# **Running Title:** Soybean Nitrogen Management: Trends & Future

# **Nitrogen Management in Soybean Crop: Current Trends and Future Directions - A Review**

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## **Novelty statement**

This review emphasizes the importance of optimizing nitrogen management in soybean farming, highlighting its impact on growth, soil health, water quality, and economics. Advanced approaches like genetic techniques and sustainable practices offer promising benefits. Effective nitrogen management enhances productivity, nutrient uptake, and soil fertility while minimizing pollution. Continued research and collaboration are crucial for sustainable soybean production.

## **Abstract**

Nitrogen management is crucial for optimizing productivity and sustainability in soybean farming. This review paper aims to provide a comprehensive analysis of current trends and future directions in nitrogen management for soybean crops. The physiological role of nitrogen in soybean growth and development, including nitrogen fixation, nodulation and assimilation, is discussed. An overview of conventional nitrogen fertilization methods, timing and application techniques, as well as their associated challenges and limitations, is presented. Advanced approaches such as precision agriculture technologies, enhanced efficiency fertilizers and biological nitrogen fixation are explored. The environmental and economic implications of nitrogen management, including its impact on soil health, water quality, biodiversity and greenhouse gas emissions, are thoroughly examined. Comparative analysis of different nitrogen management strategies and their effects on soybean growth, yield and quality are conducted. Future directions and emerging trends, such as genetic and molecular approaches and sustainable nitrogen management practices, are highlighted. The identification of knowledge gaps and research needs underscores the importance of interdisciplinary collaborations for addressing key challenges. This review paper concludes by summarizing the key findings and emphasizing the significance of effective nitrogen management for sustainable soybean production. Recommendations for future research, policy development and practical implications are provided to enhance nitrogen management practices in soybean farming, contributing to improved productivity, economic viability and environmental stewardship.

**Keywords**: Soybean, Nitrogen, Fertilizer. Nitrogen Management

## **Introduction**

## Soybean [*Glycine max (L.) Merrill*] is a versatile and economically significant crop that belongs to the legume family, Fabaceae. Originating in East Asia, particularly in China. Soybean has become one of the most widely cultivated and traded oilseed crops worldwide. It is primarily grown for its edible seeds, which have diverse applications in the food industry, as well as its high protein content, which makes it an essential source of animal feed (Abeje et al., 2021). Soybean has 38-42% Protein and 18-20% Oil content. It serves as a valuable source of protein for human consumption and livestock feed, as well as a raw material for various industries (Agarwal et al., 2013). As the demand for soybean continues to rise, optimizing its productivity and sustainability becomes paramount.

## Soybeans are a crucial crop for global food production, with a high demand for nitrogen to ensure optimal growth and yield. However, soybeans have a unique ability to obtain most of their nitrogen requirements from the air through Rhizobium bacteria forming nodules on their root system (Zveushe et al., 2023). Effective nodulation is critical for adequate nitrogen nutrition and inoculating soybean seed with group H rhizobia is necessary. While low nitrogen soils are ideal for maximizing rhizobium effectiveness, high soil mineral N can cause decreased nitrogen fixation and delayed nodule development. This review paper will explore the various factors affecting soybean nitrogen fixation, including the role of starter nitrogen, soil mineral N and crop establishment practices (Hussain, 2022)

## Nitrogen management plays a critical role in maximizing soybean productivity while minimizing environmental impacts. Nitrogen is an essential macronutrient that influences plant growth, development and overall yield. Effective nitrogen management strategies can enhance nutrient uptake efficiency, improve crop performance and reduce nitrogen losses, contributing to sustainable agricultural practices (Giller and Cadisch, 1995). By addressing the challenges associated with nitrogen management, soybean farmers can optimize their production systems and achieve long-term economic and environmental sustainability.

The objectives of this review paper encompass a comprehensive evaluation of current nitrogen management practices in soybean farming, highlighting their impact on productivity and sustainability. The scope of the review includes nitrogen fixation, nodulation, nitrogen assimilation, conventional and advanced nitrogen fertilization methods, timing and application techniques, as well as the environmental and economic implications. By critically analyzing the existing research literature, this review aims to provide valuable insights into nitrogen management for soybean cultivation and identify future research directions. The findings and recommendations presented in this review paper will contribute to the scientific knowledge base, assist agricultural stakeholders in making informed decisions and guide the development of effective nitrogen management strategies in soybean farming.

## **2. Nitrogen in Soybean Crop**

### **2.1. The physiological role of nitrogen in soybean growth and development**

The physiological role of nitrogen in soybean growth and development is of paramount importance. Nitrogen serves as a critical building block for various essential compounds in plants, including proteins, nucleic acids and chlorophyll (Barker et al., 2005). As a key component of amino acids, nitrogen is fundamental for protein synthesis, which is vital for plant structure, enzymatic activities and overall metabolism. Additionally, nitrogen plays a crucial role in energy transfer and storage processes, facilitating photosynthesis and respiration in soybean plants (Gai et al., 2017).

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| **Physiological Process** | **Role of Nitrogen** |
| Protein Synthesis | Nitrogen is a fundamental component of amino acids, the building blocks of proteins. It is essential for the synthesis of enzymes, structural proteins and regulatory proteins involved in various metabolic processes and plant development (Tariq et al., 2023). |
| Chlorophyll Formation | Nitrogen is a key component of chlorophyll, the pigment responsible for capturing light energy during photosynthesis. Adequate nitrogen availability promotes chlorophyll synthesis, resulting in efficient light absorption and energy conversion for plant growth (Muhammad et al., 2022). |
| Nucleic Acid Synthesis | Nitrogen is necessary for the production of nucleic acids, including DNA and RNA, which are essential for genetic information transfer and protein synthesis. Nitrogen is incorporated into the nitrogenous bases, forming the backbone of these nucleic acids. |
| Energy Metabolism | Nitrogen is involved in energy metabolism through its role in the synthesis of adenosine triphosphate (ATP), the primary energy currency in cells. Nitrogen is a component of ATP and is essential for energy transfer and utilization in various metabolic processes. |
| Hormone Synthesis | Nitrogen is required for the synthesis of plant hormones such as auxins, cytokinins and gibberellins, which regulate plant growth, development and response to environmental stimuli. Nitrogen availability influences hormone levels, affecting plant growth patterns and reproductive processes. |
| Nitrogen Fixation | Soybeans can establish symbiotic relationships with nitrogen-fixing bacteria, such as Bradyrhizobium japonicum. These bacteria convert atmospheric nitrogen into ammonia, which can be utilized by the plant for nitrogen nutrition. Nitrogen fixation is crucial for nitrogen availability in nitrogen-deficient soils (Zveushe et al., 2023). |

**Table 1. Role of Nitrogen in Physiological Process**

### **2.2. Process of nitrogen fixation and nodulation in soybean symbiosis**

The process of nitrogen fixation and nodulation in soybean symbiosis is a remarkable biological phenomenon that contributes significantly to soybeans' nitrogen nutrition and sustainability. This intricate symbiotic relationship between soybean plants and nitrogen-fixing bacteria, known as rhizobia, plays a vital role in optimizing nitrogen availability and reducing reliance on synthetic nitrogen fertilizers (Abebe and Deressa, 2017).

* **Rhizobium-Plant Recognition**: The process begins when soybean roots release specific chemical signals, called flavonoids, into the surrounding soil. These flavonoids attract compatible rhizobia, which perceive and respond to these signals through specialized receptor proteins. This initial recognition and signalling between the plant and rhizobia are crucial for establishing a successful symbiotic relationship (Hassan and Mathesius, 2012).
* **Nodule Formation**: Once the rhizobia are attracted to the root system, they colonize the root hairs and induce the formation of specialized structures called nodules. Nodule formation is initiated through a series of complex molecular interactions between the plant and rhizobia. The rhizobia release signalling molecules called Nod factors, which are recognized by the plant receptors, triggering cellular responses leading to nodule development (Murray, 2011).
* **Infection and Nodule Development**: The rhizobia penetrate the root hair cells through an infection thread, a tubular structure formed by the invagination of the root hair cell wall. Inside the infection thread, the rhizobia multiply and move towards the cortical cells of the root, forming a specialized zone called the symbiosome. Within the symbiosome, the rhizobia differentiate into bacteroids, which are highly specialized forms capable of nitrogen fixation (Turgeon et al., 1985).
* **Nitrogen Fixation**: The bacteroids within the symbiosome possess an enzyme called nitrogenase, which catalyzes the conversion of atmospheric nitrogen (N2) into a form that can be used by plants, such as ammonia (NH3). This process, known as nitrogen fixation, allows soybean plants to access nitrogen from the air, which is otherwise unavailable to them. The plant provides the bacteroids with a suitable environment and energy sources in the form of carbohydrates, while the bacteroids provide fixed nitrogen to the plant (Swain et al., 2013).
* **Nitrogen Assimilation:** Once the fixed nitrogen is provided by the bacteroids, the plant incorporates it into various nitrogen-containing compounds, such as amino acids and proteins. These compounds play critical roles in plant growth, development and metabolism. Nitrogen assimilation processes within the plant distribute the fixed nitrogen throughout different plant tissues, ensuring its efficient utilization in various metabolic pathways (Mus et al., 2016).

The nitrogen fixation and nodulation process in soybean symbiosis exemplifies an intricate partnership between plants and microorganisms, resulting in a sustainable and renewable source of nitrogen (Zveushe et al., 2023). This biological mechanism provides soybean plants with a significant advantage in nitrogen acquisition, reducing the need for synthetic nitrogen fertilizers, which can have environmental implications (Mahmudet al., 2020). Understanding and harnessing this symbiotic relationship is essential for optimizing nitrogen management in soybean farming, promoting sustainable agricultural practices and reducing environmental impacts (Soumare et al., 2020).

### **2.3. Nitrogen assimilation and its influence on soybean yield and quality**

Nitrogen assimilation, the process by which soybean plants incorporate and utilize nitrogen in various metabolic pathways, plays a critical role in determining soybean yield and quality. Efficient nitrogen assimilation ensures the effective conversion of absorbed nitrogen into essential compounds, such as proteins, amino acids and other nitrogen-containing metabolites, which are vital for plant growth, development and overall crop performance (Jadhavet al., 2009).

* **Protein Synthesis:** Nitrogen assimilation is directly linked to protein synthesis in soybean plants. The assimilated nitrogen is incorporated into amino acids, the building blocks of proteins, through a series of enzymatic reactions. These amino acids are then utilized to synthesize diverse proteins that serve essential functions in the plant, including enzyme activity, structural support and signalling. Optimal nitrogen assimilation is crucial for the production of a sufficient quantity and quality of proteins, contributing to the growth and development of soybean plants (Kumawat et al., 2000; Yadav and Chandel, 2010).
* **Nitrogen Allocation:** Nitrogen assimilation plays a vital role in the allocation of nitrogen within the plant. The assimilated nitrogen is distributed to different plant tissues, ensuring their proper functioning. Nitrogen is allocated to actively growing tissues, such as leaves, stems and developing seeds, where it is utilized for cell division, expansion and metabolic processes. Efficient nitrogen assimilation ensures the balanced distribution of nitrogen throughout the plant, supporting overall growth and development (Virket al., 2018).
* **Chlorophyll Production and Photosynthesis**: Nitrogen assimilation is closely linked to chlorophyll production, the pigment responsible for capturing light energy during photosynthesis. Chlorophyll synthesis requires an adequate supply of nitrogen, as it is an essential component of the molecule. Efficient nitrogen assimilation ensures optimal chlorophyll production, facilitating efficient photosynthesis and carbon fixation. Enhanced photosynthetic activity leads to increased biomass accumulation, improved energy production and ultimately higher yields in soybean crops (Yinbo et al., 2002).
* **Seed Development and Quality**: Nitrogen assimilation significantly influences seed development and quality in soybean. During seed filling, nitrogen is mobilized from vegetative tissues to developing seeds, where it is utilized for protein synthesis and accumulation. Adequate nitrogen assimilation ensures the availability of nitrogen for seed development, contributing to seed size, weight and protein content. Proper nitrogen assimilation also affects seed composition, influencing the balance of essential amino acids and overall nutritional quality (Ralli and Dhingra, 2003).
* **Nutrient Use Efficiency:** Efficient nitrogen assimilation contributes to improved nutrient use efficiency in soybean plants. When nitrogen is efficiently assimilated and utilized, the plant can maximize the benefits derived from available nitrogen sources, including soil nitrogen and nitrogen fixation. This reduces nitrogen losses to the environment and minimizes the need for additional nitrogen inputs, enhancing the sustainability of soybean farming systems ( Morshed et al., 2008).

Understanding the process of nitrogen assimilation and its influence on soybean yield and quality is crucial for optimizing nitrogen management strategies. By ensuring adequate nitrogen availability, promoting efficient nitrogen assimilation and considering crop-specific nitrogen requirements, farmers can enhance soybean productivity, improve seed quality and reduce environmental impacts. Balanced nitrogen assimilation supports the growth, development and overall performance of soybean crops, contributing to sustainable and profitable agricultural practices.

## **3. Current Nitrogen Management Practices in Soybean Farming**

### **3.1. Conventional nitrogen fertilization methods used in soybean cultivation**

Conventional nitrogen fertilization methods have been widely employed in soybean cultivation to meet the crop's nitrogen requirements. These methods aim to supply nitrogen to soybean plants through external sources, such as synthetic fertilizers, to enhance productivity and optimize yield (Anas et al., 2020). The following provides an overview of the commonly used conventional nitrogen fertilization methods in soybean farming:

* **Pre-Plant Nitrogen Application**: Pre-plant nitrogen application involves applying nitrogen fertilizers before sowing or planting soybean seeds. This method ensures the availability of nitrogen during the early growth stages when the demand for nitrogen is relatively low. Nitrogen fertilizers, such as urea or ammonium-based fertilizers are typically broadcast or incorporated into the soil before seeding or planting operations (Salvagiottiet al., 2008).
* **Side-Dressing**: Side-dressing is a practice where nitrogen fertilizers are applied during the growing season when the soybean plants require additional nitrogen. It involves applying nitrogen alongside the plant rows or between the crop rows. Side-dressing can be done using various application techniques, such as banding or injection, to place the nitrogen fertilizer close to the root zone, ensuring efficient uptake by the plants (Sharma and Bali, 2017).
* **Foliar Application**: Foliar application involves spraying nitrogen-containing fertilizers directly onto the soybean leaves. This method provides a rapid and direct supply of nitrogen to the plants, as the nutrients are absorbed through the leaf surfaces. Foliar application is often used as a supplemental nitrogen management strategy during critical growth stages or when nitrogen deficiency symptoms are observed (Jyothi et al., 2013).
* **Split Application**: Split application involves dividing the total nitrogen requirement into multiple smaller doses, which are applied at different growth stages throughout the growing season. This method aims to match the nitrogen supply with the crop's changing demand, ensuring a more efficient utilization of nitrogen by the soybean plants. Split application can help minimize nitrogen losses through leaching, volatilization, or denitrification and optimize nitrogen use efficiency (Grahmannet al.,2014).
* **Soil Testing and Recommendation**: Soil testing is a valuable tool for determining the soil's nutrient status and guiding nitrogen fertilizer recommendations. Soil samples are collected from representative areas of the field and analyzed for nutrient content. Based on the soil test results and crop nutrient requirements, nitrogen fertilizer recommendations are made to achieve optimal nitrogen supply for soybean cultivation (Dahnke and Johnson, 1990).

It is important to note that the specific nitrogen fertilization practices may vary depending on factors such as soil type, climate conditions, crop rotation and management goals. Additionally, integrating nitrogen management with other agronomic practices, such as cover cropping, precision agriculture techniques and sustainable soil management, can further enhance the effectiveness of conventional nitrogen fertilization methods in soybean farming (Wuet al., 2015).

### **3.2. Timing of Nitrogen in Soybean**

Efficient timing of nitrogen is a crucial factor in achieving optimal nitrogen management in soybean farming. This section discusses the current practices related to the timing of nitrogen in soybean cultivation. **3.2.1. Pre-Plant Application**: Pre-plant nitrogen application involves applying nitrogen fertilizers before soybean seeds are sown or planted. This practice aims to provide an initial nutrient supply for early plant growth. However, soybeans have a relatively low nitrogen demand during the early growth stages. Therefore, it is important to exercise caution to avoid excessive nitrogen application, as it may result in vegetative growth at the expense of seed yield (Salvagiotti et al., 2008).
**3.2.2 Split Application:** Split application involves dividing the total nitrogen requirement into multiple doses and applying them at different growth stages throughout the soybean growing season. This approach ensures that the nitrogen supply matches the crop's changing demands. Split applications can be timed based on critical growth stages such as vegetative growth, flowering and pod development. By synchronizing nitrogen supply with the crop's requirements, split application maximizes nitrogen use efficiency and minimizes nutrient losses (Liuet al., 2019).

### **3.3. Challenges and limitations associated with existing nitrogen management strategies**

Despite advancements in nitrogen management practices in soybean farming, several challenges and limitations persist. These challenges are supported by scientific evidence and require careful consideration to ensure sustainable soybean production. This section delves into the specific challenges and limitations associated with existing nitrogen management strategies in soybean farming, providing scientific reasoning.

* **Nitrogen Losses:** Efficient nitrogen utilization is impeded by substantial losses from the soil-plant system. Research studies have shown that nitrogen losses through leaching, volatilization and denitrification can range from 10% to 70% of the applied nitrogen. Leaching occurs when excess rainfall or irrigation carries nitrogen beyond the root zone, leading to contamination of groundwater sources (Cameron et al,*.* 2013). Volatilization is a significant concern in soybean farming as soybeans are generally grown in warm climates and ammonium-based fertilizers are susceptible to volatilization losses, especially when surface-applied without incorporation. Denitrification, which occurs in waterlogged or poorly drained soils, results in the conversion of nitrate nitrogen into gaseous forms, contributing to nitrogen losses (Kaur et al.,2020).
* **Environmental Impact:** Inadequate nitrogen management practices can have adverse environmental impacts. Excessive nitrogen applications can lead to nitrate leaching into water bodies, causing nitrate pollution. High nitrate levels in drinking water can have detrimental health effects, particularly for infants and pregnant women (Huanget al., 2018). Moreover, nitrogen runoff from agricultural fields contributes to eutrophication in freshwater systems. Eutrophication triggers excessive algal growth, depletes oxygen levels and disrupts the balance of aquatic ecosystems. The release of nitrous oxide (N2O), a potent greenhouse gas, from nitrogen fertilizers and soil microbial processes further exacerbates the environmental impact, contributing to climate change (Rabalais, 2002).
* **Soil Acidification**: Continuous nitrogen fertilizer use can contribute to soil acidification. Ammonium-based fertilizers, commonly used in soybean farming, undergo nitrification, releasing hydrogen ions that acidify the soil. Acidic soils reduce nutrient availability, particularly phosphorus, which becomes less accessible to soybean plants. Acidic conditions also affect soil microbial activity and nutrient cycling processes, ultimately impacting soybean productivity. Studies have shown that soil acidification due to long-term nitrogen fertilization can decrease soybean nodulation and nitrogen fixation, leading to reduced nitrogen availability for the plant (Zveushe et al., 2023).
* **Nutrient Imbalances**: Focusing solely on nitrogen management without considering the balance of other essential nutrients can lead to nutrient imbalances in soybean plants. Excessive nitrogen application can inhibit the uptake of other nutrients, such as phosphorus, potassium and micronutrients, resulting in deficiencies or imbalances. For example, high nitrogen levels can induce potassium deficiency symptoms, affecting soybean yield and quality. Nutrient imbalances not only affect plant growth but also increase the risk of pests, diseases and other stresses. Therefore, maintaining proper nutrient ratios and ensuring a balanced nutrient supply is crucial for optimal soybean growth and productivity (McCauley et al.,2009; Hellal and Abdelhamid, 2013).
* **Economic Viability:** The economic viability of nitrogen management practices is of paramount importance for soybean farmers. Nitrogen fertilizers represent a significant portion of the input costs in soybean production. Efficient nitrogen management practices that minimize fertilizer losses and improve nitrogen use efficiency can reduce production costs and enhance profitability. Additionally, sustainable nitrogen management practices contribute to long-term soil health, reducing the need for excessive inputs and enhancing overall farm sustainability (Mereet al., 2013).
* To overcome challenges and ensure sustainable soybean farming, adopting science-based nitrogen management strategies that incorporate precision nutrient management, site-specific factors and advanced technologies can optimize nitrogen use efficiency, minimize environmental impacts and promote long-term sustainability. (Sishodia et al., 2020).

## **4. Advanced Approaches in Nitrogen Management for Soybean Crop**

### **4.1. Precision agriculture technologies**

Precision agriculture technologies offer promising solutions for optimizing nitrogen management specifically in soybean farming. These innovative approaches enable precise and targeted application of nitrogen, ensuring optimal nutrient utilization while minimizing environmental impacts. This section explores some of the key precision agriculture technologies that have been utilized for precise nitrogen application in soybean farming, highlighting their benefits and scientific basis in relation to soybean cultivation (Zhanget al., 2002; Balafoutis et al., 2017).

* **Variable Rate Application**: Variable rate application (VRA) is a precision agriculture technique that adjusts nitrogen application rates based on spatial variability within soybean fields. By utilizing technologies such as yield monitors, soil sensors and satellite imagery, soybean farmers can create prescription maps that identify areas with varying nitrogen requirements (Grissoet al., 2011). VRA systems, equipped with GPS-guided applicators, allow for the precise application of nitrogen at different rates across the soybean field. This targeted approach ensures that nitrogen is supplied according to the specific needs of different soil and crop zones within the soybean field, optimizing fertilizer efficiency and reducing nitrogen losses in soybean production (Shams et al., 2020).
* **Sensor-based Technologies**: Sensor-based technologies play a crucial role in precision nitrogen management for soybean crops by providing real-time data on soybean plant conditions and nutrient status. For instance, optical sensors, such as active crop canopy sensors and chlorophyll meters, measure the vegetation index or chlorophyll content, which correlates with the nitrogen status of soybean plants. These sensors can be mounted on aerial platforms or ground-based vehicles to collect data at the canopy level of soybean plants (Ma and Biswas, 2015). By integrating sensor measurements with algorithms and models, soybean farmers can make informed decisions regarding nitrogen application rates and timings, ensuring that nitrogen is supplied when the soybean crop needs it most (Shah et al., 2021).
* **Remote Sensing and Satellite Imagery:** Remote sensing techniques, including satellite imagery, offer valuable information for nitrogen management specifically in soybean farming. Satellite-based sensors capture multispectral images, providing insights into soybean crop health, biomass and nitrogen stress levels (Scharf et al., 2002). By analyzing vegetation indices derived from satellite imagery, soybean farmers can identify areas within their soybean fields that require additional nitrogen inputs. This information can guide targeted nitrogen application in soybean farming, optimizing fertilizer use and minimizing wastage. Additionally, remote sensing allows for the monitoring of large-scale soybean fields, providing a comprehensive view of nitrogen dynamics across different landscapes (Nellis et al., 2009; Sishodiaet al., 2020).
* **Decision Support Systems**: Decision support systems (DSS) integrate various data sources and models to provide soybean farmers with recommendations for nitrogen management. These systems utilize inputs such as soil data, weather data, crop growth models and historical yield data to generate customized nitrogen management plans specifically for soybean cultivation (Thompson and Puntel, 2020). DSS can incorporate real-time sensor data, satellite imagery and soil testing results to refine nitrogen recommendations throughout the soybean growing season. By utilizing DSS, soybean farmers can make data-driven decisions on nitrogen application rates, timings and methods, maximizing soybean crop productivity while minimizing nitrogen losses (Khanal et al., 2020).

The utilization of precision agriculture technologies for precise nitrogen application in soybean farming offers several benefits specific to soybean cultivation. It enables soybean farmers to optimize nitrogen use efficiency, ensuring that soybean plants receive the right amount of nitrogen at the right time and in the right place within the soybean field (Schimmelpfennig, 2016). This targeted approach minimizes nitrogen losses, reduces environmental impacts and improves the overall sustainability of soybean farming. Moreover, precision agriculture technologies provide soybean farmers with valuable insights into soybean crop health and nutrient status, facilitating proactive management decisions for maximizing soybean yield and quality.

### **4.2. Enhanced Efficiency Fertilizers and their Role in Optimizing Nitrogen Utilization**

Enhanced efficiency fertilizers (EEFs) have gained significant attention in recent years as an innovative approach to optimize nitrogen utilization in soybean crops. These fertilizers are designed to improve nutrient availability, reduce nutrient losses and enhance nutrient uptake efficiency by soybean plants (Sui et al., 2013). In this section, we will discuss the different types of EEFs and their specific mechanisms of action, highlighting their role in improving nitrogen management in soybean farming.

* **Controlled-Release Fertilizers (CRFs):** CRFs are designed to release nitrogen gradually over an extended period, matching the nutrient requirements of soybean plants throughout their growth stages. These fertilizers utilize various coating materials or encapsulation technologies to control the release of nitrogen, preventing leaching and volatilization losses by providing a sustained supply of nitrogen to soybean crops, CRFs promote continuous nutrient availability, reducing the risk of nutrient deficiencies during critical growth phases (Lawrenciaet al., 2021).
* Slow-Release Fertilizers (SRFs): SRFs are formulated to release nitrogen at a slow rate, ensuring a steady supply of nutrients to soybean plants over an extended period. These fertilizers are typically composed of nitrogen sources that undergo microbial degradation or chemical reactions to release nitrogen gradually. By slowing down the release of nitrogen, SRFs minimize nutrient losses through leaching and runoff, enhancing nitrogen uptake efficiency by soybean crops. Moreover, the gradual release of nitrogen aligns with the temporal nutrient demands of soybean plants, improving nutrient-use efficiency (Al-Rawajfeh et al., 2021).
* **Stabilized Fertilizers:** Stabilized fertilizers contain additives or inhibitors that mitigate nitrogen losses through processes such as denitrification, volatilization and leaching. These additives can inhibit the conversion of ammonium to nitrate, reducing the potential for nitrogen loss through leaching. Additionally, they can inhibit the activity of nitrifying bacteria, minimizing nitrate formation and subsequent denitrification. By reducing nitrogen losses, stabilized fertilizers enhance nitrogen availability for soybean crops, maximizing nutrient utilization efficiency and minimizing environmental impacts (Trenkel, 2021).
* **Nutrient Use Enhancers**: Nutrient use enhancers are additives that improve nutrient uptake and utilization by soybean plants. They can enhance the efficiency of nutrient uptake mechanisms, increase nutrient absorption rates, or improve nutrient translocation within soybean plants. Some nutrient-use enhancers also stimulate root growth and improve root architecture, increasing the root surface area for nutrient absorption. By enhancing nutrient uptake and utilization, these additives contribute to improved nitrogen management in soybean crops, optimizing nutrient utilization efficiency and reducing nutrient losses (Halpern et al., 2015).

The use of enhanced-efficiency fertilizers in soybean farming offers several benefits in terms of nitrogen management. These fertilizers help optimize nitrogen utilization by providing a more controlled and sustained supply of nutrients to soybean crops, minimizing nitrogen losses through leaching, volatilization and denitrification. EEFs improve soybean productivity, yield and quality by improving nutrient availability and uptake efficiency. Furthermore, the reduced environmental impact associated with EEFs aligns with the goals of sustainable agriculture and promotes the long-term viability of soybean farming systems (Giller and Cadisch, 1995).

However, it is essential to note that the effectiveness of EEFs may vary depending on factors such as soil characteristics, climate conditions and specific nutrient management practices. Therefore, it is essential to consider site-specific factors and conduct field trials to determine the optimal application rates and timings of enhanced efficiency fertilizers in soybean farming (Halpern et al., 2015). Continued research and technological advancements in EEFs are crucial for further improving their effectiveness and ensuring their practicality in different soybean production systems.

### **4.3. Potential of biological nitrogen fixation as an alternative approach**

Biological nitrogen fixation (BNF) offers a sustainable and environmentally friendly approach to nitrogen management in soybean cultivation. This process involves the symbiotic relationship between soybean plants and nitrogen-fixing bacteria called rhizobia. In this section, we will explore the potential of BNF as an alternative approach for soybean cultivation, discussing its benefits, challenges and strategies for optimizing nitrogen fixation in soybean crops (Swain et al., 2013).

* **The symbiosis between Soybean and Rhizobia**: Soybean plants have the unique ability to establish a symbiotic relationship with compatible rhizobia species, predominantly belonging to the Bradyrhizobium genus. This symbiosis occurs within specialized root structures called nodules, where rhizobia convert atmospheric nitrogen into a form that is readily available to soybean plants. Through this symbiotic interaction, soybean plants can obtain a substantial portion of their nitrogen requirements without relying solely on external nitrogen sources (Hassan and Mathesius, 2012).
* **Benefits of Biological Nitrogen Fixation**: BNF offers several advantages for soybean cultivation. Firstly, it provides a natural and renewable source of nitrogen, reducing the dependence on synthetic nitrogen fertilizers and associated environmental concerns. Secondly, the nitrogen fixed by rhizobia is directly assimilated by soybean plants, enhancing nitrogen use efficiency and reducing losses to the environment. Thirdly, BNF can contribute to improved soil fertility by increasing nitrogen availability for subsequent crops in rotation systems. Additionally, BNF has the potential to reduce production costs and enhance the economic sustainability of soybean farming (Giller and Cadisch, 1995).
* **Factors Influencing Nitrogen Fixation Efficiency**: Several factors can affect the efficiency of BNF in soybean crops. The selection and inoculation of effective rhizobia strains play a crucial role in maximizing nitrogen fixation. Ensuring the presence of compatible and highly effective rhizobia populations in the soil through inoculation can significantly enhance nitrogen fixation rates. Other factors such as soil pH, phosphorus availability and the presence of other soil microorganisms can also influence nitrogen fixation efficiency. Understanding and managing these factors are essential for optimizing biological nitrogen fixation in soybean cultivation (Abebe and Deressa, 2017).
* **Strategies for Optimizing Biological Nitrogen Fixation**: Various strategies can be employed to optimize biological nitrogen fixation in soybean crops. Proper selection of rhizobia strains based on their compatibility with soybean varieties and local soil conditions is critical. Inoculation of soybean seeds or seedlings with effective rhizobia strains can enhance the establishment of the symbiotic relationship and improve nitrogen fixation rates. Additionally, optimizing soil pH, ensuring adequate phosphorus availability and implementing proper crop management practices can create favourable conditions for nitrogen fixation (Yoseph and Worku, 2014).

Although biological nitrogen fixation offers promising benefits for soybean cultivation, there are challenges to its widespread adoption. The effectiveness of BNF can vary depending on factors such as environmental conditions, soil types and the presence of indigenous rhizobia populations. In some cases, supplemental nitrogen fertilization may still be necessary, especially during periods of high nitrogen demand or when environmental conditions limit nitrogen fixation rates. It is crucial to conduct field trials, monitor nitrogen fixation efficiency and refine management practices to fully harness the potential of BNF in soybean farming (Mahmudet al., 2020).

## **5. Environmental and Economic Implications of Nitrogen Management**

The management of nitrogen in soybean crop production has significant environmental and economic implications. It is crucial to understand and address these implications to promote sustainable agricultural practices. In terms of the environment, improper use of nitrogen fertilizers can lead to soil degradation, including nutrient imbalances, reduced organic matter and increased erosion. This can impact soil health, nutrient availability and microbial activity, ultimately affecting soybean productivity. Moreover, excessive nitrogen application can contribute to water pollution through runoff and leaching, leading to eutrophication and disruption of aquatic ecosystems. Nitrogen management practices should aim to minimize nutrient losses, preserve water quality and protect biodiversity by integrating precise application techniques and conservation practices (Hellal and Abdelhamid, 2013).

From an economic standpoint, optimizing nitrogen management practices can enhance soybean yield and profitability. Properly balanced nitrogen application tailored to crop needs improves yield potential and overall performance. Efficient nitrogen management reduces input costs associated with fertilizers by minimizing nutrient losses and optimizing use efficiency. Additionally, advanced practices can qualify farmers for environmental stewardship incentives and government programs promoting sustainable agriculture. By implementing effective nitrogen management strategies, farmers can reduce production risks, increase economic returns and contribute to long-term sustainability in soybean farming (Mere etal., 2013). By considering both environmental and economic factors, stakeholders can work together to optimize soybean production while minimizing environmental impacts and ensuring economic viability.

## **6. Evaluation of Nitrogen Management Strategies**

The comparative analysis of different nitrogen management approaches play a crucial role in understanding their effects on soybean growth, yield and quality. Researchers assess the performance of various nitrogen application methods and sources to identify the most effective strategies. By measuring key growth parameters, such as plant height, leaf area index and root development, they evaluate the impact of nitrogen availability on plant growth and development. Additionally, yield parameters, including pod number, seed weight and overall grain yield, provide insights into the influence of nitrogen management on crop productivity (Niranjan et al., 2015). Moreover, researchers analyze quality attributes, such as protein content, oil composition and nutrient concentrations, to understand how nitrogen management strategies affect the nutritional value and marketability of soybean crops. Identifying key factors, including soil type, nutrient availability, weather conditions, cropping systems and the genetic characteristics of soybean cultivars, is crucial for determining the effectiveness of nitrogen management strategies (Begum et al., 2015). Considering these factors allows farmers to tailor their practices to optimize nutrient use and minimize limitations, ultimately promoting sustainable soybean farming.

## **7. Future Directions and Emerging Trends in Nitrogen Management for Soybean Crop**

### **7.1. Genetic and Molecular Approaches for Improving Nitrogen Use Efficiency**

The advancement of genetic and molecular techniques offers promising avenues for enhancing nitrogen use efficiency in soybean. Researchers can explore genetic traits and molecular mechanisms associated with efficient nitrogen uptake, assimilation and utilization in soybean plants. By identifying genes and markers associated with nitrogen use efficiency, breeders can develop soybean cultivars with enhanced nitrogen utilization capabilities. Additionally, understanding the molecular regulation of nitrogen-related processes in soybean can lead to the development of novel management strategies and targeted interventions to optimize nitrogen use efficiency and minimize nitrogen losses (Iqbal et al., 2020).

### **7.2. Innovative Strategies for Integrating Nitrogen-Fixing Bacteria into Soybean Cultivation**

Incorporating nitrogen-fixing bacteria, such as rhizobia, into soybean cultivation presents a promising approach to reducing reliance on synthetic nitrogen fertilizers. Researchers can explore innovative strategies for effectively integrating these beneficial bacteria into soybean production systems. This includes investigating the selection and use of highly efficient rhizobial strains that establish symbiotic relationships with soybean roots, fixing atmospheric nitrogen and providing a sustainable source of plant-available nitrogen. Furthermore, exploring novel inoculation techniques, such as seed coating or foliar application, can enhance the establishment and effectiveness of the symbiotic association between soybean and nitrogen-fixing bacteria (Harindintwali et al., 2021).

### **7.3. Importance of Sustainable and Precision Nitrogen Management Practices for Enhancing Soybean Productivity**

Sustainable and precision nitrogen management practices hold immense potential for improving soybean productivity while minimizing environmental impacts. Researchers and farmers should prioritize the development and adoption of strategies that optimize nitrogen application rates, timings and methods. Precision agriculture technologies, such as remote sensing, satellite imagery and sensor-based systems, can aid in site-specific nitrogen management, allowing farmers to apply nitrogen inputs precisely where and when they are needed. This targeted approach ensures efficient nutrient utilization, reduces nitrogen losses and minimizes the risk of environmental pollution. Moreover, sustainable nitrogen management practices, such as the use of cover crops, crop rotation and conservation tillage, can enhance soil health, nutrient cycling and overall system resilience, contributing to long-term sustainability in soybean farming (Sishodiaet al., 2020).

## **8. Knowledge Gaps and Research Needs**

Knowledge gaps exist in nitrogen management for soybean farming, including a limited understanding of nitrogen-soil-microbial interactions, the impact of climate change on nitrogen dynamics and the effects of management practices on long-term soil health and ecosystem services. Research needs include comprehensive field studies on emerging practices, integrated modelling approaches and interdisciplinary collaborations involving agronomists, soil scientists, microbiologists, geneticists and economists. Interactions between scientists and farmers, along with knowledge transfer through platforms, conferences and extension programs, are crucial for bridging research-practice gaps and promoting sustainable nitrogen management in soybean farming. Addressing these gaps and priorities will enhance nitrogen use efficiency, minimize environmental impacts and ensure the long-term sustainability and profitability of soybean production systems (Rejeb et al., 2020).

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**9. Conclusion**

This review paper provides valuable insights into the importance of optimizing nitrogen management in soybean farming, emphasizing the impact on soybean growth, soil health, water quality, biodiversity and economic factors. The review highlights the potential benefits of advanced nitrogen management practices, including genetic and molecular approaches, integration of nitrogen-fixing bacteria and sustainable and precision techniques. Proper nitrogen management is crucial for maximizing soybean productivity, nutrient uptake and soil fertility while minimizing environmental pollution. Continued research and policy development are necessary to advance nitrogen management in soybean farming, with practical implications for farmers, including site-specific strategies, conservation tillage, cover crops and optimized nitrogen application. Stakeholders must collaborate to promote the adoption of effective nitrogen management practices, contributing to the long-term sustainability, profitability and environmental stewardship of soybean production systems.

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