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Development of a fertilization recommendation for banana in the State of São Paulo, Brazil: steps toward sustainability

Luiz Antonio Junqueira Teixeira*[1], Edson Shigueaki Nomura[2]
[1]Researcher, Instituto Agronômico (IAC), Brazil. [2]Researcher, Agência Paulista de Tecnologia dos Agronegócios (APTA), Brazil

Autor de correspondencia:
Luiz Antonio Junqueira Teixeira
lulaiac@gmail.com

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ABSTRACT

Brazil is a leading global banana producer, but the sector faces mounting economic pressures and climate variability, necessitating more efficient and sustainable fertilization practices. In response, a dynamic recommendation system for fertilization and liming has been developed for the state of São Paulo, continuously refined through field experimentation. This system employs an integrated soil-plant diagnostic approach, underpinned by principles of soil nutrient dynamics and crop nutritional requirements. Diagnostic reliability is achieved through analytical protocols adapted for tropical soils, such as phosphorus extraction using ion-exchange resin and lime requirement determination based on target base saturation. These soil analyses are complemented by plant tissue standards specific to banana cultivars, providing a holistic view of nutritional status. The calibration and validation of recommendations are centered on field trials. These trials evaluate variables including fertilizer sources, application rates, timing, and fertilizer placement methods. Key performance indicators, such as soil fertility indices, yield, and fruit quality, are used to assess outcomes. The empirical results are synthesized into evidence-based guidelines and decision-support tools designed to optimize nutrient use efficiency and mitigate environmental impacts. By emphasizing adaptability and sustainability, this framework promotes the alignment of fertilization practices with local edaphic and climatic conditions. While developed for São Paulo, the underlying methodologies possess significant transferability to other banana-growing regions, contingent upon local validation. This scientifically-validated yet practical system serves to enhance the resilience and long-term viability of banana production systems facing evolving agronomic and environmental challenges.

Keywords: Plant nutrition, Fertilization, Liming, Sustainability

RESUMEN

Brasil es uno de los principales productores mundiales de bananos, pero el sector se enfrenta a crecientes presiones económicas y a la variabilidad climática, lo que hace necesarias prácticas de fertilización más eficientes y sostenibles. Para responder a este desafío, se desarrolló un sistema dinámico de recomendaciones de fertilización y encalado para el estado de São Paulo, continuamente perfeccionado mediante experimentación en campo. La metodología se basa en un diagnóstico integral suelo-planta, fundamentado en la dinámica de nutrientes del suelo y los requerimientos nutricionales del cultivo. La solidez diagnóstica se asegura con protocolos analíticos adaptados a suelos tropicales, como la extracción de fósforo por resina de intercambio iónico y la determinación de encalado en función de la saturación de bases deseada. Estos análisis se complementan con estándares foliares específicos de

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cultivares locales, permitiendo una evaluación completa del estado nutritivo. La calibración y validación de las recomendaciones se apoya en una red de ensayos regionales, donde se analizan fuentes de fertilizantes, dosis, épocas y métodos de aplicación. Los resultados se expresan en indicadores como evolución de la fertilidad del suelo, rendimiento comercial y calidad del fruto. La síntesis empírica genera guías técnicas y herramientas de apoyo a la decisión, orientadas a maximizar la eficiencia del uso de nutrientes y reducir impactos ambientales. Desarrollado para São Paulo, el sistema posee base metodológica sólida y alto potencial de transferencia a otras regiones bananeras, aunque requiere validación local para su implementación.

Palabras clave: Nutrición Vegetal, Fertilización, Encalado, Sostenibilidad

INTRODUCTION

Brazil ranks among the world's leading banana producers, with annual production of approximately seven million tons (Brazilian Institute of Geography and Statistics 2025). However, growers face increasing challenges from economic competition and climate variability, which demand improved fertilization strategies to sustain productivity and quality. In São Paulo, Brazil, research efforts have prioritized the development of integrated nutrient management practices aimed at enhancing yields, fruit quality, economic efficiency, and environmental sustainability.

Until the early 20th century, agriculture depended on the natural fertility of soils. In modern systems, however, sustainable banana production requires external nutrient inputs through mineral or organic fertilization (Nyombi 2019). Several conceptual frameworks guide the formulation of fertilizer and liming recommendations (Hochmuth and Hanlon 2022). Among these are the *Build-Up and Maintenance* approach, which elevates soil nutrient levels to an optimum range and sustains them through regular applications; the *Basic Cation Saturation Ratio* (BCSR), which assumes crop performance is optimized when soil cations (Ca^{2+}, Mg^{2+}, and K^{+}) occur in specific proportions; and the *Sufficiency Range* approach, which supplies nutrients only at levels required to meet crop demand. Critical evaluations of these principles are provided by McLean *et al*. (1983), Kopittke and Menzies (2007), and Hochmuth and Hanlon (2022).

In São Paulo, banana fertilization and liming recommendations were developed by the Instituto Agronômico de Campinas (IAC) and published in Technical Bulletin #100 (Teixeira *et al*. 2022). The system employs the *Sufficiency Range* approach, founded on a precise understanding of soil nutrient dynamics and banana plant nutritional needs, while incorporating sustainability principles such as replenishment

of exported nutrients and minimization of fertilization's environmental impact. These recommendations are continually refined through field experiments (Figure 1).



Figure 1. Field experiments on banana fertilization. (A) Ribeira Valley and (B) Planalto Paulista (São Paulo Plateau), Brazil.

To achieve these objectives, analytical methods tailored to tropical soils were developed and calibrated for banana cultivation. These include phosphorus extraction using ion-exchange resin and lime requirement estimation based on base saturation targets (Raij *et al*. 2001). Field trials, which generated calibration curves and evaluated crop productivity in response to different soil P assessment methods, confirmed the superiority of the resin extraction method for estimating plant-available P in tropical soils (Raij *et al*. 2022). In a comprehensive review, Quaggio (2000) compared methods for calculating lime requirements in tropical soils of Brazil. It was concluded that the base saturation method provided recommendations that resulted in the greatest yields for both annual and perennial fruit crops. Plant tissue analysis complements soil testing, with specific nutrient sufficiency ranges established for regional cultivars *(Teixeira et al*. 2007, 2023; Cantarella *et al*. 2022).

This work presents the principles underlying São Paulo's fertilizer and liming recommendations for banana and highlights its potential adaptability for tailoring recommendations to other banana-producing regions.

MATERIALS AND METHODS

Soil acidity adjustment and the supply of calcium (Ca) and magnesium (Mg) for banana cultivation are achieved by targeting an optimal base saturation of 70% of the soil's cation exchange capacity (CEC) and increasing exchangeable Mg to a minimum of 8 mmolc/dm³ (Cantarella *et al*. 2022).

Fertilizer recommendations for banana are structured for key developmental stages, establishment, and production. Rates are calculated using an integrated approach that considers soil nutrient availability, expected yield, and plant nutritional status. This method ensures nutrient demand is met, optimizes economic return, and minimizes environmental impact.

Applications of nitrogen (N), phosphorus (P), and potassium (K) are split throughout the year, synchronized with the plant's growth rhythm. As noted by Weinert and Simpson (2016), application rates are modulated phenologically, with increased inputs during warmer months to support peak growth and reduced rates during cooler periods.

Recommendations for the application of sulfur (S) and the micronutrients boron (B) and zinc (Zn) are based on soil availability and foliar concentration levels in plants.

RESULTS AND DISCUSSION

The fertilizer and liming recommendations for banana cultivation in the state of São Paulo were published by Teixeira *et al*. (2022) as a chapter in the Bulletin #100/IAC (Cantarella *et al*. 2022).

Liming requirement. The liming requirement to adjust soil acidity and supply the Ca and Mg needs for banana plants is estimated using the equation:

$$\boldsymbol{LR = \frac{CEC \times (BS_{BAN} - BS_1)}{10 \times RNP}},$$

where $\boldsymbol{LR}$ = liming requirement (t ha^{-1}); $\boldsymbol{CEC}$ = soil cation exchange capacity ($mmol_c\ dm^{-3}$); $\boldsymbol{BS_{BAN}}$ = Optimal base saturation for banana (70 %); $\mathbf{BS_1}$ = Current base saturation of the soil (%), and $\boldsymbol{RNP}$ = Relative neutralizing power of the corrective material (%).

First-year or establishment fertilization. Fertilizer rates, as presented in Table 1, should be applied based on soil analysis results, nitrogen response class, and expected productivity. P application should be omitted in soils with resin-extractable P exceeding 80 mg dm^{-3}. For soils with exchangeable K greater than 6.0 mmolc dm^{-3}, the

recommended K fertilization rate should be reduced by half. N and K fertilizers must be split into six applications. These are to be distributed at 1, 3, 5, 7, 9, and 11 months after planting, corresponding to 10, 15, 15, 20, 20, and 20 percent of the total recommended dose, respectively.

Table 1. Fertilization during the first year of the banana plantation (establishment) based on N response classes, soil nutrient content, and expected yield.

Expected Yield	N response classes[(1)]		P resin, mg dm^{-3}			K exchangeable, $mmol_c\ dm^{-3}$		
	Low	High	< 16	16 - 40	> 40	< 1.6	1.6 – 3.0	> 3.0
t ha^{-1}	kg ha^{-1} of N		kg ha^{-1} of P_2O_5			kg ha^{-1} of K_2O		
<20	90	110	160	70	40	400	150	100
20 to 30	150	190	180	90	60	600	350	150
31 to 40	210	260	200	110	80	800	550	350
41 to 50	270	340	220	130	100	*	750	550
> 50	330	410	240	150	120	*	950	750

* It is unlikely to achieve these productivities in the first harvest on soils with very low levels of exchangeable K (< 1.6 $mmol_c\ dm^{-3}$). (1) Nitrogen fertilization response classes: **low** = Planting in fallow areas or following legume crops, high soil organic matter content; **high** = Planting in areas with many years of grass or other non-legume cultivation, sandy soils, low organic matter content.

Production fertilization. Annual fertilizer applications should be determined based on foliar N concentration, soil analysis results, and expected yield, according to the rates specified in Table 2. P application should be omitted in soils with resin-extractable P exceeding 80 mg dm^{-3}. For soils with exchangeable K greater than 6.0 $mmol_c\ dm^{-3}$, the recommended K fertilizer rate should be reduced by half.

Table 2. Production annual fertilization for banana plants based on foliar N levels, soil nutrient content, and expected yield.

Expected Yield	N in leaves, g kg^{-1}			P resin, mg dm^{-3}			K exchangeable, $mmol_c\ dm^{-3}$		
	< 25	25 - 30	> 30	< 16	16 - 40	> 40	< 1.6	1.6 – 3.0	> 3.0
t ha^{-1}	kg ha^{-1} of N			kg ha^{-1} of P_2O_5			kg ha^{-1} of K_2O		
<20	130	100	80	140	50	20	420	220	120
20 to 30	200	160	120	150	60	30	450	250	150
31 to 40	300	230	170	160	70	40	510	310	210
41 to 50	380	300	230	170	80	50	570	370	270
51 to 60	460	370	280	180	90	60	630	430	330
> 60	560	450	340	190	100	70	690	490	390

Fertilizer application schedule. For rainfed banana cultivation in the State of São Paulo, where winters are colder and drier than summers, fertilizer applications containing N, P, or K should be split according to the percentages outlined in Table 3. Fertilizers must be distributed uniformly within a semicircle with a radius of

approximately 0.6 m in front of the youngest lateral shoot—that is, in the direction of the mat's progression.

Table 3. Splitting of annual N, P, and K doses for rainfed banana cultivation in the State of São Paulo.

Nutrient	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Fraction of the annual dose (%)											
N	-	20	-	15	-	-	-	15	-	20	-	30
P	-	50	-	-	-	-	-	-	-	50	-	-
K	-	20	-	25	-	-	-	15	-	20	-	20

Fertigation. For the application of N and K fertilizers via fertigation, a reduction to 80% of the recommended rates provided in establishment or production tables is advised. This practice is most effective when coupled with drip or micro-sprinkler irrigation systems. In newly planted areas, the previously outlined monthly application schedule should be maintained. In established production areas, fertigation should be performed fortnightly throughout the year.

Fertilization with S and micronutrients. Apply 30 kg ha^{-1} of S annually, particularly in soils with S-SO_4 levels below 15 mg dm^{-3} in the 20-40 cm layer, using sulfur-containing fertilizer sources or gypsum application. Deficiencies of B and Zn are common in banana cultivation in São Paulo. Apply micronutrients according to diagnostic results and the rates specified in Table 4. The lower recommended rates may be applied directly to the pseudostem after harvesting the mother plant, or into the hole left by the sucker thinning tool. Higher rates can be applied together with soil fertilizers or through fertigation. Zinc sulfate and boric acid are the preferred sources. For foliar application, micronutrient supplementation should not be combined with phytosanitary treatments.

Table 4. Critical levels of zinc (Zn) and boron (B) in soil and banana leaves indicating a risk of deficiency, and the corresponding fertilization rates for correction.

Micronutrient	Levels		Fertilization [2]	
	Soil [1]	Leaf	Soil application	Pseudostem application
	mg dm^{-3}	mg kg^{-1}	g/plant	
Zn	< 5,0	< 15	7	5
B	< 0,6	< 10	2	1

[1] Extracted with DTPA-TEA; [2] The prescribed fertilization rates were established for use with zinc sulfate and boric acid.

Green manure. It is advisable to plant an intercrop during the initial establishment phase of the banana plantation. However, this crop must not compete for water, nutrients, or sunlight. The cultivation of suitable green manure species provides benefits such as soil protection, reduction of nutrient losses through leaching and

surface runoff, and contributes to nutrient cycling through the accumulation of organic matter. Legumes have shown positive results when intercropped during the establishment of the banana plantation. In addition to the benefits common to other green manures, legumes contribute a significant amount of N to the banana plants, derived from the symbiotic fixation and subsequent accumulation of this nutrient in their biomass.

CONCLUSIONS

The fertilization and liming recommendation system for banana cultivation in São Paulo represents a dynamic, science-based framework. Through continuous refinement and validation via targeted research and field trials, this approach successfully combines scientific rigor with practical agricultural needs. It contributes to the long-term viability of banana production by enhancing productivity and fruit quality while promoting economic efficiency and environmental sustainability. The methodology serves as a replicable model for other regions aiming to develop sustainable nutrient management practices.

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