

Nutrient Deficiency in Soybean: Causes, Symptoms and Management Strategies for Sustainable Productivity

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ABSTRACT

*Soybean (*Glycine max* L.) is a globally important legume crop valued for its high protein and oil content. As a nutrient-demanding plant, soybean requires a balanced supply of macro and micronutrients for optimum growth, nodulation and productivity. Nutrient deficiencies adversely affect key physiological and biochemical processes, including photosynthesis, nitrogen fixation, enzyme activities and metabolite synthesis, leading to significant yield reductions. Nitrogen and phosphorus deficiencies impair chlorophyll synthesis, energy metabolism and protein content, while potassium deficiency reduces stress tolerance and seed quality. Micronutrient deficiencies such as iron, zinc, manganese, boron and molybdenum alter chloroplast development, enzyme functions and reproductive success, resulting in poor nodulation, low seed set, and reduced oil and protein accumulation. Beyond individual impacts, combined deficiencies often exacerbate stress responses and further limit productivity. Recent advances highlight the role of innovative strategies such as nutrient priming, foliar supplementation, nano fertilizers and the use of nutrient-efficient soybean genotypes in overcoming these limitations. This review provides a comprehensive overview of the physiological, biochemical and agronomic effects of nutrient deficiencies in soybean, with emphasis on their impact on yield and seed quality and outlines potential management and research directions for sustainable production under nutrient-limited conditions.*

Keywords: Soybean, Nutrient deficiency, Macronutrients, Micronutrients, Photosynthesis, Nodulation, Yield

Soybean (*Glycine max* L.), a member of the family *Fabaceae*, is one of the most important oilseed and legume crops cultivated worldwide. It serves as a major source of protein (approximately 40%) and oil (around 20%) for both human consumption and animal feed and contributes significantly to food and nutritional security (Hartman et al., 2011). Global soybean production has expanded to meet the increasing demand for vegetable oil, biofuels and livestock feed, yet its productivity remains constrained by a variety of abiotic and biotic stresses, among which nutrient deficiencies are particularly

critical. Plants require 17 essential nutrients for growth, of which macronutrients (nitrogen, phosphorus, potassium, sulfur, calcium and magnesium) and micronutrients (iron, zinc, manganese, boron, molybdenum, copper, chlorine, and nickel) play indispensable roles in cellular metabolism, enzyme regulation, photosynthesis, nodulation and reproductive success. Soybean, being a nutrient-demanding crop with a high protein requirement, is particularly sensitive to imbalances in nutrient availability. Deficiencies in these nutrients manifest as characteristic morphological and

physiological symptoms such as chlorosis, necrosis, stunted growth, poor nodulation and reduced seed set, ultimately reducing yield and seed quality (Marschner, 2012; Hungria & Mendes, 2015). Nitrogen and phosphorus are often the most limiting macronutrients, directly influencing chlorophyll synthesis, energy transfer and protein metabolism. Similarly, potassium is crucial for enzyme activation, osmoregulation and stress tolerance. Among micronutrients, iron deficiency commonly occurs in calcareous soils and causes severe chlorosis, while zinc deficiency leads to reduced auxin synthesis, shortened internodes and smaller seed size (Kosegarten et al., 2001; Alloway, 2008). Sulfur, magnesium, manganese, boron and molybdenum deficiencies are equally detrimental, affecting biochemical pathways, nodule activity and reproductive development. The cumulative impact of these deficiencies is decline in soybean productivity and grain quality, with wider implications for food security and agricultural sustainability. The severity of nutrient deficiencies in soybean is influenced by soil type, cropping intensity, fertilizer use and environmental conditions. For instance, continuous mono-cropping of soybean can lead to depletion of specific nutrients, while soil pH strongly influences the solubility and uptake of micronutrients such as iron, manganese and zinc. Moreover, nutrient deficiencies often interact with other abiotic stresses such as drought, salinity, and temperature extremes, further aggravating yield losses. Addressing these challenges requires a holistic understanding of nutrient functions, deficiency symptoms and their physiological and biochemical consequences. Present review aims to provide a comprehensive analysis of nutrient deficiencies in soybean, with emphasis on the physiological, biochemical and agronomic impacts of both macro- and micronutrient limitations. It highlights the interactive effects of deficiencies, their influence on yield and seed quality and discusses modern strategies for managing nutrient stress. By integrating recent advances in plant nutrition, soil science and biotechnology, this review also identifies future research directions for improving nutrient-use efficiency and ensuring sustainable soybean production under nutrient-limited environments.

1. Essential Nutrients for Soybean Growth

Soybean requires a balanced supply of macro- and micronutrients to sustain its high demand for protein, oil, and energy metabolism. Nutrients serve as structural components of biomolecules, regulators of enzymatic reactions and mediators of physiological processes such as photosynthesis, respiration, and nitrogen fixation. The essentiality of a nutrient is defined by its inability to be replaced by another element and its necessity for completing the plant life cycle (Marschner, 2012). In soybean, the requirement for nutrients is particularly high during reproductive development when demand for protein and oil biosynthesis is at peak and thus making deficiencies especially detrimental to yield and seed quality

Macronutrients

Soybean requires macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) in enormous quantities for healthy growth and development. Nitrogen is a key component of amino acids and chlorophyll, with its demand in soybean met largely by symbiotic nitrogen fixation, which is crucial for protein synthesis and seed development (Hungria & Mendes, 2015). Phosphorus is essential for energy transfer, root development, and reproductive growth, as it is a key part of ATP and nucleic acids, and its deficiency can significantly reduce yield by delaying maturity (Vance et al., 2003). Potassium is vital for osmoregulation and carbohydrate translocation and enhances stress tolerance (Pettigrew, 2008). Calcium strengthens cell walls and is important for nodule function (Marschner, 2012). As the central atom of chlorophyll, magnesium is critical for photosynthesis, and its deficiency impacts biomass and yield (Cakmak & Yazici, 2010). Sulfur a component of amino acids, supports nodulation and protein synthesis, influencing both yield and grain quality (Salvagiotti & Miralles, 2008). Together, these macronutrients are essential for the physiological processes that underpin healthy soybean production.

Micronutrients

Micronutrients, though required in trace

amounts, are vital for soybean enzymatic and metabolic functions. Iron (Fe) is essential for chlorophyll and photosynthesis; its deficiency causing interveinal chlorosis in young leaves, particularly in calcareous soils (Kosegarten et al., 2001). Zinc (Zn) acts as an enzyme cofactor and regulates auxin, and its lack results in stunted growth and poor seed quality (Alloway, 2008). Manganese (Mn) is critical for photosynthesis, and deficiency leads to interveinal chlorosis and necrotic spots (Broadley et al., 2012). Boron (B) is necessary for cell walls and reproductive development, as its deficiency can cause flower abortion and malformed seeds (Bellaloui et al., 2013). Molybdenum (Mo), a component of nitrogenase, supports nitrogen fixation, and its deficiency mimics nitrogen deficiency (Mendel & Bittner, 2006). Other key micronutrients include copper (Cu), which aids in photosynthesis and reproductive efficiency; chlorine (Cl), involved in osmoregulation; and nickel (Ni), required for urease activity and nitrogen metabolism.

Nutrient Dynamics in Soybean

The nutrient requirement of soybean varies with growth stages. During vegetative growth, nitrogen, phosphorus, and potassium demand is high to support biomass and nodulation, while during reproductive stages, nutrients like sulfur, zinc, and boron become crucial for flowering, pod filling, and seed quality (Fageria et al., 2006). Deficiency of any essential nutrient disrupts these developmental transitions, impairing both yield and grain quality. Moreover, nutrient availability is strongly influenced by soil pH, moisture, and interactions between elements. For example, high phosphorus can suppress zinc uptake, while calcium and boron deficiencies often occur together in acidic soils (Marschner, 2012). Thus, a balanced supply of macro and micronutrients is indispensable for sustaining soybean productivity, and even slight deficiencies can trigger severe physiological consequences. The following sections examine in detail the effects of individual macronutrient and micronutrient deficiencies on soybean growth, physiology, and yield.

2. Macronutrient Deficiencies in Soybean

Nitrogen Deficiency

Nitrogen plays a vital role in soybean growth as a key component of amino acids, proteins, and chlorophyll. Although soybean obtain nitrogen through biological nitrogen fixation (BNF) in symbiosis with *Bradyrhizobium japonicum*, this supply is often insufficient, particularly during reproductive stages when demand is high (Salvagiotti et al., 2008). Nitrogen deficiency is typically expressed as a general yellowing of older leaves, which can progress to premature leaf death, stunted growth, and reduced pod formation (Hungria & Mendes, 2015). This shortage disrupts photosynthesis due to limited chlorophyll, reduces protein and enzyme synthesis, and suppresses root development, further decreasing the plant's ability to fix nitrogen (Thies et al., 1991). The resulting imbalance between carbon and nitrogen allocation directs more resources toward root growth at the expense of shoot and reproductive development (Sinclair & Vadez, 2002). Ultimately, inadequate nitrogen availability severely reduces yield and seed protein content, with studies reporting up to 30–50% yield loss during flowering and pod-filling stages (Salvagiotti et al., 2008).

Phosphorus (P) Deficiency

Phosphorus is the second most important macronutrient after nitrogen, playing a central role in energy metabolism, nucleic acid synthesis, signal transduction, and membrane structure in plants. In soybean, adequate P is crucial for seedling growth, root development, nodulation, and efficient nitrogen fixation, yet its availability is often restricted in soils due to fixation with calcium in alkaline conditions or with iron and aluminum oxides in acidic soils, making it a common yield-limiting factor (Vance et al., 2003; Lynch 2011). Phosphorus deficiency typically results in stunted growth, dark green or purplish leaves, restricted root systems, poor nodulation, and reduced nitrogen fixation (Zhang et al., 2014). At the physiological level, it impairs ATP-dependent energy transfer, reduces photosynthetic carbon fixation, alters root architecture, and suppresses nodule metabolism

and nitrogenase activity (Israel, 1987). These constraints delay flowering, decrease pod number, and significantly reduce seed yield and protein content, with studies reporting up to 40% yield loss under P-deficient conditions (Zhang et al., 2014).

Potassium (K) Deficiency in Soybean

Potassium is functioning as a regulatory ion in enzyme activation, osmoregulation, protein synthesis, carbohydrate translocation, and photosynthesis rather than as a structural component of organic molecules. Adequate K supply ensures efficient stomatal regulation, stress tolerance, and biological nitrogen fixation, however intensive cropping and poor soil replenishment can lead to widespread K deficiency (Pettigrew, 2008). Symptoms of its deficiency include marginal chlorosis and necrosis of older leaves, weak stems, poor root growth, and reduced nodule activity due to impaired carbohydrate transport (Armstrong, 1998). Under physiological conditions K deficiency disrupts enzymatic processes, water balance, photosynthetic CO₂ assimilation, and assimilate transport, while also reduces stress resilience. Consequently, severe K deficiency can cause 30–50% yield losses, lower seed oil content and weight, delayed maturity, poor pod filling, and increased susceptibility to diseases such as charcoal rot (*Macrophomina phaseolina*) (Wang et al., 2013).

Calcium (Ca) Deficiency in Soybean

Calcium is vital for cell wall and membrane stability, root and pollen tube growth, and intracellular signaling (White & Broadley, 2003). Despite its abundance in soils, deficiency can occur due to poor uptake, soil acidity, or nutrient antagonism. Symptoms first appear in young tissues and include stunted growth, necrotic leaf lesions, pod abortion, and weak stems. Physiologically, Ca deficiency weakens cell walls, disrupts membrane integrity, impairs stress signaling, and reduces enzyme activity. In soybean, it also limits root hair development, nodulation, and biological nitrogen fixation, thereby restricting nitrogen supply (Singh et al., 2001).

Ultimately, calcium deficiency reduces flower retention, seed set, and seed quality, with yield losses of 20–30% reported under severe deficiency (Kopittke et al., 2011).

Magnesium (Mg) Deficiency in Soybean

Magnesium serves structural and functional roles in chlorophyll synthesis, photosynthesis, enzyme activation, and phloem transport. As the central atom of chlorophyll, Mg is indispensable for light absorption and energy transduction, while also acts as a cofactor in over 300 enzymatic reactions related to ATP synthesis, protein formation, and carbohydrate metabolism (Cakmak & Yazici, 2010; Römheld & Kirkby, 2007). Deficiency, common in acidic, sandy, or low-CEC (Low cation exchange capacity) soils and exacerbated by excessive potassium or ammonium fertilization, first appears in older leaves as interveinal chlorosis, necrosis, curling, and premature senescence. In plants Mg deficiency reduces photosynthetic capacity, impairs phloem loading and carbohydrate transport, and promotes starch accumulation in leaves while triggering oxidative stress and membrane damage (Hermans et al., 2004). These constraints hinder pod set, seed filling, and biomass accumulation, ultimately reducing seed weight, altering protein-to-oil ratios, and lowering yields by 25–35%, alongside heightened susceptibility to heat and drought stress (Römheld & Kirkby, 2007).

Sulfur (S) Deficiency in Soybean

Sulfur is required in smaller amounts than N, P, and K, but it is critical for soybean metabolism, being involved in the synthesis of sulfur-containing amino acids, vitamins, coenzymes, and metabolites like glutathione (Zhao et al., 1999; Haneklaus et al., 2007). Due to the adoption of high-yielding crop types (which remove more nutrients) and decreasing atmospheric sulfur deposition as a result of pollution management measures, sulfur shortage has become more prevalent in high-intensity agriculture. Physiologically, it limits protein synthesis, chlorophyll formation, antioxidant defense, and nitrogen fixation, thereby weakening growth and stress tolerance. Ultimately, sulfur deficiency

reduces seed weight, protein and oil content, and overall yield by 10–30%, while also impairing seed quality and germination (Salvagiotti et al., 2009).

3. Micronutrient Deficiencies in Soybean

Zinc (Zn) Deficiency

Zinc is required in small amounts but vital for enzyme activation, protein synthesis, membrane integrity, and auxin metabolism. Deficiency is common in calcareous, sandy, and highly weathered soils with low organic matter (Alloway, 2008; Cakmak, 2008). Symptoms appear first in young tissues due to Zn immobility and include interveinal chlorosis, shortened internodes, small distorted “bottle-shaped” leaves, stunted growth, and delayed flowering. Zn deficiency disrupts enzyme function, auxin biosynthesis, membrane stability, and chloroplast development, leading to reduced protein metabolism and photosynthetic efficiency. Yield losses of 30–40% have been reported, with affected plants producing fewer pods, smaller seeds, and reduced seed weight, while seeds also show lower protein content, viability, and storability (Bellaloui et al., 2013).

Iron (Fe) Deficiency in Soybean

Iron is required for chlorophyll biosynthesis, respiration, electron transport, and biological nitrogen fixation. Although abundant in soils, its low solubility in calcareous or poorly drained soils often limits availability, making soybean highly sensitive to Fe deficiency (Kosegarten et al., 2001; Hansen et al., 2004). Deficiency symptoms appear in young leaves as interveinal chlorosis with green veins, progressing to near-white tissues under severe stress, along with stunted growth, delayed flowering, and poor nodulation. Fe deficiency reduces chlorophyll synthesis and photosynthesis, disrupts cytochrome-mediated electron transport and ATP generation, impairs nitrogenase and leghemoglobin function in nodules, and weakens antioxidant defenses, thereby intensifying oxidative stress. These limitations reduce pod set, seed filling, and seed size, ultimately decreasing yield, protein, and oil content, with severe cases causing 50–70% yield losses (Hansen et al., 2004).

Boron (B) Deficiency in Soybean

Boron is required for cell wall stability, membrane integrity, sugar transport, and reproductive development, particularly during flowering and seed set. Although needed in small amounts, B deficiency is common in sandy, acidic, and drought-prone soils due to leaching and poor mobility (Shorrocks, 1997; Bellaloui et al., 2013). Symptoms appear in young tissues as thickened, brittle leaves with necrotic tips, stem cracking, delayed flowering, flower and pod abortion, and distorted growth. Deficiency weakens cell walls, disrupts carbohydrate transport, impairs nodulation, and severely reduces pollen tube growth and fertilization. Yield losses of 30–40% may occur, with fewer pods, shrunken seeds reduced seed weight, and lower oil and protein content, alongside poor germination quality (Shorrocks, 1997; Bellaloui et al., 2013).

Molybdenum (Mo) Deficiency in Soybean

Molybdenum is an essential but minimally required micronutrient in soybean, primarily involved in nitrogen metabolism through its role as a cofactor of nitrate reductase and nitrogenase, which drive nitrate assimilation and biological nitrogen fixation. Respectively needed in trace amounts, Mo deficiency can occur in acidic or sandy soils with low availability, leading to symptoms resembling nitrogen deficiency such as chlorosis of older leaves, stunted growth, poor nodulation, delayed flowering, and reduced seed development (Mendel & Bittner, 2006; Srivastava & Gupta, 1996). Deficiency suppresses nitrate reduction, reduces nitrogenase activity, impairs enzyme-mediated sulfur and purine metabolism, and lowers nitrogen accumulation in seeds, thereby decreasing protein content. Severe deficiency can reduce yield by 20–40%, resulting in fewer pods, small seeds, and poor grain quality, with problems most pronounced in soils below pH 5.5 where Mo becomes insoluble (Gupta, 1997).

4. Interactive effects of nutrient deficiency

In field conditions, nutrient deficiencies in soybean rarely occur alone, and their interactive effects can be synergistic, additive, or antagonistic, often amplifying stress beyond

single deficiencies. For instance, phosphorus enhances molybdenum uptake and nitrogen metabolism, while excess P can induce zinc deficiency (Fageria et al., 2011). Calcium and boron are interdependent for cell wall and reproductive development, with deficiency of either causing poor pod set and stem weakness. Macronutrient– micronutrient interactions also affect nodulation and nitrogen fixation: Combined stresses, such as K and Mg deficiency reducing stomatal function and photosynthesis, Fe and Mn deficiency disrupting electron transport, further weaken plants. Soil pH strongly influences nutrient availability, with acidic soils limiting Mo and Ca, and alkaline soils restricting

Fe, Zn, Mn, and B, while liming can inadvertently induce micronutrient shortages. Because overlapping symptoms complicate diagnosis, integrated soil testing, tissue analysis, and balanced fertility management are essential to address multi-nutrient deficiencies effectively (Fageria et al., 2011).

In soybean nutrient deficiencies disrupt critical physiological and biochemical processes, leading to cascading effects on growth, metabolism, and yield. Figure 1 Summarizes the impact of macro (N, P, K, Mg) and micronutrient (Fe, Zn, B, Mo) deficiencies on soybean growth and yield.

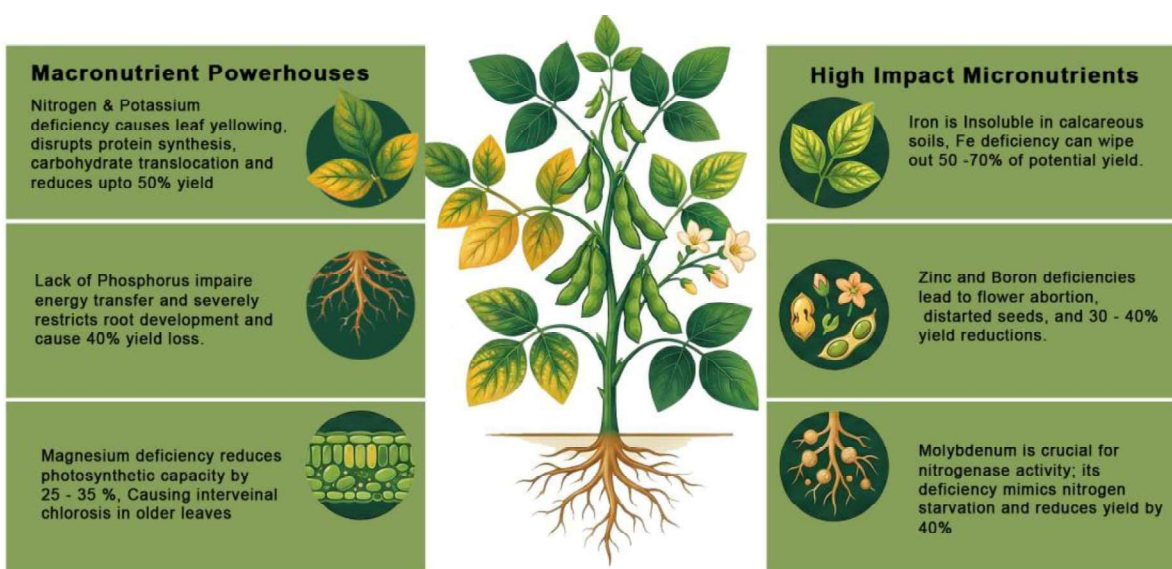


Figure 1. Effect of Macro and micronutrients deficiency on soybean growth and productivity.

Deficiencies in N, Mg, Fe, Mn, and S reduce chlorophyll biosynthesis and photosynthetic efficiency, limiting CO₂ assimilation and biomass accumulation (Salvagiotti et al., 2008; Cakmak & Yazici, 2010; Kosegarten et al., 2001; Millaleo et al., 2010). Enzymatic and energy metabolism is also impaired: P deficiency limits ATP production, Mo deficiency reduces nitrate reductase and nitrogenase activity, and K deficiency suppresses carbohydrate-metabolizing enzymes, collectively slowing growth and

delaying maturity (Mendel & Bittner, 2006). Reduced antioxidant enzyme activity under Fe, Mn, Zn, or Cu deficiency enhances ROS accumulation, causing oxidative stress, lipid peroxidation, and chloroplast damage (Mittler et al., 2022; Rao et al., 2025). Nutrient shortages also compromise nodulation and biological nitrogen fixation (BNF), as P, Mo, Ca, B, and Fe are crucial for energy supply, enzyme function, and rhizobial colonization (Liu et al., 2002; Bellaloui et al., 2013). Carbohydrate and protein

metabolism are disrupted, with K and B deficiencies hindering sugar transport, and N and S deficiencies reducing amino acid and protein synthesis, resulting in smaller seeds and poor harvest index. Additionally, nutrient imbalances affect hormone regulation: Zn deficiency lowers auxin levels, B deficiency impairs pollen

viability, and K and Mg deficiencies alter ABA signaling, collectively leading to flower abortion, reduced seed set, and poor reproductive efficiency. Figure 2 illustrates the impact of macro and micro nutrient deficiency on soybean yield.

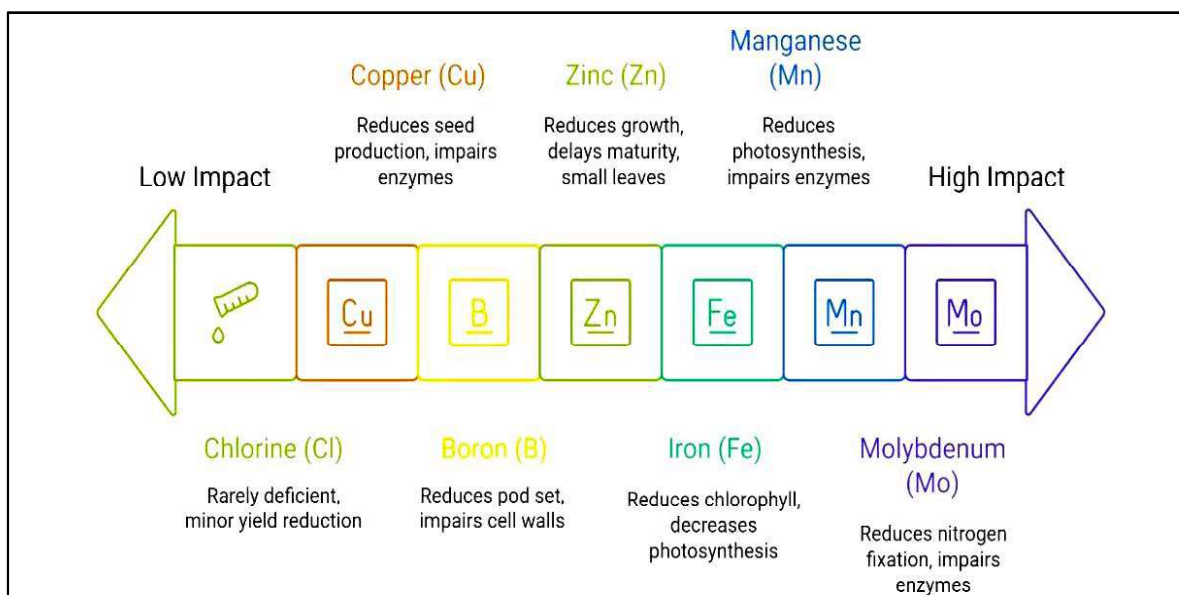


Figure 2: Micronutrient deficiencies ranked by impact on soybean yield.

5. Agronomic and Economic Implications of Nutrient Deficiency in Soybean

Nutrient deficiencies in soybean not only impair growth and physiology but also lead to significant agronomic and economic losses, with yield reductions of 30–50% from N, P, and K shortages and 10–40% from micronutrient deficiencies such as B, Fe, and Mo, especially when stresses overlap during reproductive stages (Salvagiotti et al., 2008; Vance et al., 2003; Pettigrew, 2008; Bellaloui et al., 2013; Kosegarten et al., 2001). Deficiencies also lower seed protein and oil content by 15–30%, cause malformed or poor-quality seeds, and reduce market value (Salvagiotti & Miralles, 2008). Although reduced fertilization may appear cost-saving, nutrient stress increases susceptibility to pests, irrigation demands, and long-term soil fertility decline, often raising input costs. Regionally, such deficiencies account for 30–60% of legume yield

gaps with losses up to 500 kg ha⁻¹ and \$100–200 ha⁻¹ in India due to B and S deficiencies (Singh et al., 2020). Balanced nutrient management, following the 4Rs framework, can improve yields, seed quality, and resilience while raising farm margins by 20–40% and ensuring environmental sustainability (Fageria et al., 2011).

6. Strategies for Managing Nutrient Deficiency in Soybean

Given the substantial physiological, agronomic, and economic impacts of nutrient deficiencies in soybean, it is critical to adopt integrated strategies for their prevention, diagnosis, and correction. Effective nutrient management aims not only to restore crop health and productivity but also to promote resource-use efficiency, economic return, and environmental sustainability. This section outlines key

approaches including soil and tissue testing, balanced fertilization, seed priming, biofertilizers, and advanced tools like nanotechnology and nutrient-efficient genotypes to address both macro- and micronutrient

deficiencies in soybean, as depicted in Figure 3. Addressing nutrient deficits through targeted management mitigates metabolic stress in soybean crops, securing yield stability alongside sustainable resource utilization.

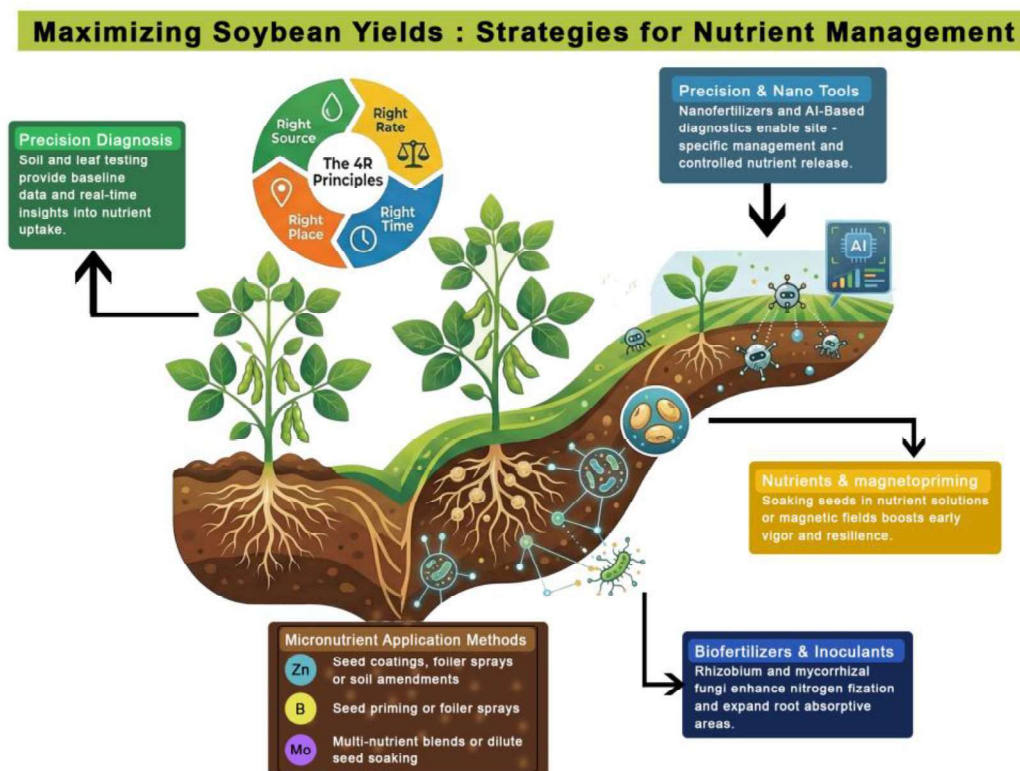


Figure 3. Strategies for managing nutrient deficiencies in soybean.

Soil and Leaf Nutrient Testing

Accurate diagnosis is the foundation of nutrient management. Soil testing assesses the baseline availability of nutrients, pH, and cation exchange capacity, enabling tailored fertilizer recommendations. Leaf or petiole tissue analysis offers real-time insights into in-season nutrient uptake and helps detect latent or combined deficiencies that may not be visually apparent (Marschner, 2012). Critical nutrient thresholds have been established for soybean tissues at various growth stages, allowing comparison against optimal values to guide corrective actions.

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Balanced and Site-Specific Fertilization

Fertilizer strategies should be customized to crop demand, soil type, and regional conditions. Macronutrients like N, P, and K are often supplied via base applications, while S, Ca, and Mg may be included in multi-nutrient blends. Micronutrients such as Zn, B, Mo, and Fe are typically applied as foliar sprays, seed coatings, or soil amendments (e.g., borax, ZnSO_4 , Mo salts). Integrated soil fertility management (ISFM) principles encourage balanced, site-specific fertilization using the 4Rs: the right source, right rate, right time, and right place (Fixen et al., 2015). Split applications and band placement techniques can improve fertilizer use

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efficiency and reduce losses.

Seed Priming Techniques

Seed priming enhances early germination and seedling vigor under nutrient stress. Nutrient priming involves soaking seeds in dilute solutions of essential nutrients (e.g., zinc sulfate, boron, molybdenum) to improve their availability during early growth. Magneto priming, where seeds are exposed to static magnetic fields, has also shown enhancement in enzymatic activity, root growth, chlorophyll content and nutrient uptake in soybean under salt conditions (Radhakrishnan, 2019). These methods are particularly effective in marginal soils where nutrient mobility is restricted.

Biofertilizers and Microbial Inoculants

Biological inputs such as Rhizobium, phosphate-solubilizing bacteria (PSB), potassium-solubilizing microorganisms (KSM), and mycorrhizal fungi enhance nutrient availability and uptake efficiency. Co-inoculation of soybean seeds with Bradyrhizobium and PSB improves nodulation, nitrogen fixation, and phosphorus mobilization. Mycorrhizae also expand root absorptive area, increasing uptake of relatively immobile nutrients like Zn and P, especially in low-input systems (Adesemoye & Kloepper, 2009). These options offer low-cost, eco- friendly alternatives to chemical fertilizers.

Foliar Feeding and Rescue Treatments

Foliar application is an effective and rapid means of correcting micronutrient deficiencies, especially during critical reproductive stages. Nutrients such as iron, zinc, boron, and manganese are effectively delivered via foliar sprays, bypassing soil fixation and improving immediate availability. Foliar feeding is especially valuable in correcting transient or secondary deficiencies under waterlogged or drought-prone conditions that limit root uptake (Fernández & Ebert, 2005).

Use of Nutrient-Efficient Genotypes

Genetic variability exists among soybean cultivars in their capacity to acquire and utilize nutrients. Breeding for nutrient-use efficiency, including traits like enhanced root architecture,

transporter activity, and internal remobilization, is a promising long-term strategy. For example, some soybean lines have been developed with enhanced phosphorus acquisition efficiency, improved zinc translocation, or tolerance to iron deficiency chlorosis (IDC). Marker-assisted selection and genome editing tools like CRISPR/Cas9 may accelerate the development of such genotypes in the future (Lynch, 2011).

Emerging Tools: Nanofertilizers and Precision Agriculture

Nanotechnology-based fertilizers, such as zinc oxide nanoparticles or nano-chelated iron, offer high surface area, controlled release, and improved nutrient use efficiency. Early studies show that nanoprimering with metal nanoparticles can significantly improve germination, root growth, and stress resilience under nutrient deficiency (Tamindžić et al., 2023). Additionally, precision agriculture tools such as remote sensing, variable-rate technology, and GPS-based soil mapping enable site-specific nutrient management, reducing waste and maximizing crop response.

7. Future research directions

Future research on managing nutrient deficiencies in soybean should focus on integrating advanced genomics, microbiome engineering, nanotechnology, precision agriculture, and climate- smart approaches to improve nutrient-use efficiency and sustainability. Genomic tools such as QTL mapping and marker- assisted selection can accelerate breeding for traits like iron deficiency chlorosis tolerance and phosphorus acquisition efficiency (Zhao et al., 2020). Engineering beneficial microbial consortia and stress-resilient biofertilizers offers eco-friendly alternatives to chemical inputs (Compant et al., 2019). Nanofertilizers provide controlled release and higher nutrient efficiency but require field-scale validation and safety assessments (Kah et al., 2019). Digital tools such as UAV imaging, remote sensing, and AI-based diagnostics enable real-time deficiency detection and variable-rate fertilization, though affordability remains a challenge for smallholders. Climate change adaptation through resilient cultivars and weather-linked nutrient management will be

crucial to maintain productivity under stress, while biofortification strategies can enhance seed zinc, iron, protein, and amino acid content to address nutritional security (Zhao et al., 2020; Compant et al., 2019; Kah et al., 2019).

8. CONCLUSION

Soybean is central to global food, feed, and biofuel systems, yet its productivity is highly constrained by nutrient deficiencies that disrupt photosynthesis, nodulation, enzymatic activity, hormonal regulation, and reproductive development, leading to yield losses of 10–50% and reduced seed protein and oil quality. These deficiencies rarely occur in isolation, instead interacting synergistically or antagonistically to exacerbate oxidative stress, impair nitrogen fixation, and diminish stress resilience. Addressing these challenges requires integrated management strategies including soil and tissue testing, balanced and site-specific fertilization, seed priming, foliar feeding, nanofertilizers, biofertilizers, and the adoption of nutrient-efficient genotypes. Advances in genomics, microbiome engineering, precision agriculture, and nanotechnology further provide promising avenues to enhance nutrient-use efficiency while safeguarding sustainability. Ultimately, ensuring balanced nutrient supply is critical not only for maximizing yield and quality but also for improving resource-use efficiency, maintaining soil fertility, and building resilient soybean production systems for future global demands.

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