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Diversity of soils in areas with the presence of *Furcraea* sp. in tropical ecosystems[1]

Diversidad de suelos en áreas con presencia de *Furcraea* sp. en ecosistemas tropicales

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[1] Reception: February 7th, 2022. Acceptance: May 30th, 2022. The present work was the result of two research projects: "Zonas de producción en cinco departamentos caracterizadas y poblaciones locales de fique caracterizadas morfológicamente" and "Poblaciones locales de fique colectadas y caracterizadas *in situ* en 5 departamentos, Cauca, Caldas, Huila, Santander del Norte y Tolima y zonas de producción caracterizadas, biofísica, socioeconómica y ambientalmente". Developed by Corporacion Colombiana de Investigacion Agropecuaria and financed by the Ministerio de Agricultura y Desarrollo Rural de Colombia.

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Abstract

Introduction. The fique, "cabuya" or "mecate" are the common names given to the species of the genus *Furcraea* that are used for the manufacture of biodegradable fibers. Their industrial and social importance in Latin American countries is significant since it is usually related to family and peasant economies. However, for this taxonomic group, the diversity of edaphic conditions in natural habitats or cultivation sites is unknown. **Objective.** To physicochemically characterize the soils in the productive systems and natural populations of fique, to determine the aspects and factors that best represent their variability. **Materials and methods.** The work was developed between 2013 and 2014, in 66 municipalities and 108 villages in 11 departments of Colombia. Passport data was recorded at the 121 sites visited, describing site conditions, including georeferencing. In each locality, soil samples were taken in the first 20 cm of depth and subsequently the following variables were determined: texture, pH, organic matter (OM), P, S, K, Mg, Ca, Al+H, CE, cations of change Ca, Mg, K, Na, cationic exchange capacity (ECEC), Ca, Mg, K, and Na. According to georeferencing, 52 agroecological zones were identified. **Results.** Populations located between 170 to 2,993 m.a.s.l. were found. The most significant factors were agroecological zone and soil texture. Among them, texture was the factor with the greatest capacity for group formation and represented 60.99 % of the variability of the sampled soils. The variables that most contribute to the variability of the soils were (Ca + Mg) / K, exchangeable Mg, K / Mg, exchangeable Ca, and ECEC. **Conclusion.** The results obtained for wild and cultivated populations indicate that the different taxa survive in diverse tropical soil conditions. It was found that the exchangeable ions had high discriminating power that could indicate diversity to the different conditions and fertility levels of Colombian soils.

Keywords: agroecology, texture, soil quality, mineral.

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Resumen

Introducción. El fique, del género *Furcraea* que son utilizadas para la fabricación de fibras biodegradables. Su importancia industrial y social en países latinoamericanos es significativa y suele estar relacionada con economías familiares y campesinas. No obstante, para este grupo taxonómico, se desconoce la diversidad de las condiciones edáficas en los hábitats naturales o sitios de cultivo. **Objetivo.** Caracterizar fisicoquímicamente los suelos en los sistemas productivos y poblaciones naturales de fique, para determinar los aspectos y factores que representan mejor su variabilidad. **Materiales y métodos.** El trabajo se desarrolló entre los años 2013 y 2014, en 66 municipios y 108 veredas de 11 departamentos de Colombia. En los 121 sitios se registraron datos de pasaporte, que describen sus condiciones, incluida la georreferenciación. En cada localidad se tomaron muestras de suelo en los primeros 20 cm de profundidad y posteriormente se determinaron las siguientes variables: textura, pH, materia orgánica (OM), P, S, K, Mg, Ca, Al+H, CE, cationes de cambio Ca, Mg, K, Na, capacidad de intercambio cationico (CICE), Ca, Mg, K y Na. De acuerdo con la georreferenciación, se identificaron 52 zonas agroecológicas. **Resultados.** Se encontraron poblaciones ubicadas entre los 170 a 2993 m s.n.m. Los factores con mayor significancia fueron zona agroecológica y textura del suelo. Entre ellas, la textura fue el factor con mayor capacidad de formación de grupos y representó en 60,99 % de la variabilidad de los suelos muestreados. Las variables que más aportaron a la variabilidad de los suelos fueron (Ca+Mg) / K, Mg intercambiable, K / Mg, Ca intercambiable y CICE. **Conclusión.** Los resultados obtenidos para poblaciones silvestres y cultivadas indican que los diferentes taxones sobreviven en condiciones edáficas diversas características del trópico. Los iones intercambiables tuvieron alto poder discriminante que podría indicar diversidad a las diferentes condiciones y niveles de fertilidad de los suelos colombianos.

Palabras clave: agroecológia, textura, calidad de suelo, minerales.

Introduction

The fique (*Furcraea sp*), of the family Agavaceae, is a xerophytic monocotyledonous species, native to the Andes of Colombia, Ecuador, and Perú (Delgado et al., 2015). The fiber extracted from the leaf is classified as biodegradable and resistant (Martínez Torres, 2018), being currently an alternative to replace petroleum-derived fibers (polypropylene yarn) for the tutored of many crops given their similar mechanical properties. It is also used in Colombia for the manufacture of handicrafts, synthetic fiber ropes, sack for export of products such as coffee, geotextiles, and fibro reinforced (Pinchao-Pinchao et al., 2019).

Fique was so important that for its utility, that during the late 20th century it was credited with the title of Colombian National Fiber (Castellanos et al., 2009). In the late decades, it fail this category, due to replacement with synthetic fibers and trends in the use of petroleum derivatives in most production systems. On the contrary, the current environmental dynamics in the world returns to the use of this natural, biodegradable, and more eco-friendly inputs and products, so their demand has recently increased.

Traditionally, fique is produced by communities of small producers, who have created a labor dependence on the production, process, and sale of different artisanal products made from the fiber, and in some cases, with profit derived by-products (fique juices). Which is evaluated for cosmetic and pharmacological applications (Águila Sánchez, 2019).

Currently, Colombia has 13 departments reported as fique producers, and the top 5 producers are Nariño, Cauca, Santander, and Antioquia (Ministerio de Agricutura y Desarrollo Rural de Colombia, 2022), which is expressed as a considerable diversity of agricultural ecosystems and also in fiber qualities, yields, and management practices. For the establishment of the crop, agroecological demands are unknown (Rodríguez Azar, 2014), and traditional

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methods are used for cultivation, management, and processing and with limited use of the plant (transforms 4 - 6 % of the leaf for fiber production), which has led to the low competitiveness of this production chain.

Recently, there have been research advances in genus *Furcraea*, among which are: the use of fibers as a reinforcement in composite materials, fiber and polymer nuance (Gómez Suárez et al., 2020), the creation of an aluminum polyethylene compound reinforced with short fique fibers (Hidalgo et al., 2012), use of fique fibers to reinforce plastics (Muñoz-Velez et al., 2014), production of eco-laminates with short fique fibers (Delvasto Arjona et al., 2001), and methane production from crop residues (Barrera et al., 2009). But the case is different for research related to the soil characteristics, nutritional requirement, and physiology of this crop.

There are reports that indicate that plants of the *Furcraea* and *Agave* genera are classified as xerophytes, plants that have adapted to survive in desert environments, in low nutritional content soils, direct incidence of dry wind, and abundant sunlight (Guevara Apráez & Vallejo Castillo, 2014). Other studies indicate that the necessary requirements for the establishment of fique plants in relation to the soil must have good drainage, clay silica texture, and acid pH at basic between 5.6 and 7 (Echeverry Martínez & Castellanos Galeano, 2002).

In Colombia, there are no reports of studies on the diversity of climates and soils where *Furcraea* plants are planted. There are also no studies on soil characteristics, species adaptation capacity, soil management, and nutritional requirements (Barrera et al., 2009). The objective of this study was to characterize physico chemically the soils in the productive systems and natural populations of fique, to determine the aspects and factors that best represent their variability.

Materials and methods

Experimental period

This research was developed in Colombia between 2013 and 2014, identifying 11 departments with the highest representation of fique in Colombia, and using information obtained from primary (key informants, municipal technical assistance units, agriculture secretariats, associations, producer associations) and secondary sources. The main producing municipalities and villages were defined, and collection routes were drawn to locate possible natural populations with the presence of cultivated and natural individuals of the genus *Furcraea*. As a result, 66 municipalities and 108 villages were prioritized, once the collection point was identified, their passports were georeferenced and lifted.

The common names of the species collected were*: "Bordo de oro", "Ceniza", "Cabuya", "Fique", "Maguey", "Pirulero", "Tunosa común",* and *"Uña de águila",* who were also reported by Casierra-Posada and Gómez (2008) and in the Environmental Guide proposed by Peñaloza Pabón (2005).

The material collected in this study was carried out under the collection permit No. 1466 of 2014, granted by the National Environmental Licensing Authority (ANLA) for the Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA).

Passport data

In the development of these two projects, soil samples were collected for physical and chemical analysis, and plant material for subsequent establishment in the field at La Selva Research Center, Rionegro, Antioquia, Colombia, where they are currently cultivated and in the process of characterization and morphological evaluation and have not been introduced to any herbarium.

A passport was prepared and filled out with the description of the accession that included scientific name and local name. Descriptors of the collection site: spatial location (country, department, municipality, village, farm) georeferencing, meters above sea level (m.a.s.l.), collection source (natural habitat, cultivated field, garden, bordering orchard, seedling paddock, and roadside). Environmental descriptors such as: topography (flat, almost flat, slightly wavy, wavy, broken, hilly, and heavily undetermined), slope shape (straight, concave, convex, terraced, complex, irregular), soil drainage (sparsely drained, moderately drainage, and well-drained), soil erosion (low, intermediate, high), and light (shaded, sunny) (Agudelo Agudelo et al., 2011).

Determination of agroecological zones

To identify the agroecological zones, it was georeferenced with a GPS receiver each of the collection sites. With that spatial information, and the crossing of cartographic information at the national, departmental, and municipal level of the Agustin Codazzi Geographic Institute and through ArcGis 9.2 software (ESRI comunity, 2016), different maps were generated with the identification of each agroecological zone. These areas, conform clearly delimited spaces, according to climate, geoform, slope, soil parent material and erosion, according to the reports with a scale of 1:500 000 (Servicio Geológico Colombiano, 2013).

Physicochemical soil analysis

Were taken 121 composite soil samples, in the first 20 cm depth, and were sent to AGROSAVIA's soil analytical chemistry laboratory, in Bogota, Colombia. The following analyses were performed: texture, pH, organic matteer (OM), phosphorus (P), sulfur (S), potassium (K), magnesium (Mg), calcium (Ca), exchangeable acidity (AI+H), electrical conductivity (EC), exchangeable cations (Ca, Mg, K, Na), and effective cation exchange capacity (ECEC) using methodologies reported by Thiex (2016).

Determination of statistical assumptions

To determinate the normality criteria for each of the variables evaluated, descriptive statistical analyses were performed, and hypothesis test were applied to meet the assumptions of normality and homoscedasticity by Shapiro-Wilk and Bartlett test. For this, the shapiro test and bartlett test commands were used, respectively (Avanza et al., 2003).

Multifactorial variance analysis

The "car" and "emmeans" packages were used to establish the influence of study factors (agroecological zone, collection source, and soil texture) on each soil quality variable, a multifactorial variance ANOVA was applied ($P \leq 0.05$). A Tukey test ($P \leq 0.05$), with respect to the most relevant factor, was applied to the differences in means.

Multivariate analysis and correlations

To reduce dimensionality and determine the variables that contributed most to the overall variability to the soil population studied, via the "factoextra" package a principal component analysis (PCA) was used to observe the behavior of the variables characterized as a whole. This was complemented by a linear discrimination analysis

(LDA), applying as discriminations factors: agroecological zones, collections sources, and soil texture, using the Package 'lda'. With the most statistically representative factors, and the parameters of the discriminatory functions were obtained which variables had the greatest power of discrimination between the factors included. In this case, the behavior of some of the soil health variables associated with the factor described above was analyzed. Correlation coefficients (r) were also determined using Spearman's correlation matrix method using the Package 'corrplot' (Zar, 1972). All these analyses were performed using the freely available statistical software R version 4.0.4 and its complement R Studio.

Results

Diversity of materials of the genus *Furcraea* in Colombia

In collections, 29 common names were identified for the species of the genus *Furcraea* and related species of the family Agavaceaea, from this list it is observed that the names: "*Bordo de oro*", "*Ceniza*", "*Cabuya*", "*Fique*", "*Maguey*", "*Pirulero*", "*Tunosa común*", and "*Uña de águila*", were reported by the producers and technical assistants of the sample areas (Table 1).

Descriptors of the collection site and identified agroecological zones

It was found in the areas visited (Table 1), that the extreme values of the altitude were located between 170 m.a.s.l. (Municipality of Zulia, Norte de Santander) and 2,993 m.a.s.l. (municipality of Cucaita, Boyaca).

Fifty-two homogeneous agroecological zones were identified (Table 1). Of them, 48 % are located in the average climate (PM, PA, QM, QP, QA and QL), 28.8 % in a cold climate (KL, KP, KM, LM, and MM), and the remaining 23 % were found in the warm climate (VM, WV, WL, WP, and WM).

Collection source

The 64 % of material are dispersed (natural habitat, garden, vegetable garden, boundary, paddock, roadside), few of them could be considered as organized, technician, and productive crops. Only 35 % are classified as a field of cultivation, that is, where producers make an economic benefit from the harvesting and processing of fiber. The materials were found in property boundaries, paddocks, and roadsides, which can also be processed and marketed as a source of economic income (Table 2). Of the 8 collection sources reported in this study, the departments of Antioquia and Boyaca are the most represented (Table 2).

Topography

The fique collections were in eight different relief (Table 3), ranging from flat terrain (27.7 %) to steeply steep terrain (8.8 %). The accessions reported in the collection source cultivated fields were found established in mountainous areas (33 %), broken (17.6 %), and wavy (11.8 %).

Soil analysis

Next, the quality characteristics of the soils with the presence of the genus *Furcraea* are exposed.

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Table 1. Geographical location of populations of the *Furcraea* sp. collected in 11 Colombia departments. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014

Cuadro 1. Ubicación geográfica de las poblaciones de *Furcraea* sp. recolectadas en once departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Department	Agro-ecological zone	Thermal floor	m.a.s.l.	Ecotype found (Common name)
Antioquia	VM45, WV6	Warm	930	NN
	PM2, PM3, PM4, PM5, PM10, PM31, PM19, PM32, QM3, QM36, QP4, QM16, ZU	Medium	1,050 – 2,000	*"Uña de águila", "bordo de oro", "penca", "cabuya", "maguey"*, NN
	KL5, KP1, KL4	Cold	2,100 - 2,287	*"Tunosa común", "uña de águila", "ceniza", "bordo de oro", "criolla"*, NN
Boyacá	LM20, LM21, MM12, MM20, MM8	Cold	2,126 - 2,663	*"Bordo de oro", "fique", "tunosa común", "uña de águila", "motua", "fique corta vida"*
Caldas	PM15, PM32	Medium	1,833 - 2,000	"Fique", "uña de águila", "aguileña",
Cauca	KM13	Cold	2,000	"Uña de águila"
	PA2, QA2	Medium	1,811 - 1,917	*"Uña de águila"*, NN
Cundinamarca	KM9	Cold	2,339	NN
	QM31	Medium	1,505	NN
	WP2	Warm	355-365	*"Fique"*
Huila	WM33, WP14, WM13, WV7	Warm	401 - 491 - 1,000	NN
La Guajira	WL3, WP4	Warm	276 - 380	*"Ayalero, pitilla", "fique de arroyo", "uña de águila", NN*
Nariño	LM11	Cold	2,217 - 2,299	*"Uña de águila", "común con espinas", "negra común", "genoya", "México"*
Norte de Santander	KM2, LM23, LM28	Cold	2,000 - 2,633	"Uña de águila", "tunosa común"
	QM22, QM25, QM27	Medium	1,325 - 1,569 - 1,649 - 1,716	*"Uña de águila"*
	WM19, WP4, WM35	Warm	345 - 748 - 953	*"Uña de águila"*
Santander	LM11, LM29	Cold	2,000 - 2,485	*"Tunosa común", "pirulero"*
	PM46, QL14, QM14, QM16, QM5	Medium	1,175 - 1,642 - 1,698 - 1,815 - 1,911 - 1,936 - 2,000	*"Uña de águila", "común con espinas", "mestiza", "tunosa", "pirulero montuna", "tunosa común", "bordo de oro*.
Tolima	PM9	Medium	1,750 -2,000	*"Bordo de oro", "uña de águila"*
	WP6	Warm	530	*"Uña de águila*", NN

NN: No name in the collection area. / Sin nombre en el área de recolección.

Table 2. Source of collection of *Furcraea* sp material, number of populations, and geographical location in 11 departments of Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Cuadro 2. Fuente de recolección de material de *Furcraea* sp, número de poblaciones y ubicación geográfica en 11 departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Source of collection	Total found populations (%)	Departments (Colombia) (%)
Natural habitat	45.0	Antioquia (41.7), Boyaca (2.98), Cundinamarca (4.34), Cauca (1.49), La Guajira (5.97), Huila (11.94), Norte de Santander (16.4), Santander (5.97), and Tolima (9.21)
Cultivated field	35.0	Antioquia (35.2), Boyaca (3.92), Caldas (5.88), Cauca (5.88), La Guajira (3.92), Huila (1.96), Nariño (7.84), Santander (29.52), and Tolima (5,88)
Garden	4.0	Antioquia (16.6), Boyaca (33.4), and La Guajira (50.0)
Vegetable Garden	10.0	Antioquia (14.28), Boyaca (7.14), Caldas (14.28), Cundinamarca (14.28), Nariño (21.46), Norte de Santander (7.14), Santander (7.14), and Tolima (14.28)
Property boundaries	1.0	Antioquia (50.0), and Caldas (50.0)
Paddock	3.3	Antioquia (20.0), Boyaca (60.0), and La Guajira (20.0)
Growth-room	1.0	La Guajira (50.0), Nariño (50.0)
Roadside	0.7	Boyaca (100.0)

Table 3. Observed data at the collection sites of *Furcraea* sp. accessions in 11 departments in Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Cuadro 3. Datos observados en los sitios de recolección de accesiones de *Furcraea* sp. en 11 departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Terrain topography	Total population %	Cultivated field* %
Flat	27.7	21.6
Almost flat	5.4	2.0
Hilly	2.7	0.0
Steeply steep	8.8	5.9
Montainous	27.0	33.3
Wavy	8.8	11.8
Slightly wavy	8.8	7.8
Broken	10.8	17.6

Texture

The four kinds of soil textures were found: sandy, clayey, slimy, and loam, with their different combinations. The highest percentage of collections were made in sites whose soils are clayey-loam (28.1 %) and in sandy-loam soils (26.45 %). The largest number of cultivated fields are found in sandy-loam soils (30.8 %) and in sandy-clayey soils (23.1 %) clayey-loam (Table 4).

Table 4. Soil texture evaluated in soils with presence of the genus *Furcraea* in 11 departments in Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Cuadro 4. Textura de suelo evaluada en suelos con presencia del género *Furcraea* en 11 departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Texture	Population (11 departments)	Cultivated field (%)
Sandy	21.49	7.7
Clayey	0.83	2.5
Sandy-Clayey	0.83	2.5
Loamy	0.83	2.5
Sandy-Loam	26.45	30.8
Clayey-Loam	28.1	23.1
Sandy-Cayey-Loam	3.31	*
Silt-Loam	5.78	10.3
Silt	7.43	10.3
Not determined	4.95	10.3

* No textures sampled in the cultivated field / * No se tomaron muestras de textura en el campo cultivado.

pH variability in soils with the presence of the genus Furcraea in tropical regions

The pH showed differences between the collection departments of the collected soils (tukey test $p<0.05$). Soils are classified between: strongly acidic (3.99) to very alkaline (8.89). The highest percentage of soils were found on strong to extremely acidic soils (38.0 %) and in moderately acidic soils (24.0 %). In cultivated fields, the highest percentage was found on strong to extremely acidic soils (56.4 %) followed by moderately acidic (15.4) neutral (15.3 %), which is the ideal percentage (soil close to 7 pH) (Table 5).

Variability of the percentage of organic material (OM) in soil with the presence of the genus Furcraea in tropical regions

Of the site's samples, 37.2 % correspond to soil with an average OM percentage between (2 - 5 %), 28 % and 26.5 % are soils with high and optimal percentage of OM, respectively (soils rich in organic matter), being in the departments of Nariño, Antioquia, Boyaca, Santander Caldas, Norte de Santander, and Cauca. It could be said that these soils are organic and do not need any kind of fertilization. In addition, in relation to cultivated fields, 46.1 % and 43.6 % are found in soils with average and optimal percentages of OM (Table 6).

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Table 5. pH of soils with the presence of the genus *Furcraea* in 11 departments in Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Cuadro 5. pH de suelos con presencia del género *Furcraea* en 11 deparametnos de Colombia, Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

pH*	Population (11 departments) %	Cultivated field %
(3,99 a 5,49) Strong to extremely acidic	38.0	56.4
(5,50-5,80) Moderately acidic	24.0	15.4
(6.03-6.48) Slightly acidic	14.9	10.3
(6,61 a 7,36) Neutral	18.2	15.3
(7,67 a 7,82) Alkaline	4.1	2.6
(8,89) Highly alkaline	0.8	**

* Scale used by AGROSAVIA's Soil Laboratory to express the results. /* Escala utilizada por el Laboratorio de suelos de AGROSAVIA para expresar los resultados.
This pH value was not found in the samples evaluated in the cultivated field. / * Este valor de pH no se encontró en las muestras evaluadas en el campo cultivado.

Table 6. Percentage of organic matter (OM) in soil with presence of the genus *Furcraea* in sampled locations in 11 departments in Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Cuadro 6. Porcentaje de materia orgánica (OM) en suelo con presencia del género *Furcraea* en lugares muestreados en 11 departamentos de Colombia, Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

OM (%)	Populations 11 departments (%)	Cultivated field (%)
Low (< 2)	8.3	10.3
Medium (2-5)	37.2	46.1
High (5-10)	28.0	*
Optimum > 10	26.5	43.6

* No samples were found in the cultivated field in this OM %. / * No se encontraron muestras en el campo cultivado con este % OM.

Variability of cation exchange capacity (ECEC) in soils with the presence of the genus Furcraea in tropical regions

The soil analysis results indicate that 56.19 % of soils have a low ECEC (<10 meq/100 g), 30.57 % have an average ECEC (>10-20 meq/100g), and 13.2 % of soils have a high ECEC (>20 meq/100g). In the areas of greatest precipitation, it has greater leaching of the interchangeable bases, which generates a lower concentration in the ECEC. If the ECEC is low implies that its value must be increased through OM, burnt lime applications and positively charged fertilizers (ammonium, potassium, magnesium, etc.) should be avoided as they could be lost by leaching.

Variability of phosphorus concentration available in soils with presence of the genus Furcraea in tropical regions (P)

The results were very variable and based on reference levels where <15 is low, from 15 to 25 is medium, from 25 to 40 ideal and >40 ppm (mg kg^{-1}). Most of the analyzed soils had low phosphorus availability (43.8 %), 19.8 % medium availability, and 36.3 % had high availability.

Variability of interchangeable acidity (AI+H) in soils with presence of the genus Furcraea in tropical regions

The laboratory results reported that 62 % of the soils have a pH greater than 5.5 with an interchangeable aluminum of 0.0 (zero), indicating that there is no toxicity problem, and the remaining 38 % have a pH below 5.5 with interchangeable Al values between 3.99 and 5.48, which would denote toxicity problems.

Description of soils in sampled regions

The soil conditions in the departments of Antioquia, Caldas, Cauca, and Nariño are of low fertility, acid and strongly acid pH, with low available P content and exchangeable bases such as Ca, Mg, and P. The soils do not present problems of Al saturation, which can be productive if their chemical properties are improved with fertilization, according to nutritional requirements (Table 7).

Table 7. Average edaphic characteristics of tropical soils with the presence of the genus *Furcraea* in 11 departament of Colombia, Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Cuadro 7. Características edáficas promedio de suelos tropicales con presencia del género *Furcraea* en 11 departamentos de Colombia, Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Department	pH	Organic matter (MO)	Phosphorus (P)	Calcium (Ca)	Magnesium (Mg)	Potassium (K)
Antioquia	Cold zone: Strongly acidic	High	Medium	High	Medium	High
	Warm zone: Neutral	Medio	High	High	High	Medium
Boyaca	Moderately acidic	High	High	High	Medium	High
Caldas	Strongly acidic to moderately acidic	Medium	Medium	High	High	High
Cauca	Strongly acidic to moderately acidic	High	Low	Low	Medium	High
Cundinamarca	Alkaline	Medium	High	High	High	High
Huila	Slightly acidic	Medium	High	High	High	High
La Guajira	Slightly acidic	Medium	High	High	Low	High
Nariño	Moderately acidic	High	Low	High	Medium	High
Norte de Santander	Moderately acidic	High	High	Medium	Medium	High
Santander	Moderately acidic	High	High	High	Medium	High
Tolima	Neutral	Medium	High	High	High	High

In the departments of Tolima, Huila, Santander, Santander del Norte, and La Guajira, there are soils with chemical properties with higher contents than in the departments of Antioquia, Caldas, Cauca, and Nariño. In addition, for the towns of Cundinamarca and Boyaca, there is medium or intermediate fertility. The soils of Tolima show better chemical properties, with medium to high natural fertility (Table 7).

Multifactorial analysis

The influence of three factors was analyzed: agroecological zone, collection source, soil texture, and their interaction on the physical and chemical variables defined in laboratory analysis with a confidence level of 95 %. The null hypothesis of independence of the factors (agroecological zone, collection source, and soil texture) on each response variable, where values less than 0.05 indicate factor-variable influence were show in Table 8, it is observed that the factors that had the greatest significance were agroecological zone and texture. The variables that were significance with the agroecological zone factor were EC and exchangeable Ca. The variables that were significance with the textures factor were OM, K, and Ca/K ratio; and variables that have significance with both factors (agroecological zone and soil texture) were pH, acidity, exchangeable Al, K, and Ca (%). The variables available P, exchangeable K, and Na (%) had significance in the three factors evaluated. The Ca/Mg

Table 8. Multifactorial ANOVA: agroecological zone, source of collection, and soil texture on the nutritional and physicochemical variables of the soil in 11 department of Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Cuadro 8. ANOVA multifactorial: zona agroecológica, fuente de recolección y textura del suelo sobre las variables nutricional y fisicoquímica del suelo en 11 departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Variable	P factors value			P interactions value		
	Agro-ecological zone	Collection source	Soil texture	Soil texture* Agro-ecological zone	Soil texture* Collection source	Collection source* Agro-ecological zone
pH	0.003*	0.643	0.000*	0.093	0.705	0.054
Electrical conductivity	0.002*	0.218	0.065	0.831	0.655	0.727
Organic material	0.395	0.992	0.001*	0.969	0.996	0.799
Available phosphorus Bray ll	0.005*	0.001*	0.001*	0.008*	0.000*	0.367
Exchangeable acidity (AL+H)	0.000*	0.862	0.000*	0.006*	0.614	0.191
Exchangeable alumium (Al)	0.000*	0.888	0.000*	0.008*	0.671	0.217
Exchangeable calcium (Ca)	0.026*	0.949	0.509	0.998	0.796	0.998
Exchangeable magnesium (Mg)	0.983	0.403	0.980	0.904	0.854	0.764
Exchangeable potassium (K)	0.009*	0.006*	0.000*	0.018*	0.058	0.867
Exchangeable sodium (Na)	0.759	0.922	0.875	0.999	0.967	0.912
Cation exchange capacity (CICE)	0.661	0.593	0.862	0.657	0.872	0.999
Calcium (%)	0.007*	0.311	0.016*	0.431	0.592	0.889
Mg (%)	0.797	0.204	0.108	0.980	0.972	0.915
K (%)	0.088	0.164	0.000*	0.065	0.039*	0.451
Na (%)	0.000*	0.000*	0.000*	0.000*	0.989	0.263
Ca/Mg	0.999	1.000	0.952	0.998	0.967	0.999
(Ca+Mg) /K	0.982	0.432	0.830	0.872	0.982	0.922
K/Mg	1.000	0.425	0.996	0.999	0.723	0.998
Ca/K	0.053	0.681	0.036*	0.672	0.932	1.000

* Factors that have a significant relationship with the response variable. / * Factores que tienen una relación significativa con la variable respuesta.

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and (Ca+Mag)/K ratios showed significant differences ($p<0.05$), this may be an indicator of the diversity of fique to the different agroecological zones and diverse soil qualities. In relation to the interaction of factors, the most representative was texture* agroecological zone with the variables P, acidity, exchangeable Al, K, and Na (%).

Lineal discriminant analysis (LDA)

As a significance of agroecological zone and soil texture factors was obtained on most soil quality variables. A lineal discriminatory analysis was performed, which allowed variables to be grouped into a discrimination function and observe which of these factors discriminates in a better way the variability of soil sample. It was found that the soil texture (Figure 1) has a greater capacity to form groups than the agroecological zone (Figure 1b) and has a better representation of the viability of the data with 60.99 % compared to 45.74 %.

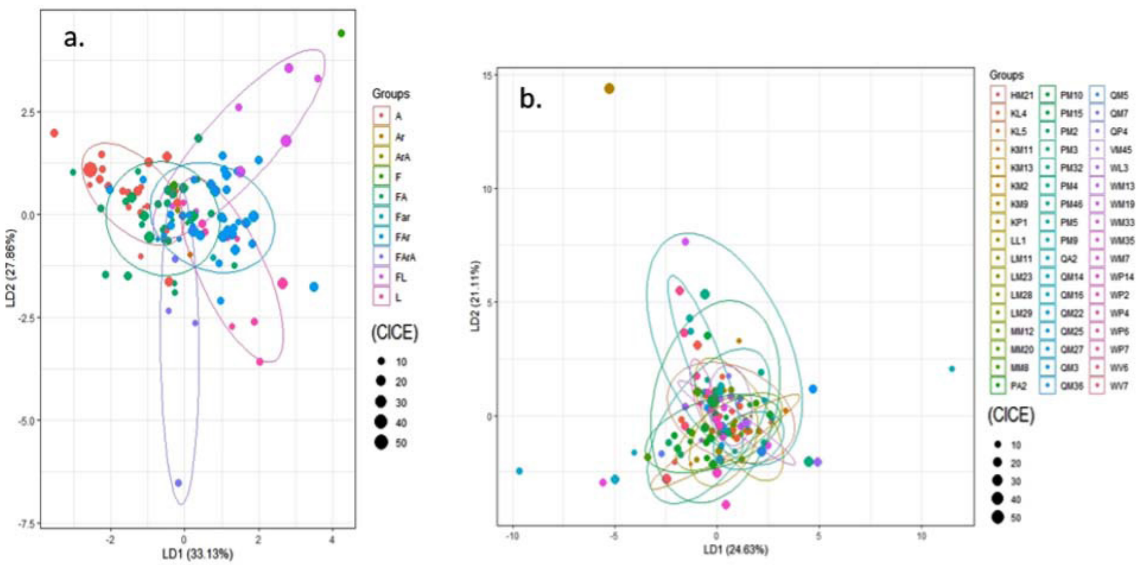

Figure 1. Linear discriminant analysis for soil quality variables with presence of the genus *Furcraea* based on soil analysis of 11 departments of Colombia, Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014. **a.** Texture as a factor of discrimination (A: sandy, Ar: clayey, ArA: sandy-clayey, F: loamy, FA: sandy-loam, Far: clayey-loamy, FARA: sandy-clayey-loamy, FL: silt loam, L: silt); **b.** Agroecological zone as a factor of discrimination according to Servicio Colombiano Geologico Agustin Codazzi (2013).

Figura 1. Análisis discriminante lineal para variables de calidad de suelo con presencia del género *Furcraea* basado en análisis de suelo de 11 departamentos de Colombia, Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014. **a.** La textura como factor de discriminación (A: arenoso, Ar: arcilloso, ArA: arcilloarenoso, F: franco, FA: franco arenoso, Far: franco arcilloso, FARA: francoarenoarcilloso, FL: francolimoso, L: limoso); **b.** Zona agroecológica como factor de discriminación según Servicio Colombiano Geológico Agustin Codazzi (2013).

Principal Component Analysis (PC)

The analysis of principal components showed that the first five PC explains 72.56 % of the total variability to the sample population, and the first three PC explains up to 41.92 % of the total variation. From this can be inferred that the quality characteristics of the soils where the genus *Furcraea* is present shows high variability and diversity in Colombian territory. The PCA analysis result displays soil quality variables in regions with the presence of the genus *Furcraea* are showed in Figure 2.

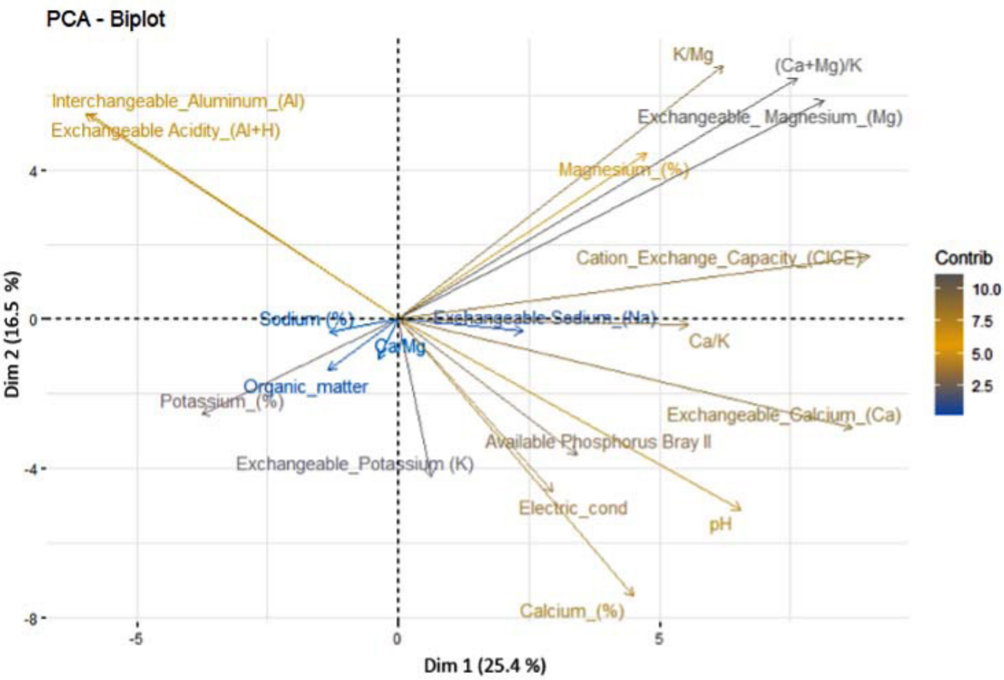

Figure 2. Analysis of principal components for soil quality variables with presence of the genus *Furcraea* based on soil analysis of 11 departments of Colombia, Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Figura 2. Análisis de componentes principales para variables de calidad del suelo con presencia del género *Furcraea* basado en análisis de suelo de 11 departamentos de Colombia, Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

The variables that contribute most to the variability of the soils where the fique is cultivated are (Ca+Mg)/K ratio, and exchangeable cations. It also indicates the versatility of the species for diversity to the different soils, especially where the populations are collected, and soil samples were taken (Figure 3).

Correlation analysis

There is a directly proportional relationship between the exchangeable bases (Ca and Mg) and the ECEC, which is as follows: for interchangeable Ca and ECEC (0.92) and ECEC with exchangeable Mg (0.77) (Figure 4). These are factors that are providing good percentage and concentration to the cationic exchange capacity of the soil, and in places where the genus *Furcraea* is cultivated, can compete for cationic exchange sites on the surface of clays, creating potassium and/or magnesium deficiencies in the plant, that will depend on the saturation of each of them in the soil solution.

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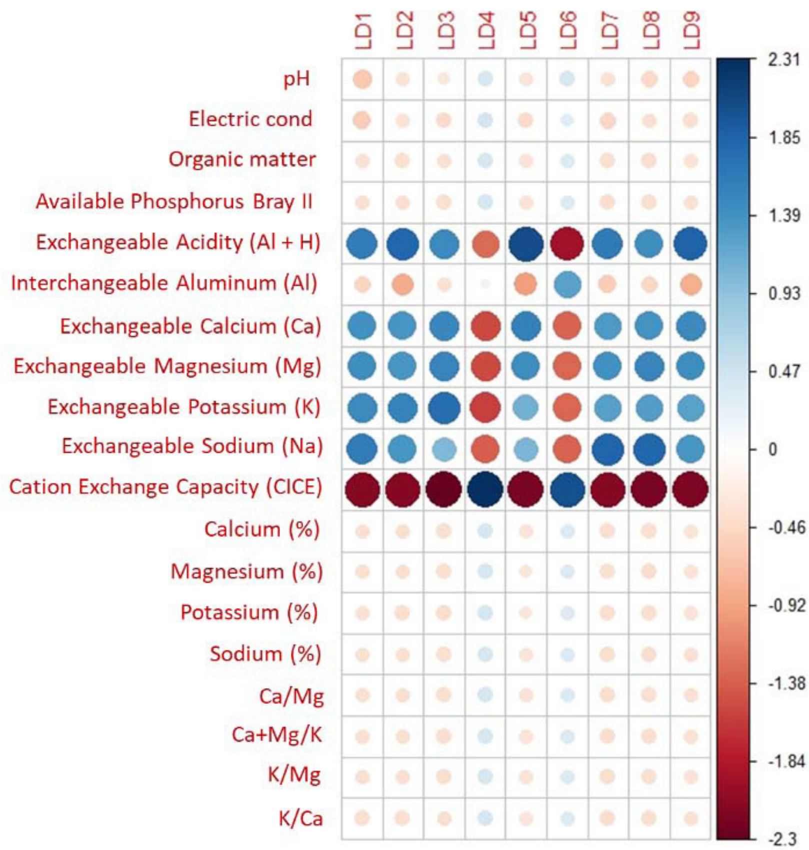

Figure 3. Discriminatory standardized weights between soils of different textures with presence of the genus *Furcraea* based on soil analysis of 11 departments of Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Figura 3. Pesos estandarizados discriminatorios entre suelos de diferentes texturas con presencia del género *Furcraea* basado en análisis de suelo de 11 departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

Discussion

The name with the widest distribution in this study was ecotype *"Uña de Aguila*", reported in eight of the eleven departments, in addition to being collected in the three thermal floors sampled (Table 1).

In terms of altitude, it was found in the areas visited (Table 1), that the extreme values of the altitude were located between 170 m.a.s.l. (Municipality of Zulia, Norte de Santander) and 2993 m.a.s.l. (Municipality of Caucaita, Boyacá). Several authors report the importance of this variable for the establishment of fique crops. The appropriate altitude is between 1300 and 2800 m.a.s.l., according to Verloove et al. (2019). Montero and Adams (1964) indicate between 1000 and 2000 m.a.s.l., in other words "temperate climates", between 1300 and 2000 m.a.s.l. Other authors indicate that this species grows well in all climates, from the coastal plains to 3000 m.a.s.l., but so far no reach has been presented that allows inferring the sites suitable for planting, development, and production of fique cultivation with sustainable environmental and economic results for producers (Peñaloza Pabón, 2005).

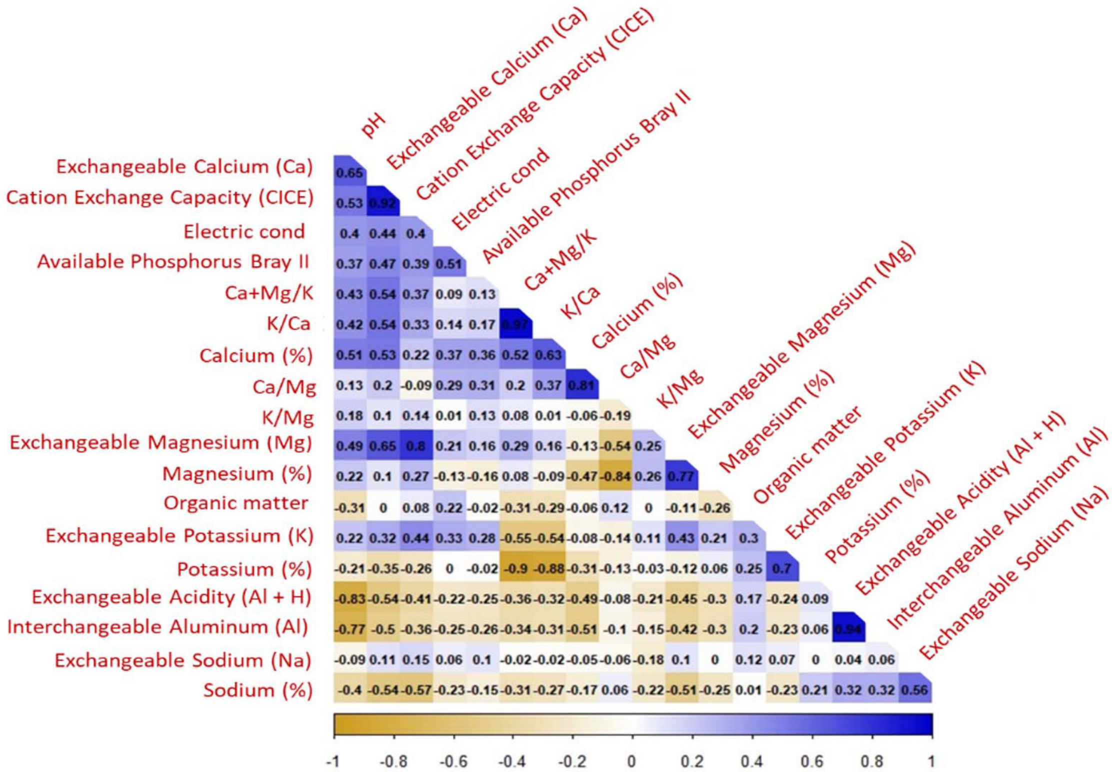

Figure 4. Analysis of correlation of nutritional variables in soils where fique accessions were collected in 11 departments of Colombia. Corporacion Colombiana de Investigacion Agropecuaria (AGROSAVIA). 2014.

Figura 4. Análisis de correlación de variables nutricionales en suelos donde se recolectaron accesiones de fique en 11 departamentos de Colombia. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA). 2014.

On the identification of agroecological zones, the genus *Furcraea* integrates various types of vegetation, this is how in Cuba they are found in semi-deciduous mesophilic forests, always green microfilm, and pines and in the xeromorph scrub on serpentine; that it is observed growing in open places since by its type of asexual propagation is adapted to the warm and humid regions where it prefers the sunniest, natural, or anthropogenic areas (Alvarez de Zayas, 1996). In Colombia, it is cultivated in different areas, including temperate and cold areas, and populations have been found spontaneously in La hoya del Dagua and in El Boqueron del Cuja and Riohacha (Casierra-Posada & Gómez, 2008).

Materials that were found in property boundaries, paddocks, and along roadsides, can also be processed and marketed as a source of income from farmers. In the departments of Cauca and Nariño the fique is grown in monoculture in compact populations, in Santander the production system is scattered plantations and on land borders, and in Antioquia it is found as a crop of cultivation and dispersed as hedgerows to separate premises and in live barriers for crops (Echeverri et al., 2015).

Species of the genus *Furcraea* are more adapted to broken terrain than to flat terrain (Moncayo & Chavarriaga, 1974), since excess water causes rotting in their organs and can induce the flowering of the plant (Pérez, 1974; Zamosc, 1981). Steep terrain should be avoided (Casierra-Posada & Gómez, 2008). It should not be an impediment to cultivating the topography of the terrain, especially if they are steep soils, because the root system of the fique is fasciculate, perennial, and with a depth of up to 3 m, which facilitates the mooring of the plant.

Studies in Colombian regions, such as coffee areas of Antioquia, Cundinamarca, Huila, Norte de Santander, Quindio, and Santander, reports that in more than 50 % of the samples collected pH is below 5 (Sadeghian Khalajabadi & Díaz Marín, 2020), it is similar to what found in this study.

The reports found show that cabuya in Colombia is found in adverse conditions, such as acid soils, low in nutrients and with little maintenance, which results in them quickly becoming unproductive (Vargas Navarro, 2010). Soils reported as moderately acidic to neutral are recommended for cultivation, since they allow faster root development and favor the first cut at an average of 3 years (Vargas Navarro, 2010). Strong to extremely acid soils and moderately acid soils, such as those reported in the study, may have higher concentrations of Al, Fe, and Mn, less microbiological activity, less decomposition of OM, and less mineralization of N, P, and S (Ituyan Pizo & Rivera Otero, 2009).

In soils found in the strong to extremely acid category, acidity is caused in other factors by the presence of Al on exchangeable surfaces, and in the soil solution. In addition, Al can impair plant growth as it can cause phytotoxicity, inhibit phosphate uptake and utilization, and reduce the uptake of other nutrients such as Ca, Mg, and K (Osorio, 2014).

The 91.7 % of the soils where fique ecotypes were found (Colombian Andean Region) have a very good percentage of OM, which favors the physical properties and structure of the soil, increases water filtration, provides nutrients to the plant, and reduces erosion. In addition, La Fundacion para la Orientacion Familiar (2015), reports that fique is a plant that rehabilitates poor and eroded soils since its root system is rich in nitrogen that accumulates as OM when it decomposes.

Species of the genus *Furcraea* as well as species of the gender *Manfreda bulbuli*fera (Castillejos-Cruz & Solano, 2008), *M. justosierrana, M. umbrophila,* and *M. verhoekiae* (García-Mendoza, 2011) develop and live in soils rich in OM. This has led to formulate as a recommendation for planting soils with percentages of OM above 3.6 % (West Analítica y Servicios, 2020).

Most of the results are between 0 and 2 (dS/m), which is related to non-salt soils and the effects of salinity are imperceptible. There is only one result with a relatively high value of 3.80 dS/m that approaches the limit value that is above 4 dS/m, where there are already problems for crop yields and the soil must start a recovering process.

The results suggest that P fixation in the soil is a limiting problem, particularly in soils derived from volcanic ashes, where high phosphate adsorption is present (Lizcano Toledo et al., 2017). It is especially stronger on the surface of the allophane and oxides and hydroxides of Fe and Al, because it presents a greater amount of adsorption sites (-OH and $-OH^{+2}$ groups). Other results of research on fique indicate that plants developed in soils with P deficiencies show purple or reddish tones in the leaf surface and poor root development (Casierra-Posada & Gómez, 2008).

According to the results found, it could be expected that some of the soils, due to the content of aluminum ions (Al^{3+}), could present an inhibition of root growth, since these could solubilize and penetrate root cells, and also hinder the absorption of water and essential nutrients such as P and Ca (Kochian et al., 2005). Associated with soil acidity there are some limiting factors such as low P availability, low Ca, Mg, and K content, phytotoxicity due to Al and Mn, among others (Osorio, 2014).

In different soil textures, it was found that the most discriminatory variables were those associated with exchangeable nutrients as ECEC (Figure 3). These bases present more variability in the system, which could be interpreted as the diversity of fique cultivation to different soil conditions and different fertility levels, moving from a low fertility sandy soil, to clay soils of higher fertility (Organización de las Naciones Unidas para la Alimentación y la Agricultura, 2013).

Particularly, soils with a high presence of clay are more physically and chemically active. These particles are responsible for soil water retention and for the cation exchange capacity (CEC) and anion exchange capacity

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(AEC), that allows the soil to retain ions (nutrients) against the leaching process. Since soil fertility is an interaction between its physical, chemical, and biological variables, it determines the capacity for plant to grown up and develop as an integral interaction. Therefore, it is necessary to deepen on the most benevolent characteristics for the genus *Furcraea* (Sánchez, 2007).

The presence of the genus *Furcraea* in soils with relatively high concentrations of Al indicates an adaptive aspect to Al intoxication, which could be related to the capacity of phenolic compounds synthesis and chelating ligands, which seem to promote the stability of Al^{3+} organic acid complexes, which partially prevents aluminum from entering root cells, due to deprotonation reactions or through inhibition of microorganisms that degrade organic acids in the rhizosphere (Carreño & Chaparro-Giraldo, 2013). This is important as it has been estimated that, between 30 and 40 % of the world's agricultural soils have acidity problems and the search for materials with their adaptation characteristics has been a frequent research topic (Carreño & Chaparro-Giraldo, 2013). However, specifically related to the genus *Furcraea* information, its adaptation to acidity conditions, relationships with the expression of adaptation genes and morphological or chemotypes conditions, are still incipient (Casierra-Posada & Gómez, 2008).

A proportion between Ca: Mg: K of 3:1:0.25 was propose as appropriate by Gélvez Rubio et al. (2020). However, given its high variability, further research on this subject is clearly required. Variables with less contribution to the variability of the total soil population were the Ca/Mg ratios, Na (%), OM, and changeable Na. This is partially explained, given that the normal relation Ca/Mg which are between 3 to 1 or 4 to 1 in almost all soils in the country. In addition, the low variability of OM concentrations is due to the capacity of the genus *Furcraea* to yield to deficient soils, since its roots enrich the soil in nitrogen and OM as the necrotic root material concentrates, leading to the formation of agricultural soil in a faster and more accentuated way, which could be useful in recovery process (Casierra-Posada & Gómez, 2008).

In addition, it is possible to visualize the inverse relationships between some variables such as pH and interchangeable aluminum, OM and (Ca+Mg)/K and K/Mg. As well as Na and ECEC, which indicate that in soils with pH 5.5 the Al^{3+} ocuppy a high proportion of the exchange sites and, therefore, there is more probability that the elements such as Ca, Mn, and K, are not available and can be lost by leaching. The pH may be an indicator of the level of Ca^{2+} availability. Usually, the increase in Ca^{2+} content is accompanied by an increase in the level of bicarbonates and carbonates, and these increase the pH of the soil. To this extent Nobel and Berry (1985) have reported that the species *Agave durangensis*, as a living group in ecosystems with a wide margin of Ca, has resulted in the accumulations of calcium oxalate crystals.

In general, sandy soils tend to have deficient levels of Ca given the high rate of leaching. In sandy soils it is preferable to apply amendments or calcium fertilizers in low quantities, in clay soil (with higher CEC) higher amounts can be applied, but less frequently (Toledo, 2016).

Regarding the decomposition process of the organic material, it can be slow, especially in soils where there are limitations for microbial activity, low temperatures (<15 °C), low pH (<5), high interchangeable Al (>2), and low availability of nutrients such as phosphorus. The annual decomposition rate of fresh OM in tropical soils is usually relatively high. While the more humified soil organic material decomposes at very low annual rates (0.1-1 %).

In tropical soils fique crops are more demanding of K and Ca, than Mg, for this reason it is important to supply this element, or give it favorable conditions so that the plant can supply the requirements, on the other hand, ecotypes can be selected from this genus that adapt more easily to adverse conditions.

Negative correlations occur in the soils studied, so the higher the amount of exchangeable acidity (Al^{+3}+H^{+}) lower pH value is observed. This show pH depend on ECEC in all soils studied, but in different proportions, indicating that they have a constitution in their mineralogy of different oxides, hydroxides, and allophanes.

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Conclusions

The soils where fique is grown show great diversity both in their fertility levels and in their variables associated with quality. This shows that tropical soils with the presence of the genus *Furcraea* present a high diversity in their quality and fertility parameters.

The main factor associated with the fertility of soils where the genus *Furcraea* is present in Colombia was its texture.

The variables that had the greatest discriminating power between soils with the presence of the *Furcraea* genus in Colombia were mainly associated with quality variables related to exchangeable ions.

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