

Review Article

Nutrient Management for Soybean Crops

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Soybean is one of the most important pulse crops in the world which supplies most of the protein and oil requirements. The efficient production of soybean crops is a constraint, with several biotic factors, abiotic factors, and crop management practices. Nutrient management is one of the important aspects for achieving higher production of crops. Effective nutrient management helps to assure the required nutrients needed for the plant without causing a significant decrease in the yield of crops. In addition to this, managing the nutrient efficiently helps the crop to cope with several types of biotic and abiotic stress. For soybean crop, altogether fifteen nutrients are needed, which comprises six macronutrients, namely, nitrogen, phosphorous, potassium, calcium, magnesium, and sulfur, which are required relatively in large amounts, and nine micronutrients which include iron, boron, zinc, cobalt, copper, manganese, molybdenum, nickel, and chlorine. These nutrients can be supplied to the plants through soil incorporation or foliar spray of commercially available fertilizers. Nutrient requirements for soybean crops vary in concentration, and deviations can cause nutrient deficiency or toxicity in soybean crops. Nutrient availability to soybean crops depends on the available nutrients in the soil solution, the form of available soil nutrients, mode of uptake of nutrients, its interaction with other soil nutrients, soil chemistry, and method of fertilizer application. This review article explores essential nutrients for sustainable soybean production in relation to the role and functions of nutrients, required concentration, and visual syndrome shown during deficiency, including findings from several researches. The review article is aimed to guide soybean farmers for effective nutrient management and academicians in reviewing the literature in soybean nutrient management.

1. Introduction

Soybean (*Glycine max* L. (Merr.)) is one of the most important pulse crops belonging to the Fabaceae family. It is among the oldest crops, which has been cultivated since 1700 BC [1]. It is cultivated in 127.60 Million ha of land with its annual production of 364.07 Million tons worldwide [2]. Due to its multiple uses, it is considered a wonder crop, and none of the soybean byproducts remains unused. Its nutritive values have been considered utmost as it contains protein (37%–48%) and oil (16%–21%) depending upon the variety and agronomic practices during production. It has higher protein contents than nonvegetarian diet, so it is also referred to as poor man meat. Along with this, it also contains other vitamins, minerals, and beneficial compounds such as isoflavones, which have multiple health benefits including protection against age-related diseases, cardiovascular diseases, osteoporosis, and cancers [3].

Soybeans are also used in vegetable oil production, feed industry, kitchen purposes, and manufacturing soy products such as nutrella, *tofu*, *nattu*, and soy drinks. Due to this, soybeans are enjoyed globally, which has caused to increase its demand by 145 percent since 1990/91 compared to other crops like rice, corn, and wheat by 31 percent, 76 percent, and 35 percent, respectively [4].

Several synergistic factors are responsible for the good yield of the soybean crop. The wise selection of variety, good agronomic practices, and strategic coping with yield constraints can robust the soybean production that can meet the future demand of soybean crops. Among the crop management practices, judicious management of plant nutrients can increase production significantly. Plant nutrients are the essential elements that are needed for growth and reproduction and can be available naturally from soil and air and artificially by the application of organic matters and commercial fertilizers [5]. Nutrients are the key factor for

production, which has a great interaction that may gain either a positive or negative effect on crop production depending upon the amount, dose, crop growth stage, combination, and balance [6]. For proper growth and development of soybean crop, altogether fifteen nutrients are required. Based on the quantity required for the crops, these nutrients can be classified as macronutrients, which are required in quantities $>0.01\%$; they are nitrogen (N), phosphorous (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg). These macronutrients perform structural and functional roles in soybean crops. Likewise, soybeans also need other micronutrients in quantity $<0.01\%$. These micronutrients are copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), boron (B), chloride (Cl), molybdenum (Mo), and nickel (Ni). These micronutrients perform enzymatic and cellular regulation functions. According to Hellal and Abdelhamid [7], the magnitude of soybean yield loss varies among the nutrients; the deficiencies of nitrogen, phosphorous, iron, boron, and sulfur can cause yield loss up to 10%, 29–45%, 22–90%, 100%, and 16–30%, respectively. Plant nutrients are also found to minimize the yield reduction through increasing resistance to disease by maximizing the inherent resistance of plants, facilitating disease escape through increased nutrient availability, and alternating the external environment to influence survival, germination, and penetration of pathogens [8].

Recent research shows that effective nutrient management is inevitable for modern soybean varieties to increase the yield directly and indirectly. According to Esper Neto et al. [9], the amounts of nutrients removed by the modern soybean varieties were greater relative to the early soybean cultivars. Thus, judicious use of nutrients should be applied for modern soybean cultivars in the required dose based on soil fertility sampling. Likewise, nutrients from diverged sources can help to achieve sustainability in production and they should be applied at the right stage of growth with suitable application procedures. This review article explores the overall nutrient management for soybean crops in relation to nutrient functions and their availability in soil and plants along with best management practices for their effective utilization.

2. Macronutrients for Soybean Crop

2.1. Nitrogen. Nitrogen is one of the primary nutrients for soybean crops. It is a structural component of chlorophyll molecules and enzymes that helps to regulate the physiological processes in soybean crops. It is required for the formation of amino acids, building blocks of a protein macromolecule, and metabolism of carbohydrates in plants, which stimulates the root growth and uptake of other nutrients. Nitrogen is the most demanded nutrient for a soybean crop; soybean crops require 80 kg of nitrogen to produce 1000 kg of seeds [10]. For achieving a higher yield in soybean crops, a higher amount of nitrogen is required and plants continue to assimilate nitrogen during both vegetative and reproductive phases [11]. Soybean plants can obtain nitrogen nutrients from three sources: biological nitrogen fixation through root nodules, nitrogen from mineralized

soil fraction in soil, and nitrogen fertilizers applied in the field. The majority of nitrogen demand in soybean crops is fulfilled through biological nitrogen fixation, which occurs in the root nodules in symbiosis association with specific microorganisms. For effective nitrogen fixation, soybean seeds are inoculated with *Bradyrhizobium japonicum* at the rate of 7 gm/kg of seed before 4–5 hours of sowing. According to Hungria et al. [12], coinoculation of soybean seeds with *Bradyrhizobium japonicum* and *Azospirillum brasilense* can significantly increase the nitrogen fixation and yield of soybean. The seed inoculation of *Bradyrhizobium* with 1.2×10^6 cells/seed and coinoculation with *Azospirillum* 1.2×10^5 cells/seed were evaluated in nine field experiments. The average yield in coinoculation treatment was calculated as 427 kg/ha compared to an average yield of 222 kg/ha on inoculation of rhizobium only. The soybean seed inoculated with *Bradyrhizobium* starts fixing nitrogen at the V2 stage, i.e., two-node stage, and fixes maximum nitrogen during the R2 stage, i.e., full flowering stage, and then starts decreasing [10]. The root nodule formation and biological nitrogen fixation depend upon the physical, chemical, and biological characteristics of the soil as well as climatic conditions such as temperature and precipitation. According to Dabesa and Tana, [13], the application of *Bradyrhizobium*, lime, and phosphorous showed considerable differences in nodulation, phenological growth, and yield of soybean in acidic soil. The factorial combination of three *Bradyrhizobium* strains (uninoculated, TAL379, LegumeFix), two levels of lime (0 and 3.12 t/ha), and four levels of P (0, 23, 46, and 69 P_2O_5 ton/ha) showed that the application of lime significantly increased the PH, plant height, number of branches per plant, 100-seed weight, seed yield, and Harvest Index (41%). Usually, a high amount of yield has been obtained from the field with the application of organic manure, fertilizers, and inoculated seeds. Soybean can also absorb and assimilate nitrogen in the form of nitrates and ammonia from soil and applied fertilizers. Fertilizers like urea (46% N), ammonium sulfate (21% N), and ammonium nitrate (34%) are used as starter doses at 20–40 kg N/ha can be applied to supply nitrogen to the growing plant. The starter dose helps to surpass the nitrogen hunger during the seedling stage. Supply of low concentration of nitrogen supports soybean growth without depressing the nodulation and nitrogen fixation in soybean crops [14]. However, foliar application of N fertilizer up to 40 kg N/ha may slightly increase the soybean yield, without significantly impairing the biological nitrogen fixation [15].

Efficient management of nitrogen fertilizers is important for achieving good yield and protein content in the soil. A high concentration of nitrogen fertilization suppresses nodulation and nitrogen fixation in soybean plants, producing low grain yield [16]. Moreover, heavy application of nitrogen fertilization can cause overluxuriant growth of shoots, lodging, poor pod formation, and higher infestation of insects and diseases [11]. In a field experiment conducted by Wu et al. [17], the application of nitrogen fertilizer at 25–30 kg/ha at drier regions and 15–20 kg N/ha before sowing is recommended to achieve a higher yield of soybean seeds. The four-year experiment with varied fertilizer and

irrigation treatment using Soil Plant Atmosphere Continuum System (SPACSYS) Model showed that the average increase of 2.4%–5.2% was recorded with the additional application of 50–100 Kg N/ha. According to Mourtzinis et al. [18], the N-application method, N-rate, and N-timing positively affect the soybean yield, and N-management can be optimized when considering the cropping system as non-N-management practices; for example, seeding rate and water management can also interact with nitrogen timing and N-rate applied. The other way to optimize N-fertilization is by adjusting the soil PH. The nodulation of soybean is adversely affected when the soil pH drops below 6. For the management of acidic soil, liming can be done. According to Nyamangara [19], liming increases root nodules, root nodules dry mass, and biological nitrogen fixation and increases the availability of soil and applied phosphorous.

2.2. Phosphorus. Phosphorous is another primary nutrient required for soybean crops for proper growth and development. It helps to store and transport the energy produced during photosynthesis, which is used for growth, development, and reproduction. It is the basic component of energy packets called ATPs and increases the efficiency of other applied nutrients. Soybean yield, protein content, oil content, nitrogen fixation, root proliferation, leaf area, and stress tolerance activity were affected by phosphorous fertilization [20–22]. Phosphorous is relatively immobile in the soil, so the plant can show deficiency symptoms if it is placed too far away from the zone areas. It reacts with other nutrients like aluminum, calcium, and iron forming orthophosphate; this reactive behavior of phosphorous makes the plant unavailable to phosphorous nutrients. The soybean plant requires 25 kg of phosphorous in the form of P_2O_5 to yield one ton of soybean seeds [23]. The demand for phosphorous is high during root proliferation, pod formation, and seed maturation stages. The soybean crop response to phosphorous depends on the available phosphorous content in the soil. In a study carried out by Ferguson et al. [24], it was found that phosphorous application is not likely to increase the seed yield if the available phosphorous concentration in soil is above 12 ppm. The application of phosphorous at the rate of 4 ppm, 8 ppm, and 12 ppm increased the maximum yield by 70%, 90%, and 100%, respectively. On further increasing of phosphorous, the percentage change in maximum yield remained constant. The phosphorous content in the harvested soybean seed ranges from 0.50% to 0.58% depending upon variety. A minimum tissue level of phosphorous should be >0.31% and 0.26%–0.50% during flowering and pod set stages, respectively [25, 26]. Phosphorous is applied through inorganic fertilizers such as superphosphate (20% P_2O_5), diammonium phosphate (DAP) (46% P_2O_5), and rock phosphate (38% P_2O_5). Several methods such as broadcasting, side banding, and seed placement techniques are practiced for phosphorous application in the soybean field. According to Abuli et al. [27], DAP is the best source for supplying phosphorous nutrients to soybean crops. Likewise, in an experiment performed by Bullen et al. [28], it was found that banding applications of phosphorous

fertilizers were more effective than broadcasting in increasing growth, seed yield, and phosphorous uptake of soybeans. Growth chamber and field experiments were carried out in Southern Manitoba in low soil available phosphorous to investigate the various placement methods and level of phosphorous in soybean. Phosphorous was applied in the solution of 100%, 50%, 25%, 12.5%, and 1% of the total soil volume. Dry matter yield, total phosphorous uptake, and utilization of fertilizer P increased at each level of applied phosphorous as the size of the phosphate band was decreased.

2.3. Potassium. Potassium is used by plants for maintaining cell turgidity, translocation of starch, water, nutrients, protein synthesis, and starch formation. Potassium helps to cope with stress, diseases, pest, and balanced uptake of other nutrients [29]. It is a mobile nutrient and plays an important role in enzyme activation during nodulation. It has a large effect on seed yield, weight, and protein but it is found to have less effect on the oil content of seeds. The soybean plant requires 53 kg of potassium in the form of K_2O to produce one ton of soybean seeds [23]. Potassium can be used in soybean crops in the form of potassium chloride (60% to 62%) and potassium sulfide (50%). For optimum production of soybean seeds, 60–100 kg K_2O /ha is recommended. The demand for potassium nutrients is less during early growth, and its demand peaks during vegetative growth. During the pod filling stage, the potassium content in the vegetative part is transferred to the seeds. According to Hoefft et al. [30], the matured soybean seed contains 60% of the total potassium content of a plant. Potassium also plays an important role in seed production in soils affected by cadmium toxicity. In excessive conditions, luxury consumption of potassium occurs, where the plant absorbs nutrients far in excess without increasing the yield significantly. In a hydroponic experiment carried out by Shamsi et al. [31], it was observed that potassium supplementation alleviated the reduction of growth, photosynthesis, and nutrient uptake in Cd-treated soybean plants. The study was undertaken to determine the effect of potassium on alleviating cadmium toxicity in soybean with two soybean varieties: Liao1 and Zhechun3, with four treatments, without Cd addition, with Cd at rate 1 μ m, K supplement at the rate of 380 mg/l, and both Cd and K supplementation. It was found that potassium supplementation alleviated the Cd stress in soybean crops. Potassium is also found to affect the biochemical concentration of different macromolecules. A significant increase in the concentration of daidzein, genistein, and total isoflavone in soybean seeds was observed with deep placement and surface placement of potassium fertilizer in low potassium concentration soil [32].

2.4. Sulfur. Sulfur is one of the most important macronutrients which enhances the growth, productivity, and oil percentage in soybean seeds. Sulfur is one of the major components of amino acids which favors oil production. Soybean crop requires 7–8 kg of sulfur to produce one ton of soybean seeds [33]. Several researches are undergoing to

enhance the sulfur use efficiency in soybean crops. Sulfur is mostly applied in soybean plants in a composite form with nitrogen and potassium. Sulfur fertilization is done with the application of ammonium sulfate, potassium sulfate, and calcium sulfate (gypsum). According to Burkitbayev et al. [34], the application of sulfur in powdered form and solute sulfur containing agrochemicals is necessary to boost the yield of soybean seed and increase the protein content in grains. The result of the experiment revealed that foliar application of sulfur in the form of agrochemicals can penetrate through plants whereas paste form application seems redundant and no increase in the yield was observed through paste application of sulfur in the soybean plant. The sulfur concentration of the third fully opened trifoliate leaf of soybean leaf at half flowering ranges from 0.15% to 0.47% [35]. According to Naeve and Shibles [36], pods accumulate sulfur from roots, leaves, and stems, until they reach half of their full size. Soybean plants grown in hydroponic solution were pulsed with ^{35}S labeled SO_4 at different discreteness during the reproductive phase. It was found that the distribution of newly acquired S within plants changed with reproductive development. Expanding leaves disproportionately accumulated large quantities of S; however, leaves' tissues seem to be dependent on newly acquired SO_4 . Sulfur is mainly applied through a foliar spray. The application of foliar spray of elemental sulfur at the early vegetative and initial flowering stage increased the yield of soybean, and the foliar application of 6 kg elemental sulfur was equivalent to a soil application of 20 kg of elemental sulfur [37]. In some cases, soybean deficit with sulfur nutrients shows symptoms of latent deficiency, in which the protein and oil content of seeds increases without an increase in the seed yield after the addition of sulfur elements. During latent deficiency, the full genotype trait is masked (Figures 1 and 2).

2.5. Calcium. Calcium is necessary for cell wall integration and cell wall stabilization and acts as a counteraction for organic and inorganic anions in vacuoles [39]. Calcium deficiency is rare in most crop species. Calcium is taken up by plants through the root and transports it to the shoot system through xylem vessels. 28 kg of calcium is required for the soybean crop to produce one ton of seed yield [23]. Calcium has direct and indirect effects on the production of soybean. Directly, it plays a positive role in nodulation and nitrogen fixation, whereas indirectly it maintains the soil pH and makes other nutrients available for the growing plant. According to Mengel et al. [40], a short supply of calcium in soybean leads to an immediate reduction in growth rate which is followed by gradual browning of root tips and ultimately death of the plant. Calcium can be supplied through liming gypsum and dolomite in soybean crops. Calcium is immobile in nature in plants, so crops can show localized deficiencies if they are present below the threshold concentration. Calcium counteracts sodium, potassium, and magnesium because this excessive application of such nutrients can lead to calcium deficiency in plants.

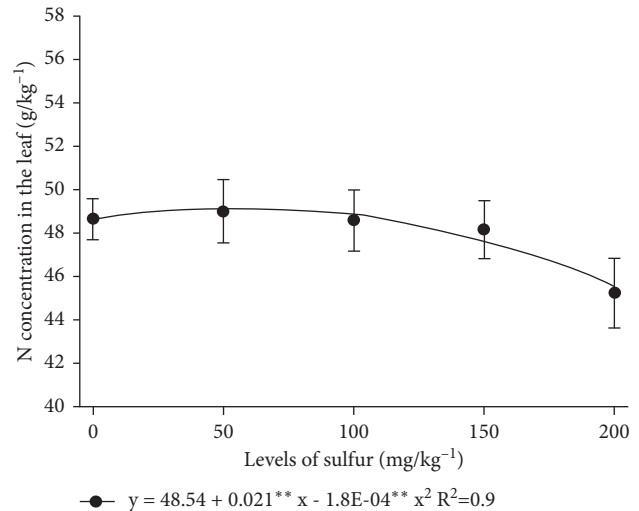


FIGURE 1: Effects on soybean leaf nitrogen content in response to different sulfur levels. *Note.* Nitrogen content in the leaf of soybean tends to decrease in concentration at different levels of sulfur nutrients applied to the plant. The figure is adapted from [38].

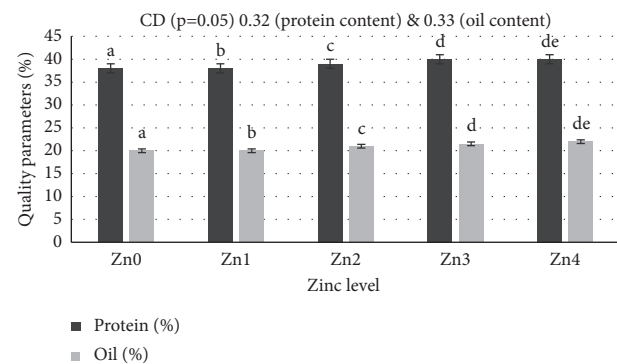


FIGURE 2: Effect of zinc on protein and oil content of soybean crop. *Note.* Four doses of Zn at the rate, 0 kg/ha, 3 kg/ha, 4 kg/ha, and 5 kg/ha were assigned as Zn0, Zn1, Zn2, Zn3, and Zn4, respectively, and their effects on protein and oil composition. The figure is adapted from [69].

2.6. Magnesium. Magnesium is one of the components of chlorophyll; it plays an important role during photosynthesis. It has a role in plant energy metabolism and protein formation. Plants can get magnesium from the inorganic rock; however, magnesium in soybean crops is supplied through dolomite. Magnesium is available in soil in the form of Mg^{2+} , which is distributed as a base cation in the soil solution. The availability of magnesium is greatly impacted by other cations of calcium, manganese, ammonium, and potassium. Twenty-two kg of magnesium is required for soybean plants to produce one ton of seed yield [23]. According to [41], soybean supplied with an adequate amount of magnesium contains a higher amount of oil and they play a positive role in oil formation in soybean. Magnesium deficiency is rare in soil, but in some cases, it can be diagnosed in coarse soil having low cation exchange capacity. According to [42], the magnesium concentration in soil significantly reduces the uptake of manganese in plants,

so the interaction between magnesium and manganese can be an important trait for the cultivation of soybean with having a greater amount of dolomite.

3. Micronutrients for Soybean Crop

3.1. Copper. Copper is one of the essential micronutrients for the growth and development of soybean crops. Though an excessive amount of copper is toxic to plants, it plays an important role in physiology and acts as a cofactor for many enzymatic reactions [43]. Copper is a component of several physiological processes such as respiration, photosynthesis, lignin synthesis, and carbohydrate metabolism. It exists in a complex form bound to minerals, but it is available to plants in the form of Cu^{2+} ions [44]. It is an immobile nutrient, so the problem of toxicity can occur due to its localized accumulation. Copper is applied to soybean in the form of copper sulfate, but commercial chelates of nutrients are available to supply copper. Animal manure is rich in copper content, so the judicious use of animal manure can prevent copper deficiency in soybean crops. According to Enderson et al. [45], copper deficiency can occur in soil having a high amount of organic matter and poorly drained soil, and the foliar spray and soil application of copper cannot correct the copper deficiency. The research was carried out to evaluate the grain yield response to foliar application of B, Cu, Mn, and Zn and the relationship between soil and plant tissue. Treatments were sprayed during V5–V6 stage and R2-R3 stage, and soil test was carried out by drying the top 15 cm depth soil at 40°C. B, Cu, Mn, and Zn were found 0.23 to 1.66 mg/kg, 1.6 to 4.6 mg/kg, 31.5 to 128 ppm, and 1.22 to 11 mg/kg, respectively. The foliar application of these nutrients was found to correct the nutritional deficiency in soybean crops.

3.2. Manganese. Manganese plays an important role in the oxidation-reduction process such as electron transport system, chlorophyll production, and its presence in essential photosystem II. It is an activator, which activates more than 35 different enzymes [46]. In soil, manganese occurs in three valences Mn^{2+} , Mn^{3+} , and Mn^{4+} , but the active absorption of manganese in plants occurs in Mn^{2+} form [47]. Manganese in soybean crops is applied through foliar application in the form of manganese sulfate. Manganese availability to soybean crops depends particularly upon tillage, organic matter content, and tillage [48]. The problem of manganese deficiency is more common in areas having flood and water fluctuations. According to Randall et al. [49], combined application of banded Mn with acid forming fertilizers during planting or foliar application during the early pod set stage is effective for the correction of manganese deficiency. Manganese applied at the rate ranging from 5 to 22 kg Mn/ha as MnSO_4 with starter fertilizer in a row at planting time appeared to be most efficient in increasing the seed yield.

3.3. Boron. Boron is an essential terrace element which plays an important role in performing several physiological

functions. Boron has an important role in cell wall biosynthesis, synthesis of carbohydrates, nodulation formation, nitrogen fixation, membrane function, root elongation, tissue differentiation, pollen germination, and growth [44]. According to [23], 55 g of boron is required to produce one ton of soybean seed yield. Boron uptake by the plants is in the form of boric acid (H_3BO_3), which is available in soil solution in a soluble form [48]. The other important source of boron is soil organic matter, which becomes available through microbial activity. The organic source of boron is typically unavailable in dry areas due to the slow rate of decomposition of organic matter. Boron is typically immobile in plants, but it is transported from root to shoot through xylem vessels and the flow is unidirectional. However, according to Rosolem [50], in soybean boron binds with polyols (cis-diol, pntol) which is present sufficiently in a large amount, which results in the mobility of boron in the phloem. The best way to supply boron for the soybean plant is the incorporation of the boric compound in soil but there is a practice of applying calcium and boron through foliar spray during the flowering stage, which favors better fertilization and grain formation and reduces the pod and flower abortion [51].

3.4. Cobalt. Cobalt plays a crucial role in the growth and development of plants. The beneficial effect of cobalt includes stem elongation, retardation of senescence, increase, drought resistance in seeds, and elongation of coleoptiles, which plays an important function during the activation of several enzymes [52, 53]. Cobalt is absorbed by plants in the form of Co^{2+} , which is available in soil solution and cation exchange sites. Cobalt is considered an important terrace element for leguminous plants, as it is found to play a synergistic effect during the nodulation and nitrogen fixation process. In an experiment in soybean carried out by Kandil et al. [54], the application of cobalt @ 12 mg/kg gave the highest growth on the length of shoots, length of roots, number of leaves per plant, number of branches per plant, fresh weight, and dry weight of roots and shoots. However, in another experiment carried out by Gad et al. [55], further increase of cobalt concentration greater than 12 mg/kg resulted in a significant decrease in growth parameters. The decrease may be due to the excess of cobalt which leads to deformation of leaves, chlorophyll content, and net photosynthesis. Cobalt is found to play synergistic roles in biological nitrogen fixation. In an experiment carried out by Jun Ma et al. [56], it was found that an antioxidant cobalt ferrite (CoFe_2O_4) nanozyme enhanced the symbiotic nitrogen fixation by 260%. Cobalt ferrite was found to reduce the reactive oxygen species (ROS) in the nodule by 56.6%, creating the superior environment for the proliferation of rhizobia ultimately forming effective nodules and acting synergistically with leghemoglobin resulting in an increase in the accumulation by 45.6%.

3.5. Iron. Iron is an essential element for all living life forms. It acts as a cofactor and component of many enzymes. In plants, it helps in chlorophyll synthesis and

TABLE 1: Visual symptoms shown by soybean crop during nutrient deficiency.

Nutrient	Visual deficiency syndrome	Citation
Nitrogen	Interveinal chlorosis at lower leaves (light green to yellow), stunted growth, necrosis of older leaves, decrease in nodulation.	[77]
Phosphorous	Dark to bluish-green leaves, interveinal chlorosis at the base of the leaves, growth retardation, sparse foliage.	[78]
Potassium	Necrosis at older leaves, small and numerous brown spots with mottling appearance, expanding blotches.	[65]
Sulfur	Upper leaves small, pale yellow-green leaves, chlorotic. Stems are thin, hard, and elongated appearing plant stunted.	[79]
Calcium	Reduced leaf expansion, primary leaves are cup-shaped when emerged. Brown spots on young leaves, premature leaf senescence occurs at severe deficiency.	Calcium Deficiency in Soybean
Magnesium	Light green to yellow chlorosis in interveinal tissues. Leaf margins are bent and older leaves and lower leaf affected most.	[65]
Iron	Interveinal chlorosis of upper and new leaves followed by stunting. With progressive severity, yellow leaves turn to white along the veins. Brown white necrotic spots occur on the edge of leaves.	[65, 78]
Boron	Yellowing and curling of leaf tips, interveinal chlorosis, and cessation of terminal leaf growth. Mottled leaves with brown necrotic spots, leaf margins are bent, and internodes are shortened.	[44, 65]
Copper	Necrosis of leaf tips and stem, yellowing of leaves, and stunted growth. Upper and medium leaves show discoloration starting from veins.	[44, 65]
Cobalt	General yellowing and stunting.	[44]
Manganese	Light green to yellow interveinal areas with distinct green leaf veins. Necrotic brown spots may develop and premature leaf fall may occur.	[65]
Molybdenum	Similar to N deficiency, leaves are pale green-yellow and twisted. At progressive deficiency leaf margins, mid-ribs, and interveinal areas become necrotic.	[65]
Chlorine	Can be mistaken with iron deficiency. Yellow leaves with dark green veins.	[44]
Nickel	Necrosis of leaf tips. Reduce in size of leaf tissues.	[44]
Zinc	Younger leaves show interveinal chlorosis. Necrotic brown leaf veins.	[65]

photosynthesis. Iron plays a critical role in DNA synthesis, respiration, photosynthesis, activation of many metabolic pathways, and prosthetic constituents of many enzymes [57]. Although iron is the fourth abundant element in the Earth crust, its deficiency is seen in beans and legumes as it is unavailable to plants for uptake. Iron is immobile within plants, so the symptoms are mostly localized in younger leaves [44]. Iron is insoluble in high PH. It is present in $\text{Fe}(\text{OH})_3$ in the soil, but soybean plants have iron nutrients in the form of Fe^{2+} form. Bicarbonate, carbonates, PH, organic matter contents, moisture, and nitrate levels affect the uptake of iron from the soil solution. Iron is applied in the form of chelates such as EDTA and DTPA, which is applied through foliar spray or soil incorporation that corrects the visual symptoms due to iron deficiency. The application of iron in the form of chelates is one of the most common strategies in Iron Deficiency Chlorosis (IDC) though it is found to have negative environmental impacts. According to Santos et al. [58], in contrast to the application of iron in the form of Fe-chelates, the application of iron as FeEDDHA with supplementation with $[\text{Fe}(\text{mpp}_3)]$ resulted in a 29% higher chlorophyll content, 32% higher root biomass, 36%

higher trifoliate Fe concentration, and twofold increase in leaf FERRETIN gene expression. Likewise, the supplementation of $[\text{Fe}(\text{mpp}_3)]$ resulted in an increase in the P, K, Zn, and Co accessed during the V5 stage and a 32% increase in the yield at the full maturity stage. Soybean seeds contain iron in the form of ferritin, resulting from the interaction between Ca, Fe(III), and protein, which is more bio-available than iron from cereals, so, soybeans are considered as the main source of nonheme iron for humans [59]. Iron gets lost through the soil due to leaching. According to Ghasemian et al. [60], the iron loss is maximum in coarse-textured soils with high PH, while excessive uptake of iron occurs in clay-textured soils with an acidic PH. The field experiment was carried out to study the effects of iron, zinc, and manganese and soybean yield in coarse-textured soil. There are three treatments of iron (0, 25, and 50 kg/ha), zinc (0, 25, and 40 kg/ha), and manganese (0 and 40 kg/ha). Treatment with 40 kg/ha zinc and manganese produced the highest seed yield of 3397 and 3367 kg/ha, respectively. However, most of the iron was found to leach in coarse-textured soil, and similar replication of the experiment was carried out in clay soil, where iron at the rate of 40 kg/ha produced the highest yield.

3.6. Chlorine. Chlorine is an essential micronutrient that plays a role in several physiological and metabolic processes including osmotic regulation of stomata, the evolution of oxygen during photosynthesis, and disease resistance and tolerance [61]. Chlorine is available in soil solution in an anion form of chloride (Cl^-) ion or in a combined form of a highly soluble salt such as sodium chloride, potassium chloride, and calcium chloride. Chlorine deficiency is mostly rare in soybean as soybean crop is less sensitive to chlorine deficiency. Chlorine accumulates in the soil through rainfall and potassic fertilizers; for example, KCl provides the majority of chlorine nutrients to the soybean plant. Chlorine toxicity is a major problem in poorly drained soil and heavy application of potassium fertilizers. According to Parker et al. [62], leaf scorch is a major symptom of soybean plants due to the application of KCl fertilizer which is found to be positively correlated with leaf and seed chlorine level and negatively correlated with seed weight and yield.

3.7. Molybdenum. Molybdenum is an essential terrace nutrient in leguminous crops, as it plays an important role during nitrogen fixation. Molybdenum is utilized by certain enzymes to perform redox reactions including nitrate reductase, xanthine dehydrogenase, aldehyde oxidase, and sulfite oxidase [63]. As it is an important nutrient for nitrogen reductase, which plays a role in the conversion of nitrates to nitrites and is a component of the nitrogenase enzyme, it is necessary for nitrogen gas to ammonia during nitrogen fixation [64]. In soil, molybdenum exists as a molybdate ion, whose movement occurs through mass flow along with transpiration movement of water, because this Mo deficiency can exacerbate in drought soil conditions. Crop availability of molybdenum is greatly affected by soil PH. It is mostly available to crop in higher PH. It also affects the absorption of Fe and a high concentration of sulfate can also induce Mo deficiency in the soil. In a field experiment carried out by de Jesús Lacerda et al. [65], it was found that molybdenum is partially mobile in the plant and the application of molybdenum in seeds and foliar spray in leaves causes a satisfactory increase in soybean productivity. Molybdenum also facilitates the uptake of other applied nutrients. According to Banerjee et al. [66], molybdenum plays an important role in nitrogen metabolism and protein formation. The application of molybdenum enhances the bioavailability of other nutrients which flourish the growth and yield of different pulse crops including soybean.

3.8. Zinc. Zinc is an essential micronutrient of a plant, which plays an important role as a component of protein, functional, regulatory, or structural components of enzymes, gene expression, and stabilizing RNA and DNA structures [67]. It is either available as a free ion or a bound state with a low molecular weight compound in soil solutions. Zinc is available in a divalent form as (Zn^{2+}) in soil which is mobile only in soil, and its transportation in the plant occurs due to diffusion. The crop availability of zinc is primarily dependent on Zn mineral solubility, the amount of zinc adsorbed in clay and organic matter, and the pH of soil. According to Aytac

and Selim [68], foliar application of zinc @ 4000 g/ha increases the seed yield, oil, and protein content of soybean seeds. The study was carried out to determine the effects of foliar application of different doses of zinc (0, 1500, 3000, and 4000 g/ha) on yield in silty clay soil using soybean cultivar A-3127 and A-3945 using cultivars as a main plot and zinc rates as a subplot for two years. The result from two years of field experiments revealed that successive zinc rates resulted in a significant increase in the oil and protein of seeds. Likewise, in another experiment carried out by Jat et al. [69], similar results were obtained. The application of zinc at the rate of 0, 3, 4, and 5 kg/ha was used as four treatments. The successive addition of zinc resulted in an increase in the oil and protein content of soybean seeds up to 3 kg/ha. However, the increase in the oil and protein content was found nonsignificant with 4 kg/ha and 5 kg/ha of zinc applied per hectare. The result suggested that the application of zinc at a rate of 3 kg/ha is optimum for harvesting the highest oil and protein content in soybean crops.

3.9. Nickel. Nickel is a recently added micronutrient, which plays an important role in the nodulation of rhizobia in soybean crops. It is an activator of the enzyme urease, which hydrolyses urea in plant tissues [70]. Nickel is available in soil solution in the form of Ni^{2+} ion, which remains adsorbed in the cation exchange site of soil. The uptake of nickel is suppressed by the high concentration of copper and zinc ions in the soil solution. In a field experiment carried out by Lavres et al. [71], it was observed that seed treatment with nickel @ 45 mg/kg increases the biological nitrogen fixation by 12%, grain dry matter yield by 84%, and aerial dry matter yield by 54%. The study was carried out with seven treatments of nickel (0, 45, 90, 135, 180, 360, and 540 mg/kg), the evaluation of chlorophyll content, urease activity, n-ase activity, and nutrient content on leaves, BNF was evaluated during R7 (grain maturity) stage, and nodulation was evaluated at R1 (flowering stage).

4. Growth Stages of Soybean and Its Response to Nutrient Application

The growth stages of soybean can be differentiated into vegetative stages (V) and reproductive stages (R). The vegetative stages are classified into different stages ranging from seedling emergence (VE) to (Vn) based on the number of fully developed trifoliolate leaves, whereas reproductive stages are classified based on flowering, pod development, and seed maturity. Different stages of soybean have a peak demand of different nutrients, uptake of some nutrients takes place at specific stages, whereas uptake of other nutrients is distributed evenly during vegetative and reproductive stages. During the emergence (VE) stage, soybean seeds imbibe 50% of water equal to their seed weight to activate the enzymatic activities within the seeds. The radical root growth takes place during this stage, and hypocotyl elongates and begins to emerge from the soil pulling the cotyledons with it. If needed, banding of P and K nutrients can be done slightly below the seeds to ensure early plant

growth, especially in cool soil [72]. The emergence stage is followed by the (VC) cotyledon stage, where plants draw food reserve and nutrients from the cotyledons. Right after the termination of the cotyledon stage, the vegetative stage is numbered based on the fully developed trifoliate leaves and stem nodes. The active nitrogen fixation takes place during the V2 stage in soybean crops. After the completion of the vegetative stage (V7 or V10), the reproductive stage is characterized by floral initiation at the third to the sixth node of the plant. The rapid accumulation of N, P, K, and dry matter starts from the R2 stage to the R6 stage. The R4 stage is crucial for seed yield. According to Barth et al. [73], the uptake of potassium (K), copper (Cu), and boron (B) accounts for 63%, 58%, and 57% during the R4 (full pod) stages; however, the uptake of phosphorous (P), nitrogen (N), and zinc (Zn) accounts for 39%, 43%, and 43% during R4 stages. The maximum uptake of potassium (K) occurs at the R1 (flower beginning) stage, the maximum uptake of boron (B) and copper (Cu) occurs at the R3 (Pod beginning) stage, and the maximum uptake of nitrogen (N), phosphorous (P), magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn) occurs at the R5 (early seed filling) stage. The nutrient accumulation in soybean plants correlates with the total biomass of the plant. In a field experiment carried out by Heard [74], it was found that the peak accumulation of phosphorous (P) and potassium (K) took place during V4 and R6 stages. Sulfur element is required for oil formation, and its requirement is at the early stages of crop growth; so to achieve higher oil content in soybean seeds, they are applied during V2 and V3 stages [75]. Most of the applied nutrient shows the greater response of applied fertilizers from the late vegetative stage to the grain filling stage. Mostly during these stages, supplemental nutrients are applied in the soybean plants through foliar application and intercultural operation. Likewise, foliar application of magnesium during the R4 stages was found to increase the metabolism in crops resulting in an increase in grain yields [76]. The judicious application of plant nutrients aligning with the optimum stage of nutrient uptake helps to use nutrients efficiently and ultimately producing a good seed yield. To conserve the nutrient resources and maximize the seed yield in soybean plants, it is advised to apply the nutrient fertilizers at a critical uptake stage.

5. Visual Symptoms Shown by Soybean Plants during Different Nutrient Deficiencies

Some of the visual symptoms shown by soybean plants during different nutrient deficiencies are listed in Table 1.

6. Conclusion

Plant nutrient management is one of the most important aspects of crop production techniques. Soybean plant needs altogether 15 plant nutrients for their growth, development, and production. Deficiency of certain nutrients or availability below the required concentration can lead the plant to show several visual symptoms manifested in leaves, stems, and roots and reduces the yield and productivity of crops.

Effective nutrient management in soybean crops to cope with biotic and abiotic stress ultimately expresses full genotypic traits. Different nutrients are required in different concentrations to meet the requirement of the soybean crop. Based on the required concentration, nutrients are divided into macro- and micronutrients. In the soybean crop, along with six macronutrients, nine micronutrients, namely, iron, boron, chlorine, zinc, manganese, molybdenum, cobalt, copper, and nickel, are needed for successful crop production. The excessive concentration of certain nutrients can also hamper the uptake and utilization of other nutrients. Thus, balanced nutrient management should be done for sustainable production. In a nutshell, the mode of nutrient uptake, functions of particular nutrients in the crop, the available form of nutrients in the soil, solution, mobility in the soil and within the plant system, and composition of nutrient fertilizer help to understand the effective nutrient management for certain crops. In addition to this, the diagnosis of visual symptoms shown by the crop during certain nutrient-deficient conditions can guide farmers to apply the required nutrients in cost-effective ways, without the aid of soil and plant tissue analysis.

Conflicts of Interest

The author declares no conflicts of interest.

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