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Predictive value of soil exchangeable potassium in mycorrhiza-inoculated banana under organic-mineral fertilization in Cuban Cambisols*

Valor predictivo del potasio intercambiable del suelo en banano inoculado con micorrizas bajo fertilización orgánico mineral en cambisoles cubanos

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Abstract

Introduction. Banana is a multi-cycle crop, with a high potassium (K) demand, and soil K analysis guides fertilization. Mycorrhizal inoculation reduces fertilizer K needs, yet soil-based K recommendations for inoculated systems remain undefined. **Objective.** To establish a soil potassium threshold for guiding fertilization in arbuscular mycorrhizal fungi (AMF)-inoculated banana crops under organic mineral fertilization. **Materials and methods.** Two experiments were conducted in Santo Domingo, Cuba, on Eutric Cambisols using the FHIA-18 cultivar. Both followed a randomized block design with four replicates. The first evaluated five organic-mineral fertilization (OMF) doses, with or without *Rhizoglomus irregulare* inoculation across mother plant and first ratoon cycles, and included measurements of yield, mycorrhizal indicators, foliar NPK concentrations, and soil fertility. The second, conducted across three crop cycles, involved combinations of OMF doses, *Canavalia ensiformis* as green manure, AMF inoculation, and mineral fertilization. In this experiment, only information about soil fertility and relative yield was used. Statistical analyses included ANOVA, while critical thresholds were identified using Cate-Nelson successive partitioning. **Results.** Banana yield increased with OMF dose, and AMF inoculation reduced the OMF requirement by 25 %, associated with higher colonization and improved K uptake. Soil exchangeable K allowed the establishment of soil K-based fertilization thresholds. Inoculation reduced the critical soil K thresholds relative to non-inoculated banana, which reflects enhanced mycorrhizal K acquisition efficiency. The canavalia reduced OMF requirements in inoculated banana but did not alter the soil K index, which remained consistent across inoculated treatments regardless of fertilizer sources. The index functioned as a sufficiency index for K fertilization. **Conclusions.** The soil K-based index established for AMF-inoculated banana defines the soil K threshold and provides a practical tool for assessing K fertilization sufficiency and guiding input adjustments under the tested edaphic conditions.

Keywords: arbuscular mycorrhizas, *Canavalia ensiformis*, fertilizer application, *Musa* spp., soil test values.

Resumen

Introducción. El banano es un cultivo de múltiples ciclos con alta demanda de potasio (K), y el análisis de K en el suelo orienta la fertilización. La inoculación micorrízica reduce los requerimientos de fertilizante potásico, aunque faltan criterios de recomendación basados en el suelo para sistemas inoculados. **Objetivo.** Establecer un umbral de potasio en el suelo para orientar la fertilización en cultivos de banano inoculados con hongos micorrízicos arbusculares bajo fertilización orgánico-mineral. **Materiales y métodos.** Se realizaron dos experimentos con el cultivar FHIA-18 en Santo Domingo, Cuba, sobre Cambisoles eútricos, ambos con diseño de bloques al azar y cuatro repeticiones. El primero evaluó cinco dosis de fertilización orgánico-mineral (OMF), con y sin inoculación con *Rhizoglomus irregulare*, en los ciclos de planta madre y retoño. Se midieron rendimiento, variables micorrízicas, NPK foliar y fertilidad del suelo. El segundo abarcó tres ciclos productivos y combinó dosis de OMF, *Canavalia ensiformis* como abono verde, inoculación micorrízica y fertilización mineral; solo se procesaron las evaluaciones de fertilidad del suelo y el rendimiento relativo. El análisis estadístico incluyó ANOVA y la partición de Cate Nelson para definir umbrales críticos. **Resultados**. El rendimiento del banano aumentó con la dosis de OMF, y la inoculación con hongos micorrízicos arbusculares redujo el requerimiento de OMF en un 25 %, asociado con una mayor colonización y una mejor absorción de K. El K intercambiable permitió definir umbrales de fertilización. La inoculación redujo estos umbrales frente al banano no inoculado por su mayor eficiencia de adquisición de K. La canavalia redujo los requerimientos de OMF en banano inoculado, sin modificar el índice de K, que se mantuvo estable en los tratamientos inoculados, independientemente del fertilizante empleado. El índice funcionó como criterio de suficiencia para la fertilización potásica. **Conclusiones.** El índice de K establecido para banano inoculado define el umbral crítico del suelo y constituye una herramienta práctica para evaluar la suficiencia de fertilización potásica bajo las condiciones edáficas evaluadas.

Palabras clave: aplicación de fertilizantes, micorrizas arbusculares, *Canavalia ensiformis*, *Musa* spp., valores de análisis de suelo.

Introduction

Banana (*Musa* spp.) is a staple food crop worldwide, with an average yield of 23.3 t ha^{-1} globally in 2023 (Food and Agriculture Organization of the United Nations [FAO], n.d.). In Cuba, banana is cultivated on more than 30,000 ha annually, yet productivity remains relatively low, not exceeding 8 t ha^{-1} (Oficina Nacional de Estadísticas e Información [ONEI], 2024). This productivity gap is largely due to nutrient limitations, as banana plants require substantial amounts of potassium (K) and nitrogen (N) to sustain high yields (González Santos, 2024). However, they require much smaller amounts of phosphorus (P) (Espinosa & Mite, 1995).

Fertilizer requirements in banana vary according to cultivar, management practices, and soil conditions. In several Latin American countries, yields of 30–40 t ha^{-1} require 600–800 kg ha^{-1} of K_2O per cycle (Figueroa & Luppi, 2017). Cuban recommendations are higher: 1,000 kg ha^{-1} of K_2O (Ministerio de la Agricultura [MINAG], 2011). These elevated K inputs likely respond to high levels of soil exchangeable bases, as most Cuban agricultural soils derive from calcareous sediments (Rivera Espinosa et al., 2023). This leads to potassium-exchangeable bases antagonism in soil, which limits K uptake efficiency in banana and increases fertilization demand (Espinosa & Mite, 1995; García et al., 1979). Understanding this interaction is essential for improving potassium management across diverse soil conditions.

The country's economic situation limits broader use of mineral fertilizers (Viktorov, 2023). Alternatively, organic fertilizers and non-conventional mineral sources have shown potential to sustain high productivity while

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reducing reliance on chemical inputs and enhancing microbiological activity and nutrient availability (Luo et al., 2018; Zhang et al., 2020). In Cuba, the recommended organic-mineral fertilization (OMF) scheme for banana includes 28 t ha^{-1} of compost and 14 t ha^{-1} of sugarcane straw ash per growth cycle (MINAG, 2011). However, widespread implementation across banana-producing regions remains constrained by limited resource availability.

The application of arbuscular mycorrhizal fungi (AMF)-based inoculants has emerged as a promising strategy to enhance nutrient uptake, improve plant growth, and reduce reliance on synthetic or organic fertilizers (Oviatt & Rillig, 2021; Schütz et al., 2018). The direct role of mycorrhizae in facilitating the absorption of key macronutrients, namely nitrogen, phosphorus, and potassium, is well established (Berger & Gutjahr, 2021; Liu et al., 2019; Wipf et al., 2019). In Cuba, inoculants based on generalist AMF strains—whose effectiveness depends on soil pH—have been successfully applied in mycotrophic crops and across contrasting soil types, with measurable reductions in the required fertilizer doses of each macronutrient (González et al., 2015; Rivera Espinosa & Espinosa-Cuéllar, 2026).

Bananas grown in Eutric Cambisols respond strongly to AMF inoculation, which leads to enhanced nutrient uptake and a 25 % reduction in NPK or OMF use (Ruiz Martínez et al., 2012). These reductions are insufficient given the limited availability of these sources. Integrating AMF-inoculated *Canavalia ensiformis* as green manure sustains effective mycorrhizal functioning and adds a substantial nutrient contribution. Its biomass recycles approximately 360, 28, and 260 kg ha^{-1} of N, P, and K, respectively, distributed evenly between the preceding and the intercropped canavalia during the mother plant cycle. This contribution supports high yields and allows reducing OMF to 25–50 % depending on the crop cycle (Simó González et al., 2016; Simó González et al., 2017).

Potassium is the main limiting nutrient for banana yield in Eutric Cambisol soils, and the K nutritional status of AMF-inoculated plants is directly dependent on mycorrhizal functioning (Simó González et al., 2020). Exchangeable soil K has proven useful for guiding potassium fertilization in banana plantations (Espinosa & Mite, 1995). Although inoculation reduces the critical soil nutrient thresholds (González et al., 2016) and diminishes K fertilizer requirements (Yuan et al., 2023), there is still no validated soil K index for guiding fertilization in inoculated crop systems, and banana is no exception. This gap limits both the broader adoption of mycorrhizal inoculants and the ability to achieve higher fertilization efficiency within integrated nutrient management strategies that rely on these inoculants.

Given that bananas are a multi-cycle crop, it is essential to recognize the relationship between soil potassium levels, yields, and the potassium supply system. In banana, K uptake for the current harvest ceases at flowering (Martin Prével, 1980; Moreira & Fageria, 2009), so the soil K available at that moment reflects the balance between the fertilization applied, the yield obtained, and the remaining exchangeable K, which in turn serves as the starting point for defining the fertilization required to sustain yield in the next cycle. Based on this, the study aimed to establish a soil potassium threshold for guiding fertilization in arbuscular mycorrhizal fungi (AMF)-inoculated banana crops under organic mineral fertilization.

Materials and methods

Two experiments were conducted on soils previously classified as Eutric Cambisols with carbonates (Espinosa-Cuéllar et al., 2023), according to the WRB system (IUSS Working Group WRB, 2022), in the experimental field of the Instituto de Investigaciones de Viandas Tropicales (INIVIT), Santo Domingo, Villa Clara province, Cuba (22°35′1.2″ N, 80°13′11.9″ W, 40 m a.s.l.). The FHIA-18 cultivar was used in both studies. The first experiment was carried out from April 2021 to December 2022, while the experiment conducted from April 2006 to October 2008 is hereafter referred to as the second experiment.

This study focused on soil analysis by integrating both experiments to evaluate exchangeable potassium levels and their relationship with banana relative yield under organic-mineral fertilization and AMF inoculation. The most recent experiment, designated here as the first, provided agronomic and mycorrhizal assessments, along with detailed insights into soil nutrient dynamics throughout the banana production cycle. The second experiment, although its agronomic and mycorrhizal results were previously published (Simó González et al., 2017), did not analyze or integrate the soil sampling data collected across growth cycles, and therefore no soil results were reported in that publication.

Although the two trials were conducted in different years, their integration is methodologically justified because the experimental conditions were highly consistent across both studies. The same soil type, cultivar, fertilization materials, planting density, irrigation regime, and agronomic management practices were used. Moreover, the use of relative yield, recommended for establishing critical soil nutrient indices by integrating data from multiple experiments with the same crop but under different edaphic and climatic conditions (Waugh et al., 1973), allows normalization of yield responses and reduces the effect of differences in absolute yield between years.

The soils exhibited chemical properties typical of Eutric Cambisols with carbonates (Table 1), particularly a slightly basic pH and high calcium and magnesium contents (Ruiz Martínez et al., 2012), with the latter explaining the low percentages of potassium in the exchangeable soil bases (García et al., 1979). The soil organic matter content was low, likely due to a history of intensive tropical root cultivation. The initial number of AMF spores was also low (<1 per g of soil), similar to other soils of this type cultivated under comparable conditions, likely due to decades of high NPK fertilizer application (Espinosa-Cuéllar et al., 2023). Initial soil properties were highly similar between trials, supporting the comparability of nutrient availability conditions.

Table 1. Initial chemical properties and mycorrhizal spore count of Eutric Cambisol soils with carbonates (0–20 cm depth). Santo Domingo, Cuba. Years 2006 and 2021.

Cuadro 1. Propiedades químicas y conteo de esporas micorrízicas al inicio de los experimentos sobre suelos Cambisoles eútricos con carbonatos (0-20 cm de profundidad). Santo Domingo, Cuba. Años 2006 y 2021.

Year	$pH\text{-}H_2O$[1]	OM[2] g kg^{-1}	P[3] mg g^{-1}	Ca[4] cmol$_c$ kg^{-1}	Mg[4]	K[4]	% K in exchangeable bases[5]	Spores[6] in 50 g soil
2006	7.85	21.01	3.10	44.94	3.24	0.40	0.82	47.50
$Z_{1-\alpha} \times S_{\bar{x}}$	±0.11	±1.19	±0.31	±1.20	±0.11	±0.09		±15.2
2021	7.79	20.8	3.19	38.46	3.21	0.40	0.95	40.50
$Z_{1-\alpha} \times S_{\bar{x}}$	±0.10	±0.11	±0.15	±2.04	±0.11	±0.10		±12.88

Each value represents the average of 8 samples. $Z_{1-\alpha} \times S_{\bar{x}}$: confidence interval ($\alpha = 0.05$, $n = 8$).
[1] **$pH\text{-}H_2O$**: pH measured in water. [2] **OM**: Soil organic matter. [3] **P**: Available phosphorus in soil. [4] **Ca**, **Mg**, **K**: Exchangeable cations. [5] **% K in exchangeable bases**: (K × 100) / (Ca + Mg + K). [6] **Spores**: Mycorrhizal spores. Chemical determinations in soil according to Paneque et al. (2010). Spore determinations according to Torres-Arias et al. (2015) / Cada valor representa el promedio de 8 muestras. $Z_{1-\alpha} \times S_{\bar{x}}$: intervalo de confianza (α = 0,05, n = 8). [1] **$pH\text{-}H_2O$**: pH medido en agua. [2] **OM**: Materia orgánica del suelo. [3] **P**: Fósforo disponible en el suelo. [4] **Ca**, **Mg**, **K**: Cationes intercambiables. [5] **% K en bases intercambiables**: (K × 100) / (Ca + Mg + K) . [6] **Esporas**: Esporas micorrízicas. Las determinaciones químicas en el suelo de acuerdo con Paneque et al. (2010). Las determinaciones de esporas de acuerdo con Torres-Arias et al. (2015).

Experiment design and treatments

The first experiment consisted of five levels of organic-mineral fertilization (OMF) (0, 25, 50, 75, and 100 %), with and without application of an inoculant formulated from *Rhizoglomus irregulare*, isolate INCAM-11/DAOM711363, for a total of 10 treatments (Table 2). The experiment was structured in a randomized block factorial design (2 × 5) with four replicates. OMF consisted of a mixture of compost and sugarcane ash, and the 100 % OMF rate (MINAG, 2011) involved applying 20 kg of compost and 10 kg of ash per plant per growth cycle. All OMF doses maintained

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a fixed 2:1 compost-to-ash ratio, which ensured consistency across treatments. Evaluations were conducted for the mother plant cycle (MP) and the first ratoon (FR).

Table 2. Different combinations of OMF doses with and without mycorrhizal inoculation, GMAMF with OMF doses, and reference treatments evaluated in both experiments (2006–2008 and 2021–2022) on Eutric Cambisol soils. Santo Domingo, Cuba.

Cuadro 2. Diferentes combinaciones de dosis de OMF con y sin inoculación micorrízica, de GMAMF con dosis de OMF y tratamientos de referencia evaluados en ambos experimentos (2006-2008 y 2021-2022) sobre suelos Cambisoles eútricos. Santo Domingo, Cuba.

Treatments	Experiment 1	Experiment 2
Absolute control	X	X
0 % OMF + AMF	X	
25 % OMF	X	
25 % OMF + AMF	X	
50 % OMF	X	
50 % OMF + AMF	X	
75 % OMF	X	X
75 % OMF + AMF	X	X
100 % OMF	X	X
100 % OMF + AMF	X	X
GMAMF		X
GMAMF + 25 % OMF + AMF		X
GMAMF + 50 % OMF + AMF		X
GMAMF + 75 % OMF + AMF		X
100 % NPK		X
75 % NPK + AMF		X

AMF: *Rhizoglomus irregulare* inoculant used both in banana (vitroplant and transplant) and in the canavalia. **OMF:** Organic-mineral fertilization; the OMF used in both trials had similar composition and relative proportions of nutrient sources. **GMAMF:** The canavalia inoculated with AMF used as green manure for banana. **NPK:** Mineral fertilization. / **AMF:** Inoculante basado en *Rhizoglomus irregulare* utilizado tanto en el banano (vitroplanta y trasplante) como en la canavalia. **OMF:** Fertilización orgánico-mineral; la OMF utilizada en ambos experimentos presentó composición y proporciones relativas similares de las fuentes. **GMAMF:** La canavalia inoculada con AMF y utilizada como abono verde para el banano. **NPK:** Fertilización mineral.

The second experiment evaluated the use of *Canavalia ensiformis* inoculated with *R. irregulare* (INCAM-11) as a preceding and intercropped green manure (GMAMF) for banana on the OMF requirements of inoculated banana (0 %, 25 %, 50 %, and 75 % OMF). Treatments with 75 % and 100 % OMF, with or without inoculation, were also studied. Finally, the experiment included an absolute control (no fertilization or inoculation), one with 100 % mineral fertilization (NPK), and another combining 75 % NPK with inoculation. In total, 11 treatments were evaluated in a randomized block design with four replicates and are summarized in Table 2. Evaluations covered the mother plant (MP), first ratoon (FR), and second ratoon (SR).

For the preceding crop, the canavalia was sown 70 days before banana planting at 0.5 m between rows and 0.2 m between plants (100,000 plants ha^{-1}). Plants grew for 60 days, were cut, and the biomass was incorporated into the soil before banana transplanting. For the intercropped system, the canavalia was sown 30 days after banana transplanting in seven rows within the 4 m banana spacing and three rows within the 2 m spacing, with the same sowing spacing and always 0.5 m away from banana rows, equivalent to 66,000 plants ha^{-1}. Intercropped plants were cut at 60 and 120 days after sowing, and the biomass was left as surface mulch over the banana rows.

Additional experimental conditions

Both experiments employed the same spatial planting distribution (4 m between double rows, 2 m between rows, and 2.4 m between plants), totaling 1,388 plants per hectare. Each experimental plot covered 144 m^2 and contained 20 plants, and all evaluations—yield, colonization frequency, mycorrhizal spores, foliar and soil analyses—were conducted on six central designated plants within a 43.2 m^2 area. Banana sucker selection and irrigation followed the Technical Guide for Banana Crop (MINAG, 2011).

The irrigation regime used (MINAG, 2011) met the high water requirements of banana for optimal development throughout the production cycles. It was applied via spraying, with three monthly applications (350 m^3) from November to February, and four monthly applications from March to May, until the spring rains began. During the rainy season, irrigation was applied only after more than 10 days without rain. Therefore, climatic conditions during both trials were comparable: temperature differences were minimal, precipitation variability had negligible effects because irrigation was applied uniformly and at sufficient intensity, effectively homogenizing moisture conditions across growth periods, and consequently, across years.

Inoculation with arbuscular mycorrhizal fungi

The inoculant was formulated from *Rhizoglomus irregulare* ([Błaszk., Wubet, Renker & Buscot] Sieverd., G.A. Silva & Oehl), specifically the INCAM-11/DAOM711363 isolate. This inoculant is recommended for mycotrophic crops cultivated in soils with a pH-H_2O range between 7 and 8 (Rivera Espinosa et al., 2020) and was used in both banana and canavalia. It was prepared as a solid formulation in a mineral substrate (Fernández Martín et al., 2000), containing 30 spores per gram, along with undetermined quantities of other infective propagules (mycelium and colonized root fragments), which were not quantified.

Inoculation of the canavalia was performed via seed coating, using an amount of inoculant equivalent to 8 % of seed weight (Rivera Espinosa et al., 2020). In banana, inoculation consisted of the application of 10 g per plant at the start of the acclimatization stage of *in vitro* plants in the nursery and 20 g per plant at the time of transplanting (Simó González et al., 2016). The inoculant was placed at the bottom of the planting hole, always below the roots and in direct contact with them.

Nutrient supply in banana plantations

The organic-mineral fertilization (OMF) consisted of separate applications of compost (19.5, 3.1, and 9.9 g kg^{-1} of N, P, and K, respectively) and sugarcane straw ash (6.6 g kg^{-1} of P and 42.8 g kg^{-1} of K). Their composition and the fixed compost-to-ash ratio remained consistent across experiments, which ensured valid comparisons. The synthetic fertilizer dose (100 % NPK) in the second experiment included 416 kg ha^{-1} of N (46-0-0) and 999 kg ha^{-1} of K_2O (0-0-50), both applied in each vegetative cycle, and 52 kg ha^{-1} of P_2O_5 (0-46-0), applied only during the mother plant cycle (MINAG, 2011).

For both organic-mineral and synthetic fertilizers, the same application method was used throughout the experiments, consistent with national technical guidelines. During the mother plant cycle (MP), fertilization was applied in two stages: Half of the dose was placed at the bottom of the planting row. The remaining dose was applied in circles around the plant 90 days after the initial application. In the ratoon cycles, fertilization was performed in two rounds: The first was made in a semi-circle in front of the pseudostem when 80–90 % of the plants from the previous cycle had been harvested. The second was carried out 60 days later. Management of banana plantations followed the recommendations outlined in the Technical Instruction Guidelines (MINAG, 2011).

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Evaluations

Although the evaluations described below were similar in both experiments, they refer specifically to Experiment 1, whose complete data are presented in this publication. The exceptions are the soil analysis and the relative yields for each treatment across productive cycles, which include data from both experiments because this information had not been previously published. For the calculation of relative yield in the treatments and cycles of Experiment 2, the absolute yield data were used exactly as reported by Simó González et al. (2017).

Soil samples and chemical determinations

Because banana is a determinate crop, nutrient absorption ceases at flowering (Martin-Prével, 1980). Banana plantations are propagated by suckers, which are selected when 80–90 % of the current cycle has been harvested and are immediately fertilized. Consequently, soil analysis at the end of harvest does not reflect the interaction between soil nutrient status, fertilization regime, and plant uptake for the cycle just completed, because it is already influenced by the fertilization applied to the emerging sucker. For this reason, soil sampling at flowering was used. This stage marks the end of nutrient uptake for the current cycle and enables linking soil analysis with fertilization doses and yields of both the current and the subsequent cycle.

Soil analysis was conducted at the beginning of each experiment with two composite samples per replicate, each consisting of 10 subsamples taken from a depth of 0–20 cm. During banana growth cycles, soil samples at flowering were collected from eight predefined locations per plant (15, 30, 45, 60, 75, 90, 105, and 120 cm), at a depth of 0–20 cm, and the samples followed a spiral pattern around the pseudostem (Simó González et al., 2017). Sampling was conducted on four plants per plot, and this procedure produced a total of 32 subsamples per plot, which were homogenized to form one composite sample per plot.

The methods employed for soil chemical determinations included the assessment of organic matter using the Walkley-Black method. Available phosphorus was extracted with ammonium carbonate solution (10 g L^{-1}, pH 9.0) and quantified by the blue color of the reduced molybdophosphoric complex. Exchangeable cations (Ca, Mg, K) were extracted using 1 M NH_4Ac at pH 7, at a soil-to-solution ratio of 1:5, and subsequently determined via flame photometry. All methodologies followed the guidelines detailed by Paneque et al. (2010).

AMF spores

The number of spores in 50 g of soil was determined both at the beginning of the experiment and at the flowering stage of each banana cycle, from soil samples collected. Spore extraction followed the wet sieving method, as described by Torres-Arias et al. (2015). Extracted spores were washed with distilled water and placed in Doncaster plates. Enumeration was performed using a stereomicroscope, with results expressed as spores per 50 g of soil.

Mycorrhizal colonization frequency

The percentage of mycorrhizal root colonization in banana was assessed using fine roots collected at the flowering stage of each cycle. Root samples from four banana plants per plot were taken during soil sampling. Approximately 200 mg of fine roots per sample were dried in a forced air-drying oven at 70 °C until constant mass, then stained with ink according to the methodology of Rodríguez Yon et al. (2015). Colonization frequency was evaluated using a stereoscopic microscope, with the line intercept method developed by Giovanetti & Mosse (1980).

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Foliar concentrations of N, P, and K in banana

Banana leaf samples for nutrient analysis were collected at the flowering stage of each cycle. The third youngest leaf from six plants per plot was selected, and a 10 cm-wide band was taken from the central area of each leaf limb (García et al., 1979). The samples were oven-dried at 70°C, ground to a fine powder (<1 mm), and analyzed for N, P, and K concentrations (g kg^{-1}) following wet digestion (H_2SO_4 + Se). The nutritional status of banana plants was assessed according to the interpretation criteria established by García et al. (1979) under Cuban conditions, which were also applied by Simó González et al. (2020) in banana plantations grown on Eutric Cambisols.

Banana yield (absolute and relative)

Banana yield was determined by weighing bunches from six plants per plot at each growth cycle. The absolute yield, expressed as t ha^{-1}, was calculated both per cycle and as the total for each treatment. In each cycle of both experiments, a maximum experimental yield was identified, and the relative yield (%) for each treatment was calculated using the maximum yield of the corresponding cycle within the same experiment. (Equation 1). In this calculation, yield represents the absolute yield of each treatment in that specific cycle.

$$\textit{Relative yield} = \textit{yield} \times 100 \,/\, \textit{yield maximum achieved} \qquad (1)$$

Statistical analysis

Normality and homogeneity of variance assumptions were tested using the Kolmogorov-Smirnov and Levene's tests. Confidence intervals ($1 - \alpha = 95$ %) were used to analyze soil properties and spore abundance at the onset of each experiment. In Experiment 1, and for each banana production cycle, a mixed-model ANOVA with a random block effect was applied to yield, foliar nutrient concentrations, and mycorrhizal indicators. Treatment differences were assessed using Tukey's multiple comparison test. Leaf N and K concentrations were related to yield via linear regression. For both experiments and production cycles, soil fertility variables measured at flowering were regressed against relative yield. All data processing (ANOVA, regressions, and decimation) was carried out using the statistical package SPSS version 21.0.

Soil K-based fertilizer index and potassium fertilization strategy

Relative yields from treatments and cycles were linked to the exchangeable soil potassium measured at flowering. The Cate-Nelson successive partitioning method (Waugh et al., 1973) was applied to identify the partition with the highest R^2 and to determine potential cutoff values for the relationship between soil K and relative yield. These cutoff values served as the basis for selecting the soil K-based fertilizer index, defined as the minimum exchangeable soil K level associated with at least 95 % of maximum yield under the lowest effective fertilization doses. The soil K index also indicates, based on the exchangeable potassium measured at flowering, whether keeping the fertilization dose is sufficient to sustain high yields in the next harvest or whether it requires adjustment.

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Results

Mother plant yield was lower ($p \leq 0.05$) than that obtained in the ratoon and represented about 66 % of it (Table 3). Except for yield, the cycle did not modify the absolute values of any evaluated variable within each treatment, so the values of each variable were similar between both cycles, and the relative behavior of the treatments remained unchanged. In non-inoculated treatments, yields increased progressively with OMF dose ($p \leq 0.05$) and reached their maximum at 100 % OMF. In inoculated treatments, yields increased up to 75 % OMF and equaled those of the 100 % OMF treatment without inoculation ($p \leq 0.05$). Across cycles, inoculated treatments receiving 25–75 % OMF consistently outperformed their non-inoculated counterparts ($p \leq 0.05$).

Table 3. Effects of OMF doses with and without AMF inoculation on yields, mycorrhizal structures, and foliar concentrations of N, P, and K in FHIA-18 banana over two production cycles on Eutric Cambisol soil. Santo Domingo, Cuba. 2021-2022.

Cuadro 3. Efectos de dosis de OMF con y sin inoculación con AMF sobre los rendimientos, las estructuras micorrízicas y las concentraciones foliares de N, P y K en banano FHIA-18 durante dos ciclos de producción en suelo Cambisol eútrico. Santo Domingo, Cuba. 2021-2022.

	Yield t ha^{-1}		Colonization %		Spores in 50 g		Nitrogen g kg^{-1}		Phosphorus g kg^{-1}		Potassium g kg^{-1}	
Treatments	**MP**	**FR**	**MP**	**FR**	**MP**	**FR**	**MP**	**FR**	**MP**	**FR**	**MP**	**FR**
Absolute control	8.60 e	9.86 e	12.00 f	14.50 e	48 g	40 f	31.5 a	30.2 a	2.03	2.08	22.9 f	22.6 e
AMF	8.20 e	10.03 e	23.75 d	30.00 d	136 d	175 d	31.2 a	30.0 a	2.03	2.08	22.6 f	22.4 e
25 % OMF	12.61d	13.59 d	13.25 ef	17.00 e	80 ef	67 f	28.6 b	27.3 b	2.05	2.08	24.6 e	23.9 d
25 % OMF+AMF	14.50 c	17.15c	30.50 c	37.50 c	195 c	210 c	27.1cd	26.8 b	2.08	2.08	27.7 c	26.7 c
50 % OMF	15.35 c	16.83c	13.75 ef	15.75 e	108 de	129 e	28.0bc	26.8 b	2.00	2.08	26.9 d	26.9 c
50 % OMF+AMF	18.20 b	22.74 b	35.75 b	49.25 b	226 b	268 b	26.9 d	25.6 c	2.13	2.13	29.7 b	29.0 b
75 % OMF	17.55 b	21.28 b	14.00 ef	15.25 e	124 d	157 e	26.8 d	25.6 c	2.08	2.08	29.4 b	28.6 b
75 % OMF+AMF	21.88 a	30.68 a	59.25 a	60.25 a	357 a	389 a	25.6 e	24.3 d	2.03	2.10	33.9 a	34.5 a
100 % OMF	22.10 a	31.13 a	13.00 ef	15.00 e	61 fg	52 f	25.8 e	24.5 d	2.00	2.08	34.2 a	34.5 a
100 % OMF+AMF	21.85 a	30.54 a	15.25 e	15.00 e	67 fg	56 f	25.6 e	24.3 d	2.05	2.13	33.8 a	34.4 a
SE	0.33*	0.40**	0.48**	0.83**	7.19**	7.05**	0.22**	0.22**	0.06 NS	0.05 NS	0.16**	0.25**

AMF: *Rhizoglomus irregulare* inoculant. **OMF:** Organic-mineral fertilization. **MP:** Mother plant cycle. **FR:** First ratoon cycle. Values with different letters in the same column are significantly different (Tukey's test, $p \leq 0.05$). **SE:** Standard error of the mean. *, **: Significant at $p \leq 0.05$ and $p \leq 0.01$. **NS:** Not significant. / **AMF:** Inoculante basado en *Rhizoglomus irregulare*. **OMF:** Fertilización orgánico-mineral. **MP:** Ciclo de planta madre. **FR:** Ciclo de primer vástago. Los valores con letras diferentes en una misma columna son significativamente distintos (prueba de Tukey, $p \leq 0,05$). **SE:** Error estándar de la media. *, **: Significativo a $p \leq 0,05$ y $p \leq 0,01$. **NS:** No significativo.

In inoculated treatments, colonization frequency and spore count increased significantly with each OMF dose up to 75 %, which produced the highest values ($p \leq 0.05$). At doses above this level, both variables decreased sharply ($p \leq 0.05$) to values similar to those of the 100 % OMF treatment without inoculation. In the remaining non-inoculated treatments colonization frequency and spore count were low, and both variables were lower ($p \leq 0.05$) than respective inoculated plants. In these treatments, colonization did not vary with OMF doses, whereas spore count increased progressively and reached its highest value ($p \leq 0.05$) at the 75 % OMF dose. These contrasting responses reflect the strong dependence of mycorrhizal development on inoculation status and OMF level.

Foliar nitrogen, phosphorus, and potassium exhibited distinct response patterns across treatments. Nitrogen showed an inverse relationship with yield ($p \leq 0.05$), with higher concentrations in low-yielding treatments and reduced values in those with greater productivity. Phosphorus remained stable, showing no significant differences among treatments ($p > 0.05$). In contrast, potassium displayed the strongest association with yield ($p \leq 0.05$), and the highest foliar concentrations occurred in the most productive treatments. Inoculation increased foliar potassium from 0 % to 75 % OMF ($p \leq 0.05$), reaching values comparable to those obtained under 100 % OMF without inoculation ($p > 0.05$), while nitrogen decreased at intermediate doses ($p \leq 0.05$). The nitrogen and potassium concentrations associated with the highest yields stabilized at 24.3–25.8 g kg^{-1} and 33.9–34.5 g kg^{-1}, respectively.

The relationship between relative yields of inoculated treatments from both experiments and crop cycles, under different OMF doses, and the corresponding soil exchangeable potassium at flowering is shown in Figure 1. The best fit ($R^2 = 0.7976$) divided the data into two populations based on a potassium threshold of 0.80 $cmol_c$ kg^{-1}. This threshold corresponds to the minimum soil K level sufficient to sustain at least 95 % of maximum yield across harvests with the lowest effective doses and was selected as the soil K-based fertilizer index for inoculated banana under OMF.

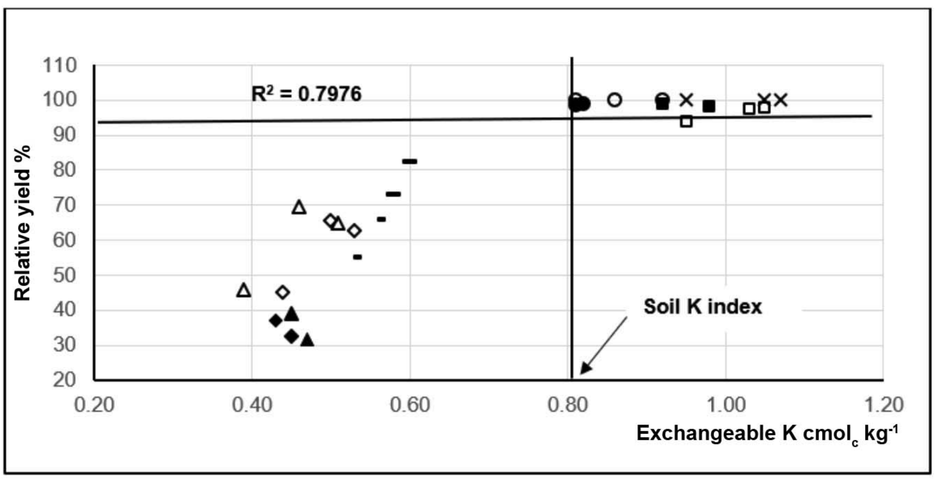

Figure 1. Partitioning of banana relative yield by soil exchangeable K in inoculated treatments across the different cycles. Data correspond to both experiments and comprise treatments with different doses of organic-mineral fertilization (OMF), as well as reference treatments. Santo Domingo, Cuba. 2006–2008 and 2021–2022.

Legend: Δ: Absolute control; ◇: AMF; -: AMF + 25 % OMF; ▬: AMF + 50 % OMF; ○: AMF + 75 % OMF; □: AMF + 100 % OMF; x: 100 % NPK. Black-filled symbols represent Experiment 1; unfilled symbols represent Experiment 2.

Figura 1. Partición del rendimiento relativo del banano en función del K intercambiable del suelo en tratamientos inoculados en los diferentes ciclos. Los datos corresponden a ambos experimentos e incluyen tratamientos tratados con diferentes dosis de fertilización orgánico-mineral (OMF), así como tratamientos de referencia. Santo Domingo, Cuba. 2006-2008 y 2021-2022.

Leyenda: Δ: Testigo absoluto; ◇: AMF; –: AMF + 25 % OMF; ▬: AMF + 50 % OMF; ○: AMF + 75 % OMF; □: AMF + 100 % OMF; x: 100 % NPK. Los símbolos rellenos en negro representan el Experimento 1, mientras que los símbolos sin relleno representan el Experimento 2.

Under these conditions, the 75 % OMF + AMF dose achieved high yields, at least 95 % of maximum yield, across all harvests from both experiments, regardless of yield differences between mother plants and ratoons. This treatment also produced the greatest values of mycorrhizal structures and foliar K concentrations (Table 3). Importantly, it maintained soil exchangeable K contents at flowering of each cycle at or slightly above the soil

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K-based fertilizer index. This consistency confirms that the selected dose not only secured maximum yields but also preserved fertilizer sufficiency throughout the studied cycles. Higher OMF doses and full NPK application did not improve yields; instead, they increased soil potassium levels (≥0.9 $cmol_c$ kg^{-1}).

The relationship between relative yields of non-inoculated treatments from both experiments, under different fertilization doses and the corresponding soil exchangeable K at flowering, showed a clear separation between low and high yield responses (Figure 2). This pattern defined a soil K-based fertilizer index with a critical threshold of 0.90 cmolc kg^{-1}, supported by an R^2 of 0.597. The highest relative yields (95–100 %) were consistently achieved only in treatments that received either 100 % OMF or 100 % NPK fertilization, while lower doses produced reduced yields. Under these conditions, the higher index value, compared to that observed in inoculated treatments (0.80 cmolc kg^{-1}), was associated with the high fertilization dose, which was required to achieve the highest relative yield.

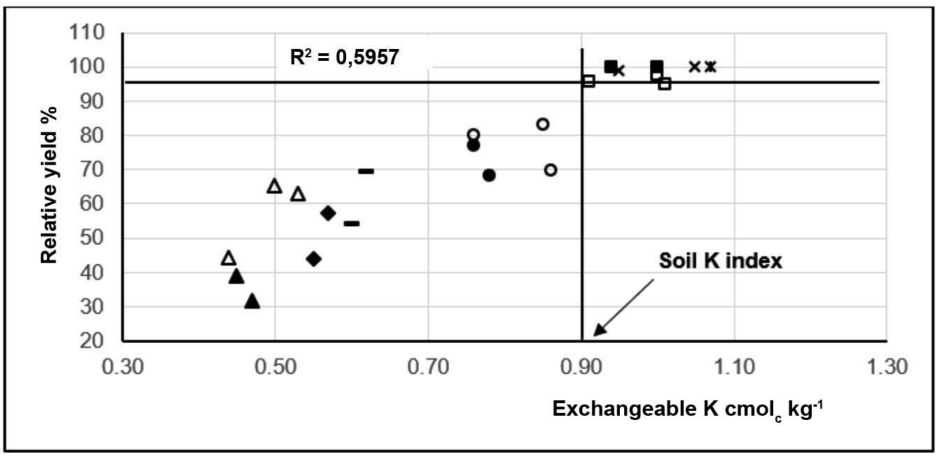

Figure 2. Partitioning of banana relative yield by soil exchangeable K in non-inoculated treatments in the different cycles. The data correspond to both experiments and comprise treatments with different doses of organic-mineral fertilization (OMF), as well as a reference treatment. Santo Domingo, Cuba. 2006–2008 and 2021–2022.

Legend: Δ: 0 % OMF (absolute control); ◇: 25 % OMF; ▬: 50 % OMF; ○: 75 % OMF; □: 100 % OMF; x: 100 % NPK. Filled symbols correspond to Experiment 1; unfilled symbols represent Experiment 2.

Figura 2. Partición del rendimiento relativo del banano según el K intercambiable del suelo en tratamientos no inoculados en los diferentes ciclos. Los datos corresponden a ambos experimentos y comprenden tratamientos con diferentes dosis de fertilización orgánico-mineral (OMF), además de un tratamiento de referencia. Santo Domingo, Cuba. 2006-2008 y 2021-2022.

Leyenda: Δ: 0 % OMF (testigo absoluto); ◇: 25 % OMF; ▬: 50 % OMF; ○: 75 % OMF; □: 100 % OMF; x: 100 % NPK. Los símbolos rellenos corresponden al Experimento 1; los símbolos sin relleno representan el Experimento 2.

The relationship between relative yields and soil exchangeable K in banana AMF–inoculated treatments combined with the canavalia and OMF doses suggested two potential partition values at 0.75 and 0.80 $cmol_c$ kg^{-1} (Figure 3), supported by a high R^2 of 0.7854. The GMAMF + 25 % OMF + AMF treatment produced high relative yields in the mother plant and first ratoon, with soil K values of 0.80 $cmol_c$ kg^{-1} and 0.75 $cmol_c$ kg^{-1}, respectively, but yields decreased in the second ratoon. The GMAMF + 50 % OMF + AMF treatment showed soil K values near 0.90 $cmol_c$ kg^{-1} in the mother plants, declining to 0.80 $cmol_c$ kg^{-1} in the ratoons while maintaining high relative yields across all three cycles.

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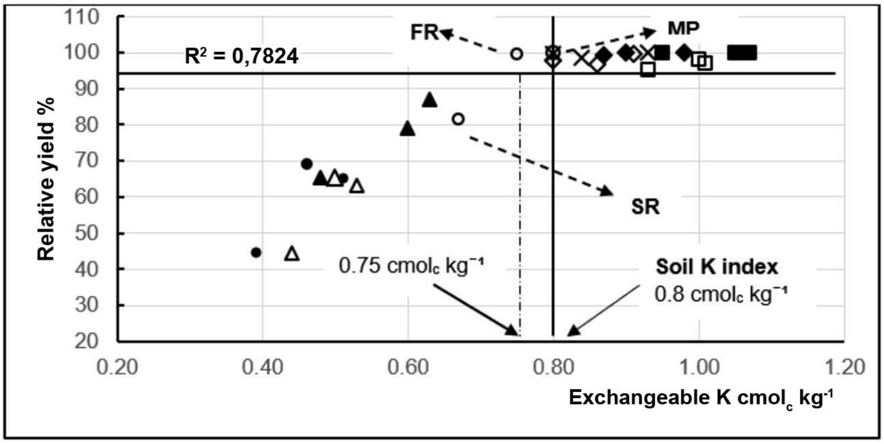

Figure 3. Partitioning of banana relative yield by soil exchangeable K in inoculated treatments that include the canavalia as green manure across the different cycles. Data correspond to Experiment 2 and comprise treatments with different doses of organic-mineral fertilization (OMF), as well as other reference treatments. Santo Domingo, Cuba. 2006–2008 and 2021–2022.

Legend: ∆: Absolute control; •: AMF; ▲: GMAMF; ○: GMAMF + 25 % OMF; ◇: GMAMF + 50 % OMF; ◆: GMAMF + 75 % OMF; x: 75 % NPK + AMF; □: 100 % OMF; ■: 100 % NPK. Dashed arrows point to the relative yields of the GMAMF + 25 % OMF treatment in each cycle (**MP:** Mother plant; **FR:** First ratoon; **SR:** Second ratoon).

Figura 3. Partición del rendimiento relativo del banano según el K intercambiable del suelo en tratamientos inoculados que incluyen la canavalia como abono verde, a lo largo de los diferentes ciclos. Los datos corresponden al Experimento 2 y comprenden tratamientos con diferentes dosis de fertilización orgánico-mineral (OMF), así como otros tratamientos de referencia. Santo Domingo, Cuba. 2006-2008 y 2021-2022.

Leyenda: ∆: Testigo absoluto; •: AMF; ▲: GMAMF; ○: GMAMF + 25 % OMF; ◇: GMAMF + 50 % OMF; ◆: GMAMF + 75 % OMF; x: 75 % NPK + AMF; □: 100 % OMF; ■: 100 % NPK. Las flechas discontinuas señalan los rendimientos relativos del tratamiento GMAMF + 25 % OMF en cada ciclo (**MP:** Planta madre; **FR:** Vástago 1; **SR:** Vástago 2).

The GMAMF + 75 % OMF + AMF treatment achieved relative yields of the same order as the highest experimental values and showed soil K contents between 0.87 and 0.98 $cmol_c\ kg^{-1}$. Based on these patterns, 0.80 $cmol_c\ kg^{-1}$ was selected as the soil K-based fertilizer index for GMAMF treatments. Non-inoculated treatments receiving higher OMF doses (100 % OMF) or the recommended mineral fertilization rate (100 % NPK) maintained high productivity but showed soil exchangeable K values above 0.90 $cmol_c\ kg^{-1}$. The inoculated treatment receiving 75 % of the mineral fertilization (75 % NPK + AMF) achieved yields comparable to the highest obtained in both experiments while maintaining soil K at 0.80 $cmol_c\ kg^{-1}$ across harvests.

The correlations between relative yields and other soil properties at flowering, such as available P, pH, and organic matter, were not significant, except for the correlation with organic matter in the second experiment. The range of soil organic matter values was relatively narrow, from 21.8 g kg^{-1} without OMF application to 26.0 g kg^{-1} at the highest OMF dose. Soil pH showed variation across OMF doses (7.2 to 7.8) but did not differ between inoculated and non-inoculated treatments. The crop cycles did not result in changes in any of these soil properties across treatments, with the exception of available P, which increased by 60 to 100 % with the applications, with larger increases in soils with lower initial P values.

Discussion

The reduction in OMF fertilization requirements observed with inoculation reflects the capacity of arbuscular mycorrhizal fungi to improve nutrient acquisition under suboptimal nutrient supply (Berger & Gutjahr, 2021).

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This mechanism explains why non-inoculated plants required the full OMF dose established by MINAG (2011), whereas inoculated plants achieved optimal performance with lower inputs, consistent with reductions in fertilizer requirements reported when inoculating other crops with AMF (Ortaş & Rafique, 2017; Rivera Espinosa et al., 2023). The decline in inoculation effects above 75 % OMF aligns with the downregulation of the symbiosis when nutrient availability satisfies plant demand, a response documented by Bhandari & Garg (2017).

The strong yield and foliar K responses to OMF indicate that potassium was the primary limiting nutrient in these Eutric Cambisol soils, where high exchangeable Ca and Mg contents restrict K availability. Similar patterns of K limitation in banana grown on Cambisol soils have been reported previously (Simó González et al., 2020). The direct effect of mycorrhizal symbiosis on potassium acquisition (Han et al., 2025; Liu et al., 2019) explains why inoculated plants reached adequate yields and optimal foliar potassium with lower OMF doses, consistent with the close association between colonization frequency and foliar potassium observed under these conditions. This improvement in potassium uptake efficiency highlights the advantage of inoculation when potassium availability is suboptimal.

Nitrogen was not limiting in this system, which accounts for the negative relationship between yield and foliar N concentration despite the high N requirements of banana (González Santos, 2024) and corresponds with the inconsistent N responses to inoculation observed. Greater K availability supplied through OMF stimulated growth and diluted foliar N until both nutrients reached optimal levels at the fertilization threshold, a pattern documented in banana (García et al., 1979; Rodríguez Gómez, 1980). The absence of a relationship between OMF dose and foliar P confirms the low P demand of bananas (Espinosa & Mite, 1995). The differentiated foliar responses of N, P, and K indicate that inoculation improves nutrition only under suboptimal supply, as indicated by Berger & Gutjahr (2021).

In Eutric Cambisol soils, the potassium-based fertilizer index for non-inoculated banana was higher than the 0.2 $cmol_c\ kg^{-1}$ reported in Central America as a rationale for intensive K fertilization (Espinosa & Mite, 1995). This difference reflects the high exchangeable Ca and Mg contents in Cuban Cambisols, which reduce the relative proportion of K to only 1.9 % of exchangeable bases and result in low potassium availability for banana due to Ca–Mg–K antagonism (Martin-Prével, 1980). This proportion becomes comparable to that found in Central American soils at much lower absolute K levels (Figueroa & Luppi, 2017). This antagonism underscores the need to consider exchangeable Ca and Mg when comparing K fertilization criteria across soils.

It was possible to integrate soil analysis with the assessment of potassium fertilization sufficiency in inoculated banana by identifying a functional threshold using the method of successive partitions (Waugh et al., 1973). The soil K-based fertilizer index obtained for inoculated plants was lower than in non-inoculated systems, which reflects the greater capacity of mycorrhizal roots to acquire plant available potassium (Berger & Gutjahr, 2021) and leads to a lower sufficiency boundary. The specific value of this index depends on the crop and appears to be influenced by soil characteristics—particularly the levels of exchangeable Ca and Mg noted above—which likely affect the value of the sufficiency threshold.

The canavalia biomass contributes to crop nutrition in inoculated banana. It returns soil derived nutrients and the N obtained through biological fixation, with combined contributions from preceding and intercropped cover reaching ~360 and 260 kg ha^{-1} of N and K in the mother plant cycle (Simó González et al., 2017). Its rapid mineralization depends not only on the low C/N ratio but also on the mycorrhizal stimulation of saprotrophic activity and the expansion of the extraradical mycelium in organic residue environments (Jansa et al., 2019; Thirkell et al., 2016). However, the inclusion of the canavalia does not modify the soil K index, which indicates that the described effects enhance nutrient release and access but do not alter the functional nature of mycorrhizal uptake.

The consistent potassium uptake capacity of the mycorrhizal symbiosis, determined by the AMF inoculant, soil conditions, and plant nutritional requirements (Smith & Read, 2008), resulted in a stable soil K fertilizer index in inoculated plants. The index remained at 0.80 $cmol_c\ kg^{-1}$ for this soil type, and this value was stable across different sources (OMF, OMF with the canavalia, and mineral fertilizer), whereas non-inoculated plants

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consistently exhibited higher values. This pattern indicates that variation in the index is attributable to mycorrhizal functioning and its superior potassium uptake capacity, independent of the fertilizer source. Likewise, the index reflects fertilization sufficiency more than soil fertility, which supports its use as a benchmark for K fertilization strategies in inoculated banana.

In AMF-inoculated systems, the soil K-based fertilization index relates exchangeable K at flowering to the yield obtained in the current cycle and guides fertilization decisions for the next harvest. When soil K remains at the threshold, the fertilization dose can be maintained; when it falls below the threshold, additional inputs are required; and when it exceeds the threshold, fertilization can be reduced without compromising yield. Thus, the index operates as a practical indicator of fertilization sufficiency, which helps address a gap, as soil K analysis is not yet employed as a fertilization criterion in inoculated systems. Incorporating foliar analysis, as proposed by Simó González et al. (2020), further enhances overall nutrient management.

The lack of significant correlations between relative yields and soil properties such as available P and pH indicates that these variables did not share the same pattern of variation as yield. Soil pH varied only with OMF doses and not with inoculation, whereas yield responded to both factors. Likewise, although available P increased between crop cycles, these increases did not translate into yield differences, consistent with the banana's low responsiveness to P fertilization (Espinosa & Mite, 1995). In contrast, the significant correlation with organic matter in the second experiment seems to reflect a collinear relationship with OMF dose, driven by the crop's response to potassium from ash and by the increase in soil OM from compost applications (Edlinger et al., 2025).

While the results are promising, additional experimental studies are needed to broaden and consolidate these findings. Such studies should include contexts involving synthetic fertilizers, alternative organic-mineral sources, and different soil types. These efforts will refine potassium management strategies and strengthen their application in AMF-inoculated banana systems.

Conclusions

Mycorrhizal inoculation reduced the organic-mineral fertilizer doses required to sustain high banana yields on Eutric Cambisols by 25 %. The soil K-based fertilizer index established for AMF-inoculated banana captured the enhanced potassium uptake efficiency of inoculated plants, which consistently exhibited lower threshold values than those of non-inoculated plants; this behavior was independent of the fertilizer source used: organic-mineral fertilizers, the canavalia combined with organic-mineral fertilizers, or NPK fertilizers. This study established the potassium threshold for inoculated banana on Eutric Cambisols, and the soil K index provides a technical, soil based criterion for defining the sufficiency of potassium fertilization. It emerges as a promising tool for potassium supply management in inoculated banana systems.

Conflict of interest

The authors declare no conflict of interest.

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