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Vulnerability of Smallholder Musaceae Producers to Foc TR4: An Exploratory Analysis in Six Latin American Countries

Vulnerabilidad de pequeños productores de musáceas frente a Foc R4T: Análisis exploratorio en seis países de América Latina

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RESUMEN

Los bananos y plátanos son fundamentales para la seguridad alimentaria y los ingresos de millones de familias en América Latina y el Caribe. Sin embargo, la marchitez causada por *Fusarium odoratissimum* (anteriormente *Fusarium oxysporum f. sp. cubense*), Raza Tropical 4 (TR4) amenaza la sostenibilidad de estos sistemas. Ante la ausencia de variedades resistentes y control efectivo, la bioseguridad es la principal estrategia de prevención. Se aplicaron 230 encuestas en Colombia, Panamá, República Dominicana, Costa Rica, Ecuador y Nicaragua para determinar el nivel de vulnerabilidad de los pequeños productores de musáceas. Mediante análisis multivariados, se identificaron tipologías de vulnerabilidad basadas en el nivel de implementación de medidas de bioseguridad y el control de la calidad del material de siembra. La distribución territorial de las tipologías reflejó la influencia de los arreglos institucionales y de la gobernanza fitosanitaria. Se recomienda implementar intervenciones diferenciadas según el nivel de vulnerabilidad: medidas mínimas de exclusión e infraestructura básica en productores altamente vulnerables; protocolos, registros y control de accesos en productores con vulnerabilidad intermedia; y vigilancia continua y trazabilidad del material vegetal en productores con baja vulnerabilidad, con el fin de reducir eficientemente el riesgo de diseminación de Foc R4T en la región.

Palabras clave: Banano; bioseguridad; marchitez por Fusarium; plátano; prevención; riesgo fitosanitario

ABSTRACT

Bananas and plantains play a crucial role in food security and rural livelihoods for millions of families in Latin America and the Caribbean. However, Fusarium wilt caused by Fusarium odoratissimum (formerly Fusarium oxysporum f. sp. cubense), Tropical Race 4 (Foc TR4), threatens the sustainability of these production systems. In the absence of resistant cultivars and effective control measures, biosecurity remains the primary strategy for prevention. To assess the vulnerability of smallholder Musaceae producers, 230 surveys were conducted in Colombia, Panama, Dominican Republic, Costa Rica, Ecuador, and Nicaragua. Multivariate analyses identified vulnerability typologies based on the degree of implementation of biosecurity measures and the level of control over planting material quality. The territorial distribution of these typologies reflected the influence of institutional arrangements and phytosanitary governance. Based on these patterns, differentiated interventions are recommended according to vulnerability level: minimum exclusion measures and basic infrastructure for highly vulnerable producers; strengthened protocols, record-keeping, and access control for producers with intermediate vulnerability; and continuous surveillance and full traceability of planting material for producers with low vulnerability. This tiered strategy may contribute to reducing the risk of Foc TR4 spread in the region more effectively and in alignment with local capacities.

Keywords: Banana; biosecurity; Fusarium wilt; phytosanitary risk; plantain; prevention

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1. INTRODUCTION

More than 400 million people worldwide depend on bananas and plantains as a fundamental source of food security and income, underscoring their strategic role in global agri-food systems (Kema et al., 2021). Bananas are currently the most traded fruit internationally, while plantains remain a staple component of local diets in many producing countries (Kallow et al., 2022). Most global production is destined for domestic consumption in producing countries, while the remaining 15% is allocated to international trade, primarily to temperate regions. Latin America and the Caribbean (LAC) is the leading exporting region, with a volume exceeding 15 million tons (FAO, 2009). In this regard, Ecuador, the Philippines, Costa Rica, Guatemala, and Colombia remain the world's leading exporters of this fruit (FAO, 2024). In the particular case of Costa Rica, bananas play a strategic role in its agro-export economy, with production concentrated in the Caribbean region. In 2023, national banana production for export exceeded 2.3 million tons, with cantons such as Matina, Pococí, and Siquirres among the country's main production areas (Voora et al., 2020).

However, the sustainability of these production systems is threatened by devastating diseases such as Fusarium wilt caused by *Fusarium oxysporum* f. sp. *cubense* (E.F. Smith) W. C. Snyder & H. N. Hansen (hereafter referred to as *Foc*). In the mid-20th century, the banana industry in the Americas, based on the susceptible Gros Michel (AAA) cultivar, was severely affected by Race 1 (R1) of this pathogen and was forced to replace plantations with resistant cultivars of the Cavendish subgroup (AAA), which has since become the predominant material worldwide (Dita et al., 2018). In the 1970s, a new race of *Foc* causing mortality in Cavendish was detected in Southeast Asia and Australia: Tropical Race 4 (*Foc* TR4) (Maryani et al., 2019). It rapidly spread to Africa and the Middle East, and since 2019 has been reported in Colombia, followed by Peru in 2021, Venezuela in 2023, and Ecuador in 2025 (Acuña et al., 2022; Azarov et al., 2024; Mejías Herrera et al., 2023). This recent incursion into Ecuadorian territory highlights the urgent need to rigorously validate exclusion measures, particularly in the Ecuadorian coastal region, where the high density of production units and the shared management of critical resources create intrinsic vulnerability and significantly increase the risk of accelerated pathogen spread (Borja et al., 2025).

Foc TR4 is a soil-borne hemibiotrophic fungus (Mon et al., 2021), that produces chlamydospores, enabling it to survive for extended periods in infected plant material, organic residues, or as an asymptomatic endophyte in alternative host plants (Mon et al., 2021; Thangavelu & Mustaff, 2012). Its most common route of spread is through the use of infected planting material. However, anthropogenic dissemination via contaminated footwear, vehicles, agricultural equipment, and the discharge of infected wastewater is a key factor in its aggressiveness (Dita et al., 2018; Ploetz, 2015; Blomme et al., 2024).

Various control strategies have been evaluated, including fungicide application, crop rotation, flood fallowing, and organic amendments; however, all have proven insufficient to control the disease, except for the use of resistant cultivars (Ghag et al., 2015; López-Zapata & Castaño-Zapata, 2019; Thangavelu & Mustaff, 2012). In parallel, biological control has gained attention due to its low environmental impact and promising results (Mon et al., 2021; Thangavelu & Mustaff, 2012). According to Ghag et al. (2015), due to the perennial nature of banana crops and the polycyclic nature of the disease, effective long-term management remains a challenge and requires the development of new management strategies. Several authors agree that the only effective way to prevent and manage the disease is through the combined implementation of quarantine practices, control of infected plant material, cleaning and disinfection using footbaths and self-service sanitation stations for farm personnel, disinfection of machinery and agricultural equipment, and treatment of wastewater, all of which can help slow its spread (Ghag et al., 2015; Izquierdo-García et al., 2021; Pegg et al., 2019).

Following the detection of *Foc* TR4 in LAC, National Plant Protection Organizations (NPPOs) and other regional entities have issued biosecurity recommendations for pathogen containment and exclusion (Dita et al., 2018; Instituto Colombiano Agropecuario [ICA], 2024). The objective of this study is to identify vulnerability patterns to Foc TR4 among smallholder Musaceae producers in six LAC countries, exploring territorial and institutional differences. This study provides a diagnostic assessment of current biosecurity conditions, with emphasis on smallholder producers, in order to identify gaps and strengths for the prevention, exclusion, containment, and management of the disease in each country.

2. MATERIALS AND METHODS

During the second half of 2022, a total of 230 surveys were conducted in six Latin American countries to assess biosecurity practices on Musaceae-producing farms. In Colombia, 49 surveys were conducted across the departments of Caldas, Quindío, Risaralda, La Guajira, and Magdalena; in Panama, 33 surveys were carried out in the provinces of Darién, Bocas del Toro, and Chiriquí; in the Dominican Republic, 30 surveys were conducted in the provinces of La Vega, Espaillat, Valverde, and Monte Cristi; in Costa Rica, 30 surveys were conducted in the cantons of Matina, Pococí, and Siquirres (Limón province); in Ecuador, 30 surveys were conducted in the provinces of Santo Domingo de los Tsáchilas, Manabí, Los Ríos, and Guayas; and in Nicaragua, 59 surveys were conducted in the departments of Masaya, Managua, Rivas, León, Matagalpa, Jinotega, and Chinandega. Producers were selected based on representativeness criteria, including the type of production system (banana, plantain, or other species of the genus *Musa*), the predominant producer typology (primarily smallholder farmers), the production destination (domestic market or export), and the strategic importance of production areas in each country.

The instrument used was a structured survey consisting of 92 questions, organized into modules covering general producer information and farm characteristics, biosecurity practices, origin and phytosanitary quality of planting material, plant health, infrastructure, equipment and tools, farm security and access control, operational staff practices, established protocols, and documentation verification. The survey design was based on contingency plans developed by OIRSA and the Colombian Agricultural Institute (ICA) (Dita et al., 2018; [ICA], 2024) and was conceived to be applied transversally, regardless of country or production system, with particular emphasis on small-scale production units. Surveys were administered by specialized technical personnel from AGROSAVIA (Colombia), INIAP (Ecuador), INTA (Costa Rica), IDIAP (Panama), INTA (Nicaragua), and IDIAF (Dominican Republic).

Once data collection was completed, questionnaires were tabulated and cleaned in RStudio for subsequent statistical processing. An initial exploratory analysis based on frequency distributions was conducted to identify variables with the greatest discriminatory power for differentiating producer typologies according to their level of technological adoption and implementation of biosecurity practices. Using this subset of variables, a multiple correspondence analysis (MCA) was performed, following recent approaches for identifying latent dimensions in categorical data (Fujiwara & Liu, 2023), in order to characterize categories and underlying structures of production systems in each country. The hierarchical clustering on principal components (HCPC) followed the approach described by Maugeri et al. (2021), which combines factorial reduction and hierarchical clustering using Ward's algorithm to obtain robust typologies based on inertia and multivariate distribution.

The resulting hierarchical structure was represented using a dendrogram indexed by inertia gain, which allowed the optimal number of clusters to be determined and enabled precise characterization of producer typologies. The analysis was complemented by a principal component analysis, based on Huygens' theorem, to decompose total variance into between- and within-group components (Jolliffe & Cadima, 2016) thereby confirming the robustness of the classification obtained.

3. RESULTS

The frequency analysis made it possible to identify the variables with the greatest discriminatory power. Although all variables were evaluated across the six countries, the prioritized ones revealed important contrasts among different components of biosecurity (Table 1). In Colombia, variables related to infrastructure, procedures, and records stood out, evidencing progress in the consolidation of routines and documentation systems. In contrast, in the Dominican Republic and Costa Rica, access control variables were more prominent, including disinfection of footwear and tools, provision of exclusive clothing, use of farm-specific footwear, and regulation of the entry of people, animals, and vehicles, highlighting their orientation toward pathogen exclusion. In Panama, the most influential variables were related to disinfection procedures and record-keeping, including traceability of production processes as a distinguishing feature, while in Nicaragua, access control variables were also prioritized, although with limitations in infrastructure and record systems. Finally, in Ecuador, variables associated with planting material had less weight, which limits the interpretation of this critical pathway for pathogen introduction.

Tabla 1. Variables prioritized in the analysis of biosecurity in six Latin American countries. *1Colombia, 2Dominican Republic, 3Panama, 4Nicaragua, 5Ecuador, 6Costa Rica

CATEGORY	PRIORITIZED VARIABLES (country*)
PROFILE	Experience in the crop[1], clones planted[3], occupation[3], machinery used for land preparation[3], type of crop[3], shared planting areas[26].
PHYTOSANITARY KNOWLEDGE AND AWARENESS	Knowledge of control strategies for Fusarium in banana or plantain[3], knowledge and/or application of *Foc* TR4 management strategies[4], farm personnel are aware of *Foc* TR4[123], presence of a person responsible for biosecurity[12345], periodic phytosanitary monitoring using established methods[1245], availability of periodic phytosanitary reports[125], reporting of suspected symptoms to the NPPO[1246].
PLANTING MATERIAL: ORIGIN, CERTIFICATION, AND PREVIOUS MANAGEMENT	Application of sanitary treatment to planting material before planting[1], planting material has phytosanitary guarantees[16], planting material has phytosanitary permits from the NPPO[126], origin of planting material[146], type of planting material purchased[16], on-farm seed production phase[1], records of planted plots and origin of planting material[6], control of entry and exit of planting material on the farm[1236], more than one planting material supplier[4], most frequent sanitary problems related to planting material[1].
PHYSICAL BIOSECURITY INFRASTRUCTURE	Presence of perimeter fences[26], perimeter fencing for animals[12356], clearly delimited areas[1236], signage in biosecurity areas[123], biosecurity infrastructure at farm entry[12346], footwear washing and disinfection system in biosecurity zones[1256], at least one washing and disinfection system in production areas[1256], physical separation between clean and dirty areas in biosecurity zones[1246], parking area with inert surface outside production areas[12356], washing and disinfection of vehicles, machinery, or agricultural implements entering or leaving the farm[1245], designated area for disinfection of vehicles, machinery, and implements before parking[12456], biosecurity areas within the farm are signposted[1].
DISINFECTION PROCEDURES AND PRACTICES	Biosecurity practices implemented[12346], frequency of biosecurity application[1235], availability of facilities for washing and disinfection of vehicles and machinery[12456], disinfection of incoming tools and equipment[123], disinfection of on-farm tools and equipment[123], no use of disinfectants[13], concentration used[13], control of sludge and wastewater flow in washing and disinfection areas[1246], cleaning of machinery before use on the farm or plots[23], removal of soil from footwear in biosecurity and production areas[12345], use of approved active ingredients at correct dosages[123].

ACCESS CONTROL OF PEOPLE, VEHICLES, ANIMALS, AND EQUIPMENT	Control of personnel transport entry[256], control of personnel entry[246], hiring of temporary workers[26], permanent staff working on other farms[26], disinfection of personnel footwear[23456], disinfection of tools by personnel[26], use of external footwear or tools not provided by the farm[26], availability of exclusive footwear for farm use[12456], provision of exclusive clothing for farm use[23], provision of farm-specific footwear to workers or visitors[12345], provision of clothing to visitors[1246], entry of external tools or equipment[124], written records of entry and exit of people[23], access to other farms[23456], uncontrolled entry of animals[1246], uncontrolled entry of people[246], presence of animals[26], control of entry of machinery, tools, and equipment[124].
RECORDS, TRACEABILITY, AND DOCUMENTATION	Records of periodic training[123], written records of entry and exit of planting material[1236], records of personnel entry and exit[12356], written records of entry and exit of vehicles, machinery, and agricultural equipment[146], periodic monitoring records[1235], records of machinery origin and use[12], consistent written records of monitoring and biosecurity[136], existence of protocols or procedures for biosecurity implementation[135], traceability in production processes[3].

The multiple correspondence analysis (MCA) was applied independently in each country, given that production and socioeconomic conditions vary substantially and determine different ways of implementing biosecurity. Thus, a country-level analysis ensures that clusters reflect the internal diversity of each national context and are not dominated by contrasts between countries. This separate application made it possible to extract representative dimensions for each context and subsequently compare the patterns identified across countries.

Using the prioritized variables, the MCA generated the factorial coordinate matrix used as input for the HCPC. This procedure made it possible to identify statistical proximity among producers within each country and to group them into homogeneous sets according to their level of adoption of biosecurity practices. The HCPC integrated the qualitative information from the selected variables with the most explanatory dimensions of the MCA, producing consistent and clearly differentiated typologies. From this process, a specific number of hierarchical groups was defined for each country, which were standardized considering the two dimensions with the greatest discriminatory power: the implementation of biosecurity measures (infrastructure, protocols, records, and access control) and phytosanitary risk associated with the management of planting material (origin, guarantees, traceability, and prior treatment).

The combination of both dimensions allowed the definition of four general categories within the factorial space, which enabled reinterpretation and standardization of clusters across countries, ensuring a coherent comparative interpretation of risk levels with respect to Foc TR4: high vulnerability (low biosecurity and high risk from planting material); vulnerability due to planting material (partial biosecurity but high risk derived from origin, lack of traceability, or inadequate management of planting material); vulnerability due to biosecurity (adequate control of planting material but deficiencies in infrastructure and protocols); and low vulnerability (high standards in both biosecurity and planting material management). The results for each country are described below.

3.1. Colombia

Four groups of farmers were identified, jointly explaining 79% of the total variability. Dimension 1, which accounts for 68.3% of the variability, is mainly associated with the implementation of biosecurity schemes (infrastructure, records, and protocols), while Dimension 2 (10.7%) is related to the origin and management of planting material (Figure 1).

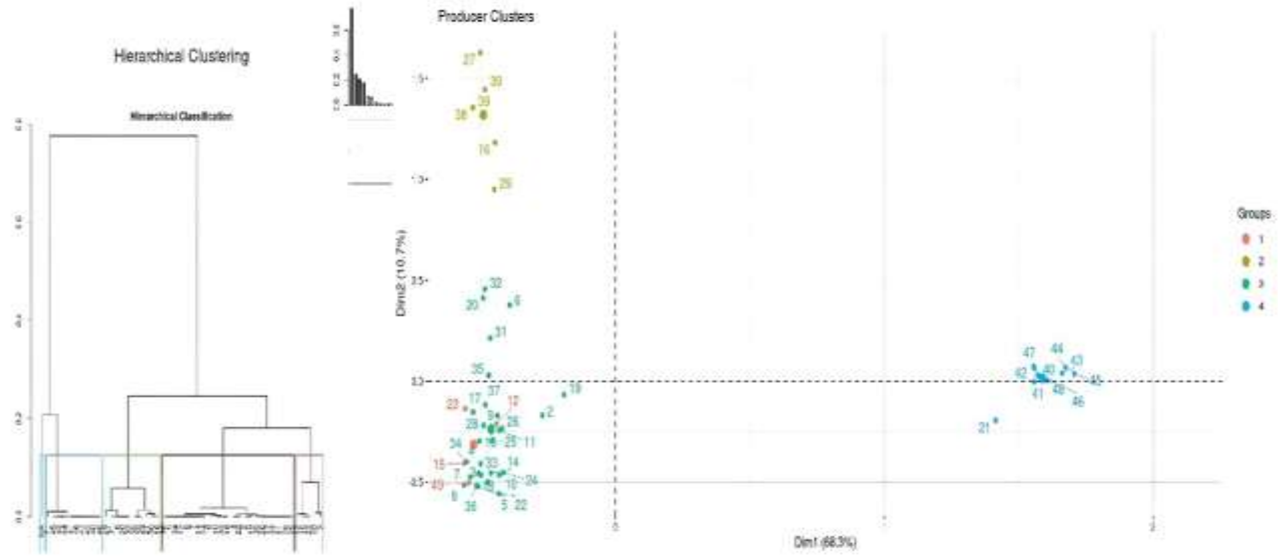

Figura 1. Producer typologies associated with their vulnerability to *Foc* TR4 in Colombia. Left: dendrogram from the HCPC analysis. Right: distribution of producers in the MCA factorial space

Cluster 1 (red, n=5; 10 %): High vulnerability. Producers with minimal or no implementation of biosecurity measures, lacking protocols and records, and with deficient access control. Planting material lacks phytosanitary guarantees and traceability. These producers are mainly concentrated in La Guajira, Magdalena, and Caldas.

Cluster 2 (yellow, n=6; 12 %): Intermediate vulnerability due to planting material. Located in Magdalena and La Guajira. They exhibit basic biosecurity practices, including occasional disinfection, with incipient protocols and records; however, their main risk factor derives from the origin and management of planting material, characterized by limited traceability, scarce phytosanitary guarantees, and minimal prior treatment.

Cluster 3 (green, n=28; 58 %): Intermediate vulnerability due to biosecurity. Producers who implement some biosecurity measures, but in an irregular manner and without systematic documentation. Although planting material is mostly sourced locally with basic controls such as pre-planting disinfection, the main gaps lie in the lack of infrastructure, formal protocols, and consistent access control.

Cluster 4 (blue, n=10; 20 %): Low vulnerability. Producers from Quindío, Risaralda, Caldas, and one producer from La Guajira with robust infrastructure (clean/dirty zones, operational footbaths, vehicle washing and disinfection systems, formal records and protocols). Planting material is not a determining factor in their classification.

3.2. Dominican Republic

In the Dominican Republic, the MCA–HCPC analysis revealed clear variations among producers according to their level of biosecurity and management of planting material. These differences made it possible to identify three clusters with contrasting levels of vulnerability to *Foc* TR4, ranging from systems with minimal measures to an isolated case with advanced practices (Figure 2).

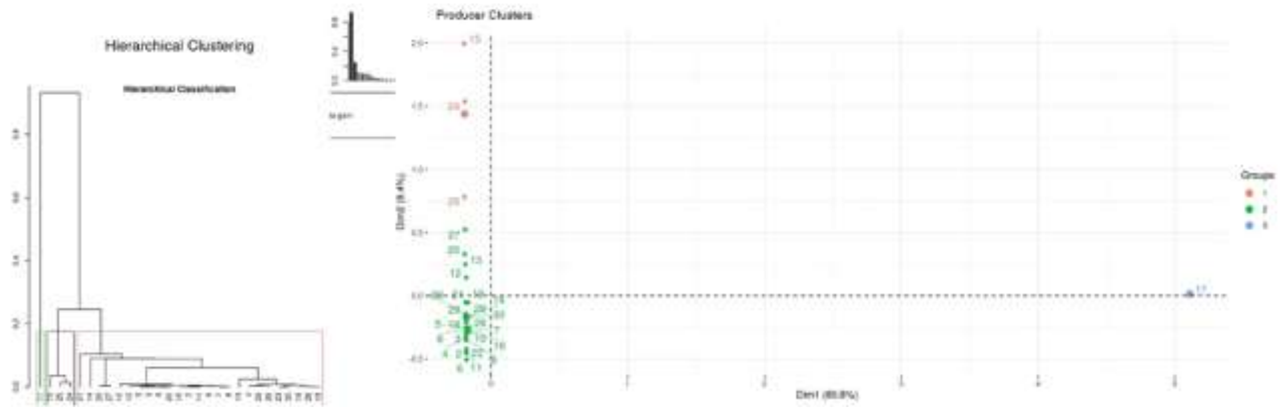

Figura 2. Producer typologies associated with their vulnerability to *Foc* TR4 in the Dominican Republic. Left: dendrogram from the HCPC analysis. Right: distribution of producers in the MCA factorial space

Cluster 1 (red, n=3; 10 %): High vulnerability. Producers located in the lower-left quadrant of the factorial space. They show very low implementation of biosecurity measures, including absence of protocols, lack of basic infrastructure (disinfection points, signage, access control), and no record-keeping. Planting material lacks phytosanitary guarantees and traceability, increasing the risk of Foc TR4 introduction and spread.

Cluster 2 (green, n=26; 86.7 %): Vulnerability due to biosecurity. This is the predominant group, located around the origin of the factorial space. They exhibit partial adoption of biosecurity practices, including some basic cleaning and disinfection procedures, occasional access control, and incipient record-keeping. Planting material is mainly sourced locally, generally without formal certification, but with basic prior management. This group represents an intermediate typology, with potential for improvement through protocol standardization and strengthening of documentation practices.

Cluster 3 (blue, n=1; 3.3 %): Low vulnerability. An isolated producer with high scores in both dimensions: highly consolidated biosecurity (complete infrastructure, formalized protocols, systematic records, and strict access control) and rigorous management of planting material (lot-level traceability, defined suppliers, and use of material with phytosanitary guarantees). Due to its atypical nature, it represents the national benchmark for best practices against Foc TR4.

3.3. Panama

Most of the variance (76.5%; Dim 1) is associated with the implementation of biosecurity schemes (infrastructure, records, access and disinfection protocols), which explains the separation of the blue and purple clusters. Dimension 2 (10.5%) differentiates producers according to the origin and management of planting material, explaining the position of the yellow cluster in the upper part of the factorial space. Together, both dimensions allow the identification of typologies ranging from highly structured biosecurity systems to producers with low adoption levels and strong dependence on locally sourced planting material.

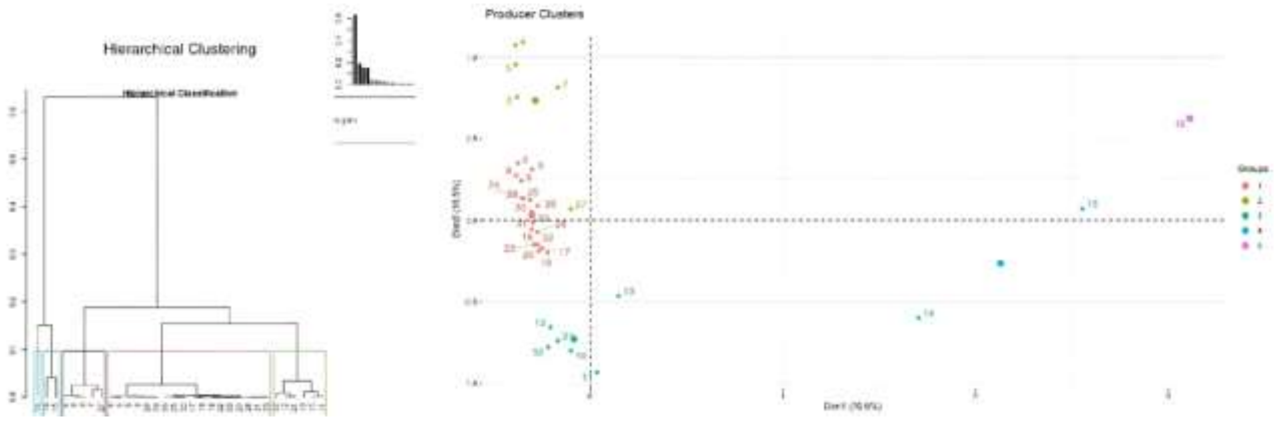

Figura 3. Producer typologies associated with their vulnerability to *Foc* TR4 in Panama. Left: dendrogram from the HCPC analysis. Right: distribution of producers in the MCA factorial space

Cluster 1 (red, n≈18; 56 %): Vulnerability due to biosecurity. This is the predominant group, characterized by partial biosecurity and inconsistencies in protocol implementation. Disinfection infrastructure is limited, records are irregular, and access control is insufficient. Although planting material is locally sourced and lacks formal guarantees, it is not the main risk factor. Vulnerability primarily derives from the low standardization of operational procedures for producing quality planting material.

Cluster 2 (yellow, n=4; 12 %): Vulnerability due to planting material. Producers whose main risk derives from the origin and management of planting material. Planting material is mostly locally sourced, without phytosanitary guarantees or formal traceability. Biosecurity is limited to basic and non-systematic practices, increasing vulnerability associated with the introduction of Foc TR4 through this pathway.

Cluster 3 (green, n=5; 16 %): High vulnerability. Producers with limited or no implementation of biosecurity measures, nonexistent or very limited infrastructure, and absence of records. Planting material comes from local sources without sanitary controls. This group represents the most vulnerable typology in the country with respect to *Foc* TR4.

Cluster 4 (blue, n=4; 13 %) y 5 (purple, n=1; 3 %): Low vulnerability. This group includes producers with high biosecurity standards, characterized by functional infrastructure, consolidated operational protocols, systematic record-keeping, and consistent access control. Although some exhibit advanced levels and others reach outstanding standards, all share a solid and sustained implementation of preventive measures.

3.4. Nicaragua

Most of the variance (65.3%; Dim 1) is associated with the implementation of biosecurity schemes (physical infrastructure, records, protocols, and access control), which explains the separation between the red–green clusters and the more advanced groups (blue and purple). Dimension 2 (4.1%) differentiates producers based on the management and origin of planting material, which explains the atypical position of the yellow cluster in the upper part of the factorial space. Overall, the results show a gradient ranging from producers with low adoption and high vulnerability to consolidated biosecurity typologies, including an isolated producer distinguished by its emphasis on planting material.

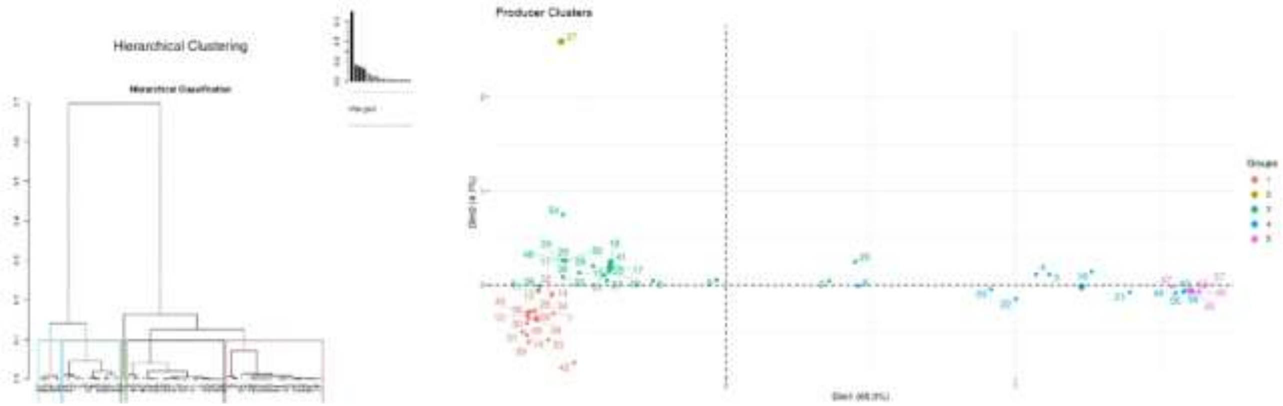

Figura 4. Producer typologies associated with their vulnerability to *Foc* TR4 in Nicaragua. Left: dendrogram from the HCPC analysis. Right: distribution of producers in the MCA factorial space

Cluster 1 (red, n≈18; 30 %): High vulnerability. Producers with limited implementation of biosecurity measures (minimal infrastructure, limited records, and incipient protocols), with no clear differentiation in planting material. This represents a vulnerable typology, characterized by basic practices and high phytosanitary risk.

Cluster 2 (yellow, n=1; 2 %): Vulnerability due to planting material. A producer distinguished by emphasis on planting material (origin, prior management, and records of origin), with low structural biosecurity. This constitutes an atypical, seed-oriented profile, whose single-case nature requires caution in interpretation.

Cluster 3 (green, n≈15; 25 %): Vulnerability due to biosecurity. Producers with low to intermediate adoption of biosecurity, including some disinfection measures and access control. Although planting material is locally sourced, it has an acceptable level of basic management; therefore, the main risk derives from gaps in biosecurity.

Cluster 4 (blue, n≈12; 20 %): Low vulnerability. Producers with high implementation of biosecurity (infrastructure, protocols, formal records, and access control), although planting material is not the main discriminating factor. This represents an advanced typology in prevention.

Cluster 5 (purple, n≈6; 10 %): Outstanding low vulnerability. Producers with fully consolidated biosecurity schemes, including robust infrastructure, comprehensive records, and standardized protocols. This group represents a benchmark typology, with higher levels of technological and phytosanitary practices.

3.5. Ecuador

Dimension 1 (51.8%) accounts for most of the differentiation and is strongly associated with the implementation of biosecurity schemes (infrastructure, protocols, records, and access control). It is the axis that clearly separates the most vulnerable groups (Clusters 1 and 2) from the more advanced ones (Clusters 6 and 7), while Dimension 2 (20%) introduces additional variation related to the management and origin of planting material (guarantees, prior treatments, and traceability), explaining the elevated position of certain singular cases.

Overall, both axes show a gradient ranging from producers with low adoption and high vulnerability to groups with outstanding practices in both biosecurity and planting material management, including one producer (Cluster 5) clearly differentiated by its unique profile.

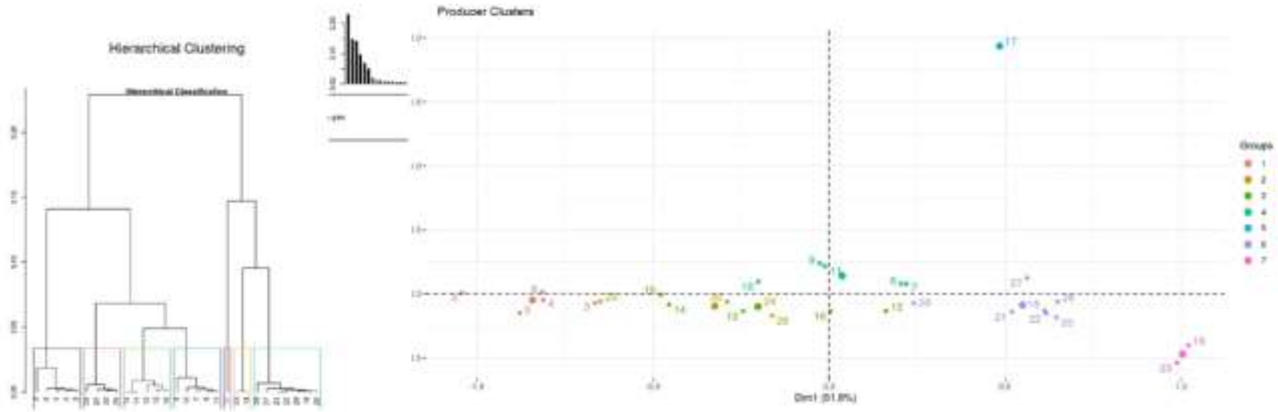

Figura 5. Producer typologies associated with their vulnerability to *Foc* TR4 in Ecuador. Left: dendrogram from the HCPC analysis. Right: distribution of producers in the MCA factorial space

Cluster 1 (red, n≈5; 12 %): High vulnerability. Producers with limited biosecurity (no consolidated protocols or records, minimal infrastructure), with no marked differentiation in planting material.

Cluster 2 (yellow, n≈3; 7 %): Vulnerability due to biosecurity. Producers with partial biosecurity measures, poorly systematized protocols, and no consistent traceability in planting material.

Cluster 3 (green, n≈8; 20 %): Vulnerability due to planting material. Producers with intermediate adoption, implementing some control measures and sporadic records; planting material is mainly locally sourced and lacks formal guarantees.

Cluster 4 (turquoise, n≈3; 8 %): Low vulnerability due to record maturity. Producers with defined infrastructure and strong operational protocols (record-keeping and monitoring), although planting material is not the main differentiating factor.

Cluster 5 (light blue, n≈1; 2 %): Outstanding low vulnerability. An atypical producer with consolidated biosecurity and complete records, clearly separated from the rest due to high scores in infrastructure and protocol-related variables.

Cluster 6 (violet, n≈6; 15 %): Low vulnerability due to maturity in access and perimeter control. Producers with structured biosecurity, including the use of exclusive footwear, soil removal practices, the presence of a designated biosecurity officer, and perimeter fencing, although variables related to planting material carry less weight.

Cluster 7 (pink, n≈2; 5 %): Low vulnerability due to infrastructure. Producers with maximum adoption of pre-parking disinfection zones, parking areas with inert surfaces, specialized biosecurity equipment, and, at the same time, strict control of planting material (traceability, phytosanitary guarantees, and origin records).

3.6. Costa Rica

The MCA–HCPC analysis made it possible to identify four groups of producers in Costa Rica. Dimension 1 (37.3%) was mainly associated with the level of implementation of biosecurity schemes (infrastructure, protocols, records, and access control), while Dimension 2 (25%) was related to the origin, management, and traceability of planting material.

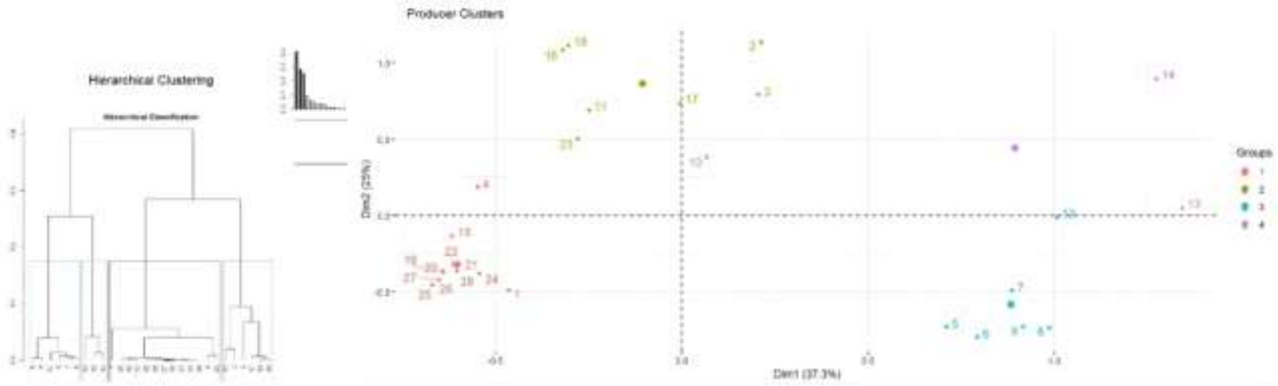

Figura 6. Producer typologies associated with their vulnerability to Foc TR4 in Costa Rica. Left: dendrogram from the HCPC analysis. Right: distribution of producers in the MCA factorial space

Cluster 1 (red, n≈9, 31 %): High vulnerability. Producers with low implementation of biosecurity measures, lacking formalized protocols and infrastructure for disinfection. Record-keeping is limited or nonexistent, and planting material management does not constitute a differentiating factor.

Cluster 2 (green, n≈11, 38 %): Vulnerability due to biosecurity. Producers with intermediate adoption: they implement certain measures such as washing or disinfection of tools and partial area delimitation, but protocols are not systematic and documentation is inconsistent. Planting material is mostly sourced through local exchanges or on-farm production, with basic prior management and no formal phytosanitary guarantees. This represents a transitional typology with potential for improvement.

Cluster 3 (blue, n≈5): Low vulnerability. Producers with strong performance in personnel control and operational standardization, but with intermediate levels in vehicle and area infrastructure and moderate traceability of planting material. However, planting material does not act as a discriminating variable in this group, as practices remain similar to those of other producers.

Cluster 4 (violet, n≈3): Outstanding low vulnerability. Producers with consolidated biosecurity, including vehicle management (pre-parking disinfection zones, parking areas with inert surfaces, exclusive equipment, and clean/dirty areas), and who also incorporate traceability and phytosanitary guarantees of planting material (type, origin, lot-level records, and NPPO permits), thus constituting the country's benchmark typology.

4. DISCUSSION

The methodological proposal of FAO (Saravia Matus et al., 2013), states that the construction of agricultural typologies should enable the distinction of production units with differentiated behaviors, constraints, and potentials, in order to guide public policies and target support instruments. Our results are consistent with this approach: through the use of MCA and HCPC applied to Musaceae producers in six Latin American countries, clearly differentiated producer typologies were identified according to their vulnerability to the incursion of *Foc* TR4, based on their level of biosecurity implementation (infrastructure, protocols, records, access control) and management of planting material (origin, guarantees, traceability), both showing high discriminatory power. In operational terms, these categories translate into a gradient of high vulnerability, vulnerability due to planting material, vulnerability due to biosecurity, and low vulnerability, which we used to harmonize the interpretation of clusters across countries. These characterizations are essential for designing differentiated and cost-effective policies, as they facilitate the adaptation of instruments such as technical assistance, co-financing of minimum infrastructure, or regulation of planting material, rather than applying homogeneous and less effective measures.

The observed factorial structure confirms that operational biosecurity constitutes the primary axis of differentiation, while the management of planting material represents a second gradient that modulates risks and practices. This pattern is expressed differently across countries. In Colombia, coefficients show very high loadings for access control, fencing, biosecurity zones, footwear disinfection, record-keeping, and periodic monitoring, which explains the prevalence of low-vulnerability typologies. This is associated with the presence of the pathogen since 2019 and the need to implement containment measures through biosecurity schemes supervised by ICA (Betancourt Vásquez et al., 2021), as well as the implementation of protocols for the importation of germplasm and propagation material and regulations for internal movement within the country (Betancourt Vásquez et al., 2021; [ICA], 2024).

In the Dominican Republic, there is an almost complete dominance of the operational axis: the level of implementation of protocols and access control explains most of the variance, while standardization (designation of a responsible person, signage) and vehicle management define the transition from intermediate to outstanding clusters. In Costa Rica, this pattern is consistent with a context of reinforced phytosanitary prevention against *Foc* TR4, in which surveillance, operational biosecurity, and institutional coordination have played a relevant role (Presidencia de la república & Ministerio de la agricultura y Ganadería, 2021). Within this framework, control of personnel and operational standardization structure the variance, while infrastructure for vehicles and areas (parking zones with inert surfaces, washing equipment, clean and dirty areas) marks the qualitative step toward outstanding low vulnerability; traceability and phytosanitary guarantees of planting material consolidate this profile. In Panama, a gradient of adoption and standardization (protocols, records, signage) predominates, such that advanced clusters emerge when operations shift from intermittent practices to integrated systems including vehicle-related infrastructure. In Ecuador, the quality of access control (people and vehicles) differentiates clusters within the low-vulnerability group: some with operational strength and others with comprehensive infrastructure coverage. Although, at the local level, planting material showed low discriminatory weight for Ecuador, a specific analysis of the Ecuadorian coastal region reveals that the lack of traceability in the origin of planting material is a latent vulnerability factor that must be addressed through local certification protocols (Borja et al., 2025). Finally, in Nicaragua, planting material plays a more prominent role (origin, multiplicity of suppliers) and, together with monitoring and reporting, explains the differentiation between vulnerability levels, reinforcing the need for seed governance and control of effluents and vehicles. These differences are consistent with technical literature linking the reduction of *Foc* TR4 risk to the simultaneous deployment of physical, operational, and traceability barriers (Ritter et al., 2024; Saravia Matus et al., 2013).

From a policy and extension perspective, typologies allow the definition of staged intervention pathways: basic measures for vulnerable groups (exclusion, access control, fencing, disinfection points, and minimum record-keeping); standardization for groups with vulnerability due to biosecurity (formal protocols, signage, designated biosecurity officer, internal audits); and auditing and strengthening of planting material traceability for low-vulnerability groups aiming to reach outstanding levels. This logic aligns with previous experiences showing that typologies accelerate technological adoption and optimize resource allocation (Nabahungu et al., 2025; Sinha et al., 2022). Furthermore, the independent implementation of MCA by country avoids aggregation bias and captures internal variability, while rigorous handling of missing data strengthens analytical validity and prevents artifacts such as spurious single-producer clusters.

Comparatively, our results align with other studies regarding the multivariate logic of reducing heterogeneity and grouping into interpretable clusters to guide policy; the difference lies in the discriminant variables. For example, Staver et al. (2023) uses socioeconomic factors to explain technological adoption in Bangladesh, whereas the present study focuses on technical–sanitary dimensions for phytosanitary risk management in the context of *Foc* TR4. Integrating both approaches would allow prioritization of biosecurity measures while simultaneously using socioeconomic determinants to define support and extension instruments, maximizing both phytosanitary impact and economic feasibility. Likewise, the work of Azarov et al. (2024) highlights the importance of developing context-specific typologies to guide differentiated pathways of sustainable development. Although their focus is on livelihood capitals, their methodological approach converges with ours and reinforces the idea that typologies are not an end in themselves, but a tool for differentiated decision-making in heterogeneous territories. In our case, sustainability is linked to phytosanitary resilience: groups with high biosecurity and traceability represent sustainable trajectories, while vulnerable groups face higher risks of productive exclusion.

The principles of integrated management of Fusarium wilt reinforce this interpretation: prevention and containment depend on the combination of biosecurity measures and control of planting material (Blomme et al., 2024), precisely the two dimensions that structure our typologies. In contexts where resistant varieties are not available, advanced typologies represent resilience pathways, while vulnerable ones require urgent interventions in exclusion, quarantine, and traceability. In addition, the diagnostic dimension is crucial: Roberts et al. (2024) highlight that the reliability of an assay is directly related to the rigor applied during its validation, implying that producers with strong infrastructure and record systems are better positioned to sustain continuous monitoring and respond early.

Evidence from Peru suggests that biosecurity adoption among smallholder organic producers tends to focus on basic measures, without integration into formal protocols (Staver et al., 2023). This is consistent with several vulnerable and intermediate clusters identified in our analysis, where sanitary measures are adopted for immediate agronomic benefits rather than as part of coordinated surveillance schemes. In contrast, advanced clusters in regions with active surveillance (e.g., La Guajira and Magdalena in Colombia) show more complete configurations aligned with commercial standards. This contrast suggests that sustainable adoption is enhanced when biosecurity is integrated with market requirements and productivity goals, rather than being framed as an isolated requirement. In this context, the concept of pathological markets (Wang & Chien, 2024) provides a broader perspective: microorganisms act as structuring agents that reshape markets and practices. Our typologies reflect these dynamics: advanced groups integrate the transformative capacity of microorganisms through robust biosecurity, while intermediate groups rely on speculative care practices (e.g., informal selection of planting material or use of amendments). Furthermore, the pressure from regulated markets drives advanced adoption, explaining the geographic concentration of certain clusters in export-oriented areas. Thus, biosecurity adoption depends not only on technical capacities, but also on the interaction between pathogens, markets, and institutions, which implies the need for coordinated interventions at multiple levels.

A central element emerging from the analysis is the role of institutional arrangements and phytosanitary governance. In line with the view of plant protection as a public good (Garcia-Figuera et al., 2021), individual action is insufficient to sustain prevention, raising collective action challenges. Our data show this relationship with varying intensity across countries: in Colombia, low-vulnerability clusters are concentrated in the Coffee Region (Kema et al., 2021), while in Panama and Costa Rica, the greater presence of advanced typologies is consistent with territories where technical assistance and active surveillance operate (e.g., Chiriquí and Pococí), although the cluster–territory statistical interaction is not reported in this manuscript. In Nicaragua and Ecuador, more heterogeneous profiles are observed, with a higher proportion of vulnerable typologies in several regions. This is consistent with Kusters et al. (2020), who emphasize that effective governance integrates local capacities and territorial cooperation. Consequently, strengthening territorial governance, nursery certification, and technical support systems is as strategic as promoting the adoption of biosecurity practices. In particular, the heterogeneity observed in Ecuador is consistent with the multidimensional typification reported by Borja et al. (2025), which confirms that the persistence of vulnerable typologies is associated with structural limitations in the articulation between biosecurity and the economic capacity of smallholder producers.

Overall, the typologies obtained not only describe current conditions but also represent phytosanitary resilience trajectories in the face of *Foc* TR4 from systems at risk of productive exclusion to sustainable configurations capable of maintaining surveillance and early response. Under this logic, public and private interventions should progress sequentially: (i) access control and operational culture (control of entry of people and animals, designated biosecurity officer, records, and signage); (ii) vehicles, areas, and effluents (pre-parking disinfection zones, inert parking surfaces, exclusive washing equipment, and separation of areas); and (iii) planting material (formal suppliers, phytosanitary guarantees, permits, and lot-level traceability). This pathway, consistent with comparative evidence (Ritter et al., 2024; Saravia Matus et al., 2013; Nabahungu et al., 2025; Sinha et al., 2022; Staver et al., 2023), transforms typologies into operational and functional tools to guide more precise, efficient, and sustainable phytosanitary policies for this pathosystem in the región.

CONCLUSIONS

The typology analysis based on MCA–HCPC made it possible to identify three differentiated trajectories of biosecurity adoption in response to *Foc* TR4 in Musaceae production systems: vulnerable, transitional, and advanced. These trajectories are primarily structured around two dimensions with high discriminatory power: the implementation of biosecurity measures (infrastructure, protocols, records, and access control) and the management and traceability of planting material (origin, phytosanitary guarantees, and prior treatment). These dimensions not only explain differences among producers but also reflect how production systems internalize phytosanitary risk.

The territorial distribution of typologies shows that biosecurity adoption does not depend solely on individual technical capacities, but also on the presence of institutional arrangements and phytosanitary governance networks. Regions with organized producer associations and active surveillance exhibit a higher prevalence of advanced typologies, while territories with weak technical assistance and limited regulation of planting material tend to concentrate vulnerable or intermediate typologies.

These findings provide a strategic basis for differentiated interventions: for vulnerable groups, actions should focus on exclusion measures and basic infrastructure strengthening; for transitional groups, priority should be given to standardization of protocols and record-keeping; and for advanced groups, the focus should be on auditing, continuous monitoring, and certification of planting material. Overall, the constructed typologies become operational and functional tools for risk management, guiding more precise, efficient, and sustainable policies in response to the growing threat of *Foc* TR4 in Latin America and the Caribbean.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest associated with the conduct, analysis, or publication of this study.

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