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Spectral and Phenological Response of Banana (*Musa* AAA, Simmonds) to Organic Bio-Inputs Based on *Trichoderma spp. and Bacillus spp.*, in the Central Littoral Region of Ecuador: An Evaluation Using UAV and NDVI Index
Respuesta Espectral y Fenológica del Banano (*Musa* AAA, Simmonds) a Bioinsumos Orgánicos Basados en *Trichoderma spp. y Bacillus spp.* en la Región Litoral Central del Ecuador: Una Evaluación Mediante VANT e Indice NDVI

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SUMMARY

Banana (*Musa*, AAA, Simmonds), is a globally significant crop, yet its sustainable production faces physical, biological, and social challenges. This study evaluated the impact of two organic bioinputs, an *in situ* formulated fungal consortium and a commercial bacterial product on the agronomic and spectral response of banana using UAV and spectral technology in Los Ríos province, Ecuador. A completely randomized design was implemented with three treatments: T1 (*in situ* fungal consortium of *Trichoderma* spp. and *Paecilomyces lilacinus*), T2 (commercial bacterial consortium of *Bacillus* spp.), and T3 (control). A DJI Mavic 3M drone equipped with multispectral sensors was used to calculate the Normalized Difference Vegetation Index (NDVI) at 6 and 28 weeks after treatment, alongside phenological measurements at 28 weeks. Both bioinputs significantly improved NDVI values compared to the control ($p < 0.05$). T1 showed the best performance with a final NDVI of 0.82 (22.2% improvement over the control), followed by T2 at 0.78 (16.8% improvement). Strong and significant positive correlations ($p < 0.01$) were found between NDVI and all agronomic variables: plant height (r = 0.8167), pseudostem diameter (r = 0.8572), and leaf number (r = 0.8330). The Kruskal-Wallis analysis confirmed significant differences among all treatments, highlighting the superiority of the *in-situ* consortium (T1), developed with local samples, due to its better adaptation to regional conditions. The strong correlations validate NDVI as a non-destructive and precise indicator of banana structural growth. This study demonstrates that organic bioinputs, particularly locally formulated multifunctional consortia, can significantly enhance the physiological and agronomic status of banana crops, while UAV-based remote sensing provides an efficient tool for rapid assessment and decision-making in precision agriculture programs for banana cultivation.

Index words: *precision agriculture, plant biostimulation, spectral indices, remote sensing, rhizobacteria*.

RESUMEN

El banano (*Musa*, AAA, Simmonds), es un cultivo de importancia global, pero su producción sostenible enfrenta desafíos físicos, biológicos y sociales. Este estudio evaluó el impacto de dos bioinsumos orgánicos –un consorcio fúngico formulado *in situ* y un producto bacteriano comercial– en la respuesta agronómica y espectral del banano mediante tecnología VANT y espectral en la provincia de Los Ríos, Ecuador. Se implementó un diseño completamente al azar con tres tratamientos: T1 (consorcio fúngico *in situ* de *Trichoderma* spp. y *Paecilomyces lilacinus*), T2 (consorcio bacteriano comercial de *Bacillus* spp.) y T3 (control). Se utilizó un dron DJI Mavic 3M equipado con sensores multiespectrales para calcular el Índice de Vegetación de Diferencia Normalizada (NDVI) a las 6 y 28 semanas, junto con mediciones fenológicas a las 28 semanas. Ambos bioinsumos mejoraron significativamente los valores de NDVI en comparación con el control ($p < 0.05$). T1 mostró el mejor desempeño con un NDVI final de 0.82 (22.2% de mejora sobre el control), seguido por T2 con 0.78 (16.8% de mejora). Se encontraron correlaciones positivas fuertes y significativas ($p < 0.01$) entre el NDVI y todas las variables agronómicas: altura (r = 0.8167), diámetro del pseudotallo (r = 0.8572) y número de hojas (r = 0.8330). El análisis de Kruskal-Wallis confirmó diferencias significativas entre todos los tratamientos, destacando la superioridad del consorcio in situ (T1), desarrollado con muestras locales y mejor adaptado a las condiciones regionales. Las fuertes correlaciones validan al NDVI como un indicador no destructivo y preciso del crecimiento estructural del banano. Este estudio demuestra que los bioinsumos orgánicos, particularmente los consorcios multifuncionales formulados localmente, pueden mejorar significativamente el estado fisiológico y agronómico del cultivo, mientras que la teledetección basada en VANT ofrece una herramienta eficiente para la evaluación rápida y la toma de decisiones en programas de agricultura de precisión para el banano.

Palabras clave: *agricultura de precisión, bioestimulación vegetal, índices espectrales, percepción remota, rizobacterias*.

INTRODUCTION

Banana (*Musa* AAA, Simmods), is a globally significant fruit crop (Martínez-Solórzano and Rey-Brina, 2021), vital for food security and a cornerstone of the economy in many tropical regions, including Ecuador, one of the world's leading exporters (FAO, 2024). However, sustainable banana production faces considerable challenges, including pest and disease pressures, soil degradation, and over-reliance on synthetic agrochemicals, which can have detrimental environmental impacts (Omer *et al*., 2024). In this context, organic bioinputs such as biofertilizers and biopesticides derived from microorganisms offer a promising alternative for enhancing plant growth, soil health, and crop resilience while aligning with principles of regenerative agriculture (Fahad *et al*., 2022).

A critical barrier to optimizing the use of these bioinputs is the lack of efficient, non-destructive methods for monitoring their effects on crop physiology and development throughout the growing cycle (Bertola, Ferrarini, and Visioli, 2021). Traditional agronomic assessments often rely on destructive, time-consuming, and costly methods, such as manual measurements of pseudostem diameter and leaf counting, which hinder timely decision-making (Beaumelle *et al*., 2023). Recent advancements in remote sensing, particularly through Unmanned Aerial Vehicles (UAVs or drones), provide a powerful solution. UAVs equipped with multispectral sensors can capture high-resolution data to compute vegetation indices like the Normalized Difference Vegetation Index (NDVI) (Aeberli, Johansen, Robson, Lamb, and Phinn, 2021), which is a proven proxy for photosynthetic activity, chlorophyll content, and overall plant vigor (Gargiulo *et al*., 2020).

While the individual potential of bioinputs and UAV-based monitoring is recognized, there is a scarcity of studies that integrate these technologies to quantitatively assess the impact of specific organic amendments on the agronomic cycle of banana. Furthermore, the efficacy of bioinputs can be highly dependent on their formulation and adaptation to local edaphoclimatic conditions, highlighting the need to compare locally produced consortia against commercial products.

Therefore, this study aimed to bridge this research gap by evaluating the influence of two types of organic bioinputs, a locally formulated fungal consortium and a commercial bacterial product on the agronomic and spectral response of banana. The specific objectives were: 1) To determine the effect of the bioinputs on the phenological development of banana plants, 2) To analyze the crop's agronomic condition using NDVI derived from UAV multispectral imagery, and 3) To identify the relationships between spectral response and key agronomic parameters.

MATERIALS AND METHODS

Study Site and Agroclimatic Conditions

The research was conducted in a commercial banana farm located in Buena Fe, Los Ríos Province, Ecuador (0.7191871° S, 79.4388981° W; WGS84) (Figure 1). The site is characterized by a flat topography and a tropical humid forest climate. The average temperature is 25.2 °C, with relative humidity between 85 and 90%, annual rainfall between 2950 and 3300 mm, and 4 to 6 h of daily sunshine.

Experimental Design and Treatments

The study employed a completely randomized design (CRD) (Edelstein *et al*., 2024) with three treatments and three replications per treatment. Each experimental plot measured 81 m² (9 × 9 m) and contained 10 homogeneous banana plants of the Williams variety (*Musa* AAA, Simmonds), totaling 90 plants. The experimental plots were established within a uniform block of the farm, where historical management practices and soil conditions have been consistently homogeneous according to the farm's records. The three treatments were randomly distributed within this block to ensure that any differences observed could be attributed solely to the applied bioinputs.

The treatments evaluated were: T1 A fungal consortium composed of *Trichoderma asperellum*, *T. atroviride*, T. harzianum, and *Paecilomyces lilacinus*, with a total concentration of 1×10^9 conidia g^{-1} (equally distributed among species). (*In situ*: it is a bioinput developed in the laboratory using soil samples taken from banana plantations in the region.): T2 (Commercial): A bacterial consortium composed of *Bacillus subtilis*, *B. amyloliquefaciens*, and *B. licheniformis*, with a total concentration of 2×10^9 CFU g^{-1}. T3 (Control): No application of bioinputs.

All other agronomic practices (irrigation, weeding) were standardized across all plots to isolate the effect of the bioinputs. Baseline fertilization was the same for all treatments and followed the farm's standard program. Pre-experimental soil analysis showed adequate levels of organic matter (3.2%) and pH (6.8), with N, P, and K values within the crop's sufficiency range. The NPK regime was based on the optimal doses: 358 kg ha^{-1} of N and 596 kg ha^{-1} of K_2O, distributed throughout the cycle via fertigation (two weekly applications), complemented by monthly phosphorus applications (DAP, 50 kg ha^{-1} of P_2O_5) at the beginning of the cycle. The NPK dose was kept constant across all treatments to ensure that any differences observed could be attributed solely to the bioinputs.

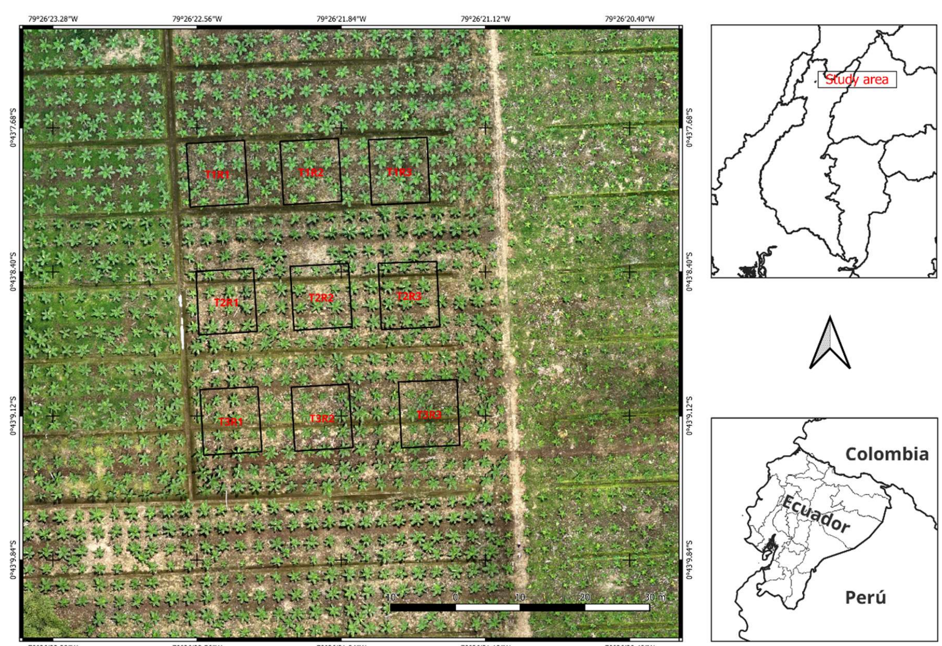

Figure 1. The image shows the location of the experimental site in Ecuador, specifically in Los Ríos province. The main ortomosaic presents an aerial view of the study area, where experimental banana crop plots are observed organized in a system of rectangular blocks delimited by internal access roads. The plots are identified with alphanumeric nomenclature (T1,R1-R3; T2, R1-R3; T3, R1-R3). Scale: 1:500.

The *in-situ* fungal consortium (T1) was developed in our laboratory using a solid-state fermentation process on a local substrate. The final product contained *Trichoderma asperellum*, *T. atroviride*, *T. harzianum*, and *Paecilomyces lilacinus* at a total concentration of 1 × 10^9 conidia g^{-1}, with purity >95% verified by plating on selective media. The formulation was applied as a soil drench at a dose of 50 g per plant (equivalent to 5 × 10^{10} conidia per plant), diluted in 1 L of water. Three applications were made throughout the trial: at planting (week 0), and at 8 and 16 weeks after the initial application. The commercial bacterial consortium (T2) consisted of *Bacillus subtilis*, *B. amyloliquefaciens*, and *B. licheniformis* with a total concentration of 2 × 10^9 CFU g^{-1}. The product was applied according to the manufacturer's recommended dose of 2 L ha^{-1}, diluted in 200 L of water, using a soil drench application at the same three time points as T1 (weeks 0, 8, and 16). The application interval of eight weeks was chosen to maintain a continuous presence of the bioinputs in the rhizosphere during the most active vegetative growth phase of banana.

Agronomic Variables Assessment

The two evaluation periods (6 and 28 weeks after treatment) were selected based on banana phenology: 6 weeks corresponds to the early vegetative establishment phase, when root development and initial leaf expansion are critical; 28 weeks coincides with the maximum vegetative growth stage, just before flowering, when canopy cover and photosynthetic activity reach their peak, allowing for the integrated assessment of bioinput effects on plant vigor and physiological status (Nyombi *et al*., 2009).

28 weeks after the establishment of the experiment, three key agronomic variables were assessed to characterize the vegetative development of banana plants: plant height, pseudostem diameter, and the number of functional leaves. Plant height (cm) was measured from the base of the pseudostem to the insertion point of the youngest leaf using a flexible tape measure, serving as an indicator of vegetative vigor and apical growth. Pseudostem diameter (cm) was recorded at a standardized height of 30 cm from the base using a digital caliper, reflecting the plant's structural robustness and its ability to support the developing bunch. The number of leaves was determined by systematically counting, from the youngest to the oldest, only those leaves with more than 50% of their leaf area green and photosynthetically active, excluding senescent or damaged leaves; this parameter served as an indicator of metabolic activity and physiological response to the applied treatments (Miao *et al*., 2022).

Spectral Data Acquisition and Processing

Spectral data were acquired using a DJI Mavic 3M drone (DJI, Shenzhen) equipped with a multispectral sensor (green: 560 nm, red: 650 nm, red edge: 730 nm, and near-infrared: 860 nm) and a 20-megapixel RGB sensor with a 4/3" CMOS array. Flights were conducted in April 2024 between 10:00 a.m. and 2:00 p.m. The flight was conducted at an altitude of 80 m, yielding a spatial resolution of 4.4 cm $pixel^{-1}$ for the multispectral bands and 2.4 cm $pixel^{-1}$ for RGB, calculated using the formula GSD = (altitude × pixel size) / focal length. Georeferencing was ensured through a D-RTK 2 mobile station, achieving an absolute accuracy of ±8 cm horizontally and ±15 cm vertically. Flights were under controlled environmental conditions: cloud cover of 65% ± 5%, wind speed of 1.3 m s^{-1}, and average irradiance of 700 ± 100 W m^{-2}. Double-grid flight paths were implemented with 80% front and side overlap, a constant drone speed of 5 m s^{-1}, and the drone's integrated spectral sensor was used for real-time irradiance compensation.

The images were processed using Agisoft Metashape Professional v2.2.2. (Agisoft LLC, San Petersburgo) (Bhandari *et al*., 2023). Multispectral and RGB images were imported together with their metadata and GNSS/RTK logs to ensure centimeter-level georeferencing, using the WGS 84 / UTM zone 17S coordinate reference system. In the initial stage, advanced algorithms for detection and matching homologous points were applied to align the images, estimate their relative positions, and perform camera autocalibration of internal parameters. Subsequently, a dense point cloud was generated through stereo correlation, from which the digital surface model (DSM) and orthorectification were derived. Maximum density and quality processing parameters were used to ensure geometric accuracy in the orthomosaics. Finally, manual radiometric calibration was performed using NIST-certified MicaSense reference panels (50% reflectance), with pre- and post-flight readings taken at ± 5° from the solar incidence angle, in accordance with the ASTM E2590-22 protocol (Poortinga *et al*., 2018). The result was radiometrically homogeneous RGB and multispectral orthomosaics in TIF format.

The Normalized Difference Vegetation Index (NDVI) was calculated for the initial stage (6 weeks) and final (28 weeksafter treatment application), using the standard formula (1) (Sishodia, Ray, and Singh, 2020). To extract precise NDVI values for each experimental plot, the OTSU thresholding method was applied. OTSU is an automated image segmentation technique that identifies an optimal threshold by maximizing the interclass variance between pixel groups (Yin *et al*., 2022), enabling the separation of banana canopy pixels from background soil. This process generated binary masks distinguishing banana vegetation from soil, ensuring that only relevant canopy pixels contributed to the NDVI calculation per plot. Where: NIR = Reflectance in the near-infrared band (840 nm); Red = Reflectance in the red band (650 nm). All these procedures were carried out using the NumPy and SciPy libraries in Python (Harris *et al*., 2020; Virtanen *et al*., 2020).

In banana, NDVI has been widely validated as a reliable indicator of photosynthetic activity, canopy cover, and overall plant vigor, with strong correlations to key agronomic traits such as pseudostem diameter and leaf area (Machovina, Feeley, and Machovina, 2016). Its sensitivity to changes in vegetative development makes it particularly suitable for assessing the response of banana plants to bioinput applications across different phenological stages.

$$\text{NDVI} = (\rho\_\text{NIR} - \rho\_\text{Red}) / (\rho\_\text{NIR} + \rho\_\text{Red}) \qquad (1)$$

Statistical Analysis

For each experimental plot, the 10 plants were averaged to obtain a single value for each agronomic and spectral variable, which constituted the experimental unit (n = 3 per treatment). The statistical analysis was conducted using Python. Data normality was assessed with the Anderson – Darling test; since the data violated the assumption of normality ($p < 0.05$), non-parametric methods were employed. The Kruskal–Wallis test ($\alpha = 0.05$) was used to evaluate significant differences in both spectral (e.g., NDVI) and phenological variables across treatments. When significant effects were detected, post-hoc pairwise comparisons were performed using Duncan's multiple range test. Additionally, the strength and direction of associations between agronomic variables (plant height, pseudostem diameter, leaf count) and NDVI were quantified using Spearman's rank correlation coefficient.

RESULTS AND DISCUSSION

Spectral Response to Bioinput Applications

NDVI evolution in banana plants (Figure 2.) under three different treatments throughout the crop cycle (6 to 28 weeks). During the initial phase (6 weeks), all treatments exhibited homogeneous NDVI values (T1: 0.58; T2: 0.57; T3: 0.57), indicating similar vegetative vigor and photosynthetic activity across experimental plots at baseline. By the final evaluation (28 weeks), significant treatment divergence became evident: T1 (laboratory-developed bioinput) achieved the highest NDVI value (0.82), representing a substantial increase of 0.24 units of NDVI (Δ); T2 (commercial bioinput) showed an intermediate response (0.78, Δ = 0.21); while the control treatment (T3) displayed the lowest final value (0.67, Δ = 0.10). This differential response pattern demonstrates that both bioinputs enhanced vegetative development compared to the control, with the laboratory-formulated fungal consortium (T1) producing superior spectral performance (Figure 2). The magnitude of NDVI gain suggests that T1 significantly improved photosynthetic efficiency and plant physiological status throughout the growth cycle, whereas the commercial bacterial product (T2) provided intermediate benefits, highlighting the importance of bioinput composition in modulating banana plant performance under field conditions.

The Kruskal-Wallis test confirmed that these differences in final NDVI were statistically significant (H = 7.2, $p = 0.0273$). The post-hoc Duncan test (Table 2) further delineated three distinct statistical groups, indicating that all treatments differed significantly from each other ($p < 0.05$) (Table 1). The absolute improvement of T1 over the control was 22.2%, while T2 showed a 16.8% improvement. T1 also maintained a significant 4.6% advantage over T2.

The progressive divergence in NDVI trajectories, culminating in significant differences at 28 weeks (H = 7.2, $p = 0.0273$), demonstrates the efficacy of bioinputs in enhancing vegetative development and photosynthetic capacity in banana cultivation. The superior performance of T1 (NDVI = 0.82, Δ = 0.24) compared to T2 (NDVI = 0.78, Δ = 0.21) and the control (NDVI = 0.67, Δ = 0.10) aligns with previous research highlighting the relationship between NDVI values and banana plant vigor. The diameter and height of the pseudo-stem are important morphological parameters of banana plants, which can reflect the growth status and vitality (Miao *et al*., 2022), and these structural characteristics are strongly correlated with spectral indices such as NDVI.

Table 1. Composition and concentration of the bioinputs applied in the trial. The in situ bioinput corresponds to a fungal consortium developed from soil samples taken from local banana plantations, whereas the commercial bioinput is composed of bacteria. Concentrations are expressed in conidia per gram (conidia g^{-1}) for fungi and colony-forming units per gram (CFU g^{-1}) for bacteria.

Bioimput	Consortium	Concentration
In situ (T1)	*Trichoderma asperellum*	5 × 10^8 conidia g^{-1}
	Trichoderma atroviride	5 × 10^8 conidia g^{-1}
	Trichoderma harzianum	5 × 10^8 conidia g^{-1}
	Paecilomyces lilacinus	5 × 10^8 conidia g^{-1}
	Total	1 × 10^9 conidia g^{-1}
Comercial (T2)	*Bacillus subtilis*	1 × 10^9 CFU g^{-1}
	Bacillus amyloliquefaciens	5 × 10^8 CFU g^{-1}
	Bacillus licheniformis	5 × 10^8 CFU g^{-1}
	Total	2 × 10^9 CFU g^{-1}

The 22.2% improvement in final NDVI achieved by the laboratory-developed fungal consortium (T1) over the control treatment represents a substantial enhancement in photosynthetic efficiency and overall plant health. This T1 bioinput, formulated with a multi-species *Trichoderma consortium (T. asperellum, T. atroviridae, and T. harzianum*) complemented with *Paecilomyces lilacinus* at a total concentration of 1 × 10^9 conidia g^{-1}, demonstrated superior bioactivity compared to the commercial bacterial formulation. Different *Trichoderma* strains had different degrees of antagonism to *F. oxysporum*, and the combination of Trichoderma wettable powder treatment significantly increased banana yield (Wei *et al*., 2025). The synergistic action of these fungal species, particularly the Trichoderma spp., is well-documented for their capacity to enhance nutrient solubilization, promote root development, and induce systemic resistance mechanisms in banana plants (Oliveira-Almeida *et al*., 2022). This magnitude of response is consistent with findings in precision agriculture applications, where plant height is an important agronomic trait that not only affects crop yield, but is also related to resistance to abiotic and biotic stresses (Wei *et al*., 2025). The spectral signature captured by NDVI integrates multiple physiological processes, including chlorophyll content, leaf area, and canopy architecture, suggesting that the T1 Trichoderma - based consortium positively influenced these key determinants of crop productivity through multiple modes of action including mycoparasitism, antibiosis, competition, and induced systemic resistance (Manganiello *et al*., 2021). The balanced composition of this four-species fungal consortium, with each species contributing 5 × 10^8 conidia g^{-1}, likely provided complementary functional traits that collectively enhanced plant performance beyond what single-strain inoculants could achieve in banana cultivation systems.

The intermediate performance of the commercial bacterial bioinput (T2), while still significantly superior to the control (16.8% improvement), indicates that microbial composition and functional diversity play critical roles in determining bioinput efficacy. This T2 formulation, comprising *Bacillus subtilis* (1 × 10^9 CFU g^{-1}), *B. amyloliquefaciens* (5 × 10^8 CFU g^{-1}), and *B. licheniformis* (5 × 10^8 CFU g^{-1}) at a total concentration of: 2 × 10^9 CFU g^{-1}, demonstrated substantial plant growth-promoting activities in banana cultivation. *Bacillus amyloliquefaciens* Bs006 and *Pseudomonas fluorescens* Ps006 promoted banana growth similarly or even slightly superior to 100% chemical fertilization (Gamez *et al*., 2019), highlighting the strong potential of bacterial consortia in tropical crop systems. Furthermore, the plant height and pseudostem diameter of banana increased by 11.68% and 11.94%,

Table 2. *Post-hoc* Duncan test results for NDVI differences between treatments(*), expressed as absolute difference and relative percentage improvement. In situ bioinput (T1), commercial bioinput (T2), Control (T3).

Comparison	Absolute Difference NDVI	Percentage of Improvement
T1 vs T3*	0.1494	22.20%
T2 vs T3*	0.1136	16.80%
T1 vs T2*	0.0359	4.60%

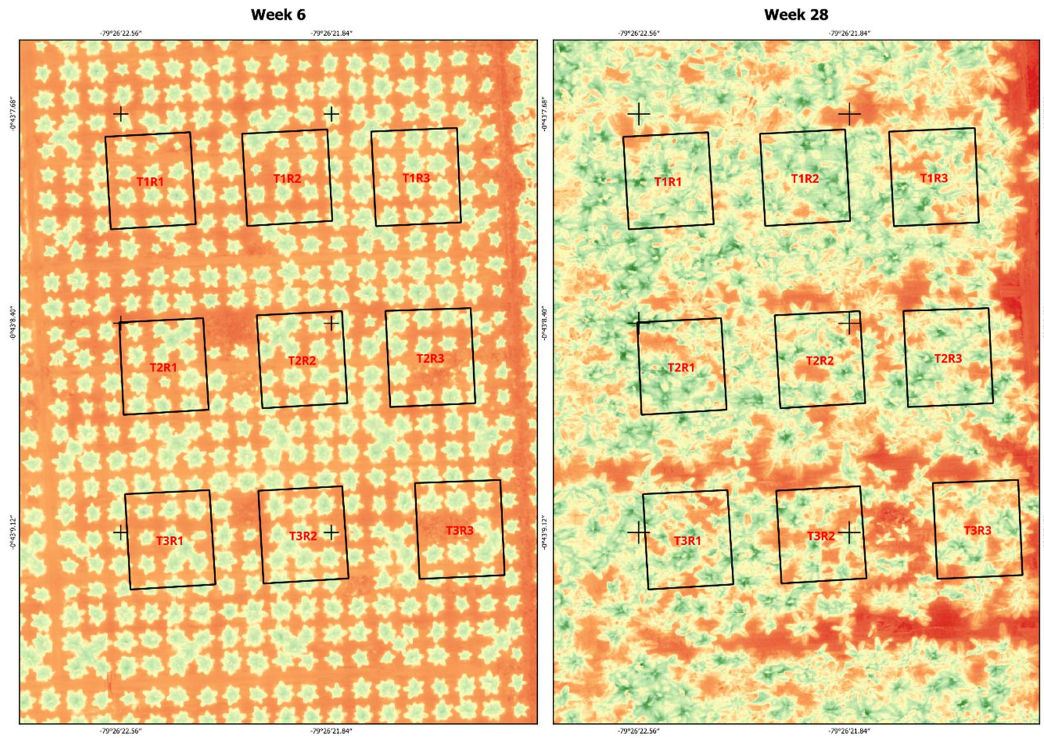

Figure 2. NDVI orthomosaics of the experimental plots at 6 and 28 weeks of growth. Effects of bioinputs on banana vegetative vigor throughout the growth cycle. Scale: 1:500

respectively, after *B. amyloliquefaciens* QST713 application (Tian *et al*., 2023), demonstrating the capacity of Bacillus species to enhance key morphological parameters associated with productivity. The 4.6% advantage maintained by T1 over T2 throughout the evaluation period suggests that the laboratory formulated fungal consortium may possess enhanced capacity for nutrient mobilization, root colonization, or stress mitigation compared to the commercial bacterial formulation. Bacillus species produce antibiotics through Non-Ribosomal Peptide Synthase (NRPS) and Polyketide Synthase (PKS) genes, with *B. amyloliquefaciens* containing bacillomycin D, which is effective in antagonizing banana wilt (Gu *et al*., 2017). However, the superior performance of the Trichoderma-based consortium suggests that fungal biocontrol agents may offer more comprehensive benefits through mycoparasitism, broader enzymatic activity, and more robust colonization patterns under field conditions. This differential response underscores the importance of bioinput selection based on specific crop requirements, environmental conditions, and the multifunctional mechanisms required to optimize plant performance in complex agricultural systems.

Relationships Between Agronomic and Spectral Variables

Spearman's correlation analysis revealed strong, positive, and highly significant ($p < 0.01$) relationships between the measured agronomic variables and the NDVI (Table 3). The number of leaves showed the strongest correlation with plant height (r = 0.9360). Furthermore, NDVI was strongly correlated with pseudostem diameter (r = 0.8572), number of leaves (r = 0.8330), and plant height (r = 0.8167).

The strongest correlation was observed between plant height and leaf number (r = 0.9360), which was expected given that each new leaf in banana represents a new growth point in the pseudostem, composed of overlapping leaf sheaths. This intimate structural relationship is well-documented in banana physiology.

The high correlation between NDVI and pseudostem diameter (r = 0.8572) is particularly significant. Diameter is a key indicator of structural robustness and bunch support capacity. This strong association suggests that the vegetative vigor and photosynthetic activity captured by NDVI are directly linked to the plant's physical development and structural biomass accumulation (Aeberli, Phinn, Johansen, Robson, and Lamb, 2023). This finding is supported by recent research using UAVs, where vegetation indices have been shown to be strongly correlated with biomass and structure parameters in perennial crops. The equally strong correlations of NDVI with height (r = 0.8167) and leaf number (r = 0.8330) reinforce that this index is a reliable integrator of overall growth status (Yánez-Cajo *et al*., 2025).

Table 3. Spearman's correlation matrix between agronomic variables and NDVI.

Variable	Plant Height	Pseudostem Diameter	Number of Leaves	NDVI
Plant Height	1	0.874	0.936	0.8167
Pseudostem Diameter	-	1	0.892	0.8572
Number of Leaves	-	-	1	0.833
NDVI	-	-	-	1

The superiority of the in-situ consortium (T1), composed of *Trichoderma spp*. and *Paecilomyces lilacinus*, in promoting higher NDVI and, by extension, better agronomic development, can be explained by synergistic mechanisms. It has recently been reported that *Trichoderma* strains not only act as biocontrol agents but also function as potent biostimulants (Alfiky and Weisskopf, 2021). They modulate the expression of growth-related genes in plants, improve nutrient use efficiency (especially nitrogen and phosphorus), and promote root system development, leading to increased water and nutrient uptake (Rezaee, 2025). *Paecilomyces lilacinus* is a recognized microbial nematicide. Its inclusion in the consortium likely reduced the pressure from parasitic nematodes on the roots, a common subclinical stress in banana that limits nutrient and water uptake. The combination of these microorganisms could create a healthier and more growth-facilitating rhizospheric environment, translating into greater foliar biomass (chlorophyll) and photosynthetic activity, captured by a higher NDVI.

On the other hand, the commercial bacterial consortium (T2) of *Bacillus spp*. also showed significant effectiveness, although lower than T1. Bacillus species are known for their ability to solubilize phosphates, fix atmospheric nitrogen, and produce phytohormones such as auxins (Han *et al*., 2022). These activities promote plant growth and can explain the 16.8% improvement in NDVI compared to the control. The performance difference with T1 could be attributed to the fact that the bacterial consortium, although effective, may not have addressed other limiting factors as comprehensively, such as the suppression of pathogenic fungi or nematodes (Wang *et al*., 2023), or perhaps because the in-situ formulation of T1 was better adapted to the specific soil and microbiome conditions of the experimental site, as suggested by the literature on the importance of contextual specificity in microbial inoculations (Greenfield *et al*., 2022; Wang *et al*., 2023).

CONCLUSIONS

The strong correlations validate NDVI as a non-destructive and precise proxy for the structural growth of banana. The results demonstrate that the application of bioinputs, particularly multifunctional consortia such as T1, can significantly improve the physiological and agronomic status of the crop. This improvement is efficiently quantified using UAV-based remote sensing, offering a powerful tool for rapid assessment and decision-making in integrated management and precision agriculture programs for banana cultivation.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

Not applicable.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHORS' CONTRIBUTIONS

Conceptualization, Formal analysis, Validation, Project administration, Methodology, and Funding acquisition: D.Y.C.; Methodology and Investigation: A.V.C.M.; Investigation: D.Y.C., A.V.C.M., F.C.G., F.P.P., and F.M.C.; Writing – original draft preparation: D.Y.C., A.V.C.M., F.C.G., F.P.P., and F.M.C.; Writing – review and editing: D.Y.C., F.C.G., F.P.P., F.M.C., and A.V.C.M.

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