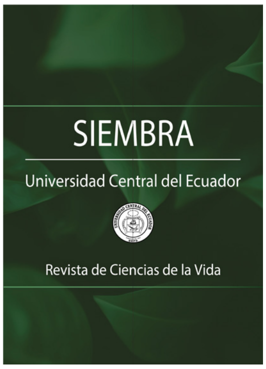
Arbuscular mycorrhizal fungal (AMF) communities associated with mango cv. sugar (Mangifera indica L.) crops in Magdalena, Colombia



Comunidades de hongos micorrízicos arbusculares (HMA) asociados al cultivo de mango cv. azúcar (Mangifera indica L.) en Magdalena, Colombia

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Abstract

Arbuscular mycorrhizal fungi represent one of the most prevalent group organisms in the rhizosphere. They are present in more than 200,000 plant species. Despite their pervasive distribution in ecosystems, only 322 species have been formally described to date. The present study aimed to characterize the diversity of AMF communities in two mango-producing areas in the Magdalena Department, Colombia. To this end, the following steps were taken: (i) the identification of the morphospecies present, (ii) the comparison of communities through diversity indices, (iii) the determination of soil chemical properties, and (iv) the relationship between these properties with species richness, selected using principal component analysis [PCA]. The study yielded 25 morphospecies, distributed across six families and ten genera. Of these, three key morphospecies *Cetraspora pellucida*, *Glomus sinuosum* and *Gigaspora margarita* were identified as the most frequent. The highest diversity values were observed in Santa Marta, with the San Pablo farm demonstrating the highest values for Shannon and Simpson indices (1.63 and 0.78, respectively), while the Las Palmeras farm exhibited the highest value for the Pielou uniformity index (0.97). This study reports, for the first time, the occurrence of AMF species associated with mango cv. sugar crops in the localities of Santa Marta and Ciénaga.

Keywords: diversity index, *Mangifera indica*, mycorrhizas, spore abundance, species richness, sugar mango.

Resumen

Los hongos micorrízicos arbusculares son uno de los organismos más abundantes en la rizósfera y se pueden encontrar en más de 200.000 especies de plantas. A pesar de su gran distribución en ecosistemas, hasta el momento solo se han descrito 322 especies. El objetivo del presente estudio fue caracterizar la diversidad de las comunidades de hongos micorrízicos arbusculares presentes en dos áreas productoras de mango cv. azúcar en el departamento de Magdalena, Colombia. Para ello se llevó a cabo: (i) la identificación de las morfoespecies presentes, (ii) la comparación de las comunidades a través de índices de diversidad, (iii) la determinación de las propiedades químicas de los suelos, y (iv) la relación entre estas propiedades con la riqueza de especies, seleccionadas mediante análisis de componentes principales [ACP]. Como resultado se encontró un total de 25 morfoespecies, representadas en seis familias y diez géneros, permitiendo identificar tres morfoespecies claves: *Cetraspora pellucida*, *Glomus sinuosum* y *Gigaspora margarita* como las especies más frecuentes. Los mejores valores en los índices de diversidad se encontraron en Santa Marta, siendo la finca San Pablo la que obtuvo los valores más altos en los índices de Shannon y Simpson (1,63 y 0,78, respectivamente), mientras que la finca Las Palmeras fue la que obtuvo el mayor valor en el índice de uniformidad de Pielou con un valor de 0,97. Reportándose por primera vez la ocurrencia de especies de HMA asociadas a cultivos de mango cv. azúcar en las localidades de Santa Marta y Ciénaga.

Palabras clave: índice de diversidad, *Mangifera indica,* micorriza, abundancia de esporas, riqueza de especies, mango cv. azúcar.

1. Introduction

Most of terrestrial plants form some kind of symbiotic association with mycorrhizal fungi (van der Heijden et al., 2015) from which 1.5% belong to ericoid mycorrhizae, 2.0% belong to ectomycorrhizae [EcM], 10% belong to orchidoid-type mycorrhizae, and 72% are associated with arbuscular mycorrhizal fungi [AMF] (Brundrett & Tedersoo, 2018). The last association is the oldest and most extended in the whole planet. All these fungi play a key role in terrestrial ecosystems because they regulate the life cycle of diverse nutrients, influence the soil structure and the functionality of ecosystems (van der Heijden et al., 2015). AMF is among the most abundant organisms in the rhizosphere, which is associated with more than 200 000 species of plants. Despite their wide distribution in the ecosystem, it has been officially described only 317 species at the moment (Goto & Jobim, 2024).

The composition and richness of the AMF communities depend on both the host plant and environmental conditions. In the case of crops, communities also depend on agronomical management because its intensification leads to a decrease in the natural diversity of AMF species (Öpik et al., 2006; Verbruggen et al., 2010; de Pontes et al., 2017). The identification of native species of AMF is a vital factor to understand the changes in community composition and how their diversity could affect ecosystems (Cofré et al., 2019).

The South American tropic is recognized by its wide biological and microbiological diversity. The richness of AMF can be well appreciated in different ecosystems associated with different types of plants (angiosperms and gymnosperms). For example, tropical forests are widely colonized by AMF and ectomycorrhizae (Cofré et al., 2019). However, this diversity has not been well studied. From the available publications (110 articles in total) on the AMF morphospecies in South America, it was found only six articles from Colombia, which identified six genres and 20 species of AMF (Cofré et al., 2019). According to Peña-Venegas and Vasco-Palacios (2019), Colombia was one of the first countries in South America to study AMF, but no article has referred the diversity of AMF associated to mango crop cv. sugar (*Mangifera indica*).

Mango is a tropical fruit originated in India. This country is the highest producer and has 22% of the total cultivated fruit area, which is 2.3 million of hectares and 24 million tones of yield. (FAOSTAT, 2021). In Colombia, mango crop produced 10.31 t ha^{-1} yield. The main producers of mango are the departments of Tolima, Cundinamarca and Magdalena (Ministerio de Agricultura y Desarrollo Rural [MADR], 2020). Mango is found mainly as fresh produce in the local market, and some traditional varieties are used in the agroindustry. The main varieties cultivated at national level are common mango, chancleto, coastal, sugar, apple, queen and Tommy Atkins. This last one is destined for exportation (Aguilar Corrales et al., 2018). From these varieties, the cv. sugar is cultivated in 2978 ha, where it has an average yield of 13.87 t ha^{-1} (Agronet, 2020).

Some studies have been done to know the diversity of AMF associated to mango crops worldwide (Abdelhalim et al., 2014; Belay et al., 2014; Cortés Mercado et al., 1996; Govindan et al., 2020; Jiang et al., 2020; Mohandas, 2012; Mullath et al., 2019). However, in Colombia there are no available publications on the diversity of AMF communities associated to mycorrhizal soil in mango cv. sugar. Therefore, the present study aimed to characterize the diversity of the AMF communities in two productive zones of mango cv. sugar in the Magdalena department, at the municipalities of Santa Marta and Cienaga. The activities performed were: (i) The identification of morphospecies, (ii) comparison between communities through diversity indices, (iii) Determination of the chemical properties of soils, and (iv) The relationship between these chemical properties with selected species richness resulted from a principal component analysis [PCA].

2. Materials and Methods

2.1. Study Area

The study was done in the municipalities of Santa Marta (11°14′10″N and 74°12′06″W, at 2 m a. s. l., with semi-arid warm weather) and Cienaga (11°00′24″N and 74°14′48″W, at 3 m. a. s. l., with semi-arid warm weather) from the Magdalena department, Colombia. In each municipality, six mango cv. sugar (*Mangifera indica* L.) producer farms were chosen for a total of 12 sample points (mango cv. sugar tress) (Figure 1). For Santa Marta, the points of La Madona [LMa], San Pablo [SP], Avile [A], La Milagrosa [LMi], Rafael Barrios [RB] and Las Palmeras [LP] were selected. For Cienaga, the points of Eden [E], El Volcan [EV], Por Fin [PF], Miche Mary [MM], Las Margaritas [LMar] and El Triunfo [ET] were selected. Three trees of mango cv. sugar were randomly selected in each sample point, and one compound sample of approximately 1 kg of rhizosphere soil was taken. Each sample was collected in a radius of 2 m around each tree with the purpose of taking most of the active primary roots. On the other hand, from each compound soil sample, a portion (500 g approx.) was taken to analyse its chemical properties.

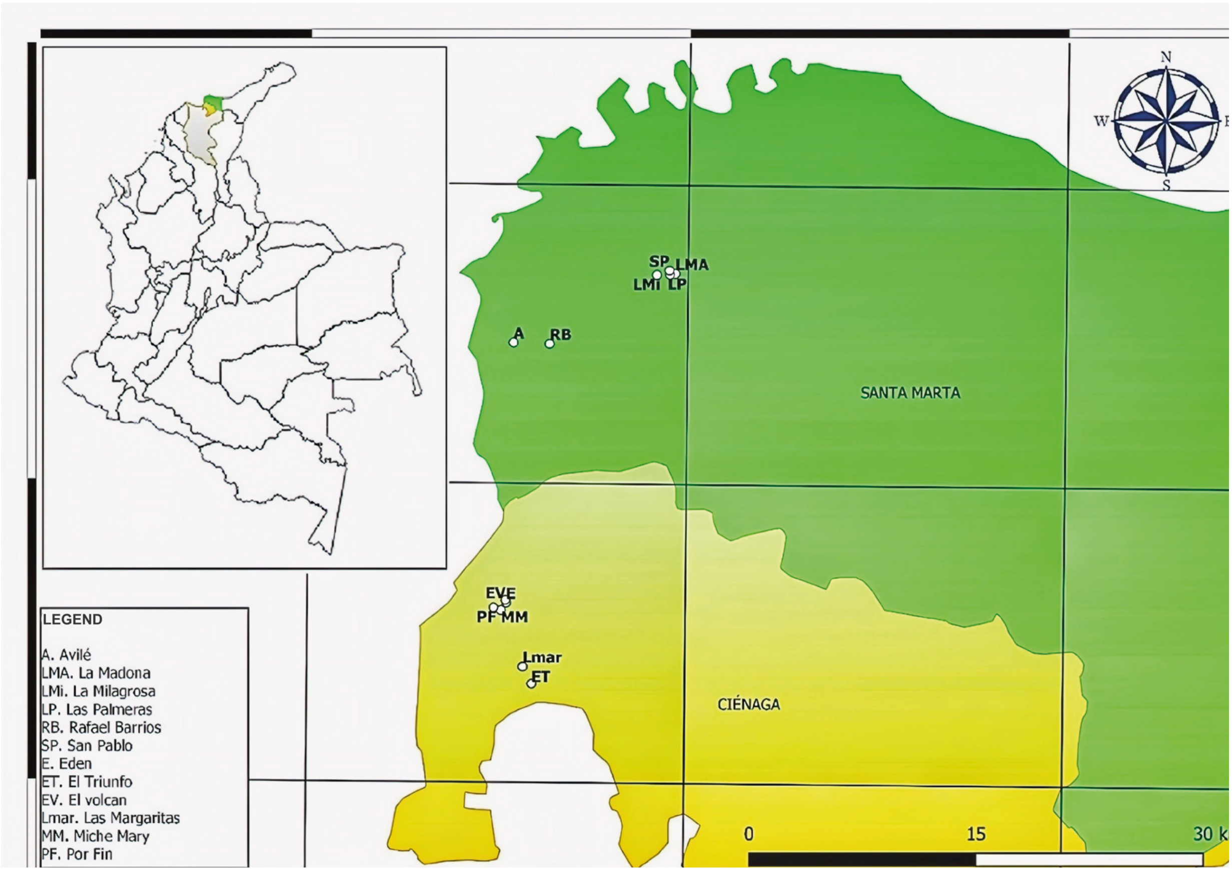

Figure 1. Mango cv. sugar producing farms in the department of Magdalena, Colombia, from which rhizospheric soils samples were taken to obtain AMF spores.

2.2. Chemical Analysis of the soil

The rhizosphere soil samples were taken at 20 cm depth and were dried up at 40 °C, then were ground and sieved to 2 mm. The pH in soil-water suspension 1:2.5 (p/v) was measured, as well as the effective cation exchange capacity [ECEC] by the sum of exchangeable cations, organic matter [OM] by the Walkley & Black method, available phosphorous [P] by the method Bray II, exchangeable Mg and Na extracted with CH_3COONH_4 1M pH 7.0, and available Cu, Fe, and Zn extracted by NTC5526:2007 extraction by Olsen with modifications. The samples were analyzed in the analytical chemical research laboratory Tibaitata of Agrosavia. The chemical analysis was done in the three farms where the highest abundance of AMF spores was recorded, in Santa Marta (LM, SP and A) and Cienaga (E, EV and PF) (Table 1).

2.3. Isolation, quantification, morphological characterization, abundance, and AMF spore richness

The morphological characterization of spores and sporocarps of AMF, from rhizosphere soil samples in mango cv. sugar crop, started with the isolation and quantification through decanting and suspension of spores in a saccharose gradient, following the methodology of Gerdemann & Nicolson (1963).

After the isolation and quantification, the spores and sporocarps were grouped considering morphological characteristics like color, shape, form and size. The mount for microscopic observation was done with polyvinyllactic acid-glycerol [PVAG] (Koske & Tessier, 1983), then mixed with the Melzer's reactant in proportion 1:1 (v/v) (Brundrett et al., 1994). For the microscopic analysis of the characteristics of spores, a light microscope (Zeiss; Primostar) was used with magnification up to 100X. the identification was done based on the characteristics of the spores: formation of the spore (glomoid, acaulosporoid, entrophosporoid, gigasporoid, and scutellosporoid), formation of the sporocarp, size and color, structure and wall stain, and characteristics of germination. All these morphological characteristics were contrasted with the available information in the websites: *International Culture Collection of Arbuscular* and *Vesicular-Arbuscular Mycorrhizal Fungi* (https://invam.ku.edu/), from professors Janusz Blaszkowski (http://www.zor.zut.edu.pl/Glomeromycota_2/Home.html) and Bruno Tomio Goto (https://biologiademicorrizas.wixsite.com/glomeromycota/es), as well as the website of Schüßler (http://www.amf-phylogeny.com/), which offer detailed description for most of the international accepted AMF species. Additionally, scientific publications give support for the classification of genres or species (Chimal-Sánchez et al., 2020; Corazon-Guivin et al., 2019; de Souza et al., 2018; Lin et al., 2019; Oehl et al., 2008, 2011, 2019; Sieverding et al., 2014; Torres-Arias et al., 2017).

After the spore and sporocarps identification at morphological level, the abundance and morphospecies richness were determined in each sample. The abundance [A] was calculated by the quantity of AMF spores 10 g^{-1} of soil, and the richness [R] as the quantity of morphospecies found in each sample.

2.4. Structure of the AMF communities

The relative abundance [RA] was calculated through the percentage ratio between species in a sample with respect to the total of found individuals. The frequency of isolations occurrence [FI] was calculated by determining the percentage of samples from which a genre or a species was isolated among all the samples, highlighting its distribution according to the equation [1], proposed by Brower et al. (1990):

$$FI = \frac{\text{No. of samples in which a species/morphospecies is detected}}{No.total\ of\ analysed\ samples}\ x\ 100 \qquad [1]$$

The morphospecies were classified as dominants (FI > 50 %), very common (31 < FI ≤ 50 %), common (10 < FI ≤ 30 %) and rare (FI < 10 %). The indices of diversity: Shanon- Wiener [H´], Simpson's dominance [D], and the uniformity of Pielou [J'] were calculated for each sample, and among the 12 collected samples through the library vegan (Oksanen et al., 2020) and biodiversityR (Kindt & Coe, 2005) with the software R® 4.3.2.

2.5. Statistical Analysis

An ANOVA test and comparison of measurements of Tukey tests were performed, after the assumptions of normality and homogeneity of variances, to assess the chemical analysis of the soil and density of spores (in 10 g of soil). In addition, the relationship between morphospecies was explored using the chemical characteristics of the soil, standardizing the variables in a principal component analysis [PCA] through the software R ® 4.3.2 with libraries factoextra, FactoMineR and ggplot2, in all cases the value $p < 0.05$ was used.

3. Results

3.1. Chemical Analysis of the soil

The sampling points presented pH values that varied from slightly acidic to slightly basic, ranging from 6.5 to 7.8. Chemical analysis results from the soil varied among sampling points, and significant differences were found between them. Point A, located in Santa Marta, presented the highest values for most of the analysed elements, especially for the phosphorous contents, where values of 131.58 mg kg^{-1} were registered (higher than in other sampling sites, Table 1). However, this value did not influence the richness of AMF because less rich values were found in the sampling points LP and RB (Table 2). On the other hand, the results from CE showed that these soils did not present salinity conditions.

Table 1. Chemical analysis of soils associated with mango cv. sugar (*Mangifera indica*) crops at the municipalities of Santa Marta and Ciénaga, Department of Magdalena, Colombia.

Properties*	Unit of measure-ment	Sampling Points					
		Santa Marta			Cienaga		
		LM	SP	A	E	EV	PF
pH	1:2.5	6.58 ± 0.14^{b}	6.47 ± 0.15^{b}	7.83 ± 0.15^{a}	7.67 ± 0.34^{a}	7.50 ± 0.21^{a}	7.11 ± 0.26^{ab}
CE	ds. m^{-1}	0.26 ± 0.03^{abc}	0.24 ± 0.03^{bc}	0.70 ± 0.23^{a}	0.64 ± 0.18^{ab}	0.34 ± 0.08^{abc}	0.16 ± 0.01^{c}
OM	%	1.13 ± 0.06^{ab}	1.26 ± 0.18^{ab}	1.43 ± 0.20^{a}	0.74 ± 0.17^{b}	1.03 ± 0.05^{ab}	0.81 ± 0.26^{ab}
Phosphorous	mg. kg^{-1}	10.29 ± 2.78^{b}	32.90 ± 9.17^{b}	131.58 ± 34.55^{a}	38.18 ± 14.19^{b}	46.04 ± 13.76^{b}	24.23 ± 10.74^{b}
Sulphur	mg. kg^{-1}	1.62 ± 0.19^{b}	1.69 ± 0.43^{ab}	3.13 ± 5.83^{a}	1.87 ± 1.61^{ab}	2.19 ± 0.81^{ab}	1.64 ± 0.48^{b}
ECEC	cmol(+). kg^{-1}	11.67 ± 0.43^{b}	10.12 ± 0.74^{b}	18.90 ± 2.87^{a}	11.75 ± 2.98^{b}	9.52 ± 0.78^{b}	14.67 ± 1.34^{ab}
Borum	mg. kg^{-1}	0.07 ± 0.02^{b}	0.10 ± 0.03^{b}	0.90 ± 0.09^{a}	0.53 ± 0.23^{ab}	0.47 ± 0.24^{ab}	0.24 ± 0.08^{b}
Calcium	cmol(+). kg^{-1}	9.14 ± 0.36^{ab}	7.97 ± 0.62^{b}	13.47 ± 2.06^{a}	7.86 ± 2.41^{b}	7.49 ± 0.82^{b}	11.37 ± 0.85^{ab}
Magnesium	cmol(+). kg^{-1}	2.23 ± 0.11^{b}	1.76 ± 0.11^{b}	4.00 ± 0.79^{a}	2.52 ± 0.74^{ab}	1.28 ± 0.07^{b}	2.48 ± 0.38^{ab}
Potassium	cmol(+). kg^{-1}	0.17 ± 0.01^{b}	0.19 ± 0.03^{b}	0.98 ± 0.10^{a}	0.40 ± 0.18^{b}	0.52 ± 0.28^{ab}	0.50 ± 0.12^{ab}
Sodium	cmol(+). kg^{-1}	0.39 ± 0.01^{b}	0.43 ± 0.04^{a}	0.64 ± 0.20^{ab}	0.96 ± 0.44^{a}	0.49 ± 0.06^{b}	0.57 ± 0.09^{ab}
Iron	mg. kg^{-1}	6.37 ± 10.91^{ab}	8.41 ± 19.60^{a}	2.79 ± 1.82^{c}	2.83 ± 1.05^{c}	3.19 ± 5.24^{c}	3.63 ± 3.05^{bc}
Copper	mg. kg^{-1}	1.00 ± 0.0^{a}	1.15 ± 0.20^{a}	1.29 ± 0.45^{a}	1.27 ± 0.86^{a}	2.12 ± 10.32^{a}	1.00 ± 0.0^{a}
Magnesium	mg. kg^{-1}	1.72 ± 0.32^{a}	1.85 ± 0.43^{a}	1.11 ± 0.08^{a}	1.17 ± 0.11^{a}	1.09 ± 0.07^{a}	1.58 ± 0.42^{a}
Zinc	mg. kg^{-1}	1.00 ± 0.0^{a}	1.39 ± 0.46^{a}	1.29 ± 0.64^{a}	1.59 ± 3.06^{a}	11.05 ± 13.76^{a}	1.00 ± 0.0^{a}

* CE: Electrical Conductivity; OM: Organic Matter; ECEC: Cation Exchange Capacity. Different letters mean significant differences according to Tukey's multiple range comparison test ($p < 0.05$).

Table 2. Spore abundance, relative spore density, and i.solation frequency of AMFs identified from 12 sampling points of mango cv. sugar crops at two localities in Magdalena, Colombia.

Family / morphospecie AMF	A	RD %	FI %*
Acaulosporaceae			
Acaulospora excavata Ingleby and C. Walker	10	1.5	25**C**
Acaulospora scrobiculata Trappe	26	4	16.7**C**
Acaulospora mellea Spain and N.C. Schenck	3	0.5	8.3**R**
Acaulospora sp1 Gerdemann and Trappe	22	3.4	8.3**R**
Ambisporaceae			
Ambispora sp Walker, Vestberg and Schuessler	10	1.5	8.3**R**
Gigasporaceae			
Gigaspora margarita W.N.Becker and I.R.Hall	106	16.3	58.3**D**
Gigaspora sp1 Gerd. y Trappe emend. C. Walker and F.E. Sanders	5	0.8	16.7**C**

Family / morphospecie AMF	A	RD %	FI %*
Glomeraceae			
Funneliformis mosseae C. Walker and A. Schüssler	4	0.6	8.3**R**
Funneliformis sp1 Walker and Schüssler, emend. Oehl, Silva and Sieverding (Glomus group Aa1)	2	0.3	8.3**R**
Glomus sinuosum R.T. Almeida and N.C. Schenck	109	16.7	66.7**D**
Glomus taiwanense R.T. Almeida and N.C. Schenck	30	4.6	25**C**
Glomus microcarpum Tul. and C. Tul	58	8.9	16.7**C**
Glomus macrocarpum Tul. and C. Tul	7	1.1	8.3**R**
Glomus sp1 Tul. and C. Tul	6	0.9	8.3**R**
Glomus sp2	14	2.1	33.3**MC**
Glomus sp3	8	1.2	8.3**R**
Glomus sp4	26	4	8.3**R**
Glomus sp5	1	0.2	8.3**R**
Glomus sp6	2	0.3	8.3**R**
Rhizoglomus fasciculatum G.A. Silva and Oehl	3	0.5	8.3**R**
Rhizoglomus intraradices Sieverd., G.A. Silva and Oehl	2	0.3	8.3**R**
Septoglomus constrictum G.A. Silva and Oehl	40	6.1	8.3**R**
Racocetraceae			
Cetraspora pellucida Oehl, F.A. Souza and Sieverd	142	21.8	66.7**D**
Racocetra sp Oehl, F.A. Souza and Sieverding	10	1.5	8.3**R**
Scutellosporacea			
Scutellospora calospora C. Walker and F.E. Sanders	6	0.9	16.7**C**
Total AMF:	652	100%	
25 morphospecies			

* A: spore abundance (10 $^{g-1}$ soil); RD: relative density; FI: Isolate Frequency of Occurrence. Species class according to FI (D: Dominant, MC: Very common, C: Common and R: Rare).

3.2. Morphologic characterization, abundance and spore richness of AMF

A total of 652 spores of AMF in 10 g^{-1} soil were identified from 36 samples taken from the municipalities of Santa Marta and Cienaga, identifying 25 morphospecies represented by six families and 10 genres (Table 2). The highest species richness was registered in the SP sample point and the highest abundance of spores (in 10 g^{-1} soil) at the A point (Figure 2). The highest abundance of spores was obtained from *Cetraspora pellucida* (Oehl, F.A. Souza & Sieverd.) with 142 spores in 10 g^{-1} soil, followed by *Glomus sinuosum* (R.T. Almeida & N.C. Schenck)*, Gigaspora margarita* (W.N. Becker & I.R. Hall)*, Glomus microcarpum* (Tul. & C. Tul) and *Septoglomus constrictum* (G.A. Silva & Oehl) with 109, 106, 58 and 40 spores in 10 g^{-1} dry soil, respectively.

In Figure 3, some representative morphospecies are presented isolated from rhizospheric soil of mango cv. sugar in the municipalities of Santa Marta and Cienaga.

3.3. Community structure of AMF

From the total families, 11% belong to Acaulosporaceae, 2 % to Ambisporaceae, 21 % to Gigasporaceae, 45 % to Glomeraceae, 20 % to Racocetraceae and 1 % to Scutellosporaceae, having most of representation from the families Glomeraceae and Gigasporaceae.

It was identified a total of 141 morphospecies at species level and 11 at genre level. The highest number of morphospecies found belong to the genre *Glomus* (10) and *Acaulospora* (4), becoming the 40% and 16% of the total, respectively.

The 60% of the morphospecies of AMF found were classified as rare, 24% as common, and 4% as very common. The dominant morphospecies present in 8 of the 12 sampling points were represented by *Cetraspora pellucida* Oehl, F.A. Souza & Sieverd (FI = 66,7 %, RA = 21,8 %), *Glomus sinuosum* R.T. Almeida & N.C. Schenck (FI = 66,7 %, RA = 16,7 %) and *Gigaspora margarita* W.N. Becker & I.R. Hall (FI = 58,3 %, RA = 16,3 %) (Table 2).

Morphospecies like *Acaulospora mellea* Spain & N.C. Schenck, *Ambispora* sp., *F. mosseae* C. Walker & A. Schüssler, *G. microcarpum* Tul & C. Tul, *G. macrocarpum* Tul & C. Tul, *Glomus* sp1., *Racocetra* sp. and *Scutellospora calospora* C. Walker & F.E. Sanders were found only in Santa Marta, while *Acaulospora* sp. 1., *Gigaspora* sp. 1., *Funneliformis* sp. 1., *Glomus* sp. 3, 4, 5 and 6, *R. fasciculatum* Sieverd., G.A. Silva & Oehl and *Rhizoglomus intraradices* Sieverd., G.A. Silva & Oehl ere found in Cienaga (Figure 4).

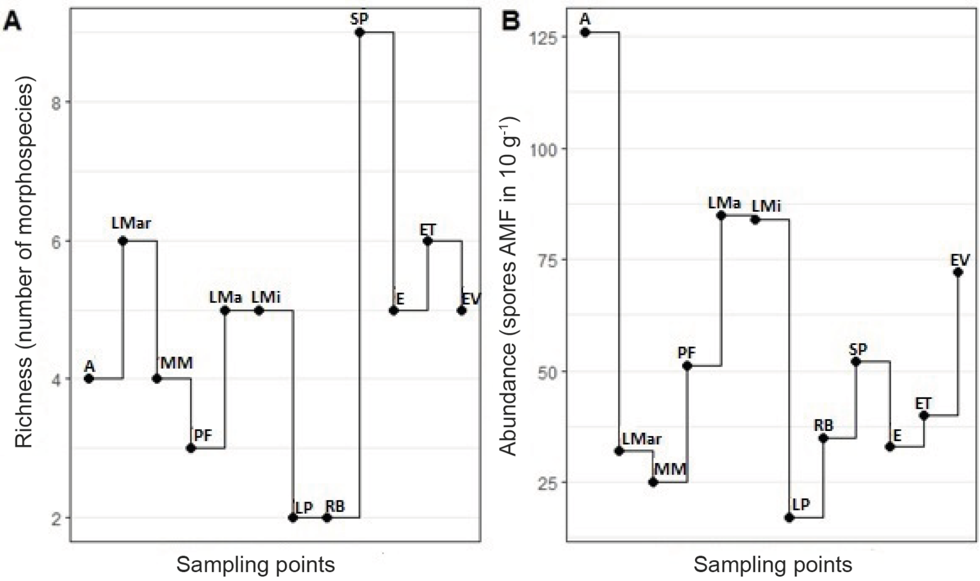

Figure 2. Morphospecies richness registered at each sampling point (A) and AMF spore abundance in 10 g[-1] soil (B).

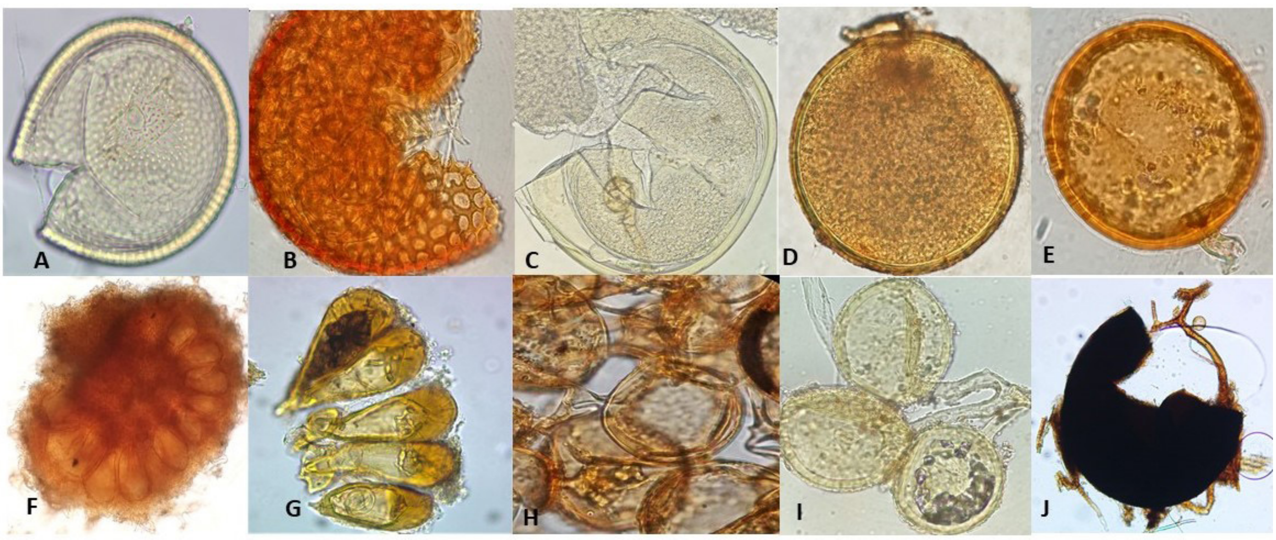

Figure 3. AMF spores found in rhizospheric soils associated at mango cv. sugar *(Mangifera indica)* crops at the municipalities of Santa Marta and Ciénaga. *A. Acaulospora scrobiculata* (Trappe); B. *Acaulospora excavata* (Ingleby & C. Walker); C. *Cetraspora pellucida* (Oehl, F.A. Souza & Sieverd.); D. *Gigaspora margarita* (W.N. Becker & I.R. Hall); E. *Glomus microcarpum* (Tul. & C. Tul); F. *Glomus sinuosum* (R.T. Almeida & N.C. Schenck); G. *Glomus taiwanense* (R.T. Almeida & N.C. Schenck)*;* H. *Rhizoglomus intraradices* (Sieverd., G.A. Silva & Oehl)*;* I. *Rhizoglomus fasciculatum* (G.A. Silva & Oehl); J. *Septoglomus constrictum* (G.A. Silva & Oehl).

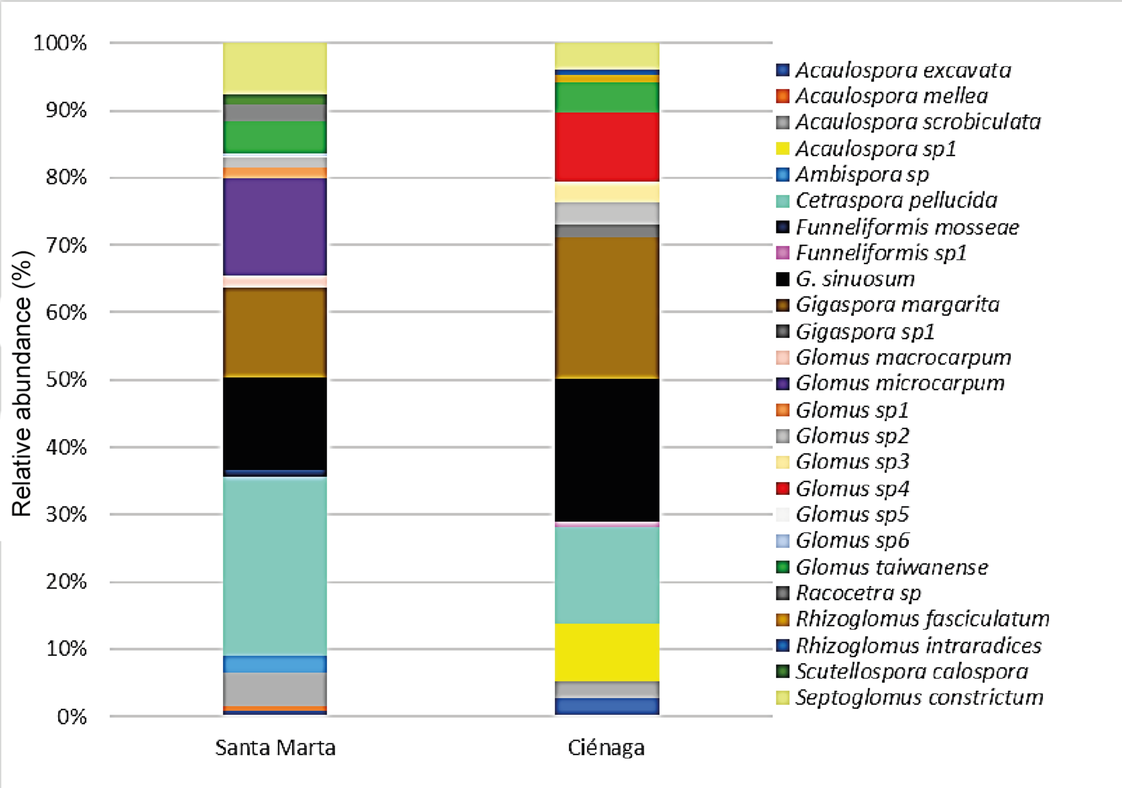

Figure 4. Relative abundance of AMF morphospecies at each sampling site in Santa Marta and Ciénaga.

The relative abundance of the two localities was characterized by having a higher proportion of *Cetraspora pellucida* Oehl, F.A. Souza & Sieverd. in Santa Marta and by *Glomus sinuosum* R.T. Almeida & N.C. Schenck and *Gigaspora margarita* W.N. Becker & I.R. Hall in Cienaga (Figure 4).

The highest Shannon diversity index was obtained in the point SP in Santa Marta with a value of 1.96, followed by LMar from Cienaga with a value of 1.63, which indicates good conservation conditions of the AMF. On the contrary, the lowest species diversity was found at the point RB from Santa Marta with a value of Shannon index of 0.59. A similar trend was observed for the dominance with the Simpson index, where the sampling points SP and LMar had the highest values (0.83 and 0.78, respectively). While RB presented the lowest values, with a dominance of 0.40 (Figure 5).

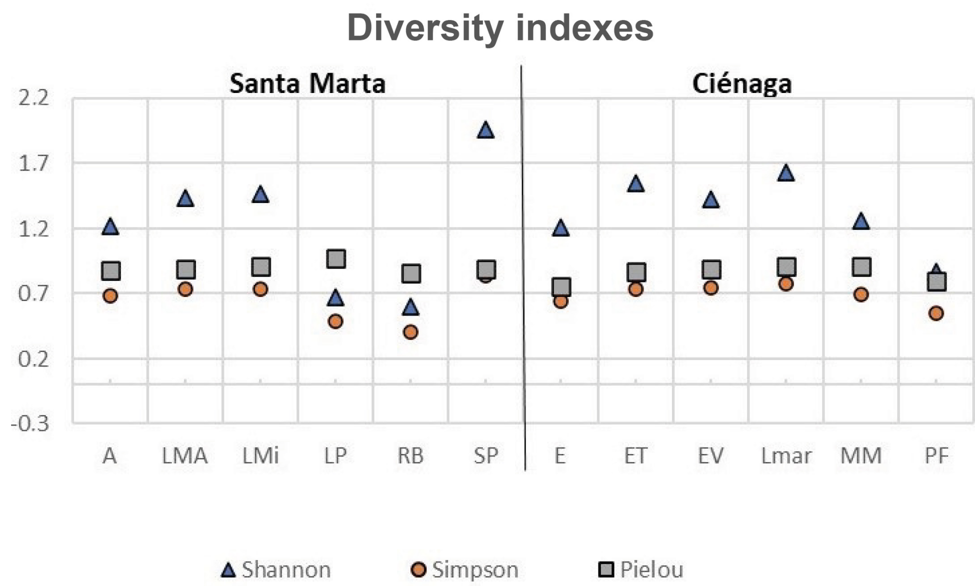

Figure 5. Diversity indices applied to describe AMF communities collected at different sampling points of mango cv. sugar (Mangifera indica) crops at Magdalena, Colombia.

The uniformity index of species of Pielou measures the proportion of observed diversity in relation to the maximum expected diversity. This index can have values between 0 and 1, where 1 corresponds to situations where all the species are equally abundant (Magurran, 1988). The highest index of Pielou was recorded in LP from Santa Marta with a value of 0.97, followed by LMar with a value of 0.90. All the morphospecies of LP were balanced in abundance with respect to the rest of the LP in other locations because their Pielou value was closer to 1 (Figure 5).

On the other hand, the results of ACP showed the relation of the communities of AMF from the sites with the chemical characteristics of the soil. This analysis, whose main axes explain 63.1% of the variability—39.8% of the total variance in the first component and 23.3% in the second component (Figure 6)—showed that *Cetraspora pellucida* Oehl, F.A. Souza & Sieverd presented a positive association significant to P (0.94), OM (0.72) and pH (0.57) (Figure 6). On the other side, *Glomus sinuosum* R.T. Almeida & N.C. Schenck presented a positive correlation significant in S (0.98), P (0.97), B (0.95), K (0.94) pH (0.80), Mg (0.71), and Ca (0.62); while *Gigaspora margarita* W.N. Becker & I.R. Hall presented a negative correlation significant in P (-0.75), B (-0.75), K (-0.70), S (-0.72) and pH (-0.64) (Figure 6).

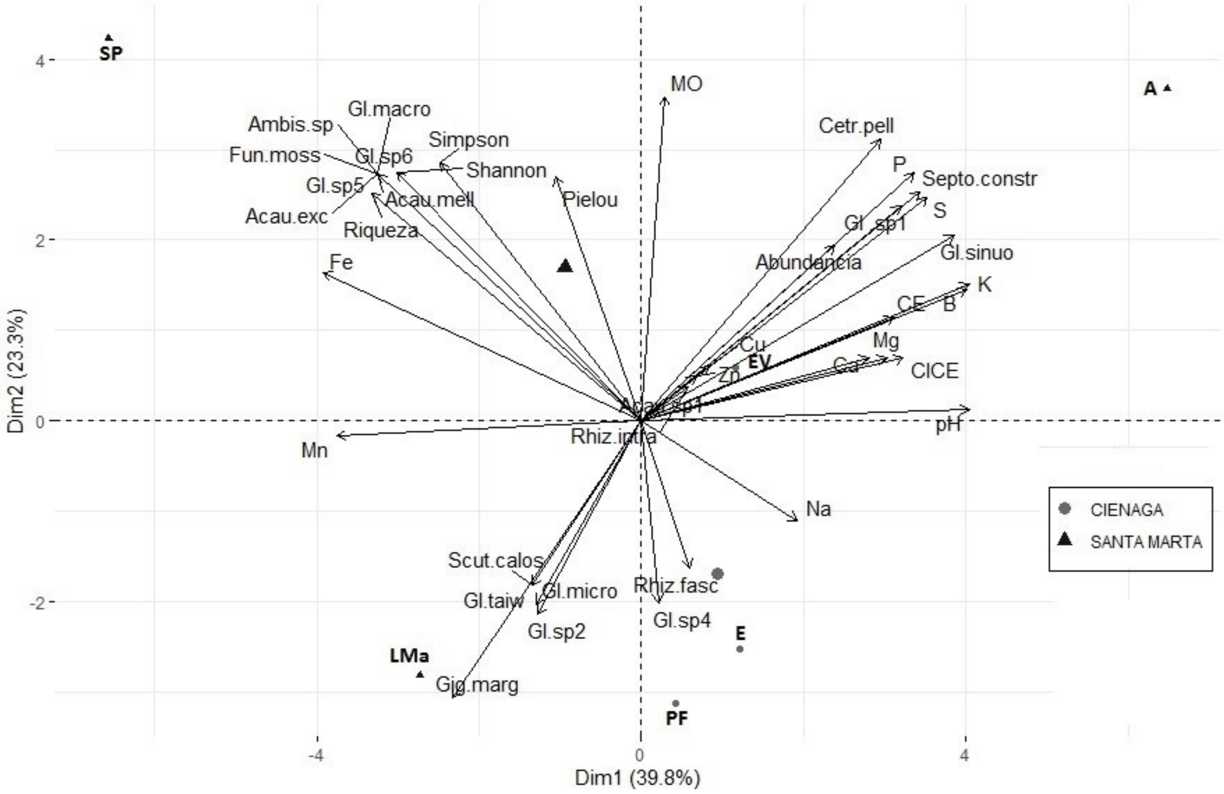

Figure 6. Principal component analysis with the morphospecies found in the rhizospheric soil of mango cv. sugar crop and soil chemical attributes at the different sampling points. *Ambispora* sp. (Ambis sp), *Glomus macrocarpum* (Gl. macro), *Funneliformis mosseae* (Fun. moss) C. Walker & A. Schüssler, *Acaulospora excavata* (Acau. exc), *Acaulospora mellea* (Acau. mell), *Glomus* sp.1. (Gl. sp.1), *Glomus* sp.2. (Gl. sp.2), *Glomus* sp.5. (Gl. sp.5), *Glomus* sp.6. (Gl. sp.6). *Cetraspora pellucida* (Cetr. pell), *Septoglomus constrictum* (Septo. constr), *Glomus sinuosum* (Gl. sinuo), *Rhizoglomus intaradices* (Rhiz. intra), *Rhizoglomus fasciculatum* (Rhiz. fasc), *Scutellospora calospora* (Scut.calos), *Glomus microcarpum* (Gl. micro), *Glomus taiwanensis* (Gl. taiw), *Gigaspora margarita* (Gig. marg).

4. Discussion

AMF diversity present in mango cultivar has not been well studied at a global scale with a few reports in Colombia (Abdelhalim et al., 2014; Govindan et al., 2020; Jiang et al., 2020; Mullath et al., 2019). This study is the first work done to know the diversity of AMF associated to mango cv.sugar crop.

Having into account other studies done in mango, and comparing the results with the present article, the richness of the morphospecies can be considered high because a total of 25 morphospecies were reported distributed in 6 families and 10 genres, in comparison to the numbers found in other countries: Mexico, Sudan, United Arab Emirates, India and Ethiopia, in which between 4 to 18 morphospecies of AMF were reported (Abdelhalim et al., 2014; Belay et al., 2014; Govindan et al., 2020; Mullath et al., 2019). Belay et al. (2014). Abdelhalim et al. (2014) found 18 morphospecies distributed in *Acaulospora, Ambispora, Archaeospora, Diversispora, Entrophospora,* and *Septoglomus*; three for *Claroideoglomus,* two for *Funneliformis,* five for *Glomus*, and two for *Paraglomus*. On the other hand, Belay et al. (2014) found a morphospecies for *Rhizophagus*, two morphospecies for *Acaulospora*, *Claroideoglomus*, and five for *Funneliformis*. Govindan et al. (2020) evaluated, instead, the status of the AMF present in five improved varieties and two hybrids of mango crops, finding a total of 10 species belonging to 5 genres, one of *Acaulospora* and *Gigaspora*, two of *Claroideoglomus* and *Sclerocystis* and four of *Glomus.* All these results suggested that soils associated to the mango cv. sugar crop in the Colombian Caribbean, specifically in the zones with major production (Santa Marta and Cienaga), the diversity of the AMF spores is considerably superior. It has been identified 25 morphospecies distributed with one for *Ambispora*, *Cetraspora*, *Racocetra*, *Septoglomus* and *Scutellospora*, two for *Gigaspora*, *Rhizoglomus* and *Funneliformis*, four for *Acaulospora* and ten for *Glomus*.

In a study about two management systems done in mango, one undergoing organic management and another under conventional management, a higher number of morphospecies were found in soils under organic management with a total of 6 species represented by 4 families and 3 genres. Meanwhile, the one under conventional management reported 4 species distributed in 2 families and 2 genres (Mullath et al., 2019). This situation shows that crop management can affect the communities of AMF.

Another factor that could influence the behaviour of the AMF communities is the vegetative season of the crop and the genotype. Studies done by Adriano Anaya et al. (2008) in 4 mango cultivars observed that the density of the spores could vary with the vegetative season and the cultivated variety. The density of the spores found in this study was low to medium with variables that oscillated between 17 and 126 spores in 10 g^{-1} soil (Adriano Anaya et al., 2008). On the other hand, the studies by Cortés Mercado et al. (1996) in Mexico and Jiang et al. (2020) in China, found values of 147.3 and 103 spores per g^{-1} of dry soil, respectively.

It has been showed that the genres belonging to the Gigasporales order reproduce mostly by spores, and this is the reason by which it cannot survive in perturbed ecosystems (Abdelhalim et al., 2014). On the other side, in this study the morphospecies *Gigaspora margarita* and *Cetraspora pellucida,* belonging to the order Gigasporales, were the most frequent because the soils where mango cv. sugar cultivars (*Mangifera indica*) are cultivated in the department of Magdalena are sandy and do not have environmental disruptions. Research done has demonstrated that the density of the spores of the species *Gigaspora* and *Scutellospora* (some reclassified as *Cetraspora)* is reduced significantly with conventional tillage because the spored are bigger than the other genres and families of AMF and they could be more susceptible to physical damage (Allen et al., 2003; Boddington & Dodd, 2000; Lekberg et al., 2007). De La Providencia et al. (2005) found abundant spores of the order Gigasporales in sandy soils but not in clay vertisols where expansion and contraction soil processes could drastically affect the hyphae of Gigasporales.

Similarly to this study, in Indian soils, *Gigaspora margarita* was also found as one of the most frequent morphospecies (FI = 57.1 %) (Govindan et al., 2020). Additionally, this morphospecies has been evaluated in mango grafts under greenhouse conditions with other AMF species. It has been found that *Gi. margarita* had the best response to growth (plant height, stem diameter and biomass) and nutrition (phosphorous absorption) of the plant, as well as the reduction of the graft mortality in greenhouse condition as a seedling (Reddy & Bagyaraj, 1994).

Despite the soil conditions where mango cv. sugar is cultivated in the department of Magdalena, it was observed the natural symbiotic association between mycorrhizae and mango plants. *Gigaspora margarita* W.N. Becker & I.R. Hall, *Glomus sinuosum* R.T. Almeida & N.C. Schenck and *Cetraspora pellucida* Oehl, F.A. Souza & Sieverd, were the most frequent morphospecies present. These species are less frequent AMF in most of agroecosystems around the country. Vaast et al. (1997) highlights the response to different levels of P available from some species of AMF, where a better response can be obtained from one species to another due to their different capacity to fix P from soils. Meanwhile, the relationship among *C. pellucida*, *G. sinuosum, Septoglomus constrictum, Glomus* sp. 1 and *Acaulospora* sp. 1 showed a better response to the fixing [P] capacity in the evaluated locations, as well as a greater interaction of these species with sulphur [S], potassium [K], Borum [B], calcium [Ca], copper [Cu], zinc [Zn], organic matter [OM], electric conductivity [EC] and the effective cation exchange capacity [ECEC], coinciding with the reports explaining how AMF significantly favors the concentrations of OM, K, Zn , Ca and Cu, depending on the AMF species (Wu et al., 2011).

5. Conclusion

It was reported for the first time the presence of the AMF species associated to mango cv. sugar in the departments of Santa Marta and Cienaga, Magdalena, Colombia. A great richness of morphospecies was found in comparison to other studies at global scale. The identification of key morphospecies (dominants) like *Gigaspora margarita* and *Cetraspora pellucida*, found in this study, suggests that these two species are the most adapted and most competitive in the habitat/conditions where mango crops is cultivated. However, more studies are needed (maybe at the molecular level) to identify the diversity associated to the plant roots, as well as their subsequent propagation under greenhouse conditions. Under these conditions, new morphospecies can be found and rescue all the richness of AMF. This could lead to a future evaluation based on the functional compatibility of these fungi under different stress conditions.

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Contributor roles

- Urley Adrian Pérez-Moncada: investigation, methodology, visualization, writing – original draft, writing – review & editing.
- Marlon José Yacomelo-Hernández: conceptualization, investigation, funding acquisition, writing – review & editing.
- Francisco Fabián Carrascal-Pérez: validation, writing – review & editing.
- Wilmar Alexander Wilches-Ortiz: formal analysis, validation, writing – review & editing.
- Luciano Ramírez: validation, writing – review & editing.
- Diana Paola Serralde-Ordoñez: validation, writing – review & editing.
- Andrea María Peñaranda-Rolon: validation, writing – review & editing.
- Margarita Ramírez-Gómez: investigation, methodology, conceptualization, funding acquisition, writing – review & editing.

Ethical Implications

Ethics approval not applicable.

Conflicts of Interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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