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Management of Nutrients in Soybean (*Glycine max*) Crops: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

Effective nutrient management is crucial for maximizing soybean (*Glycine max*) yield, promoting sustainable farming methods, and satisfying worldwide food requirements. This paper analyses significant discoveries and optimal methods in nutrient management for soybean crops, with a

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focus on the cruciality of efficient techniques to optimize yield, quality, and environmental conservation. Soybeans have distinct nutritional needs during their many growth stages, with nitrogen (N), phosphorus (P), potassium (K), and micronutrients playing vital roles in plant growth, yield formation, and stress resistance. Optimal fertilization, determined through soil analysis and considering the specific requirements of the crops, is crucial for providing sufficient nutrients while minimizing negative environmental consequences such as nutrient runoff, leaching, and greenhouse gas emissions. Novel developments and advancements, such as precision agriculture, variable rate fertilization, and smart fertilizers, present inventive methods to enhance the efficiency of nutrient management procedures. These technological improvements allow for the precise distribution of nutrients to specific areas, using data to make informed decisions and improve the efficiency of resources. This ultimately leads to better crop performance and sustainability. In addition, efficient nutrient management enhances soil health, increases resistance to both living organisms and non-living environmental pressures and ensures economic sustainability for farmers. Soybean producers may achieve optimal yields, quality, and profitability while minimizing environmental hazards by implementing integrated nutrient management systems, including organic amendments, and closely monitoring crop nutrition. To summarise, this review emphasizes the significance of nutrient management in soybean production, emphasizing the necessity for comprehensive strategies that take into account agronomic, environmental, and economic factors. Ongoing research, innovation, and information sharing are crucial for improving nutrient management strategies and guaranteeing the long-term sustainability of soybean cropping systems.

Keywords: Nutrients; soybean; nutrient management; nutrient requirements; crop nutrition; amino acids.

1. INTRODUCTION

The soybean, scientifically known as Glycine max L. Merrill, is a legume species that originates from East Asia [1]. It is cultivated on a large scale primarily for its edible bean, which has a wide range of applications. Defatted soybean meal is a cost-effective and substantial protein source for animal feed and various prepared meals [2]. The nutritious value of this product is exceptional, with high protein content (40-42%) and a significant amount of oil 20% [3]. Additionally, it is abundant in vitamins, minerals, salts, and other vital amino acids. Furthermore, soybean protein has a significant amount of lysine, a nutrient that is lacking in most cereals. By adding soybean protein to cereal flour, the nutritional value of the grain is enhanced [4]. Soybeans are a significant leguminous crop that can have a residual nitrogen effect on subsequent crops, which is comparable to 35-40 kg N ha^{-1} [5]. The crop generates a substantial quantity of biomass, consequently improving the soil's organic matter content. Due to its short-duration characteristics, it can be cultivated as a beneficial intercrop or mixed crop with maize, sorghum, pigeon peas, and cotton. It offers effective protection against rain and wind, hence reducing soil erosion. The soybean plant is utilized as fodder and cake, serving as a highly concentrated feed for cattle. Various variables impact the production of soybeans. Improper nutrient management is a significant contributing factor to reduced productivity. Therefore, it is necessary to conduct a review focused on appropriate nutrition management to enhance soybean productivity. Effective nutrient management plays a crucial role in soybean agriculture since it significantly impacts the health, productivity, and quality of the crop [6]. Optimizing soybean growth and sustaining robust plant development throughout the growing season is contingent upon effectively balancing important nutrients, including nitrogen, phosphorus, and potassium [7]. Efficient nutrient management strategies lead to increased absorption efficiency of nutrients, improved resilience to both biotic and abiotic stressors, and ultimately, higher crop output [8]. In addition, using effective nutrient management strategies enhances soil health and fertility, hence promoting the long-term agricultural sustainability of soybean production systems [9].

2. NUTRIENT REQUIRMENT OF SOYBEAN

Optimal soybean growth is dependent on a harmonious combination of vital nutrients, with each nutrient fulfilling a crucial function in different physiological processes. Soybeans require nitrogen (N), phosphorus (P), and potassium (K) as key macronutrients. These nutrients are essential for vital processes like photosynthesis, energy transfer, and root formation [10]. In addition, soybeans necessitate supplementary macronutrients such as calcium (Ca), magnesium (Mg), and sulphur (S) to achieve proper growth and development. These nutrients play a crucial role in maintaining structural integrity, activating enzymes, and synthesizing proteins [11]. In addition, micronutrients such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo) play a crucial role as enzyme cofactors, in electron transport, and hormone regulation. They are necessary for maintaining appropriate metabolic function and overall plant health [12].

2.1 Each Nutrient Plays a Crucial Role in Soybean Plant Development and Yield

2.1.1 Nitrogen (N)

Nitrogen is necessary for the production of chlorophyll, which is crucial for photosynthesis and the promotion of plant growth. Optimal nitrogen supply during crucial developmental phases promotes the expansion of leaf area, accumulation of biomass, and ultimately, increases yields [10].

2.1.2 Phosphorus (P)

Plays a crucial role in several energy transfer activities, such as ATP generation, as well as in root formation and the initial establishment of plants. In addition, it plays a role in the process of blooming, pod formation, and seed development, hence impacting the overall production and quality of soybeans [10].

2.1.3 Potassium (K)

Is essential for controlling stomatal function, water uptake, and osmotic potential in plants. It also improves plant resilience to environmental challenges including drought and disease. In addition, potassium enhances the effectiveness of nutrient absorption and aids in the movement of carbohydrates, which in turn promotes the filling of seeds and the development of crop production [10].

2.1.4 Calcium (Ca)

Is a vital element that plays a crucial role in maintaining the structure and stability of cell walls. It also supports root development, facilitates the absorption of nutrients, and enhances the general health and strength of plants. Optimal calcium levels bolster plant resilience against physiological illnesses including blossom end rot, thereby enhancing crop output and fruit quality [11].

2.1.5 Magnesium (Mg)

Is a vital component of chlorophyll molecules and plays a crucial role in photosynthesis, activating enzymes, and facilitating energy metabolism. Additionally, it has a crucial function in the movement of nutrients throughout the plant, which has a direct effect on the plant's development, productivity, and the quality of its seeds [11].

2.1.6 Sulphur (S)

Is an essential element for protein synthesis, enzyme activation, and nitrogen metabolism. It has a crucial role in affecting the growth, nodulation, and nitrogen fixation of leguminous crops such as soybeans. Optimal sulphur availability promotes increased seed protein content and overall crop yield [10].

3. SOIL FERTILITY MANAGEMENT

Effective soil fertility management is essential for the successful cultivation of soybeans since it directly impacts plant growth, crop output, and the long-term sustainability of agricultural practices. It enhances the availability of nutrients, improves soil health, and increases agricultural output while reducing negative effects on the environment. Soil testing is used to create nutrient management programs using the information obtained from soil tests [13]. Precision agriculture technologies facilitate the management of nutrients in specific areas. The implementation of organic amendments, cover crops, and conservation tillage practices enhances the integrity and adaptability of soil [14]. Implementing agricultural rotations that include leguminous crops can effectively increase soil nitrogen levels, hence decreasing the need for synthetic fertilizers. Adopting sustainable approaches for managing soil fertility maximizes crop productivity, preserves resources, and guarantees sustained success in agriculture [15].

3.1 Various Methodologies can be Utilized to Evaluate the Fertility Level of Soil and Regulate the Soil's pH to Achieve the Best Possible Soybean Yield

3.1.1 Soil testing

Performing soil testing is a fundamental method for evaluating the fertility level of soil. Soil samples are gathered from typical regions of the field and examined for nutrient concentrations, pH, and other characteristics. Soil testing yields significant data regarding nutrient deficits or imbalances, enabling farmers to make well-informed choices regarding fertilizer applications [12].

3.1.2 Soil pH

Testing is important because it has a substantial impact on the availability of nutrients and the activity of microorganisms in the soil. Measuring soil pH with a pH meter or pH test kit allows for the identification of the soil's acidity, neutrality, or alkalinity. Soybeans flourish in soil with a pH level between 6.0 and 7.0, which is slightly acidic to neutral. Modifications may be required if the soil pH deviates from the ideal range [11].

3.1.3 Lime use

The use of agricultural lime is a widely used technique to increase the pH of acidic soils. Lime is composed of calcium and magnesium compounds that counteract soil acidity and enhance the accessibility of nutrients. The optimal lime application rate is determined by the soil's buffering capability, the desired pH level, and the specific needs of the crop [11].

3.1.4 Acidifying additions

such as elemental sulphur or ammonium sulphate, can be used to decrease the pH of alkaline soils. These amendments undergo chemical interactions in the soil, resulting in the release of acidic ions and a steady decrease in soil pH over time. Vigilant surveillance is crucial to prevent excessive acidification and imbalances in nutrients [11].

3.1.5 Precision Agriculture Technologies

The use of precision agriculture technologies, such as electromagnetic conductivity (EM) mapping and remote sensing, can offer detailed information about soil qualities and variations within fields. By utilizing this information, specific soil management techniques such as applying lime and fertilizer at varying rates can be employed to maximize soil pH and nutrient concentrations [12].

3.2 Optimizing Soybean Yield and Quality Requires Addressing Nutritional Deficits through Fertilization. Here are a Few Often-Employed Techniques

3.2.1 Broadcast fertilization

Evenly distributing fertilizers across the soil surface is a traditional approach to remedy deficits in nutrients. Deficient nutrient-containing fertilizers in granular or powdered form are evenly distributed across the field using broadcast spreaders. By incorporating into the soil by tillage or irrigation, soybean plants can efficiently ingest nutrients [17].

3.2.2 Banding

Banding fertilizers refers to the practice of applying highly concentrated bands of fertilizers directly in the soil, close to the seed row or plant roots. This technique improves the accessibility of nutrients to soybean plants at important stages of growth, resulting in a higher efficiency of nutrient absorption and a reduction in the loss of fertilizers through leaching or volatilization [18].

3.2.3 Foliar feeding

Foliar fertilization is the process of directly delivering nutrient solutions to the leaves of soybean plants via spray treatments. This approach is especially efficient for dealing with nutrient deficits during periods of accelerated plant development or when the availability of nutrients in the soil is restricted. When nutrients are taken in through the leaves, they are quickly moved to the parts of the plant that are actively growing. This helps the plant respond quickly to any signs of nutrient deficit [17].

3.2.4 Variable rate fertilization

By employing precision agricultural technologies, it becomes possible to implement site-specific nutrient management strategies that are informed by soil fertility maps and crop yield potential. Variable rate fertilization is a technique that modifies the amount of fertilizer applied in different areas of a field to account for variations in soil nutrient levels. This ensures that nutrients are provided where they are needed and maximizes the efficiency of fertilizer use [18].

3.2.5 Soil amendments

By incorporating soil amendments like lime, gypsum, or organic matter, one might indirectly alleviate nutrient deficits by enhancing soil structure, pH, and nutrient accessibility. The amendments mentioned in the study by Sawyer et al. [17] improve the ability of the soil to retain nutrients and decrease the loss of nutrients through leaching. This creates a beneficial soil condition that promotes the growth of soybean roots and the uptake of nutrients.

4. NUTRIENT APPLICATION TECHNOLOGY

Effective nutrient delivery strategies are crucial for optimizing nutrient absorption, promoting crop development, and maximizing soybean production. Methods encompass broadcast fertilization, banding, foliar application, seed treatment, and drip irrigation systems. Broadcast fertilization equally disperses fertilizers throughout the soil, whereas banding specifically targets the active roots to enhance the efficiency of nutrient absorption [19]. Foliar spraying provides nutrients directly to the leaves, while seed treatment guarantees the availability of nutrients at an early stage. Drip irrigation systems efficiently supply solutions directly to the root zone, reducing losses and maximizing crop uptake. The selection of the approach is contingent upon the richness of the soil, the growth phase of the crop, and the availability of resources [20].

4.1 Various Techniques of Nutrient Application in Soybean Agriculture Offer Distinct Advantages and Varying Levels of Efficacy

4.2.1 Broadcast application

Evenly distributing fertilizers across the soil surface is a widely employed technique. It is economically efficient and well-suited for operations on a broad scale. Nevertheless, it can lead to nutrient losses due to leaching or volatilization, as well as uneven fertilizer distribution over the field, which can impact the overall efficacy of the process [17].

4.2.2 Band application

Banding fertilizers entail the strategic placement of concentrated nutrient bands in the soil, usually close to the seed row or plant roots. This technique improves the efficiency of nutrient absorption by directing the distribution of fertilizer to areas where the roots are most actively absorbing nutrients. The banding application method also decreases nutrient fixation in the soil, resulting in enhanced efficacy as compared to broadcast treatment [18].

4.2.3 Foliar application

Foliar fertilization involves the direct administration of nutrients to soybean leaves by spray treatments. This approach offers a rapid infusion of essential nutrients at crucial periods of growth or as a response to symptoms of nutrient insufficiency. Foliar feeding is a useful method for providing micronutrients and addressing nutrient deficits. However, it may not fully satisfy the nutrient requirements of soybean crops [17].

4.2.4 Seed treatment

Seed treatment is the process of applying nutrient solutions or fertilizers to soybean seeds before planting. This approach guarantees prompt nutrient accessibility to sprouting seeds and young seedlings, stimulating robust root formation and early-stage growth. Seed treatment is a viable method for delivering micronutrients and correcting certain nutritional deficits [18].

4.2.5 Drip irrigation

Drip irrigation systems transport nutritional solutions precisely to the root zone of soybean plants via a network of tubes or emitters. This approach offers meticulous management of nutrient application rates and timing, resulting in minimal nutrient losses and maximizing nutrient absorption by crops. Drip irrigation is highly efficient in arid climates or locations with restricted water resources [21].

4.3 The Timing and Rates of Nutrient Administration have a Considerable Impact on the Productivity of Soybeans

4.3.1 Application timing

The timing of nutrient administration affects the accessibility of nutrients to soybean plants during crucial growth phases. Ensuring the presence of nitrogen, phosphorus, and potassium during the early stages of growth is crucial for stimulating robust vegetative growth, root formation, and nodulation. Supplementing nutrients in the later stages of the growing season, particularly during the blooming and pod-filling phases, improves the process of seed filling, grain growth, and the overall potential for higher yield. Applying nutrients at the right time aligns with the crop's nutrient requirements, guaranteeing efficient absorption and utilization of nutrients during the entire growth period [22].

4.3.2 Application rates

Accurate nutrient application rates are essential to fulfill the nutritional needs of soybean crops while avoiding nutrient deficits or overabundance. Soil analysis and nutrient recommendations, which are determined by desired crop yield objectives, aid in establishing optimal fertilizer quantities. Excessive use of nutrients can result in environmental contamination, imbalances in nutrient levels, and financial losses, while insufficient use may restrict crop development, potential yield, and profitability. Optimizing soybean productivity and sustainability requires careful consideration of nutrient rates concerning crop demand and soil fertility status [23].

4.3.3 Split application

Dividing nitrogen treatments into many doses throughout the growth season can enhance the efficiency of nutrient uptake and reduce nutrient losses. Dividing nitrogen applications, such as splitting them, enables improved coordination with soybean growth phases and minimizes the chances of nitrogen leaching or volatilization. Split applications also cater to the fluctuating nutritional demands of soybean crops by adapting nutrient availability to align with changing physiological needs and environmental variables [22].

4.3.4 Starter fertilization

Applying starter fertilization during planting can improve the initial development and establishment of soybeans in the early stages. Proximal application of starter fertilizers provides easily accessible nutrients, such as phosphate and micronutrients, to enhance fast root growth and nutrient absorption in seeds or seedlings. Applying starter fertilization to soybean seedlings enhances the effectiveness of nutrient absorption, especially in soils that have a limited nutrient supply or are cold during planting [17].

5. NUTRIENT MANAGEMENT PRACTICES

Effective nutrient management strategies are essential for preserving soil fertility, promoting crop growth, and ensuring sustainable agricultural production in soybean agriculture. The practices encompassed in this list are soil testing, balanced fertilization, organic amendments, precision agricultural technologies, and conservation tillage practices. Soil testing yields significant data regarding soil nutrient levels, pH, and organic matter content, enabling farmers to devise tailored strategies [24]. Optimizing nutrient use efficiency, minimizing input costs, and reducing environmental impacts can be achieved by balancing fertilization with organic amendments, implementing crop rotations using leguminous crops, and utilizing precision agricultural technologies. Conservation tillage measures, such as no-till or reduced tillage, enhance soil health, increase water infiltration, and promote nutrient retention [25]. These practices play a crucial role in sustainable nutrient management and soil conservation initiatives. Soybean growers can achieve optimal crop yield, improve soil fertility, and ensure long-term sustainability in agricultural production systems by implementing integrated nutrient management strategies [26].

5.1 Adopting Optimal Techniques for Nutrient Management, Such as Balanced Fertilization, is Essential for Maximizing Soybean Yield and Promoting Sustainable Farming Practices. Here are a few crucial suggestions

5.1.1 Soil testing

Perform regular soil testing to evaluate nutrient levels and pH, providing fertilizer recommendations based on soil fertility and crop needs. Soil testing yields significant data that may be used to create personalized nutrient management strategies that are specifically designed for the unique characteristics of a particular field [11].

5.1.2 Nutrient Budgeting

Create nutrient budgets to calculate the nutrient needs of soybean crops and align them with nutrient inputs from fertilizers, organic amendments, and residues from previous crops. Nutrient budgeting is a method used to ensure that the soil maintains a proper balance of nutrients, avoiding both deficiencies and excesses. This approach optimizes the efficiency of fertilizer use and minimizes negative impacts on the environment [12].

5.1.3 Employ an integrated

strategy for managing nutrients by combining synthetic fertilizers with organic amendments, cover crops, and crop rotations. Integrated nutrient management improves soil fertility, stimulates biological activity, and enhances nutrient cycling, leading to long-term crop yield and soil health [11].

5.1.4 Balanced Fertilization

Employ balanced fertilization by utilizing fertilizers that contain an equitable proportion of nitrogen (N), phosphorous (P), and potassium (K), in addition to secondary and micronutrients. This approach ensures that the nutritional requirements of soybean crops are met at various stages of growth. Optimizing plant nutrition, minimizing nutrient imbalances, and maximizing yield potential can be achieved by carefully balancing nutrient inputs [17].

5.1.5 Technologies for precise agriculture

Employ precision agriculture technologies, such as GPS-guided variable rate application and remote sensing, to enhance nutrient management methods. Precision agriculture allows for the targeted application of nutrients based on variations in soil parameters and crop needs, resulting in improved efficiency in nutrient utilization and decreased input expenses [12].

5.2 The Strategies for Nutrient Management, Farmers can Improve Soybean Yield, Profitability, and Ecological Sustainability

5.2.1 Nutrient runoff

The surplus of nutrients, specifically nitrogen, and phosphorus, can seep into groundwater or be transported from the soil surface by runoff, polluting surface water bodies including lakes, rivers, and streams. Nutrient runoff is a significant factor in the process of eutrophication, which leads to the growth of excessive algae and a decline in water quality. This poses risks to both aquatic ecosystems and human health [27].

5.2.2 Soil acidification

Soil acidification occurs when acidic fertilizers are used excessively or when nitrogen-based fertilizers are applied in excessive amounts. This process lowers the pH of the soil and decreases the availability of nutrients. Soil acidification has a detrimental effect on soil structure, reducing microbial activity and impeding the ability of plants to absorb nutrients. This eventually harms crop output and the overall health of the soil [28].

5.2.3 Greenhouse gas emissions

High levels of nitrogen fertilization can enhance microbial activity in the soil, resulting in elevated emissions of nitrous oxide (N_2O), a strong greenhouse gas that contributes to climate change. Excessive fertilization worsens N_2O emissions, intensifying both global warming and the environmental consequences linked to agricultural practices [29].

5.3 Methods for Reducing the Negative Effects of Excessive Fertilization on the Environment Encompass

5.3.1 Precision nutrient management

Implement precision agriculture technologies to customize nutrient inputs based on unique field conditions and crop needs. By utilizing variable rate application, soil mapping, and remote sensing techniques, it becomes possible to strategically apply nutrients in specific areas, resulting in optimized fertilizer use efficiency and reduced surplus nutrient inputs [28].

5.3.2 Soil testing and nutrient budgeting

Perform periodic soil tests to evaluate the fertility level of the soil and create nutrient budgets to estimate the amount of nutrients needed for crop growth. Soil testing provides guidance for fertilizer recommendations by assessing the specific nutrient requirements, hence minimizing the chances of excessive application and nutrient leakage into the environment [17].

5.3.3 Use of controlled-release fertilizers

Implement the use of controlled-release fertilizers, which progressively release nutrients over time to align with the pace at which crops absorb them. Controlled-release fertilizers are designed to reduce nutrient leaching, runoff, and volatilization, hence improving nutrient usage efficiency and minimizing environmental consequences [28].

By employing these measures, farmers can reduce the dangers associated with excessive fertilization and encourage environmentally sustainable practices for managing nutrients in agriculture.

6. NUTRIENT INTERACTIONS AND CROP RESPONSE

The interplay between nutrients is crucial for the growth and development of soybeans, as it directly affects how the crop responds to different nutrition management strategies. Comprehending these interactions is crucial for maximizing nutrient absorption, utilization, and agricultural output. Nitrogen (N), phosphorus (P), and potassium (K) are essential macronutrients that work together synergistically to facilitate a range of physiological activities in soybean plants. Nitrogen facilitates the growth of plants, the process of photosynthesis, and the synthesis of proteins [30]. On the other hand, phosphorus is crucial for the development of roots, the transmission of energy, and the initiation of flowering. Potassium has a crucial role in maintaining water balance, activating enzymes, and enhancing stress tolerance mechanisms in plants. These functions contribute significantly to the general health and productivity of plants [10]. Micronutrients, including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), play a role in regulating biochemical and physiological processes in soybeans, in conjunction with macronutrients. These micronutrients function as cofactors for enzymes, transporters of electrons, and regulators of hormone synthesis. They have an impact on plant development, nutrient absorption, and responses to stress [16]. The crop's reaction to nutrient management strategies is contingent upon the equilibrium and accessibility of vital nutrients in the soil. Optimal nutrient delivery throughout the growing season is achieved by balanced fertilization, which is determined by soil testing and crop requirements. This promotes vigorous plant growth, flowering, pod set, and seed filling. The presence of nutrient deficits or imbalances can hinder the growth of plants, decrease their potential output, and undermine the quality of crops. This emphasizes the significance of maintaining optimal levels of nutrients [17].

Soybean growers may achieve maximum crop yields, quality, and profitability, as well as promote environmental sustainability and soil health in agricultural production systems, by optimizing nutrient interactions and providing balanced nutrition. Ongoing investigation and advancement in nutrient management are crucial for improving soybean productivity and ability to withstand changing environmental conditions.

6.1 The Interplay between Several Nutrients is Crucial for the Growth and Development of Soybeans

6.1.1 Nitrogen (N) and Phosphorus (P)

The presence of nitrogen affects the absorption and utilization of phosphorus in soybean plants. Sufficient nitrogen stimulates root development and improves the efficiency of phosphorus absorption, resulting in enhanced nutrient intake and utilization. In contrast, a lack of phosphorus might hinder the process of nitrogen assimilation and decrease the efficiency of nitrogen utilization, hence affecting the growth and production of soybeans [10].

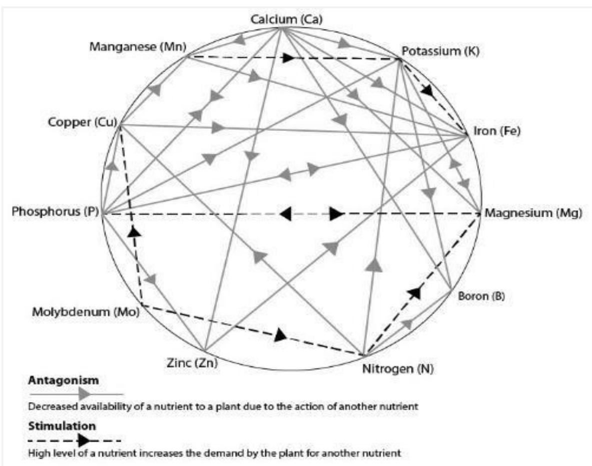

Fig. 1. The interactions between different nutrients
Source: Nutrient interactions in the soil in: www.jseco.co.uk/services/facts-advice/

6.1.2 Nitrogen (N) and Potassium (K)

Have a synergistic effect on soybeans, controlling multiple physiological processes. Nitrogen improves the absorption and movement of potassium inside the plant, facilitating the transportation of water and nutrients, activation of enzymes, and regulation of osmotic pressure. Optimal nitrogen and potassium nutrition enhance soybean's ability to withstand drought stress, resist diseases, and prevent lodging, ultimately resulting in increased yield and improved quality [10].

6.1.3 Phosphorus (P) and Potassium (K)

They play a crucial role in maintaining the nutritional balance and promoting optimal growth of soybean plants. Phosphorus enhances the absorption and utilization of potassium by promoting the growth of roots, the division of cells, and the activation of enzymes. Potassium improves the movement and absorption of phosphorus, which helps with energy metabolism, photosynthesis, and stress tolerance mechanisms in soybean plants [10].

6.1.4 Micronutrients

Including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), play a crucial role in regulating biochemical and physiological processes in soybeans by interacting with macronutrients. These micronutrients function as cofactors for enzymes, transporters of electrons, and regulators of hormone synthesis. They have an effect on plant development, the absorption of nutrients, and the stress reaction. The presence of imbalances in the availability of micronutrients can have an impact on both the productivity and quality of soybeans. This emphasizes the significance of maintaining a balanced approach to nutrient management, as highlighted by Mallarino and Bruulsema [16].

Comprehending these interactions between nutrients is essential for optimizing techniques in managing nutrients and achieving the highest possible yield and quality of soybeans.

6.2 The Response of Soybean Crops to Nutrient Management Strategies

6.2.1 Yield and productivity

The use of appropriate nutrient management strategies, such as maintaining a balanced fertilization regimen and applying nutrients at the right time, will greatly improve the yield and productivity of soybeans. Optimal plant development, flowering, pod set, and seed filling, leading to increased yields and improved crop quality, are achieved by ensuring sufficient nutrient availability throughout the growing season [17].

6.2.2 Nutrient use efficiency

Optimal nutrient management enhances nutrient use efficiency by maximizing the absorption, utilization, and movement of vital nutrients by soybean plants. Implementing a combination of balanced fertilization, soil testing, and precision nutrient treatments allows for the optimal matching of nutrient supply to crop demand. This approach minimizes nutrient losses to the environment and maximizes the efficiency of nitrogen uptake by crops [22].

6.2.3 Disease and stress tolerance

Optimal nutrient management improves soybean's ability to withstand and recover from diseases, pests, drought, and nutrient deficits, therefore increasing its resistance to biotic and abiotic stresses. Optimal nutrition promotes plant health, enhances resistance to diseases, and strengthens mechanisms for coping with stress, hence minimizing the likelihood of reduced crop yields and enhancing the ability of crops to withstand unfavorable growth conditions [11].

6.2.4 Seed quality

Nutrient management strategies have an impact on various parameters of soybean seed quality, including size, weight, protein content, oil content, and germination rate. Optimal nutrition provision during the stages of seed development and maturity improves the process of seed filling, nutrient composition, and storage reserves. As a result, the seeds produced are of higher quality, leading to enhanced market value and performance [17].

6.2.5 Environmental sustainability

The use of sustainable nutrient management strategies helps to promote environmental stewardship by minimizing the loss of nutrients, limiting the production of greenhouse gases, and protecting the quality of soil and water. Implementing precise nutrient applications, adopting soil conservation measures, and employing nutrient recycling strategies are effective methods to increase agricultural sustainability while reducing the negative environmental effects caused by nutrient runoff, leaching, and pollution [12].

Through the implementation of efficient nutrient management strategies, farmers may maximize the response of soybean crops, attain increased yields, enhance the quality of seeds, and improve the environmental sustainability of agricultural production systems.

7. FUTURE DIRECTIONS AND RECOMMENDATIONS

Advancements in technology are transforming the way nutrients are managed in soybean farming. This enables farmers to closely track soil nutrient levels, crop well-being, and environmental factors with exceptional precision. These instruments facilitate the application of fertilizers in specified locations, maximizing the efficiency of fertilizer use and minimizing environmental consequences [31]. State-of-the-art nutrient sensors offer instantaneous data, empowering farmers to make well-informed choices on nutrient management strategies. Smart fertilizers progressively release nutrients over time, whereas biological nutrient solutions optimize nutrient cycling and crop performance by leveraging positive interactions between soil bacteria and plants [32]. These technologies enhance the long-term viability of agriculture.

7.1 Highlight Emerging Trends and Technologies in Nutrient Management for Soybean Production

7.1.1 Precision agriculture

Precision agriculture technology, such as GPS-guided equipment, remote sensing, and data analytics, allow for the precise regulation of nutrients in soybean production at specific locations. Through the process of mapping the differences in soil qualities and crop performance across a given area, farmers can strategically apply nutrients to specific locations, thereby maximizing the efficiency of fertilizer use and reducing negative effects on the environment [17].

7.1.2 Variable rate fertilization

Variable Rate Fertilization (VRF) systems modify the amount of fertilizer applied to fields by considering current soil and crop data. Variable Rate Fertilization (VRF) allows for the creation of personalized nutrient recommendations based on the unique soil fertility levels, crop needs, and desired yields. This optimizes the distribution of nutrients while minimizing the expenses associated with inputs [18].

7.1.3 Nutrient sensors and monitoring devices

Advanced nutrient sensors and monitoring systems provide real-time monitoring of soil nutrient levels, plant nutrition status, and environmental variables. These technologies offer farmers immediate information to make informed decisions regarding nutrient management, allowing them to proactively change fertilizer applications and crop management practices [21].

7.1.4 Smart fertilizers

Smart fertilizers are specifically formulated to release nutrients based on plant requirements, soil moisture levels, or prevailing environmental circumstances. Controlled-release fertilizers are designed to release nutrients slowly over some time. This helps to reduce the loss of nutrients through leaching, runoff, or volatilization. At the same time, it ensures that soybean crops have a continuous supply of nutrients. Smart fertilizers enhance the efficiency of nutrient utilization and minimize the environmental consequences linked to traditional fertilization methods [28].

7.1.5 Biological nutrient management

Biological nutrition management involves utilizing the advantageous relationships between plants, soil microorganisms, and rhizosphere creatures to improve the process of nutrient cycling, soil fertility, and overall plant health. Biofertilizers, microbial inoculants, and plant growth-promoting rhizobacteria (PGPR) enhance the process of nutrient mobilization, fixation, and uptake, hence enhancing the availability and utilization of nutrients by soybean plants [33].

These developing trends and technologies have the potential to completely transform the way we control nutrients in soybean production. They can also contribute to the long-term viability of agriculture and help us address the difficulties of providing food for a rapidly increasing global population.

7.2 The Nutrient Management Practices in Soybean Production, Consider the following Recommendations

7.2.1 Carry out periodic soil testing

Before planting, do soil tests to evaluate soil fertility levels and pH. Utilize soil test outcomes to create personalized nutrient management strategies designed to meet the precise requirements of soybean crops [11].

7.2.2 Employ balanced fertilization

Administer fertilizers that contain a harmonious proportion of nitrogen (N), phosphorous (P), and potassium (K), in addition to secondary and micronutrients, according to soil test recommendations and the needs of the crop. Proper fertilization maintains an ideal balance of nutrients to support the optimal growth and development of soybeans [17].

7.2.3 Embrace precision agriculture technologies

Employ precision agriculture tools like GPS-guided equipment, soil sensors, and variable rate technology to execute location-specific nutrient management strategies. Precision agriculture allows for the precise and targeted application of nutrients, which optimizes the efficiency of fertilizer use and reduces negative effects on the environment [18].

7.2.4 Practice nutrient stewardship

Implement nutrient stewardship principles, specifically the 4Rs, using the appropriate source, applying the correct rate, timing it correctly, and placing it in the proper location. Select suitable fertilizer sources, provide nutrients at specified levels, synchronize treatments with crop growth stages, and distribute fertilizers in the areas of the field where they are most required [17].

7.2.5 Ensure crop nutrition monitoring

Continuously monitor the nutritional status of soybean crops over the whole growth period by employing techniques such as tissue testing, chlorophyll meters, or remote sensing technologies. Implementing regular monitoring enables the early detection of nutrient deficits or imbalances, facilitating prompt remedial measures and modifications to nutrient management strategies [11].

7.2.6 Integrate organic amendments

Incorporate organic amendments, such as compost, manure, or cover crops, into nutrient management, plans to enhance soil fertility, increase organic matter levels, and optimize nutrient cycling. Organic additions have a crucial role in promoting long-term soil health and sustainability by improving nutrient availability and minimizing the need for synthetic fertilizers [12].

By adhering to these suggestions, farmers can enhance nutrient management techniques, enhance soybean yields and quality, and foster environmental sustainability in agricultural production systems.

8. CONCLUSION

Implementing effective nutrient management strategies, such as maintaining a proper balance of fertilizers and applying them at the appropriate times, greatly improves both the quantity and quality of soybean crops. Insufficient or disproportionate amounts of nutrients can hinder the growth of plants, lower their capacity for producing crops, and undermine the quality of the harvest. This emphasizes the significance of maintaining optimal levels of nutrients. Sustainable nutrient management practices aim to encourage environmental stewardship by minimizing the loss of nutrients, decreasing the production of greenhouse gases, and protecting the quality of soil and water. Implementing precise nutrient applications, adopting soil conservation measures, and employing nutrient recycling strategies are key factors in achieving agricultural sustainability and reducing the negative environmental effects caused by nutrient runoff, leaching, and pollution. Optimal nutrient management improves the ability of soybeans to withstand and recover from both living (biotic) and non-living (abiotic) challenges, such as diseases, pests, drought, and nutrient deficits. Optimal nutrition promotes plant health, enhances resistance to diseases, and strengthens systems to withstand stress, hence minimizing the likelihood of reduced crop yields and enhancing the ability of crops to thrive in challenging growth conditions. Enhancing nutrient management strategies enhances the economic viability of soybean production by maximizing crop yields, minimizing input costs, and increasing profitability for farmers. Efficient resource utilization and sustainable agricultural production systems are achieved by balanced fertilization, precision nutrient treatments, and soil health management measures. Efficient fertilizer management is essential for attaining maximum soybean production results, reducing environmental harm, and fostering agricultural sustainability. Through the adoption of optimal strategies for nutrient management, farmers can maximize crop productivity, improve the utilization of resources, and guarantee the long-term sustainability and adaptability of soybean production systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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