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Response of banana nutrition and yield to fertilizer application methods in tropical sandy soils

Respuesta de la nutrición y el rendimiento del banano a los métodos de aplicación de fertilizantes en suelos arenosos tropicales

UNIVERSIDAD NACIONAL DE COLOMBIA

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ABSTRACT

Low fertilization efficiency in sandy soils is a critical challenge for banana productivity. This study assessed the impact of four fertilizer application methods on key edaphic and plant performance indicators in banana (*Musa acuminata* AAA cv. Williams) crops grown in sandy soils of the Colombian Caribbean. A complete production cycle study across three commercial plantations used a randomized complete block design with five replicates. Treatments were: T1 (soil drench), T2 (soil fertilization + pseudostem microinjection), T3 (soil + foliar fertilization), and T4 (conventional soil fertilization, used as the commercial control). Measured variables included soil properties (pH, EC, OM, texture, bulk density, macro and micronutrients) and plant metrics (plant height, number of functional leaves, number of bunches per PU, bunch weight, total cumulative weight, pseudostem diameter, macro and micronutrients), selected for their direct relevance to nutrient retention and crop performance in high-leaching environments. Analysis of variance and Tukey's test (P<0.05) showed that T3 consistently produced the best agronomic outcomes. It achieved the highest fresh bunch weight (23.0±1.7 kg), total yield (1122.9±85.4 kg), and foliar nutrient concentrations. This treatment also significantly improved key soil fertility indicators (total N, exchangeable K, Ca, Zn), without adverse effects on soil pH or salinity. Daughter plants exhibited lower nutritional status than mother plants, suggesting reduced uptake efficiency in early growth. The combined soil + foliar approach optimizes nutrient availability, enhances banana productivity, and provides a robust, efficient management strategy for sustainable crop production in leaching environments.

Palabras clave:
Nutrición del banano
Densidad aparente
Colocación de fertilizantes
Análisis foliar
Eficiencia en el uso de nutrientes
Suelos arenosos

RESUMEN

La baja eficiencia de la fertilización en suelos arenosos es un desafío crítico para la productividad del banano. Este estudio evaluó el efecto de cuatro métodos de aplicación de fertilizantes en indicadores edáficos y vegetativos claves del rendimiento en cultivos de banano (*Musa acuminata* AAA cv. Williams) cultivados en suelos arenosos del Caribe colombiano. Se llevó a cabo un estudio en un ciclo de producción en tres plantaciones comerciales, utilizando un diseño de bloques completos al azar con cinco repeticiones. Los tratamientos fueron: T1 (drench), T2 (edáfico + microinyección), T3 (edáfico + foliar), y T4 (convencional, solo edáfico). Las variables medidas incluyeron propiedades del suelo (N, K, Ca, Zn, pH, CE, densidad aparente) y métricas de la planta (peso del racimo, manos por racimo, diámetro del pseudotallo, N, K, Zn y Cu foliares), seleccionadas por su relevancia directa en la retención de nutrientes y el rendimiento de los cultivos en entornos de alta lixiviación. El análisis de varianza y prueba de Tukey (P<0,05) mostraron que T3 (edáfico + foliar) produjo de manera consistente los mejores resultados agronómicos. Alcanzó el mayor peso promedio de racimo, (23,0±1,7 kg), rendimiento total 1122,9±85,4 kg y concentración foliar de nutrientes. Este tratamiento también mejoró significativamente indicadores clave de fertilidad del suelo (N total, K, Ca y Zn intercambiables), sin efectos adversos sobre el pH o la salinidad del suelo. Las plantas hijas mostraron un estado nutricional inferior al de las plantas madre, lo que sugiere una menor eficiencia de absorción en las primeras etapas de crecimiento. El enfoque combinado de fertilizante edáfico + fertilizante foliar optimiza la disponibilidad de nutrientes, mejora la productividad del banano y proporciona una estrategia de gestión sólida y eficiente para la producción sostenible del cultivo en entornos de lixiviación.

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Bananas (*Musa acuminata* AAA cv. Williams) is a crop of major socioeconomic importance for Colombia, particularly in the Caribbean region. However, its productivity in sandy soil predominant in this area is compromised by structural limitations, including low cation exchange capacity (CEC<4 cmol (+) kg^{-1}), a critically low organic matter content (<1%), and high hydraulic conductivity. These properties promote accelerated nutrient leaching, with reported nitrogen losses between 30 and 60% of applied amounts, drastically reducing nutrient use efficiency (NUE) and yield potential (Chandel et al. 2024; Panigrahi et al. 2021).

These inherent properties lead to rapid leaching of essential nutrients. For instance, studies in similar tropical sandy soil have documented nitrogen leaching losses ranging from 30 to 60% of the applied N severely reducing nutrient use efficiency (NUE) and constraining yield potential. Although conventional fertilization programs define rates based on crop requirements and phenology, this approach is insufficient in sandy soils. The relationship between soil nutrient content and actual banana yield under these conditions remains unclear (Khangura et al. 2023). Furthermore, the availability of macro and micronutrients is often limited, despite high applications rates (Reyes-Pallazhco et al. 2023; Osman 2018) (e.g., 200-300 kg N ha^{-1}, 30-50 kg P_2O_5 ha^{-1}, and 500-1,000 kg K_2O ha^{-1} per cycle) highlighting a critical gap between application and efficiency plant uptake (Chandel et al. 2024; Topcuoğlu 2021).

Therefore, there is a clear need to move beyond the traditional approach focused solely on dosage (Aguirre et al. 2015). It is necessary to develop and validate applications methods that more effectively integrate soil properties, root absorption dynamics, and crop physiology. Alternative methods such as pseudostem injection, foliar fertilization, or localized drenching have shown potential for improve NUE in other systems (Guevara et al. 2021; Islam et al. 2023). However, their comparative efficacy (Guimarães et al. 2020), mechanisms of action, and comprehensive impact (plant-soil) on banana crops in sandy soils of the Colombian Caribbean have not been sufficiently explored (Aman et al. 2025; Srivastava et al. 2021).

To address this knowledge gap, the present study aims to evaluate the effects of different fertilizer applications methods on banana nutritional status, soil chemical properties, and agronomic performance under low-fertility sandy soils conditions of the Colombian Caribbean.

MATERIALS AND METHODS

Experimental site

The field experiment was conducted during 2023 and 2024 production cycles in three commercial banana plantations of the Cavendish subgroup, located in the municipality of Zona Bananera (Magdalena, Colombia). The productive units were identified as UP1 (10°47'19"N, 74°09'23"W), UP2 (10°45'03"N, 74°07'08"W), and UP3 (10°47'10"N, 74°09'00"W), within the geographic limits of 10°39' - 10°55'N and 74°06' – 74°17'W.

The study area (Zona bananera), was characterized by a tropical warm and dry climate, with altitudes below 500 meters above sea level (masl), a mean annual temperature of 28 °C, and annual precipitation ranging from 1,000 to 2,000 mm. From a geomorphological perspective, the region corresponds to a foothills landscape, with fan-shaped relief, alluvial plains, and gently terraced slopes (1 – 3%). Soils were derived from shallow to moderately deep fluvial-marine deposits, presenting low salinity, seasonal fluctuations of the water table, and fine to medium textures. According to Soil Taxonomy, soils were classified as Typic Ustipsamments, Typic Ustorthents, and Typic Haplustolls (Aguirre-Forero et al. 2018).

Methodology

The study was established in three commercial banana plantations (*Musa acuminata* AAA cv. Williams), selected based on their agronomic history and the predominance of sandy soils classified as Typic Ustipsamments, as confirmed by core sampling and laboratory particle-size analysis.

The experiment followed a completely randomized block design. Four fertilization strategies were evaluated as treatments: Liquid soil fertilization (Drench) (Llanos Ríos et al. 2021), Foliar (Islam et al. 2023; Patil et al. 2018), conventional soil fertilization (Guimarães et al. 2020), and injection into pseudostem (Guevara et al. 2021; Islam et al.

2023) (Table 1). Each treatment was replicated five times per productive unit, resulting in a total of 60 experimental units, each consisting of 12 plants.

An absolute control was not included due to the commercial nature of the plantations, where nutrient omission was not agronomically or operationally feasible. From a methodological standpoint, conventional soil fertilization was therefore considered the reference treatment, as it represents the standard nutrient management practice in the region and allowed comparative evaluation of alternative fertilization methods under realistic production conditions.

All fertilization treatments were designed to provide comparable total nutrient inputs over the production cycle, although differences in application method and nutrient availability dynamics were inherent to each strategy.

Table 1. Evaluated treatments, products and application frequency.

Treatment	Application method	Quantity/plant	Applications	Nutritional composition (% - g L^{-1})
1	Drench: Liquid fertilization to soil	200 mL	8 each 15 days	Physical mixture N–K (17–0–28) enriched with Ca (0.5%), Mg (1%), and S (2%)
2	Injection into the mother's pseudostem + edaphic fertilization.	60 mL per plant (injection) + 120 g per plant (edaphic)	2 in the vegetative phase and in the reproductive phase	Free amino acid solution (35.2%) with N (5.7%) and K_2O (29%); highly soluble solid N–P–K supplement
3	Edaphic + Foliar application	Integrated fertilization (macro + micro + anti-stress)	8 applications each 15 days	Amino acids (35.2%), N (5.7%) and K_2O (29%); soluble N–P–K fertilizer (10.2–55.1–11.6) with micronutrients; anti-stress mixture (N–P–K–Mg) with micronutrients
4	Edaphic application (nutritional control)	120 g per plant	8 each 15 days	Physical N–K mixture (17–0–28) enriched with Ca (0.5%), Mg (1%) and S (2%)

The aim of this study was not to compare equivalent fertilizer doses or identical nutrient formulations, but rather to evaluate different fertilizer application strategies as implemented under commercial banana production conditions. Consequently, fertilizer types, formulations, and application rates differed among treatments. Each fertilization strategy was designed to meet the nutritional requirements recommended for banana cultivation in the region, considering both crop demand and prevailing soil fertility conditions. Therefore, the observed differences in plant performance reflect the combined effect of application method, nutrient availability, and synchronization between nutrient supply and plant uptake, which is representative of real-world fertilization practices in commercial banana systems. Future research should evaluate adjustments to nutrient proportions and the frequency of foliar applications based on plant phenological stages and the specific nutrient retention capacity of each soil.

Plant material

The cultivar Williams (Cavendish subgroup) was used, established at a planting density of 2,000 plants per ha. Plants were selected at an early flowering stage, exhibiting homogeneous growth, pseudostem heights exceeding 100 cm, and a minimum of 10 fully functional leaves, in order to reduce intra-treatment variability. Mother plants were identified using coded plastic tags indicating treatment, replication, experimental unit, and initiation date.

Soil sampling and analysis

Soil samples were collected prior to trial establishment and subsequently between the onset of flowering and bunch filling, a phenological stage characterized by high nutrient demand in banana. Sampling was conducted from 0–20 cm soil layer, corresponding to the zone of highest root density and nutrient uptake activity in banana crops, particularly in sandy soils.

Composite samples were obtained from each unit and analyzed in duplicate following standard laboratory protocols (ISO/IEC 17025:2017). Soil pH and electrical conductivity were determined by potentiometry. Texture was determined using the Bouyoucos hydrometer method, bulk density by the core method, and organic matter content by the Walkley–Black procedure. Total nitrogen was quantified using Kjeldahl method. Exchangeable Ca, Mg, K and Na were extracted with 1 N ammonium acetate at pH=7 and measured by atomic absorption spectrophotometry. Available phosphorous was determined by the Bray method, sulfur by manual spectrophotometry, and micronutrients (Fe, Mn, Cu, Zn, and B) by atomic absorption spectrophotometry.

The plantations soils were characterized by a pH=5.9 and an electrical conductivity (EC) of 0.2 dS m^{-1} (potentiometry), soil texture (Bouyoucos), bulk density (a) of 1.6 g cm^{-3} (core method), soil organic matter (OM) of 1% (Walkley-Black), total nitrogen (TN) of 0.1% (Kjendahl), calcium (Ca) of 3.1 cmol(+) kg^{-1}, magnesium (Mg) of 1 cmol(+) kg^{-1}, potassium (K) of 0.1 cmol(+) kg^{-1}, and sodium (Na) of 0.2 cmol(+) kg^{-1} (Extraction with 1 N ammonium acetate at pH=7 and measured by atomic absorption spectrophotometry), phosphorus (P) of 86 mg kg^{-1} (Bray procedure), sulfur (S) of 24.4 mg kg^{-1} (soil extract, manual spectrophotometry), iron (Fe) of 91 mg kg^{-1}, manganese (Mn) of 13.8 mg kg^{-1}, copper (Cu) of 40.7 mg kg^{-1}, zinc (Zn) of 3.4 mg kg^{-1}, and boron (B) of 0.3 mg kg^{-1} (atomic absorption spectrophotometry).

Leaf sampling and analysis

Leaf sampling was performed during two productive cycles (mother plants and daughter plants), concurrently with soil sampling. The uppermost fully expanded functional leaf was selected, and tissue was collected from the central portion of the lamina (Sun et al. 2020), following established diagnostic criteria for banana.

Samples were immediately frozen using liquid nitrogen to prevent enzymatic activity and nutrient redistribution, ensuring preservation of tissue integrity prior to laboratory analysis. Chemical analyses were conducted in duplicate. Macronutrients (N, P, K, Ca, Mg, S, and Na) were expressed as percentages of dry matter, while micronutrients (Fe, Mn, Cu, Zn, B, and Cr) were expressed in mg kg^{-1} of dry matter.

Vegetative and yield parameters

In each cycle, dates from flowering to harvest were collected to measure plant height (H) in cm, number of functional leaves (NL), pseudostem diameter (PsD) in cm, number of bunches per PU (NB), fresh bunch weight (FBW) in kg, and total cumulative weight (TW) in kg ha^{-1}. Total yield was calculated as the cumulative fresh weight of harvested bunches per experimental unit and extrapolated to a per-hectare basis, considering the established planting density. No additional corrections for plant density were required, as stand uniformity was maintained throughout the experiment.

Data analysis

Data were analyzed using Analysis of variance (ANOVA) under a completely randomized block design. Prior to analysis, assumptions of normality and homogeneity of variances were calculated. When significant differences were detected, means were compared using the Tukey-test at the *P*=0.05 level of significance. Pearson Correlation analysis at *P*=0.05 level of significance was applied to nutrient foliar contents and agricultural parameters using Statistica 13.3 and R statistical software.

RESULTS AND DISCUSSION

Soil analysis

The results of the soil analyses per production unit are shown in Table 2. Initial results indicated that the evaluated soils possess low natural fertility. The pH ranged from 5.70 to 6.30, indicating a slightly acidic reaction, typical of tropical soils, which are generally suitable for banana crops (Mihai et al. 2023). Even so, values close to 5.7 may limit the availability of essential nutrients, such as phosphorus, calcium, and magnesium (Agegnehu et al. 2021; Mihai et al. 2023). Bulk density values (1.52–1.60 g cm^{-3}) were acceptable for agricultural soils; coupled with the low organic matter content (<2%), these findings confirm a predominantly sandy texture and a soil structure with limited aggregation (Kumar et al. 2019), as well as poor water and nutrient retention capacity. Such characteristics reflect soils with a reduced capacity to form organo-mineral complexes. Electrical conductivity (0.19–0.25 dS m^{-1}) was within normal ranges, indicating an absence of salinity (Tessema et al. 2022) and favorable conditions for root development. Concerning total nitrogen levels, they were low (0.05–0.06%), consistent

Table 2. Average data of soil properties from the samples collected by PU in two productive cycles.

Characteristic		Initial results			Final results			
	Units	PU1	PU2	PU3	PU1	PU2	PU3	R.V
pH		5.76±0.2a	5.7±0.25a	6.30±0.3b	5.8±0.1ab	5.6±0.3a	6.3±0.4b	5.5-6.5
Da	g cm^{-3}	1.52±0.05a	1.6±1.2a	1.59±0.5a	1.5±0.03a	1.6±1.3a	1.6±0.5a	
Sand	%	78	75	70	78	75	70	
Clay	%	8	8	10	8	8	10	
CE	dS m^{-1}	0.24±0.6a	0.19±0.3a	0.25±0.7a	0.25±0.6a	0.24±0.4a	0.27±0.6a	
MO	%	1.05a	0.90a	1.01a	0.9a	1.0a	0.9a	
NT	%	0.05±0.003a	0.06±0.001a	0.05±0.004a	0.07±0.001a	0.15±0.003a	0.15±0.001a	0.01-0.02
CICE	cmol(+) kg^{-1}	4.66±0.2a	3.92±0.17a	4.98±0.5a	4.7±0.19a	4.59±0.25a	4.8±0.4a	
Na	cmol(+) kg^{-1}	0.23±0.02a	0.23±0.01a	0.28±0.01a	0.25±0.03a	0.20±0.03a	0.20±0.01a	<1.0
Ca	cmol(+) kg^{-1}	3.09±0.05a	2.40±0.01b	3.72±0.03a	6.43±0.024	6.32±0.02a	6.32±0.04a	3-6
Mg	cmol(+) kg^{-1}	1.15±0.07a	0.68±0.01b	1.09±0.02a	1.67±0.05a	1.16±0.06a	1.16±0.03a	1-3
K	cmol(+) kg^{-1}	0.19±0.01a	0.13±0.015a	0.10±0.02a	0.21±0.01a	0.17±0.023a	0.17±0.19a	0.2-0.5
P	mg kg^{-1}	75.0±1.65a	123±0.05b	60.7±1.83a	74.7±1.35a	79.3±1.05a	79.3±1.24a	10-20
S	mg kg^{-1}	19.8±1.17a	30.3±2.03a	23.2±1.2a	15.4±1.03a	11.1±0.06a	11.1±0.09a	12-20
Fe	mg kg^{-1}	109±4.77a	69.4±3.02a	95.2±3.2302a	98.5±3.45a	87.2±2.99a	87.2±2.23a	
Mn	mg kg^{-1}	14.6±0.06a	11.6±0.03a	15.3±0.08a	15.3±0.02a	15.8±0.01a	15.8±0.04a	
Cu	mg kg^{-1}	65±10.5a	23.5±6.06b	33.7±9.06b	49.0±12.2a	55.7±10.02a	55.7±6.04a	
Zn	mg kg^{-1}	5.46±0.7a	3.2±0.4a	1.67±0.3a	5.03±0.5a	6.39±0.8a	6.39±0.2a	3-15
B	mg kg^{-1}	0.306±0.02a	0.38±0.01a	0.29±0.01a	0.23±0.01a	0.204±0.02a	0.24±0.02a	0.2-0.7
Texture		Sand to sand-loamy						Loamy

Means with the same letters are not statistically different from each other (Tukey>0.05). R.V: Reference values by Topcuoğlu (2021).

with the reduced organic matter (OM) content, thereby confirming the system's limited capacity to meet the N demands of the banana crop. Nitrogen is the most required and absorbed nutrient throughout both the vegetative and reproductive stages (Nofal and Rezk 2021).

Cation exchange capacity (CEC) exhibited moderate values (3.92–4.98 cmol(+) kg^{-1}), typical of sandy soils with low organic matter content. This observation aligns with the findings of Chaudhary et al. (2025), who noted that sandy soils exhibit agronomic limitations due to their low nutrient concentration and poor retention capacity, which affects their natural fertility. Nonetheless, these soils can be used effectively for banana production if adequate fertilization strategies and appropriate management technologies are implemented. So, improving technological and financial conditions enables sandy soils to support tropical crops efficiently, such as bananas, thereby enhancing productivity while reducing traditional soil limitations. This scenario necessitates adjusted fertilization practices, including split doses and more frequent applications to minimize losses through leaching (Chaudhary et al. 2025). The green manure, as well as crop rotation, need to be implemented, along with adequate irrigation.

Among the exchangeable cations, calcium and magnesium were within acceptable ranges, although specific deficiencies were identified in PU 2. This observation indicates the degree of leaching in sand soil (Osman 2018). Exchangeable potassium levels were low across all sampling points (0.097–0.185 cmol(+) kg^{-1}), falling below crop requirements, thereby highlighting the need to prioritize its inclusion in fertilization programs due to high demand for nutrients from bananas grown in soils prone to salinity, mainly with sodium salts, and low fertility (Leonel et al. 2020). Phosphorus exhibited high spatial variability (60.7–123 mg kg^{-1}), with evidence of over-fertilization in PU 2, possibly due to the accumulation of previous applications. Leonel et al. (2020) highlights this observation, noting that higher levels of phosphorus increase the commercial value of bananas resulting in better yields.

Regarding micronutrients, copper levels were low at PU 2 and 3. Zinc exhibited widespread deficiency, particularly at PU 3 (1.67 mg kg^{-1}), while iron, manganese, and boron were within adequate ranges for tropical crops.

Following treatment's application, the final soil analysis revealed significant improvements in key nutrients concentrations, particularly total nitrogen, potassium, calcium, magnesium, zinc, and copper. Nitrogen increased to 0.146%, indicating greater availability and a probable improvement in the mineralization of organic matter. Calcium and magnesium contents doubled in some areas, enhancing cation balance and neutralizing negative charges in the rhizosphere, conditions that indirectly favor the uptake of other essential nutrients, such as potassium and phosphorus.

Potassium levels generally increase, reaching values close to 0.21 cmol(+) kg^{-1}, representing a marked improvement in the availability of this critical element for both bunch yield and quality. Phosphorus, by contrast, showed a slight decrease at all points (e.g., UP 2: from 123 to 79.3 mg kg^{-1}), likely due to high crop uptake during active growth stages. Nonetheless, final levels remained within an adequate range.

Sulfur (S) levels declined across all points, possibly due to leaching or high crop demand, thereby justifying its inclusion in future fertilization plans. In contrast, zinc and copper concentrations increased, especially at PU 3 (from 1.67 to 6.39 mg kg^{-1} zinc), exceeding critical sufficiency thresholds.

As expected, no substantial changes were observed in the soil physical properties (pH, bulk density, or OM), confirming that the treatment effects were predominantly chemical rather than structural. Table 3 shows the results of leaf content per production unit for the mother plant and the daughter plant.

Foliar analyses

Foliar analyses revealed differences in nutrient concentration between mother and daughter plants across the three PU evaluated (Table 3). In general, nitrogen (N) levels were within the appropriate range for *Musa* spp. (>2.2%), with slightly higher values observed in daughter plants, particularly in PU 2 (2.76%), suggesting effective absorption during the early vegetative stage.

Phosphorus (P) showed adequate concentrations in mother plants (0.194–0.22%) but exhibited a significant decrease in the daughter plants of PU 3 (0.141%). This

Table 3. Leaf content in mother and daughter plants in tree PU located at Zona Bananera of Magdalena.

Characteristic	Units	Mother plant			Daughter plant		
		PU1	PU2	PU3	PU1	PU2	PU3
N	%	2.29±0.03	2.6±0.004	2.42±0.001	2.26±0.15	2.76±0.08	2.39±0.24
P	%	0.20±0.01	0.22±0.00	0.19±0.03	0.22±0.02	0.22±0.04	0.14±0.009
K	%	2.9±0.20	3.3±0.03	2.77±0.001	3.77±0.39	3.03±0.37	2.06±0.15
Ca	%	0.51±0.001	0.75±0.001	0.69±0.03	0.54±0.03	0.65±0.11	0.44±0.07
Mg	%	0.24±0.001	0.25±0.004	0.23±0.06	0.24±0.01	0.25±0.01	0.24±0.02
S	%	0.19±0.002	0.22±0.003	0.20±0.001	0.18±0.01	0.25±0.04	0.12±0.02
Na	mg kg^{-1}	102±16.2	61.5±4.01	65±3.05	86.3±6.14	108±10.6	110±3.93
Fe	mg kg^{-1}	118±7.07	106±0.001	117±0.02	75.3±4.3	79.9±8.74	65.5±3.37
Mn	mg kg^{-1}	238±15.9	320±0.001	299±0.6	263±32.15	278±31.4	216±29.54
Cu	mg kg^{-1}	11.7±0.22	8.2±0.001	10.4±0.06	11.7±0.13	8.56±2.04	9.67±0.60
Zn	mg kg^{-1}	21±0.176	24.5±0.002	90.4±0.01	19±1.03	15.8±3.76	17.9±0.90
B	mg kg^{-1}	47.7±5.39	31.4±0.001	63.2±0.001	43.7±6.59	21.1±8.13	16.8±5.01
Cr	%	1.16±0.149	0.74±0.001	0.97±0.001	1.11±0.08	0.66±0.11	0.93±0.11

observation differs from that reported by Cândido et al. (2025), who, working with the Belluna variety, found higher macronutrient contents in the daughter plants. The reduction in P foliar content may be attributed to a combination of soil limitations. Primarily, soil acidity promotes the P fixation through adsorption to Al and Fe oxides (Mitra et al. 2023), this condition is aggravated by its negative impact on the biomass and activity of phosphate-solubilizing microorganisms, further limiting the mobilization of P form organic and inorganic reserves that generate a radicular competition between plants and microorganisms (Wang et al. 2021). Regarding potassium (K), the daughter plants in PU 1 displayed the highest values (3.77%). In contrast, in PU 3, it decreased to 2.06%, falling below the critical threshold (>2.4%), which could negatively affect carbohydrate transport and fruit filling.

Calcium (Ca) and magnesium (Mg) levels were generally lower in the daughter plants, especially in PU 3 (Ca: 0.435%, Mg: 0.241%), in line with their limited mobility in the plant and previously identified soil deficiencies, particularly at PU 2. Sulfur (S) showed a significant decrease in the daughter plants of PU 3 (0.122%), which could compromise amino acid synthesis and nitrogen metabolism efficiency. In terms of micronutrients, iron (Fe) levels decreased in daughter plants, with the lowest concentration observed in PU 3 (65.5 mg kg^{-1}), although this level still falls within an acceptable range. Cândido et al. (2025) reported higher foliar Fe in "Belluna" banana for the first crop season. Zinc (Zn) exhibited high variability. The mother plant in PU 3 reached an atypically high value (90.4 mg kg^{-1}). In comparison, the daughter plants showed considerably lower concentrations (15.8–19 mg kg^{-1} Zn), suggesting a possible functional deficiency linked to low soil availability. This finding suggests that zinc (Zn) application is necessary to increase banana yield as reported by Meya et al. (2020). Copper (Cu) and manganese (Mn) levels remained stable and within adequate ranges across all samples.

Boron (B) levels decreased in daughter plants, with the lowest value recorded in PU 3 (16.8 mg kg^{-1}), which potentially affected meristematic growth and reproductive processes. In this context, Álvarez-Herrera et al. (2025) reported that acidic soils are often deficient in boron and that their application can significantly enhance fruit yield and quality.

Overall, the foliar results indicate a general trend of reduced macro- and micronutrient concentrations in the daughter plants, particularly in PU 3. This pattern suggests lower absorption efficiency during the early stages of development, likely due to limiting soil conditions and the low availability of mobile elements, such as K, Zn, and B. These findings underscore the need for phenologically differentiated

nutritional management strategies adapted to the specific soil conditions of each productive unit.

In support of this, Nyombi (2020) highlights the critical role of potassium in the physiology and productivity of *Musa* spp. The same author, in studies conducted in Uganda, found that the highest yields were achieved through soil application of K, even under conditions of low foliar concentration of N and K. In particular, the 400N–50P–250K treatment was associated with higher absorption efficiency and productivity. Meanwhile, the most successful treatments in the second cycle (daughter plants) exhibited lower foliar concentrations of N, P, and K, indicating greater nutrient use efficiency.

Agronomic parameters

Significant differences were observed in fresh bunch weight (FBW), with the highest value documented at PU 2 (24.41 kg), followed by PU 1 (21.20 kg) and PU 3 (19.69 kg). This difference is likely linked to increased nutrient availability, particularly nitrogen and potassium, as well as improved absorption efficiency (Guimarães et al. 2020), as indicated by both foliar and soil studies.

Plant height (H) was marginally elevated at PU 1 (312 cm), exhibiting no significant differences from the other PU, indicating a relatively homogeneous vegetative response. The higher number of hands (NH) and greater fresh bunch weight (FBW) noted at PU 2 indicate superior allocation of assimilates to reproductive structures facilitated by more balanced nutritional conditions, as indicated by Deus et al. (2020), Chamling and Bhowmick (2021), and Chaudhary et al. (2025). The number of bunches per PU (NB) was most significant at PU 1 (50.15), followed by PU 2 (49.56) and PU 3 (43.88). This pattern may be associated with the soil concentrations of Ca, N, and K, which are essential elements for flowering and fruit development (Meya et al. 2020). The number of hands per bunch (NH) was most significant at PU 2 (7.10), indicating better-structured bunches with increased commercial value. The minimum NB value was observed at PU 3 (6.42), corresponding with its reduced fruit bunch weight (FBW).

Pseudostem diameter (PsD) was marginally larger at PU1 (68.66 cm), followed by PU2 (68.20 cm) and PU3 (67.09 cm). This characteristic is positively related to structural resilience and the plant's capacity to sustain bigger bunches.

The total cumulative weight (TW) was markedly greater at PU2 (1,210.21 kg), followed by PU1 (1,060.66 kg) and PU3 (862.67 kg). This trend substantiates the direct correlation among soil fertility, plant nutritional condition, and productivity, results that are consistent with the experiences of Olivares et al. (2020). PU3 has deficiencies in K, P, S, and micronutrients, including Zn and B.

Effect of treatments on agronomic performance

The treatments evaluated showed notable differences in agronomic performance (Table 4). Treatment T3 (soil + foliar fertilization) produced the highest average FBW (23.00 kg), followed by T4 (conventional soil application), T2 (soil + microinjection), and T1 (drench application). These results suggest that combining soil and foliar fertilization enhances nutrient absorption efficiency during reproductive stages, resulting in heavier and more compact bunches.

Table 4. Agronomic performance by fertilizer application method.

Treatment	Fresh bunch weight (kg)	Hands (No.)	Pseudostem diameter (cm)	Total yield (kg)
T1 – Drench	21.3±1.8^{b}	6.79±0.07^{b}	67.9±1.4^{b}	1000.6±92^{c}
T2 – Soil + microinjection	22.8±1.6^{ab}	6.88±0.07^{ab}	68.2±1.2^{ab}	1045.8±88^{b}
T3 – Soil + foliar	23.0±1.7^{a}	6.94±0.07^{a}	69.4±1.1^{a}	1122.9±85^{a}
T4 – Conventional soil	22.0±1.5^{b}	6.79±0.07^{b}	68.0±1.3^{ab}	1043.9±90^{b}

Means ± standard deviations. Different letters within each column indicate significant differences according to Tuckey's test ($P \leq 0.05$).

The improved performance of T3 reflects the combined influence of fertilizer application strategy and nutrient composition. While the broader nutrient spectrum supplied in T3 enhanced plant nutrition, integrating soil and foliar

applications likely improved nutrient uptake efficiency under sandy soils conditions. These results highlight the importance of combining adequate nutrient supply with appropriate delivery methods in commercial banana production systems.

These results are consistent with those of Zhang et al. (2020), who reported that bananas responded more favorably to liquid fertilizers at recommended dosages, resulting in significantly increased yields compared to traditional soil fertilization. The application of nutrient solutions enhances nutrient bioavailability and promotes their assimilation under active physiological conditions, making this an effective strategy in intensive production systems.

Plant height (H) showed the highest value (314.4±5.67 cm) in T3, indicating improved vegetative development. The other treatments showed slightly lower values, with no marked differences. A similar pattern was observed in PsD, where T3 reached the highest average value (69.40±1.1 mm), followed by T2 and T4, reinforcing the link between structural plant robustness and productive potential.

T3 showed a slightly larger number of bunches (NB) (48.80±3), while treatment T4 (commercial control) reported the lowest (46.72), accompanied by a higher standard deviation (±8.52), suggesting greater variability among experimental units. For the number of hands per bunch (NH), T3 again recorded the highest value (6.94±0.57), surpassing all other treatments, indicating more compact and commercially desirable bunches.

The highest pseudostem diameter values were observed, with significant differences (P<0.01) in treatment 3 (69.4±2.14 cm) and treatment 4 (68.03±2.2 cm). These results differ from those reported by Galvis et al. (2013), who obtained homogeneous results. However, these authors agree on the importance of this parameter in achieving a greater number of hands, which depends on the stages before differentiation. These stages are the same ones that control the circumference of the pseudostem.

Total weight (TW) is considered the key indicator of productivity per experimental unit. T3 achieved the highest TW (1122.91±85 kg ha^{-1}), followed by T2 (1045.83±88 kg ha^{-1}), T4 (1043.93±9.0 kg ha^{-1}), and T1 (1000.56±92 kg ha^{-1}). These findings confirm that combined soil and foliar fertilization (T3) resulted in superior agronomic performance, with positive effects on both vegetative and reproductive traits. The superiority of this treatment is attributed to its enhanced efficiency in nutrient absorption and utilization.

These results align with those of Islam et al. (2023), who concluded that foliar fertilization complements soil fertilization effectively, reducing deficiencies and improving nutrient availability at critical phenological stages. The synergy between application methods enhances nutrient use efficiency, resulting in higher banana yield and fruit quality.

Correlation between foliar and agronomic variables

The correlation analysis of foliar content in mother and daughter plants (Figure 1), revealed linear relationships with agronomic variables. The Pearson correlation coefficient is represented visually by a color scale.

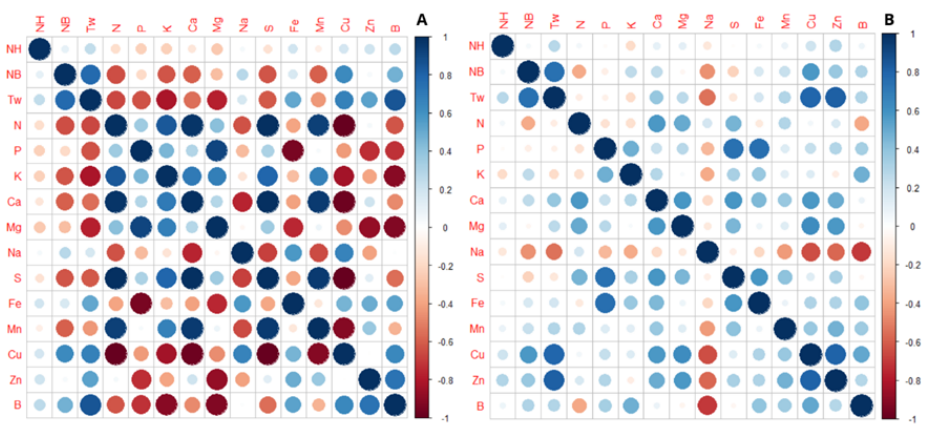


Figure 1. Correlation matrix of leaf content with agronomic variables in mother plants (A) and daughter plants (B).

The correlation matrix for mother plants revealed a strong positive correlation between the number of bunches (NB) and total weight (TW), as well as with foliar contents of N, K, and Ca, indicating that these nutrients are directly associated with yield.

Total weight (TW) was strongly correlated with P, K, Ca, and Zn, suggesting these elements play a key role in biomass accumulation. K, in particular, showed a high correlation with NB and TW due to its role in the translocation of photoassimilates, sugar transport, and cell growth, particularly in early stages of daughter plants (Chaudhary et al. 2025; Olivares et al. 2020). This observation is consistent with findings in other *Musaceae* production systems, reinforcing the need for adequate K supply to support vigorous early growth and subsequent reproductive success. N correlated with P and K, reflecting a synergistic interaction in macronutrient uptake and distribution and highlighting the importance of considering nutrient balance rather than focusing on individual nutrient levels (Rengel et al. 2022). Ca and Mg showed a positive and significant correlation, indicating good availability in the soil-plant system or complementary effects on nutrition.

Among the micronutrients, zinc (Zn) exhibited a positive relationship with total weight (TW) and the number of bunches (NB), highlighting its role in enzymatic and physiological functions associated with productivity. Boron (B) showed moderate correlations with NH, reinforcing its importance in cell division and meristem growth (Chaudhary et al. 2025). Since B deficiency can affect early tissue formation and yield potential, especially in acidic and sandy soils, it is essential to consider it in the fertilization plans.

The correlation matrix for mother plants (Figure 1A) indicates that yield and agronomic performance are strongly influenced by the availability and foliar accumulation of K, P, Ca, and Zn, as well as N, which serves as a structural base. These nutrients exhibited significant relationships with production variables (NB, TW), highlighting their importance in fertilization programs, particularly during fruit development (Aguirre et al. 2015). This approach adheres to Smith et al. (2018), which emphasizes the importance of nutrition at each specific stage of development.

When analyzing the correlation matrix of foliar content in daughter plants (Figure 1B), functional relationships were identified between nutritional status and agronomic variables related to early development. Total weight (TW) showed a strong positive correlation with K and a moderate correlation with N and P, indicating the importance of these macronutrients in early biomass accumulation (Rengel et al. 2022). This highlights the crop's high demand for K during the initial stages, where it directly influences cell expansion and sugar transport. NB correlated positively with K, Ca, and Zn, indicating their role in reproductive development. N, P, and K correlations were consistent and significant, demonstrating their synergistic role in basal nutrition and early growth.

Micronutrients, such as B, showed positive associations with NB and NH, reinforcing their importance in cell division and tissue elongation during the vegetative stages (Meya et al. 2020). Deficiency, common in acidic and sandy soils, may compromise the formation of new tissues if not corrected promptly. Fe, Mn, and Cu showed less consistent correlations with development variables.

The daughter plant matrix shows that K, N, P, Ca, Zn, and B are key for early growth, leaf development, and the formation of initial reproductive structures. These associations suggest that early-stage yield potential can be improved through fertilization strategies that prioritize these nutrients.

Comparing the correlation matrices, potassium (K) emerged as the nutrient with the greatest number of significant positive correlations, particularly with TW and NB, confirming its central role in yield across both juvenile and reproductive stages. Notably, the correlation between K and TW was stronger in daughter plants, suggesting greater sensitivity to K deficiencies during early development when root systems are still forming and energy demands are high.

Nitrogen (N) showed consistent correlations with P and K in both generations, indicating a stable synergistic interaction during absorption. In mother plants, these relationships extended to variables such as the number of hands (NH) and total weight (TW), indicating a broader integration of N in advanced reproductive processes. Calcium (Ca) and magnesium (Mg) showed positive

correlations, more pronounced in mother plants, where they were associated with NB.

Zinc (Zn) showed a positive correlation with yield variables in both matrices, but its influence was more substantial in the mother plants. In contrast, Boron (B) showed greater relevance in daughter plants, correlating with NH and NB and reaffirming its role in early development, cell differentiation, and meristem growth.

Finally, the structure of correlations between foliar and agronomic variables varies across different phenological stages. In mother plants, correlations were more complex and diversified, reflecting ongoing reproductive processes. In daughter plants, correlations were more focused, dominated by essential nutrients such as K, N, P, Zn, and B that sustain vegetative growth. These findings reinforce the importance of stage-specific nutritional management (prioritizing K, B, and Zn in early stages and reinforcing Ca, Mg, and P during fruiting). A phonologically and site-specific fertilization strategy could improve nutrient efficiency and maximize banana yield in low-fertility soils.

CONCLUSION

The combined study showed that the Soil + foliar fertilization treatment (T3) was most effective in enhancing banana growth and yield in sandy soils. This superior performance is attributed to increased nutrient-use efficiency enabled by dual-pathway nutrient supply, which optimizes both foliar nutrient uptake and soil nutrient availability. This integrated approach mitigates nutrient losses and ensures nutrient concentration throughout critical phenological stages.

From a nutritional dynamic's perspective, this method promoted a more balanced uptake of macronutrients — primarily nitrogen, potassium, and calcium — which enhanced the pseudostems' structural integrity and optimized source-sink relationships during bunch filling.

Consequently, the results validate integrated fertilization as a sustainable intensification strategy for banana cropping systems on sandy or nutrient-deficient soils. This practice increases nutrient recovery efficiency, minimizes environmental losses, and enhances crop resilience, profitability, and environmental sustainability in tropical agroecosystems. However, observed variability across production units underscores the necessity for site-specific fertilization protocols. These should be based on integrated soil-plant diagnostic monitoring and precise nutrient management adjustments that maximize crop potential while preserving ecological balance.

Further development of adaptive nutritional management strategies is recommended. Future research should evaluate adjustments to nutrient proportions and the frequency of foliar applications based on plant phenological stages and the specific nutrient retention capacity of each soil.

CONFLICT OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could be perceived as influencing the work presented in this article.

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