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Review

Managing Micronutrients for Improving Soil Fertility, Health, and Soybean Yield

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Abstract: Plants need only a small quantity of micronutrients, but they are essential for vital cell functions. Critical micronutrients for plant growth and development include iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl), and nickel (Ni). The deficiency of one or more micronutrients can greatly affect plant production and quality. To explore the potential for using micronutrients, we reviewed the literature evaluating the effect of micronutrients on soybean production in the U.S. Midwest and beyond. Soil and foliar applications were the major micronutrient application methods. Overall, studies indicated the positive yield response of soybean to micronutrients. However, soybean yield response to micronutrients was not consistent among studies, mainly because of different environmental conditions such as soil type, soil organic matter (SOM), moisture, and temperature. Despite this inconsistency, there has been increased pressure for growers to apply micronutrients to soybeans due to a fact that deficiencies have increased with the increased use of high-yielding cultivars. Further studies on quantification and variable rate application of micronutrients under different soil and environmental conditions are warranted to acquire more knowledge and improve the micronutrient management strategies in soybean. Since the SOM could meet the micronutrient need of many crops, management strategies that increase SOM should be encouraged to ensure nutrient availability and improve soil fertility and health for sustainable soybean production.

Keywords: macronutrient; nutrient deficiency; nutrient uptake; site-specific nutrient management; soil organic matter

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1. Introduction

Soybean (*Glycine max* L.) is one of the most cultivated legume crops in the world. In 2019, its global production was about 334 million metric tons from a harvested area of 121 million hectares [1]. In the U.S., soybean is the second largest crop after corn (*Zea mays* L.) and is primarily grown in the Midwest region, where about 75% of the total agricultural area (38.5 million hectares) is used for corn and soybean productions [2]. The U.S. Midwest is one of the most productive agricultural regions in the world, producing over 33% of the world's corn and 34% of the world's soybeans [1]. Soybeans belong to the Fabaceae family, and they provide approximately 50% of edible oil around the world [3]. The usage of soybeans ranges from human consumption to animal feed to non-food products. In the U.S., soybeans are planted in May and early June and harvested in late September and early October [4]. Farmers commonly grow soybeans in crop rotation with corn. Although commercial fertilizer is applied to less than 40% of soybean acreage [4], over the years, extensive use of primary macronutrients, especially in corn, has resulted in micronutrient deficiency, poor soil fertility, and low soybean productivity.

Plants need 17 essential nutrients for their growth and production. Three basic elements, hydrogen (H), oxygen (O), and carbon (C) are available from air and water. Nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) are considered macronutrients, while micronutrients include iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl), and nickel (Ni). Plant micronutrient requirement is lower than the macronutrient requirement. Hence, micronutrient deficiencies are less common than macronutrient deficiencies in soybean, but they are essential for critical cell functions [5,6]. Micronutrient deficiency can reduce plant growth, yield, and quality, thereby affecting the health and productivity of animals and human beings [7–9]. Currently, the micronutrient deficiency in arable soil is a global problem [10,11].

The micronutrients typically studied for soybean are Mn, B, Zn, and Mo [12,13]. The extensive use of N fertilizers, especially after the WW-II on corn, wheat (*Triticum aestivum* L.), and other small grains, has resulted in a high yield, which encouraged researchers and scholars to explore the possibility of yield increase using different nutrients [14]. Interest in micronutrients has increased in recent years because of increased nutrient removal rates by newly developed high-yielding cultivars [15]. The plant uptake of micronutrients largely depends on their availability in the soil [16]. Positive yield responses on various crops, including soybean, were observed when micronutrients were applied with macronutrients [17].

Crop production is affected by multiple environmental stresses, including disease and pest infestations, low soil fertility, and inadequate water supply [18,19]. If we feed the soil, it will feed us; therefore, only productive soil that provides all essential nutrients required by plants can support successful crop production. Maintaining soil fertility to an optimum level is necessary to produce healthy plants, maximize crop yield, and sustain soil health. In recent years, soil quality and soil health have been receiving more attention among the scientific community because healthy soils provide the foundation for food production, water conservation, nutrient cycling, climate change mitigation, and biodiversity conservation [20]. The concept of soil health and soil quality was started in the 1980s as a comprehensive approach beyond fertility management to address soil degradation problems. The Food and Agriculture Organization of the United Nations (FAO) [21] describes soil health as the "capacity of soil to function as a living system, with the ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health". Successful soil health management involves understanding the need for all the essential nutrients and related soil physical, chemical, and biological processes to produce crops and support the farm economy (Figure 1).

Legume-based cropping systems improve soil fertility and health in different ways, such as the availability of soil organic matter (SOM) rich in N and P concentrations [24]. Legume crops such as soybeans can increase SOM by supplying biomass, organic carbon, and N [25] and increase the population of nodule-forming bacteria, Rhizobia [26]. Benefits of legumes include increasing SOM, improving soil porosity and structure, recycling nutrients, buffering soil pH, diversifying the microscopic soil flora and fauna, and breaking the pest and disease cycle [27]. The SOM plays a crucial role in micronutrient availability and their uptake by plants [28]. The presence of chelating organic compounds in soils could increase the availability and solubility of micronutrients. For example, the chelation of metal elements such as Zn and Fe with SOM is essential for transporting these elements to the root system [29].

There are several reports on micronutrient management in soybean on individual field levels and a few on regional scales [6]. In this paper, results are examined and summarized from existing studies on the use of micronutrients in soybean across the globe. We reviewed the literature on various micronutrients and their availability, discussed their deficiency symptoms, and yield responses to soybeans. Micronutrient application methods and variable application rates are also considered. We focused on studies from the U.S. Midwest, the largest soybean producing region in the world, but also recapped relevant studies from other parts of the world. The objective was to synthesize evidence relating to the application of micronutrients in soybean and better understand its importance for improving fertility and the overall health of soils and soybean grain yield in the U.S. Midwest and beyond.

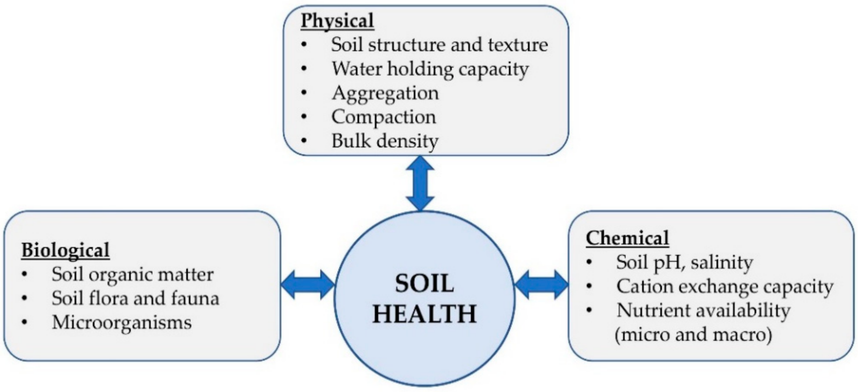

Figure 1. Biological, physical, and chemical components of soil health. (Source: modified from Moebius-Clune [22] and Hills et al. [23]).

2. Micronutrient and Soil Fertility

Two primary objectives of soil nutrient management are to improve soil fertility and meet the nutrient requirements of growing crops. Improving soil fertility is an important agronomic practice for profitable crop production and ensuring soil health. Healthy soils encompass a diverse community of soil flora and fauna that help minimize disease and pests, promote beneficial symbiotic relationships, decompose and recycle essential plant nutrients, and improve soil structure and nutrient holding capacity [21].

A soil nutrient management plan describes the selection of the right source of nutrients for application at the right rate, at the right time, and in the right place [30]. The major role of soil nutrients in soil fertility and ecosystem functions is related to their effect on crop yield. Furthermore, soil fertility and health are influenced by the increased rate of decomposition of high C:N ratio organic matter applied to the soil [31]. Fertilizer application increases microbial activity and enhances the organic matter decomposition, although a few studies reported that added fertilizer did not affect the decomposition of high C:N materials [32]. However, rational use of fertilizers for several years could lead to increased SOM in the soil profile, thereby improving soil fertility, health, and crop yield [33,34]. Studies showed that the increased availability of certain micronutrients, such as Mn and Zn, was highly related to the higher SOM application rates [35–37].

The availability of micronutrients in the soil is also influenced by fertilizers and cropping practices incorporating crop residue in soil [38]. Continuous use of synthetic fertilizers without organic supplements damages the soil's physical, chemical, and biological properties and causes environmental pollution [39]. In contrast, regular use of organic residues significantly improves soil physical, chemical, and biological properties, and hence, soil health [40,41]. Therefore, the balanced application of organic and inorganic fertilizer is recommended in crop management programs for improving soil health and increasing yield [42,43]. The use of organic amendments in the form of compost, farmyard manure (FYM), green manure, and even incorporation of plant residues in soil was noted to be beneficial as they provided some amounts of micronutrients essential for plant growth and development [28,44].

The edaphic and biological factors in the soil, such as redox potential (a measure of electrochemical potential), soil pH, microbial activity, and organic matter, also influence the micronutrient availability to plants [44]. Similarly, micronutrient concentration in crops increased with green manure application along with organic and inorganic fertilizers [45,46]. The SOM acts as a source of nutrients and increases the population of the microbial community, sequestration of soil organic carbon, and nutrient availability to plants [28,47–49]. As such, soil organisms are actively involved in processes such as nutrient cycling, N_2 fixation, decomposition, and mineralization of the SOM [50]. Application of organic manures and crop residues with synthetic fertilizers results in higher fertilizer use efficiency [51].

Micronutrients are generally available in acidic soils and are often unavailable at high pH. Soil pH is a key characteristic that affects the solubility and availability of plant nutrients. As shown in Figure 2, Fe, Mn, B, Cu, and Zn are mostly available between pH 5 and 7, and Mo is mostly available at pH higher than 7. At a low pH (<5), the solubility of Al, and Fe is high but low for molybdenum. Soil pH also affects the microbial community size and activity in the soil, which are responsible for breaking down organic matter and ensuring most chemical transformations in the soil to make nutrients available for plants [27].

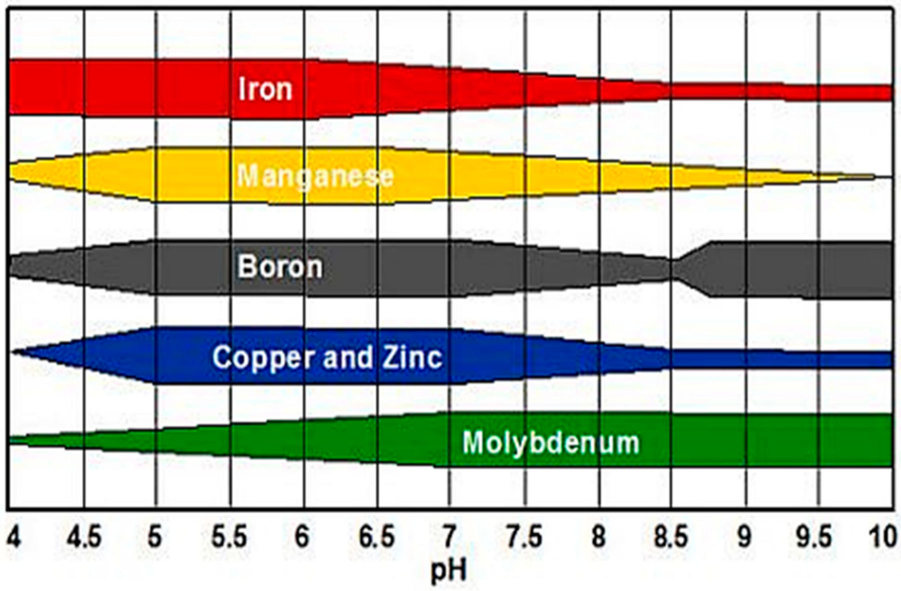

Figure 2. Relative availability of micronutrients by soil pH. (Source: adapted from Truog [52]).

3. Micronutrient Deficiency in Soybean

Micronutrient deficiencies can be detected by visual symptoms on crops and by testing soil samples and plant tissues. Plant symptoms, including stunted growth and leaf chlorosis, may have a variety of causes, including disease/pest infestations, herbicide damage, nutrient deficiencies, or adverse environmental conditions [53]. The deficiency of any one of the 17 essential plant nutrients can limit soybean yield. A nutrient concentration below the sufficiency range or critical value implies deficiency symptoms, and deficient plants respond to the nutrient application [54]. Micronutrients are needed in small amounts, and their adequate concentrations in plants are generally below the 100 ppm level (Table 1).

Many cultivated soils are abundant in Fe, on average, having a total concentration of 20–40 g kg^{-1} soil [56]. However, Fe deficiency is a major problem in soybean production, especially in semiarid environments where carbonates (soluble salts) do not leach easily due to low rainfall [53] (Table 2). The Fe^{+3} becomes less soluble in semiarid environments and slows the conversion to Fe^{+2} for uptake by plants [57]. Iron deficiency results in chlorosis between the veins, especially in younger leaves of soybean. In severe conditions, brown necrotic spots are observed near the leaf margin. However, soybean cultivars differ in their tolerance of Fe deficiency. Some cultivars show complete chlorosis at mild deficiency levels, while others remain normal [58]. Iron is the central component of leghemoglobin for soybean and other legume crops, a nodular component that protects nitrogenase from decomposition by oxygen (O_2) inside root nodules. Therefore, an adequate supply of Fe supports root nodulation and atmospheric N_2 fixation [14].

Table 1. Range of concentrations and adequate concentrations of different nutrient elements in plants (dry weight basis). (Source: Lohry [55]).

Element	Range of Concentrations (ppm)	Adequate Concentration (ppm)
Iron (Fe)	20–600	100
Boron (B)	0.20–800	20
Manganese (Mn)	10–600	50
Zinc (Zn)	10–250	20
Copper (Cu)	2–50	6
Molybdenum (Mo)	0.10–10	0.10
Chlorine (Cl)	10–80,000	100
Nickel (Ni)	0.05–5	0.05

Table 2. Soil conditions that favor micronutrient deficiencies in soybean.

Micronutrient	Soil Characteristics Favoring Deficiency in Soybean	References
Iron (Fe)	Soils with high pH (>7.4), soluble salts, and/or calcium carbonate levels, and low SOM.	Butzen [53], Kaiser et al. [59]
Boron (B)	Alkaline or strongly acidic soils in high rainfall areas or under drought conditions (low rainfall).	Lohry [55]
Manganese (Mn)	Medium and fine-textured soils with high pH (>6.5), low SOM, and poor drainage.	Butzen [53], Ritchey [60], Graham et al. [61], Boring and Thelen [62]
Zinc (Zn)	Sandy soils with a near-neutral pH (6.5), high P levels, low SOM, and cool wet soil conditions.	Bruns [14], Mengel [63], Culman et al. [64]
Copper (Cu)	Alkaline peat musk soil with pH between 7 and 8 and highly leached sandy soils.	Sinclair [58]
Molybdenum (Mo)	Highly acidic soils (pH < 5.8) that are strongly weathered and leached.	Butzen [53], Ritchey [60], Culman et al. [64]
Chlorine (Cl)	Occasionally on sandy soils in dry areas.	Sinclair [58]
Nickel (Ni)	Soils poor in extractable Ni.	Freitas [65]

Boron has very important physiological roles such as enzyme activities, cell elongation, protein synthesis, pollen germination, fruit/grain formation, and yield improvement [66–68]. Boron deficiencies have been observed in several agronomic and horticultural crops, where the soil is alkaline or strongly acidic and in soils high or very low in organic matter content [55] (Table 2). Boron is rarely deficient in clay soils, but coarse and well-drained sandy soils are generally low in B content [69]. Studies have observed a close relationship between B availability and primary cell wall formation. For example, Hanson [70] reported that around 90% of cellular B is localized in the cell wall fraction. Therefore, abnormalities in the cell wall and the organization of middle lamella are the early symptoms of B deficiency in plants [71]. Because soybean plants are relatively tolerant of B deficiency, only small responses to B fertilization have been observed for soybean [72,73]. Boron application can be toxic to soybean with broadcast application rates of about 2.2 kg ha^{-1} [59,74].

Manganese (Mn) availability in soils is influenced by various factors, such as SOM, pH, $CaCO_3$, and redox conditions. Soybean is sensitive to Mn deficiency; hence, its deficiency is a problem in different parts of the world, including the U.S. Midwest [75]. Manganese deficiency is more likely to occur on soils with low moisture content, high soil pH, and low

SOM [53,60,62] (Table 2). Since Mn is relatively immobile in soybean, deficiency symptoms appear on younger leaves as interveinal chlorosis (leaf veins are green, but areas between the veins are yellow). Manganese deficiency in Kentucky has occurred on medium and fine-textured soils with a pH of 6.5 or greater [60], while in Minnesota, soybean responded to Mn when grown on soils with a pH greater than 7.4 [59].

Although soybean is less sensitive to Zn, deficiency symptoms are more common in soybean plants growing on sandy soils with low SOM content [14,63,64] (Table 2). Removal of topsoil through the process of erosion can also increase the Zn deficiency of soil [76,77]. Zinc is essentially immobile in plants, and deficiency symptoms often appear in newer or younger leaves [14]. In soybean, Zn deficiency results in stunted plant growth and chlorotic leaves, with premature lower leaf abscission and poor pod set [14]. An oppositive relationship is identified between Zn and Mn. Severe Zn deficiencies in soybean are often associated with high Mn concentrations in plant tissue, especially in young leaves [78,79].

Copper is specifically required for the synthesis of lignin needed for cell wall strengthening [80]. Like most of the other micronutrients, it is immobile in plants, and deficiency symptoms will first appear in new growth or young leaves. Alkaline peat musk soil, highly leached, and sandy soil with pH between 7 and 8 have a better chance of Cu deficiency [58] (Table 2). Overall light chlorosis, necrotic leaf tips, and loss of turgor in young leaves are the symptoms of Cu deficiency. The problem with Cu toxicity is more common than the toxicity of other micronutrients because Cu is a central element in several pesticides, mainly fungicides [14]. Copper toxicity can result in low protein metabolism as well as low N_2 fixation in soybean [81].

Molybdenum is required by the plants at the lowest concentrations of all essential elements and its level ranges between 0.2 and 5.0 mg kg^{-1} soil [82]. Highly weathered and leached soils that have pH below 5.8 are associated with reduced Mo availability [53,60,62] (Table 2). When the soil pH decreases, it results in the strong adsorption of Mo on oxides of Fe, Al, and Mn [83,84]. The major function of Mo in soybean is to facilitate nodule formation and N_2 fixation by rhizobium bacteria (*B. japonicum*). Thus, biological N_2 fixation will be affected when Mo is deficient [85,86]. Like those of ordinary nitrogen deficiency, general chlorosis of young plants and chlorosis of oldest leaves are the most visible symptoms of Mo deficiency in soybean [58].

Chlorine plays an important role in gas exchange, photosynthesis, and disease resistance in plants. Although Cl deficiency is rarely observed, chlorosis and wilting of young leaves are generally associated with Cl deficiency. Instead of deficiency, Cl toxicity is a serious problem in soybean production in most of the U.S. southern states, where the precipitation is limited. In these areas, the poorly drained soils will accumulate more Cl on the upper soil profile causing Cl toxicity [87,88]. After applying Cl-containing fertilizer, Cl toxicity in soybean was also found in the poorly drained soils of Georgia [89].

Nickel deficiency in soybean occurs in soils poor in extractable Ni [65]. Field-grown soybean plants with Ni deficiency may not show visible leaf symptoms (hidden deficiency) [60]. Therefore, most studies on Ni in plants have been conducted in the context of toxicity than deficiency [90–93]. Plants cannot complete their life cycle without an adequate supply of Ni [94] because it is a structural component of urease [95], the enzyme that is responsible for converting urea to ammonia [96,97]. Therefore, legumes that are dependent on N_2 fixation may be particularly susceptible to an inadequate Ni supply.

4. Micronutrients Management

An appropriate method of micronutrient application depends on the element and its formulation (liquid or dry), the severity of the deficiency, and the plant growth stage at which the deficiency symptoms are being addressed. Soil and foliar application are the major routes of micronutrient application. Soil application is generally preferred for most nutrients if deficiencies are known prior to or at the beginning of the growing season. Micronutrients banded with other fertilizers at planting are usually more effective over a longer period than foliar-applied micronutrients. Soil application also makes the nutrients available to the plant at the earliest [53].

Micronutrients, Cu, Mn, Mo, Fe, Cl, B, and Zn with limited mobility may benefit from band application near soybean roots [98]. However, a small fraction of nutrients reaches the plant system through soil application and the remaining amount goes to waste through leaching in soil, causing land and water pollution [99]. Overall, the utilization of the soil-applied fertilizers is low in calcareous and alkaline soil due to high fixation and less mobility of the nutrients [100,101]. In contrast, foliar spray is the fastest way to cope with the deficiency and translocate micronutrients in plant organs [102]. The foliar spray also improves plant resistance against disease, pests, and drought [103]. Plant leaves not only capture light and CO_2 but also can absorb nutrients through the cuticle, cuticular cracks and imperfections, stomata, trichomes, and lenticels, which have long been recognized and used in nutrient management programs [104,105]. The foliar application also minimizes the leaching loss of nutrients which is more common in soil application [99].

Like in many other grain crops, soybean nutrient demand increases at the time of flowering and grain filling. Foliar application of micronutrients during this period helps to complement soil nutrient supply. Furthermore, most foliar micronutrient supplements can be mixed and sprayed with herbicides and other pesticides. A meta-analysis by Joy et al. [106] suggested that foliar application with Zn was more efficient/cost-effective than soil application for enhancing Zn concentrations in various crops. Foliar applications of Mn were most effective in soybean when applied at the early blossom or early pod set stage or in multiple applications at these stages [107]. Foliar application of B increased its concentration on soybean grains but did not increase the yield [108]. Soybean seed yield showed a small response to soil-applied Mn and Zn, but when micronutrients were foliar-applied, seed yield decreased, likely due to some leaf damage caused by foliar feeding [109]. Therefore, the effectiveness of foliar micronutrient applications varies significantly concerning their solubility and ingredients such as salts, surfactants, complexes, or chelates [110]. There are ongoing discussions about the different effects of micronutrient delivery to plants as soil vs. foliar [106,111].

In recent years, site-specific (or variable rate) nutrient management that uses modern technology and tools, such as remote sensing, Geographic Information System (GIS), and Geographical Positioning System (GPS) is becoming popular among growers [112]. Researchers have mostly focused on the site-specific management of macronutrients, and few investigations have been conducted with respect to site-specific micronutrient management, which is even scarce in the case of soybean. Variations in the micronutrient contents of soils depict an intrinsic nature and properties of soils [113–115]. Foroughifar et al. [114] utilized the Geostatistics and GIS techniques to characterize the spatial variability of soil properties, including micronutrients. They found the spatial distribution of micronutrients varied with soil sedimentation sequence, underground water levels, and underlying pedological and hydrological processes. Geostatistics and GIS techniques were also applied to understand the spatial dependency of bioavailable micronutrients in the rice (*Oryza sativa* L.) field, where the spatial distribution of the micronutrients was significantly correlated to the soil formation factors [116].

Eze et al. [117] compared uncertainties and correlations in spatial process models for the distribution of Zn in the topsoil of a semiarid environment and found geostatistical modeling as a decision-making tool in soil micronutrient management because it could map spatial heterogeneity and uncertainty. Vasu et al. [115] illustrated that the large-scale spatial variability mapping of soil micronutrients is a prerequisite for implementing site-specific nutrient management in the semiarid tropical regions. Wang et al. [118] found some similarity of spatial structure between soil pH and the grain Cu, Fe, Mn, and Zn, and by analogy, similar spatial variation was observed between SOM and DTPA-extractable micronutrients in the soil. Udeigwe et al. [119] examined the fixation pattern and kinetics of plant-available DTPA-extractable Cu, as well as basic soil properties that influence Cu availability in semiarid soils, while Zhao et al. [120] used geostatistical methods for identifying the possible spatial distribution of Cu. Eze et al. [121] used the sequential gaussian simulation (SGS) to map the spatial distribution of Cu concentration and modeled the spatial uncertainties for arable dryland in central Botswana. Furthermore, Kriging-based techniques are used to better understand the spatial variation of micronutrients in different parts of the world [118,122].

5. Soybean Micronutrients Uptake and Yield Response

Micronutrients are essential elements that plants use in small quantities. For most micronutrients, crop uptake is less than 2.0 kg ha^{-1} (Table 3). Despite this low requirement, deficiency of micronutrients limits the critical plant functions, resulting in abnormal plant growth and reduced yield and quality. In this condition, even the use of other inputs such as macronutrients and water can be wasted. This situation is clearly illustrated by Liebig's Law of minimum; every field contains a maximum of one or more and a minimum of one or more nutrients [65]. Crop yields are regulated by the factor in greatest limitation, and yields can be increased only by correction of that limiting factor. When that limitation is overcome, yields are then regulated by the next important limiting factor. This process is repeated, with stepwise yield increases, until there are no remaining limiting factors. All successful agricultural producers use this important principle knowingly or unknowingly [65].

Table 3. Approximate per-hectare micronutrient uptake by soybeans. (Source: adapted from Mengel [63]).

Micronutrient	Nutrient Uptake (kg/ha) by 4000 kg/ha Soybean
Iron (Fe)	1.91
Manganese (Mn)	0.67
Zinc (Zn)	0.22
Boron (B)	0.11
Copper (Cu)	0.11
Molybdenum (Mo)	0.01

In different studies, soybean yield response to micronutrient applications was inconsistent because of different genetic resources, management factors, and environmental conditions such as soil mineralogy, pH, organic matter, moisture, temperature, and aeration. Therefore, identifying genetic and environmental factors affecting soybean micronutrient uptake and crop removal could help growers to implement better nutrient management strategies. Studies, especially on the application of micronutrients such as Zn and Fe, showed an improvement in yield and yield components in various crops [123–125]. The use of micronutrients also helped plants to minimize the impact of drought. For example, foliar spray of Fe and Mo on soybean reduced the damages caused by water deficit conditions and increased the yield compared to the control treatment that did not receive both Fe and Mo [126].

According to Ross et al. [127], when B was applied to the plants grown with low B levels and visual deficiency symptoms, soybean yield increased from 4% to 130% in Arkansas. They reported that an application of 0.28 to 1.12 kg B ha^{-1} was sufficient to produce maximum soybean yield in the area. In Georgia, increasing rates of soil-applied B significantly increased the soil, leaf, and grain B concentration [128]. In Missouri, foliar application of 0.56 kg B ha^{-1} was found to be the appropriate rate for increasing the number of pods per branch, but the application of 1.12 kg B ha^{-1} increased the seed size and resulted in the highest yield per plant [129]. In contrast, Oplinger et al. [130] summarized 29 trials across Missouri, Illinois, Ohio, and Wisconsin and found yield increases only in four sites on B-sufficient soils. The excess use of B (2.24 kg ha^{-1}) reduced soybean yields in the Coastal Plains of the Southeastern U.S. [131]. Bellaloui [132] in Mississippi found increased seed protein and oleic acid and decreased linolenic acids in foliar B-applied soybean.

A study in 40 sites of Iowa showed that foliar application of Zn, Mn, Cu, and B increased their concentration in the trifoliate leaf and seed but did not increase soybean grain yield [108]. In contrast, a study from Australia showed that foliar application of Zn before flowering increased soybean grain yield by 13% to 208% at different locations [133].

In the Mn-deficient soils of Wisconsin, Mn applied both to the soil and the foliage increased yield compared to the soil or foliage independent application [107]. Soybean grain yield increased up to 2518 kg ha^{-1} in the coastal region of Virginia when $MnSO_4$ was foliar applied at the rate of 1.12 kg Mn ha^{-1} at vegetative and reproductive growth stages [134].

A micronutrient mixture that included B, Fe, and Zn sprayed at the five-leaf growth stage of soybean did not show any yield response in 18 sites of Iowa [135], and the application of different levels of B, Cu, and Zn did not significantly affect soybean yield in Virginia [136]. A foliar fertilizer containing Zn, Mn, Fe, and B increased soybean yield by 2.4% within the northern Corn Belt, but resulted in a 0.7% yield decrease within the central Corn Belt [137]. The addition of B, Cl, Mn, and Zn did not increase soybean grain yield and had a marginal impact on soybean grain quality in Minnesota [70]. They also reported that soybean grain protein and oil concentration were only marginally impacted by B or Cl and were not impacted by Mn or Zn.

In the case of Cl, toxicity is more studied than deficiency. Toxicity of Cl is caused by an accumulation of Cl in the upper soil profile, especially on poorly drained soils and with limited precipitation [87,88]. For example, soybean was grown in the poorly drained soils of Georgia and the application of Cl-containing fertilizer exhibited leaf scorching due to Cl toxicity, resulting in reduced grain yield [89]. A study in Missouri showed that the application of Cl fertilizer increased the mean trifoliate Cl concentration in 60 cultivars tested [87]. Knowledge on the effect of Ni on soybean production is still limited, but Ni fertilization increased soybean yield under both the greenhouse [138,139] and field conditions [60].

Soybean yield response to micronutrients has been reported from the other parts of the world, as well. For example, Barbosa et al. [140] conducted a soybean field study in Brazil using different doses of fertilizers containing micronutrients (6.8% Mn, 3.9% Zn, 2.1% Fe, 1.2% Cu, and 1.1% B) and found the increased soybean yield from 33.6% to 79.7% compared to the control. In India, Vyas et al. [141] applied Zn, Mo, and B with FYM in soybean and reported an 18.2% higher grain yield with the combined use of Zn and FYM compared to other treatments. The Zn alone increased the soybean yield by 11.4% compared to the control treatment. Dwivedi et al. [142] applied Cu, Zn, B, and Mo using both soil and foliar methods in soybean–wheat cropping systems and reported a significantly greater yield of soybeans with micronutrients either alone or in the mixture. In another study, Shivakumar and Ahlawat [143] found the application of 5 kg Zn ha^{-1} with crop residue and FYM increased soybean yield. They also found a residual effect of micronutrient application with crop residue and FYM in the following wheat crop with significantly greater yield.

In Iran, Ghasemain et al. [103] applied different rates of Zn, Fe, and Mn in soybean and reported the highest grain number, seed weight per plant, pod number, biomass, and grain yield of soybean in a field study with Zn and Mn applied at 40 kg ha^{-1}. Kobraee et al. [144] used three different rates of Zn (0, 20, and 40 kg ha^{-1}), Fe (0, 25, and 50 kg ha^{-1}), and Mn (0, 20, and 40 kg ha^{-1}) and found significantly higher grain yields at 40 kg ha^{-1} of Zn, 50 kg ha^{-1} of Fe, and 40 kg ha^{-1} of Mn. A study conducted by Gheshlaghi et al. [145] used foliar application of Zn and Mn micronutrients in irrigated soybean and found significantly greater yield with the application of Zn. Furthermore, they found that the micronutrient application, especially Zn, significantly increased seed quality by increasing the oleic, linolenic, and linoleic saturated fatty acids in soybean. A similar result (higher pod number per plant and grain yield using Zn and Fe) was also reported by Heidarian et al. [123]. Kobraei et al. [146] found the accelerated formation of proteins, RNA, and DNA due to the application of Zn.

Zahoor et al. [147] evaluated the response of micronutrients, Fe, Mo, and Co in a soybean field study in Pakistan. They reported that Fe and Mo significantly increased the shoot length, shoot dry weight, nodules per plant, nodules fresh weight, thousand seed weight, and soybean yield (42.3% greater yield compared to the control). The activation of different enzymes in N_2-fixing bacteria due to the application of Fe, Mo, and Co might have increased the number of nodules and yield [148]. Eisa et al. [149] conducted a field study in Egypt using three cultivars of soybean and three rates of Fe, Zn, and Mn with phosphorus fertilizer as a foliar application at 30 and 45 days after planting. They reported a significant increase in soybean seed quality (proteins, P, K, Fe, Zn, and Mn content) and yield in all cultivars. The increased yield and quality of soybeans were likely due to the positive and regulatory effect of micronutrients on different enzymes and overall plant metabolism [150]. In Russia, foliar application of liquid fertilizer containing Cu at the early boom stage of soybean increased the 1000 seed weight [151]. In Ukraine, foliar application of fertilizers containing a high concentration of Mo, Mn, and B helped soybean plants to form more pods and seeds, resulting in increased seed weight and yield [152].

6. Conclusions

A good soil fertility management plan for a farm is a long-term strategy. Yield maximization is possible only when the plant nutrients are available to meet the crop demand. Thus, maintaining soil fertility and health is essential to plant health and, consequently, to animal and human health. Studies show that several factors likely influence the soybean response to micronutrients, including the location and soil condition, soil pH, cultivar, seasonal rainfall/irrigation, and the use of SOM. Therefore, basic knowledge of what, how much, when, and how to apply fertilizer is an essential part of a soybean nutrient management plan to ensure a high yield. In many cases, soil or foliar-applied micronutrients at rates recommended according to soil test results was effective for increasing soybean yield. Some studies have indicated the importance of plant tissue analysis, as well, but it is only useful in diagnosing nutritional deficiency problems during the crop growing season. Hence, plant analysis is recommended in conjunction with regular soil testing. Most studies evaluating soybean yield response to foliar application of micronutrients have shown mixed results. Therefore, any additional foliar feeding should be considered under conditions that do not jeopardize the production cost. Studies are also needed to test the feasibility of variable rate technologies in micronutrients on a site-specific basis to increase profits and decrease nutrient loss.

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