fe relative to NPK alone, demonstrating the potential for synergistic effects among nutrient sources (Kihara et al., 2024). Similarly, combined Fe + Zn + B application has produced substantial improvements in maize growth, grain yield, and nutrient concentration compared with untreated crops (Dawar et al., 2025). More recent evidence indicates that combining soil and foliar Zn can further improve maize productivity and cob yield compared with either approach alone (Sarmaha et al., 2025). Consequently, integrated management based on soil testing, crop demand, application timing, and nutrient interactions provides a more rational approach than indiscriminate micronutrient application.

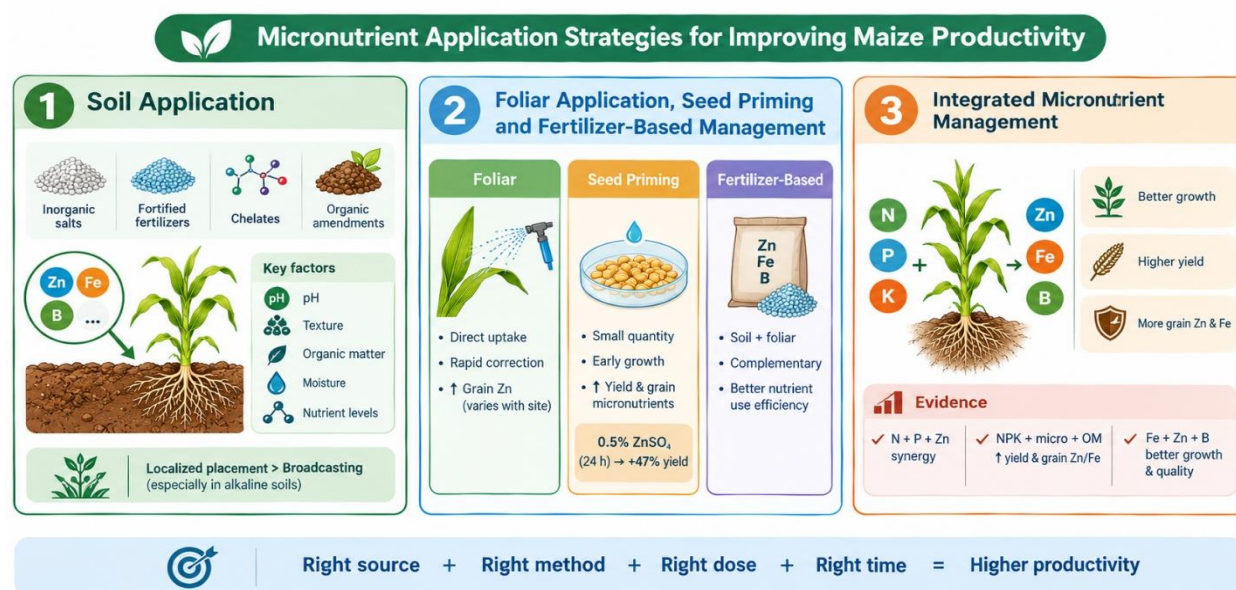


Figure 5: Micronutrient Application Strategies for Improving Maize Productivity through Soil, Foliar, Seed, and Integrated Nutrient Management

Future Perspectives and Sustainable Micronutrient Management in Maize

Biofortification and Nutritional Quality of Maize Grain

Biofortification represents an important future strategy for improving the nutritional quality of maize while maintaining its role as a major staple and feed crop. Conventional breeding, agronomic biofortification, and molecular approaches can be combined to increase the concentrations and bioavailability of zinc (Zn), iron (Fe), provitamin A, and other nutritionally important components in maize grain. Considerable genetic variation exists for grain Zn and Fe concentrations, providing opportunities for developing nutritionally superior maize cultivars (Agrawal et al., 2012). Genetic biofortification is particularly attractive because once a high-micronutrient cultivar is developed and adopted, the nutritional trait can be delivered through seed without requiring farmers to repeatedly purchase additional inputs (Maqbool & Beshir, 2019). Multinutrient breeding should receive greater attention because human diets based heavily on maize may simultaneously lack several nutrients. Goredema-Matongera et al. (2021) emphasized the potential of developing maize with multiple nutritional attributes rather than focusing exclusively on a single micronutrient. Such cultivars could combine high Zn and Fe concentrations with provitamin A, improved protein quality, high yield, and adaptation to abiotic stresses. Agronomic biofortification can complement genetic improvement by supplying Zn or Fe through soil, foliar, or seed treatments. A global meta-analysis found that combining Zn and/or Fe with NPK increased maize grain Zn and Fe concentrations by approximately 31% relative to NPK alone, although responses varied with soil and management conditions (Kihara et al., 2024).

Factors Affecting Micronutrient Availability and Application Efficiency

The efficiency of micronutrient management is strongly influenced by soil, plant, environmental, and management factors. Soil pH, organic matter, texture, moisture, carbonate content, and concentrations of competing ions can substantially affect micronutrient availability. Zinc availability, for example, generally declines in high-pH and calcareous soils and can also be influenced by phosphate and bicarbonate concentrations (Alloway, 2009). Therefore, soil testing should form the basis for determining whether micronutrient application is required and which application method is most appropriate. Genotype × environment interactions are another important consideration. Agrawal et al. (2012) demonstrated significant environmental effects and genotype × environment interactions for grain Fe and Zn concentrations in maize, with Fe showing particularly strong environmental variation. Consequently, micronutrient-efficient or biofortified genotypes should be evaluated across multiple environments before large-scale recommendation. Application rate, nutrient source, placement, timing, crop growth stage, rainfall, irrigation, and interactions among nutrients also influence fertilizer-use efficiency. In Pakistan, successful Zn biofortification depends on overcoming soil, environmental, genetic, socioeconomic, and adoption-related constraints (Rehman et al., 2020).

Research Gaps, Future Directions, and Sustainable Micronutrient Management

Future research should move from evaluating individual micronutrients toward integrated nutrient-management systems that simultaneously address crop productivity, grain nutritional quality, economic returns, and environmental sustainability. More multi-location and multi-year experiments are required to establish critical soil and plant thresholds, optimum rates, application timings, and genotype-specific responses. Kihara et al. (2024) identified substantial gaps in globally available maize grain Zn and Fe data, highlighting the need for standardized sampling, laboratory analysis, and reporting across environments. Molecular breeding, genomic selection, marker-assisted breeding, and functional genomics can accelerate the development of maize genotypes with improved micronutrient uptake, transport, remobilization, and grain accumulation (Maqbool & Beshir, 2019). Future programs should also investigate interactions between Zn, Fe, and other nutrients rather than treating each nutrient independently. Precision agriculture, sensor-based nutrient diagnosis, variable-rate application, biofertilizers, and controlled-release or nano-enabled fertilizers represent additional avenues for improving nutrient-use efficiency. Nano-fertilizers may facilitate targeted nutrient delivery and controlled release, although their environmental safety, long-term behavior, economic feasibility, and regulatory requirements require careful evaluation before widespread adoption (Liu & Lal, 2015; Xiao et al., 2026).

Ultimately, sustainable micronutrient management should integrate soil testing, balanced fertilization, improved genotypes, organic nutrient sources, precise application, and nutritional-quality assessment. Such an integrated approach can help increase maize productivity while improving grain nutritional value and minimizing unnecessary fertilizer losses. Future research should therefore evaluate micronutrient management not only in terms of yield response but also nutrient-use efficiency, profitability, environmental sustainability, grain bioavailability, and farmer adoption.

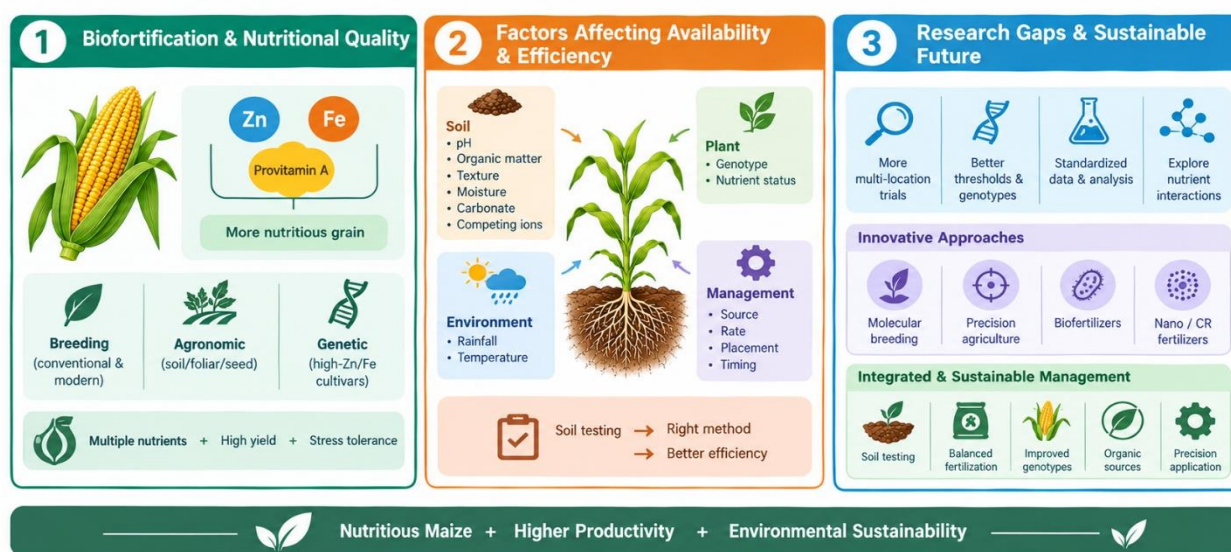


Figure 6: Future Perspectives for Biofortification and Sustainable Micronutrient Management in Maize.

Conclusion

Micronutrient management plays a vital role in improving maize growth, physiological performance, yield components, grain yield, and overall productivity. Adequate application of zinc, iron, manganese, boron, copper, and molybdenum can enhance nutrient uptake, photosynthesis, plant development, and reproductive performance, particularly under deficient soil conditions. The effectiveness of micronutrient application depends on nutrient source, application method, dose, soil properties, environmental conditions, and interaction with macronutrients. Integrated approaches combining soil application, foliar feeding, seed priming, and biofortification offer promising opportunities for sustainable maize production. Future research should focus on site-specific nutrient management, efficient formulations, genetic biofortification, and environmentally sustainable technologies to improve productivity and nutritional quality.

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