

6. Improved Nutrient Management Strategies for Enhanced Nutrient Mobilisation, Assimilation, and Yield of Soybean

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Introduction

Soybean (*Glycine max* L. Merr.) stands as a cornerstone of global agriculture, serving as a primary source of high-quality protein for food and animal feed, as well as a critical source of vegetable oil. As the world's population grows, the demand for soybean products continues to escalate, placing immense pressure on growers to maximise yields in a sustainable and environmentally responsible manner. Achieving this goal hinges on the intricate and often complex process of nutrient management. The challenge extends beyond simply providing a sufficient quantity of nutrients; it requires a sophisticated understanding of how the plant acquires, transports, and utilises these essential elements throughout its life cycle. The efficiency of nutrient management is governed by two fundamental physiological processes: nutrient mobilisation and assimilation. Mobilisation refers to the movement of nutrients from the soil solution into the plant's root system and their subsequent translocation to various plant tissues. This process is a dynamic interplay between soil properties, root

architecture, and the activity of beneficial soil microbes. Assimilation, on the other hand, is the biochemical transformation of inorganic nutrients into organic compounds, for example, the conversion of nitrate (NO_3^-) into amino acids or phosphate (PO_4^{3-}) into ATP. This critical phase determines the plant's ability to produce biomass and, ultimately, to yield a high-quality harvest. A breakdown in either process, whether due to nutrient unavailability, antagonistic soil conditions, or inefficient internal transport, can severely limit the crop's genetic potential.

1. Understanding Nutrient Dynamics in Soybean

Soybeans, a high-yield crop, exhibit a unique nutrient acquisition profile that differs from many other field crops, primarily due to their remarkable ability to form a symbiotic relationship with nitrogen-fixing bacteria. While this symbiosis provides the majority of its nitrogen needs, the plant's high demand for other macro and micronutrients, particularly phosphorus (P), potassium (K), and sulphur (S), necessitates a careful and well-timed nutrient management strategy.

Complex interactions among soil physicochemical properties, root system architecture, and plant physiological processes heavily influence the efficiency of this system.

- **Nitrogen (N) - The Cornerstone of Protein Synthesis:** Soybean's nitrogen requirement is exceptionally high, particularly during the seed development and pod-filling stages. Early in its growth cycle (V1-V2 stages), the plant relies on a small amount of soil-available N. However, the dominant source of N, accounting for up to 70% of the total plant N, is symbiotically fixed from the atmosphere by *Bradyrhizobium* and other *Rhizobium* species residing in root nodules. The process is highly energy-intensive for the plant, requiring a significant allocation of carbohydrates to the roots to support the bacterial colonies. The most critical period for nitrogen management is during reproductive growth. As the plant transitions from the vegetative to the reproductive stage, it mobilises a substantial portion of the nitrogen stored in its leaves. It stems from a process known as remobilisation or nutrient reallocation to support the protein-rich seeds in the developing pods. Inefficient remobilisation can

lead to premature leaf senescence and a direct reduction in final yield.

- **Phosphorus (P) - The Energy Currency:** Phosphorus is indispensable for virtually all metabolic processes, serving as a key component of ATP, nucleic acids (DNA, RNA), and cell membranes. However, its low mobility in the soil and high propensity to be "fixed" by soil cations, such as calcium, iron, and aluminium, make it one of the most common limiting nutrients. Soybeans have evolved several strategies to acquire P, including secreting organic acids from their roots to solubilise bound P and forming a symbiotic relationship with arbuscular mycorrhizal (AM) fungi. These fungi extend the effective root surface area, allowing the plant to access P from beyond the depletion zone around the roots.
- **Potassium (K) - The Osmotic Regulator and Transporter:** Potassium is not incorporated into organic compounds but plays a pivotal role as a metabolic activator and osmotic regulator. It is essential for maintaining cell turgor, opening and closing stomata for gas exchange, and activating over 80 different enzymes. Critically, K is the primary driver of phloem transport, facilitating the movement of sugars

(photosynthates) produced in the leaves to the high-demand "sinks," such as the developing pods and seeds. A deficiency in K directly impairs this transport system, leading to a buildup of carbohydrates in the leaves and a subsequent reduction in seed fill.

- **Essential Micronutrients:** While required in smaller quantities, several micronutrients are vital for soybean health and productivity. These include iron (Fe), which is crucial for chlorophyll synthesis and N fixation; manganese (Mn), a key activator in photosynthesis; and molybdenum (Mo), which is a required cofactor for the enzyme nitrogenase, the catalyst for symbiotic N fixation. Ensuring the availability of these micronutrients is a foundational step in any effective nutrient management program.

2. Strategic Fertiliser Application

The paradigm of nutrient management has shifted from simply applying nutrients to strategically delivering them with a high degree of precision, timing, and source selection. Conventional methods, which often involve broadcasting fertilisers across the entire field, frequently result in significant nutrient losses through volatilisation, leaching, and fixation to soil colloids. Modern, strategic approaches aim to maximise nutrient use efficiency (NUE)

by synchronising nutrient supply with the crop's physiological demand, thereby minimising environmental impact and maximising economic returns.

a) *Placement and Timing*

The location and timing of fertiliser application are critical determinants of nutrient availability and uptake.

- **Band Placement:** This method involves applying fertiliser in a concentrated band either below or to the side of the seed row at planting. For immobile nutrients, such as phosphorus (P) and many micronutrients, band placement is particularly effective. It localises the nutrient in the root zone, creating a high-concentration reservoir that is readily accessible to the developing roots. This strategy is superior to broadcasting, as it significantly reduces the surface area where nutrients can interact with soil minerals and become "fixed" or immobilised. Studies have shown that band-placed phosphorus (P) can be up to three times more efficient than broadcast phosphorus, especially in soils with high clay content or low pH.
- **Split Application:** The timing of nutrient application can be as important as the quantity applied. Split application involves dividing the total fertiliser dose into smaller, more manageable

applications throughout the growing season. This practice is particularly beneficial for highly mobile nutrients, such as potassium (K) and nitrogen (N). A small dose of starter N can support early vegetative growth before the soybean plant's nitrogen-fixing nodules are fully active. Similarly, a split application of K can ensure a continuous supply during the critical reproductive stages, especially during pod fill when the demand for K-driven sugar translocation is at its peak. This approach mitigates the risk of nutrient loss and ensures that nutrients are available when the plant needs them most.

b) *Enhanced-Efficiency Fertilisers (EEFs)*

EEFs are a new generation of products designed to improve NUE by controlling the rate, timing, and location of nutrient release.

- **Slow- and Controlled-Release Fertilisers (SRFs & CRFs):** These fertilisers are typically coated with a polymer or other material that regulates the release of nutrients into the soil solution. The release rate is often controlled by soil temperature and moisture. By gradually releasing nutrients, these products minimise the risk of nutrient leaching, a significant

concern for highly soluble nutrients like nitrates (NO_3^-). This controlled release profile more closely matches the plant's nutrient uptake curve, resulting in higher efficiency and reduced environmental losses.

- **Fertilisers with Inhibitors:** These products contain specific compounds that target and slow down the biochemical processes responsible for nutrient loss.
 - **Urease Inhibitors:** Urease is an enzyme that rapidly hydrolyses urea into ammonium (NH_4^+) and carbon dioxide (CO_2). This process can lead to significant nitrogen (N) losses through ammonia (NH_3) volatilisation, particularly in warm, moist soils. Inhibitors like N-(n-butyl) thiophosphoric triamide (NBPT) temporarily block the urease enzyme, allowing urea to remain in its more stable form until the soil or plant roots can absorb it.
 - **Nitrification Inhibitors:** These compounds, such as dicyandiamide (DCD), slow down the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) by nitrifying bacteria. Nitrate is highly susceptible to

leaching from the root zone, particularly during periods of heavy rainfall. By maintaining N in the less mobile ammonium

form, these inhibitors extend the nutrient's residency in the soil and improve its availability for plant uptake.

Table 1.1 Types of Enhanced-Efficiency Fertilisers (EEFs)

EEF Type	Mechanism of Action	Target Nutrient(s)	Key Advantage
Slow-Release	Coated granules, controlled release	N, P, K	Releases nutrients gradually, matching plant demand
Urease Inhibitors	Blocks the urease enzyme	N (from urea)	Reduces ammonia volatilisation losses
Nitrification Inhibitors	Slows the conversion of ammonium to nitrate	N	Reduces nitrate leaching and denitrification

3. Biostimulants and Biofertilizers

Beyond conventional and enhanced-efficiency fertilisers, a new frontier in sustainable nutrient management involves the use of biostimulants and biofertilizers. These inputs are not designed to supply nutrients directly in large quantities but rather to enhance the plant's natural ability to acquire and utilise them. They function by improving the soil's biological health and the plant's physiological processes, leading to more efficient nutrient mobilisation and assimilation.

a) Biofertilizers: The Microbial Facilitators

Biofertilizers are products containing living microorganisms that, when applied to soil, seeds, or plants, colonise the rhizosphere and promote plant growth by increasing the supply or availability of primary nutrients. In soybean production, their role is to

unlock the significant nutrient reserves often trapped in the soil.

- Phosphate-Solubilising Bacteria (PSB):** A large portion of soil phosphorus (P) is present in insoluble organic and inorganic forms, making it unavailable for plant uptake. Microorganisms such as *Bacillus* and *Pseudomonas* species act as PSB, producing organic acids (e.g., gluconic acid, lactic acid) and phosphatases that solubilise bound P. This process converts unavailable P into the plant-available forms of monobasic (H_2PO_4^-) and dibasic (HPO_4^{2-}) phosphate ions.
- Potassium-Solubilising Bacteria (KSB):** Similar to P, a significant amount of soil potassium (K) is found in insoluble forms within silicate minerals. KSB, including species of *Bacillus* and *Aspergillus*, secretes

organic acids that chelate and release K from these minerals, thereby improving its accessibility to the soybean roots.

- **Nitrogen-Fixing Bacteria:** While the symbiotic relationship with *Rhizobium* is paramount for soybeans, free-living nitrogen-fixing bacteria like *Azotobacter* and *Azospirillum* can also contribute a minor, supplementary amount of N to the plant, further reducing the need for synthetic nitrogen fertilisers.

b) Biostimulants: The Plant and Soil Conditioners

Biostimulants are diverse substances or microorganisms that, when applied to plants, enhance physiological processes, making them more resilient to abiotic stress and improving nutrient uptake and use efficiency. They act on the plant itself, rather than solely on the soil.

- **Humic and Fulvic Acids:** These complex organic molecules are derived from the decomposition of plant and animal matter. When applied, they

improve soil structure, increase the soil's cation exchange capacity (CEC), and chelate micronutrients such as iron (Fe), zinc (Zn), and manganese (Mn). This chelation protects the nutrients from precipitation and keeps them in a soluble, plant-available form. Furthermore, they can directly stimulate root growth, leading to a larger surface area for nutrient and water absorption.

- **Seaweed Extracts:** These extracts are rich in plant growth hormones (e.g., auxins, cytokinins, gibberellins), amino acids, and micronutrients. They have been shown to enhance nutrient uptake, improve overall plant vigor, and increase tolerance to stresses such as drought and salinity.
- **Amino Acids:** When applied as foliar sprays, amino acids act as biostimulants by serving as precursors for protein synthesis and as a readily available form of nitrogen that can be quickly assimilated by the plant, particularly during periods of high demand.

Table 1.2 Mechanisms and Benefits of Biofertilizers and Biostimulants

Input Type	Primary Mechanism	Key Benefit for Soybean	Example
Biofertilizer	Solubilizes bound nutrients	Increases nutrient availability in soil	Phosphate-solubilizing bacteria
Biostimulant	Enhances plant physiology & root growth	Improves nutrient uptake and use efficiency	Humic acids, seaweed extracts
Synergy	Improves soil health and root-microbe interaction	Optimized nutrient access, reduced stress	Combined application of both

4. Genetic and Agronomic Synergies

Maximizing the effectiveness of improved nutrient management strategies requires

their integration with complementary genetic and agronomic practices. While strategic fertilization and the use of biostimulants address the "supply side" of the nutrient equation, these synergies address the "demand side" by ensuring the plant itself is genetically and environmentally primed to utilize those nutrients most efficiently. This holistic approach is essential for achieving the highest possible yields and improving the overall sustainability of soybean production.

- **Rhizobia Inoculation and Symbiotic Optimization:** The symbiotic relationship between soybean and nitrogen-fixing bacteria is the cornerstone of its high-protein yield. However, this symbiosis is not a passive process. It must be actively managed. The use of a high-quality, strain-specific *Rhizobium* inoculant at planting is non-negotiable, particularly in fields with no prior history of soybean cultivation or where conditions are suboptimal. An effective inoculant ensures a robust and efficient nodule population, capable of meeting the crop's massive nitrogen demand, especially during the critical seed-filling stage. Furthermore, managing soil pH, minimizing soil compaction, and ensuring adequate soil moisture are

all agronomic practices that directly enhance the viability and effectiveness of the *Rhizobium* population.

- **Cover Cropping for Soil Health:** The use of cover crops, particularly leguminous species like crimson clover or hairy vetch, is a powerful agronomic tool for improving soil health and nutrient cycling. These crops, when terminated before or at the time of soybean planting, contribute significant amounts of organic matter to the soil. This organic matter not only enhances soil structure, water-holding capacity, and microbial diversity but also acts as a slow-release reservoir for nutrients. Leguminous cover crops specifically fix atmospheric nitrogen, which, upon their decomposition, becomes available to the subsequent soybean crop. In this way, cover crops create a more resilient and biologically active soil environment that is inherently more efficient at mobilizing and retaining nutrients.
- **Variety Selection with Nutrient Use Efficiency (NUE) Traits:** Modern plant breeding has made significant strides in developing soybean varieties with enhanced Nutrient Use Efficiency (NUE). These varieties are genetically predisposed to acquire, translocate, and utilize nutrients more effectively than

older cultivars. Key traits targeted by breeders include:

- **Robust Root Systems:** Varieties with deeper, more extensive root systems are better equipped to explore a larger soil volume, increasing their access to water and immobile nutrients like phosphorus and potassium.
- **Efficient Nutrient Transporters:** Genetic markers for highly active nutrient transporter proteins can be selected for, allowing the plant to absorb and move nutrients from the soil solution to its internal tissues with greater efficiency.
- **Improved Remobilisation:** Breeding for varieties that are highly efficient at remobilising nutrients from vegetative tissues to the developing seeds is crucial for maximising yield. This trait ensures that the plant does not prematurely shut down nutrient transport to the pods, leading to a more complete and uniform seed fill.

5. Conclusion

The future of soybean cultivation lies in a fundamental shift from traditional, reactive nutrient management to a proactive,

integrated, and science-based approach. The strategies explored in this article ranging from precision fertilizer placement and the use of enhanced-efficiency fertilizers to the strategic application of biostimulants and biofertilizers are not isolated techniques but interconnected components of a holistic system. The true power of these innovations is realized when they are synergistically combined with sound agronomic practices, such as cover cropping, and the selection of genetically superior soybean varieties with high nutrient-use efficiency.

This integrated approach directly addresses the core challenges of nutrient mobilization and assimilation, ensuring that the soybean plant receives the right nutrient, in the right amount, at the right time. By optimizing the plant's internal physiology and enhancing the biological activity of the soil, these strategies do more than just increase yield; they fundamentally improve nutrient use efficiency (NUE). This is a critical metric for both economic profitability and environmental stewardship. Higher NUE means less nutrient loss to leaching and volatilization, which in turn reduces the environmental footprint of agriculture, including the emissions of greenhouse gases and the contamination of water bodies.

In a world demanding both increased food production and greater environmental sustainability, the adoption of these advanced nutrient management strategies is no longer a choice but an imperative.

Continued research and development in this area will further refine these tools, paving the way for a more resilient, productive, and sustainable global soybean industry.

Table 1.3 Comparison of Nutrient Management Strategies for Soybean

Feature	Conventional Strategy	Improved Strategy
Fertilizer Application	Broadcast, single application	Band placement, split application
N Sources	Synthetic fertilizers	Biological N fixation, minimal starter N
P & K Sources	Soluble mineral fertilizers	Enhanced-efficiency fertilizers, biofertilizers
Nutrient Loss	High (leaching, fixation)	Low (controlled release)
Root Health	Dependent on soil conditions	Enhanced by biostimulants & biofertilizers
Overall Efficiency	Low to moderate	High

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