

## Optimization of Nitrogen and Phosphorus Fertilization for Improving Sugarcane Yield and Sucrose

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### Abstract

Nitrogen (N) and phosphorus (P) are the most critical macronutrients limiting sugarcane (*Saccharum officinarum* L.) productivity and sucrose accumulation. Nitrogen drives vegetative growth, photosynthetic capacity, canopy development, and stalk elongation, while phosphorus is essential for early root establishment, tillering, energy transfer (ATP), and sucrose metabolism. However, low nutrient use efficiency, rapid P-fixation in tropical soils, and imbalanced application often result in suboptimal yields and environmental concerns such as nitrate leaching and N<sub>2</sub>O emissions. Optimal management follows the 4R Nutrient Stewardship principles (Right source, rate, time, and place) with recommended N:P<sub>2</sub>O<sub>5</sub>: K<sub>2</sub>O ratios around 5:1:5 and split N applications aligned with crop demand. Combined N and P fertilization enhances enzyme activities (e.g., SPS for sucrose synthesis), delays senescence, improves root architecture, and increases cane yield, sugar recovery, and stalk quality. Integration of controlled-release fertilizers, nitrification/urease inhibitors, phosphate-solubilizing bacteria, and precision agriculture tools (VRT, grid sampling, UAV monitoring) further boosts efficiency while reducing losses. This review synthesizes physiological, biochemical, and agronomic evidence to establish best practices for maximizing sugarcane yield and sucrose content while promoting sustainable nutrient management in diverse agro-ecological zones.

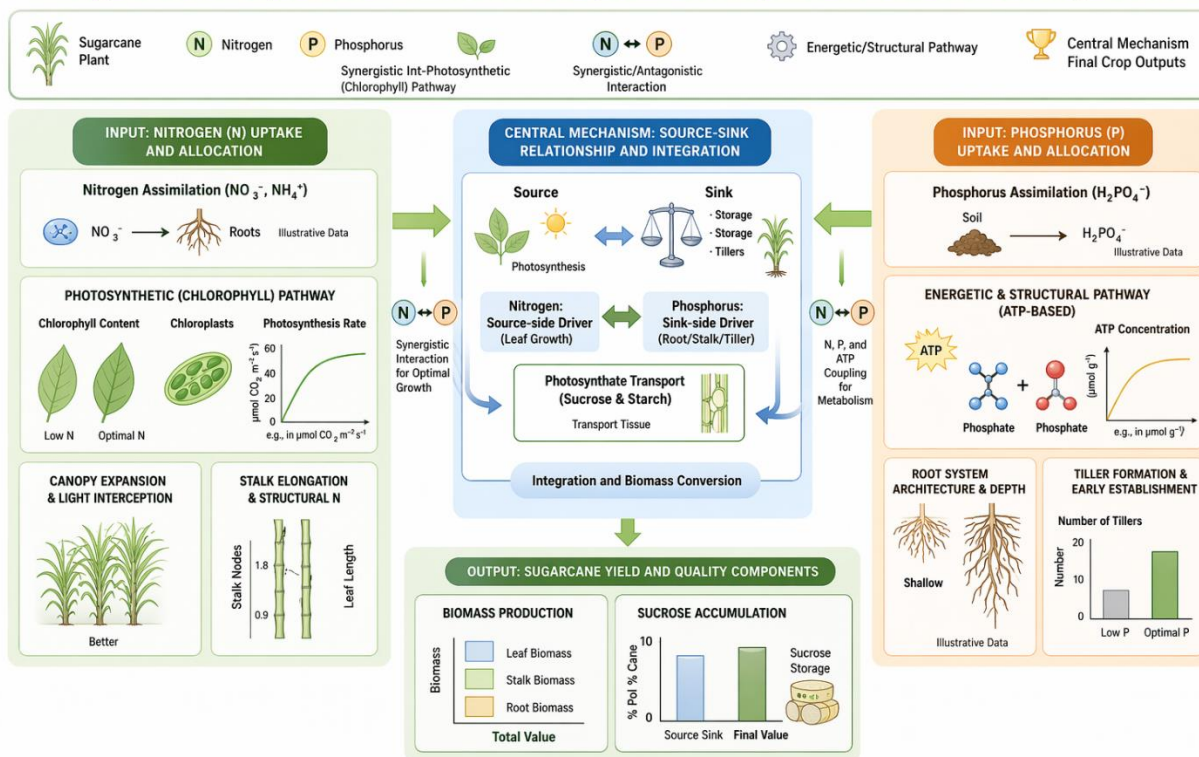
**Keywords:** Sugarcane Nutrition, Nitrogen Phosphorus Optimization, Nutrient Use Efficiency, Sucrose Accumulation, 4R Nutrient Stewardship, Controlled-Release Fertilizers, Phosphate-Solubilizing Bacteria, Precision Agriculture, Sustainable Fertilization, *Saccharum Officinarum*

### 1. Introduction

Sugarcane (*Saccharum officinarum* L.) represents one of the most vital agricultural commodities globally, serving as the primary source for over 80% of the world's sugar and a significant portion of its bioethanol (Luo et al., 2023). As a C<sub>4</sub> perennial grass, it is characterized by high photosynthetic efficiency and an immense capacity for biomass accumulation, which necessitates substantial nutrient inputs (Wang et al., 2021). Among these, nitrogen (N) and phosphorus (P) are the most critical limiting factors for achieving high stalk yields and optimal sucrose concentrations (Anas et al., 2021). However, the management of these nutrients is historically inefficient, with global nitrogen use efficiency (NUE) often falling below 50% and phosphorus being subject to rapid immobilization in tropical soils (Bhat et al., 2017). The challenge for modern agronomy lies in balancing the heavy nutrient demand of the

crop with the need to minimize environmental footprints, such as nitrate leaching into groundwater and greenhouse gas emissions from nitrous oxide ( $N_2O$ ) (Talha Aslam et al., 2024). This report provides an exhaustive analysis of the physiological, biochemical, and technological dimensions of N and P optimization, drawing on global research to define best practices for sustainable production (Mao et al., 2023). The integrated roles of nitrogen and phosphorus in regulating sugarcane growth and sucrose accumulation are illustrated in Figure 1. This conceptual framework highlights the synergistic interaction between these nutrients in optimizing crop productivity.

**Figure 1. Conceptual Framework of Nitrogen and Phosphorus Interaction in Sugarcane**



## 2. Physiological Framework of Nitrogen in Sugarcane Development

Nitrogen is the primary driver of vegetative growth in sugarcane, acting as a core constituent of chlorophyll, amino acids, proteins, and nucleotides. Its availability directly influences the rate of photosynthesis and the expansion of the crop canopy, which are the foundations of biomass production (Zeng et al., 2020).

### 2.1. Photosynthetic Capacity and Nitrogen Partitioning

The relationship between leaf nitrogen and photosynthetic rate is mediated by the partitioning of N into the photosynthetic apparatus. In the  $C_4$  pathway utilized by sugarcane,  $CO_2$  is initially fixed by phosphoenolpyruvate carboxylase (PEPCase) in the mesophyll cells to form  $C_4$  acids, which are then decarboxylated in the bundle sheath cells to release  $CO_2$  for fixation by ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) (Ghannoum et al., 2011). Nitrogen supply determines the concentration and activity of these enzymes. Research indicates that specific leaf nitrogen (SLN) is positively correlated with the net  $CO_2$  assimilation rate ( $A$ ), stomatal conductance ( $g_s$ ), and transpiration ( $E$ ) (Basnayake et al., 2015). High N conditions can nearly double the mean values of these physiological traits in responsive genotypes, whereas low-N environments lead to a drastic decline in photosynthetic efficiency and the premature degradation of chloroplast proteins (Robinson et al., 2011).

Furthermore, nitrogen plays a critical role in leaf senescence. Adequate N supply delays the onset of senescence, maintaining green leaf area for a longer duration. This delay is particularly important during the maturation stage, as it ensures a continuous supply of photoassimilates to the stalk for sucrose accumulation (Muchow et al., 1996). Conversely, N deficiency leads to accelerated remobilization of nitrogen from older leaves to younger tissues, reducing the overall photosynthetic capacity of the canopy and limiting the potential for biomass accumulation (Thorburn et al., 2017).

## 2.2. Vegetative Growth and Yield Components

The impact of nitrogen on sugarcane yield is primarily realized through the enhancement of millable cane number, stalk height, and stalk diameter. Nitrogen fertilization stimulates the division of internode cells, leading to longer and thicker stalks (Desalegn et al., 2023). Studies have shown that increasing N levels from 210 to 300 kg/fad can increase the number of millable canes per unit area by nearly 19% (Bekheet et al., 2018). However, this growth response is non-linear; while tonnage increases with N rate, the incremental gain often decreases after reaching an optimal threshold (Abhiram et al., 2025). Excessive nitrogen fertilization, while promoting high biomass, can have several detrimental effects. High N levels often promote vigorous vegetative growth at the expense of stalk structural integrity, increasing the risk of lodging or bending, which complicates mechanical harvesting and reduces recoverable sugar (Boschiero et al., 2020). Furthermore, excessive N maintains high levels of moisture and reducing sugars in the stalk, effectively delaying the maturation process and inhibiting the accumulation of sucrose (Xue et al., 2021).

**Table 1. Comparison of Cane Yield and Sucrose Percentages Across Different Sugarcane Varieties and Nitrogen Rates.**

Variety	N Rate (kg/ha)	Cane Yield (tons/ha)	Sugar Yield (tons/ha)	Sucrose (%)
D42/58	100	153.34	10.25	15.81
NCo-334	100	102.49	8.51	14.50
ROC22	225	High	-	High
YT 55	-	154.10	20.40	-
<i>(Data adapted from Burayu et al., 2023; Zeng et al., 2020)</i>				

## 3. Phosphorus Dynamics: Solubility, Fixation, and Root Development

Phosphorus is an essential macronutrient for energy transfer (ATP), cellular division, and the synthesis of structural components such as phospholipids and nucleic acids. In sugarcane, its role is most prominent during the early stages of establishment and in the regrowth of ratoon crops (Zambrosi et al., 2015).

### 3.1. The Challenge of Soil P-Fixation

A significant challenge in sugarcane nutrition is the low bioavailability of phosphorus in tropical and subtropical soils, particularly Oxisols. Most phosphate fertilizers applied to the soil are rapidly immobilized through adsorption by iron (Fe) and aluminum (Al) minerals, forming insoluble Al-P and Fe-P complexes (Hu et al., 2025). In many sugarcane-growing regions, the P-fixation rate can be as high as 60–70%. This creates a "legacy P" compartment a significant reservoir of total soil phosphorus that remains largely inaccessible to the plant (Sindhushree et al., 2025).

### 3.2. Root System Architecture and Tillering

Phosphorus is the primary nutrient responsible for the development of a vigorous root system. Adequate P availability during the first 30–60 days after planting is critical for early root establishment,

which in turn determines the plant's ability to uptake water and other nutrients later in the season. Phosphorus deficiency manifests as poor root expansion, slender stalks, and reduced tillering (Zambrosi et al., 2015).

Tillering is a vital component of sugarcane yield, as it defines the final population of millable canes. Phosphorus promotes the formation of tillers and reduces tiller mortality (Zambrosi et al., 2017).

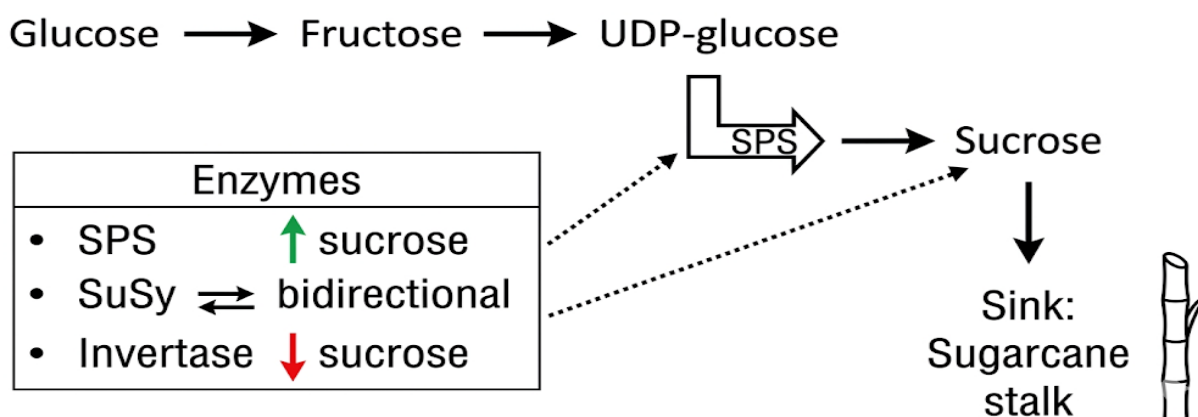
#### 4. Biochemical Pathways of Sucrose Synthesis and Regulation

The storage of sucrose in the sugarcane stalk is governed by the source-sink relationship, a complex interplay between the photosynthetic leaves (source) and the parenchymatous tissue of the stalk (sink) (Verma et al., 2011).

##### 4.1. Enzymatic Control of Sucrose Metabolism

The enzymatic regulation of sucrose synthesis and degradation is summarized in Figure 2. This pathway illustrates the central role of SPS and invertases in determining sucrose accumulation in sugarcane stalks.

Figure 2. Biochemical Pathway of Sucrose Synthesis in Sugarcane



The accumulation of sucrose is an actively regulated biochemical process involving several key enzymes (Zhu et al., 2013):

1. Sucrose Phosphate Synthase (SPS): The primary enzyme responsible for sucrose biosynthesis from UDP-glucose and fructose-6-phosphate in the cytosol. SPS activity is positively correlated with sucrose concentration (Ma et al., 2020).
2. Sucrose Synthase (SuSy): Catalyzes a reversible reaction but primarily cleaves sucrose in sink tissues to provide carbon for growth (Bilska-Kos et al., 2020).
3. Invertases (SAI, CWI, NI): These enzymes hydrolyze sucrose into glucose and fructose. Soluble acid invertase (SAI) is most active in immature internodes. High sucrose genotypes exhibit a reduction in SAI activity as stalks mature (Jamali et al., 2023).

Table 2. Key Enzymes Involved in Sugarcane Sucrose Metabolism and Their Impact on Accumulation.

Enzyme	Function	Relationship to Sucrose Accumulation
SPS	Sucrose biosynthesis	Positive Correlation (Verma et al., 2011)
SuSy	Sucrose cleavage/synthesis	Variable (drives growth) (Verma et al., 2011)
SAI	Sucrose hydrolysis (Acid)	Negative Correlation (Verma et al., 2011)

NI	Sucrose hydrolysis (Neutral)	Negative Correlation (Verma et al., 2011)
CWI	Apoplastic cleavage	Regulates phloem unloading (Verma et al., 2011)

## 5. Synergistic Nitrogen-Phosphorus Interactions and Nutrient Ratios

Optimization of sugarcane fertilization requires a focus on the interaction between N and P, as the availability of one often influences the uptake and utilization of the other (Boschiero et al., 2020).

### 5.1. The 5:1:5 Ratio and Soil Enzyme Activity

Experimental data suggests that the absorption ratio of N, P, and K by sugarcane is typically 2:1:2. However, for optimal yield and quality, a fertilization ratio of approximately 5:1:5 (N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O) has been recommended (Hu et al., 2025). Nitrogen fertilization has a synergistic effect on phosphorus uptake by stimulating root biomass and increasing soil enzymes like acid phosphatase, which enhance the mineralization of organic P (Jing et al., 2022).

### 5.2. Interaction with Water and Micronutrients

Nutrient use efficiency is tightly linked to water availability. Water increases the accumulation of N and P in leaves by facilitating mass flow in the soil. Moreover, imbalanced fertilization neglecting potassium (K) and micronutrients such as zinc (Zn), iron (Fe), and boron (B) can limit the response to N and P (Ebbisa, 2022).

**Table 3. Impact of Combined Micronutrient Application on Sugarcane Yield and Sugar Recovery Improvements.**

Treatment	Cane Yield Increase (%)	Sugar Recovery Increase (%)
NPK Only	Base	Base
NPK + Zn	1.1	1.0
NPK + Fe	1.7	1.4
NPK + B	2.1	2.0
NPK + Zn+Fe+B	11.5 - 13.7	5.9 - 7.3
<i>(Data adapted from Khan et al., 2023)</i>		

## 6. Modern Fertilization Management Strategies

To address the low efficiency of traditional broadcasting, several advanced management practices have been developed, focusing on the 4R Nutrient Stewardship framework: Right Source, Right Rate, Right Time, and Right Place (Bruulsema, 2022).

### 6.1. Split Application and Timing Adjustments

The demand for nitrogen follows a sigmoid pattern, with the highest requirement during the grand growth stage. Splitting the nitrogen application into 3–4 doses throughout the first 90–120 days ensures that N is available when the plant's growth rate is at its peak (Bekheet et al., 2018).

### 6.2. Fertilizer Placement and Depth

Deep fertilization (15–20 cm) places the nutrients closer to the main root distribution area and reduces the risk of ammonia volatilization and surface runoff. In acidic karst soils, deeper placement has been shown to increase N and P uptake by up to 20% while reducing leaching by 30–40% (Xiong et al., 2023).

## 7. Enhanced Efficiency Fertilizers (EEFs) and Biostimulants

### 7.1. Controlled-Release Fertilizers (CRFs)

Controlled-release fertilizers, such as polymer-coated urea, match the plant's uptake curve and

minimize the peak concentration of ammonium in the soil, reducing volatilization (Skocaj et al., 2017).

## 7.2. Nitrification and Urease Inhibitors

Urease inhibitors (UIs) prevent the rapid hydrolysis of urea to ammonia, while nitrification inhibitors (NIIs) slow the conversion of ammonium ( $\text{NH}_4^+$ ) to nitrate ( $\text{NO}_3^-$ ), which is prone to leaching. These technologies can reduce soil  $\text{N}_2\text{O}$  emissions by up to 19.1% (Abhiram et al., 2025).

## 7.3. Phosphate-Solubilizing Bacteria (PSB)

Microbial biostimulants, particularly phosphorus-solubilizing bacteria such as *Bacillus velezensis*, represent a sustainable approach to enhancing P bioavailability. Inoculation with PSB has been shown to increase net  $\text{CO}_2$  assimilation by 49% (Sindhushree et al., 2025).

## 8. Precision Agriculture in Sugarcane Nutrition

Precision agriculture (PA) leverages technology to manage field variability, optimizing input use and increasing farm profitability (Zaman, 2023).

### 8.1. Variable Rate Technology (VRT) and Mapping

Variable rate technology (VRT) uses high-resolution soil fertility maps to apply the "right rate" of fertilizer or lime at specific locations. In Louisiana, VRT for lime application significantly decreased total usage by targeting acidic zones (Beyer, 2025).

**Table 4. Modern Precision Agriculture Technologies and Their Practical Functions in Sugarcane Nutrient Management.**

PA Technology	Tool/Mechanism	Function in Sugarcane
GPS Guidance	Satellite Auto-Steer	Reduces soil compaction and crop damage (Zaman, 2023)
Grid Sampling	GIS-based sampling	Identifies spatial variability in NPK and pH (Beyer, 2025)
VRT	Map-based applicators	Adjusts fertilizer rate on-the-go (Zaman, 2023)
UAVs/Drones	Multispectral sensors	Monitors crop health and applies ripeners (Zaman, 2023)
Yield Monitors	Harvester sensors	Documents yield variability for future plans (Beyer, 2025)

## 9. Global Best Management Frameworks: Case Studies

### 9.1. Australia: The SIX EASY STEPS Program

The Australian sugar industry uses the "SIX EASY STEPS" (6ES) program, which recommends nitrogen rates based on Soil Organic Carbon (SOC) content. This has reduced nitrogen applications by approximately 22% compared to traditional practices, lowering runoff risks to the Great Barrier Reef (SRA, 2010).

## 10. Economic and Environmental Sustainability

The economic viability of sugarcane is heavily dependent on fertilizer costs, which can represent up to 30% of farm expenses. Integrating organic byproducts, such as filter cake and bagasse, offers a pathway to reduce mineral fertilizer dependence (Xu et al., 2021).

## 11. Conclusions

Optimizing nitrogen and phosphorus fertilization is fundamental to enhancing sugarcane yield, sucrose

content, and overall productivity while minimizing environmental impacts. Nitrogen primarily governs vegetative vigor, photosynthetic efficiency, and biomass accumulation, whereas phosphorus is crucial for root development, tillering, energy metabolism, and early establishment. Their synergistic application at balanced ratios (approximately 5:1:5 N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O) significantly improves cane tonnage, sugar recovery, and stalk quality by supporting key enzymatic pathways (e.g., SPS, SuSy) and delaying senescence. However, excessive N without adequate P leads to luxurious vegetative growth at the expense of sucrose accumulation, while poor P management exacerbates fixation and low availability in tropical soils. Adoption of precision strategies split and timed applications, deep placement, controlled-release fertilizers, nitrification inhibitors, phosphate-solubilizing microbes, and site-specific variable rate technology markedly increases nutrient use efficiency and reduces losses. Integration with organic amendments and micronutrients further sustains soil health and long-term productivity. To close yield gaps and support sustainable intensification, future efforts should focus on genotype-specific recommendations, real-time sensor-based monitoring, and region-specific best management practices. Balanced, science-driven N and P fertilization will be essential for meeting global sugar and bioenergy demands while safeguarding environmental resources.

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