Chemical characterization of soils cultivated with rice in the municipality of Majagual, subregion of La Mojana, Sucre, Colombia

Caracterización química de suelos cultivados con arroz en el municipio de Majagual, subregión de La Mojana, Sucre, Colombia

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Resumen

Introducción— La subregión de La Mojana se relaciona con riqueza natural, conformada por humedales, los ríos Cauca, Magdalena y San Jorge, un ecosistema único, conservando especies vegetales y animales, de hábitat frágil con importancia para el equilibrio ambiental del Caribe y Colombia. El agroecosistema arrocero principal motor de la economía agrícola, involucra componentes propios indicadores de sostenibilidad y productividad, donde las propiedades químicas de los suelos constituyen un factor importante para la rentabilidad de la empresa arrocera.

Objetivo— Realizar una caracterización química de los suelos arroceros de secano mecanizado de Majagual-Sucre, bajo dos condiciones topográficas (bajos y altos).

Metodología— Se tomaron 32 muestras de suelos y se evaluó— pH, Materia Orgánica (MO), fósforo y cationes disponibles, capacidad de intercambio catiónico y microelementos. Se utilizó estadística descriptiva, Análisis de Componentes Principales (ACP), conglomerados de varianza mínima de Ward.

Resultados— Para ambas topografías el pH fue ligeramente ácido, MO, fósforo, potasio, sodio y boro bajos. En la topografía alta registró mayor contenido de azufre, hierro y zinc y en la topografía baja registro mayor concentración de calcio, magnesio, CIC y manganeso. El ACP conllevó a reducción de las dimensiones iniciales de 14 a 4 que acumularon la varianza total explicada de la extracción de los 4 componentes con un 71,63%.

Conclusiones— Se identificaron las concentraciones de nutrientes en los suelos cultivados con arroz en la subregión de La Mojana, los cuales son una guía en los planes de fertilización de acuerdo con las condiciones topográficas de los lotes.

Palabras clave— Agroecosistema; arroz; nutrientes disponibles; secano; sostenibilidad; suelo; topografía

Abstract

Introduction— The La Mojana subregion is related to natural wealth, made up of wetlands, the Cauca, Magdalena and San Jorge rivers, a unique ecosystem, conserving plant and animal species, of fragile habitat with importance for the environmental balance of the Caribbean and Colombia. The rice agroecosystem, the main engine of the agricultural economy, involves its own components that are indicators of sustainability and productivity, where the chemical properties of the soils constitute an important factor for the profitability of the rice company.

Objective— To carry out a chemical characterization of the mechanized rainfed rice soils of Majagual-Sucre, under two topographical conditions (low and high).

Methodology— 32 soil samples were taken and the following were evaluated— pH, Organic Matter (OM), phosphorous and available cations, cation exchange capacity and microelements. Descriptive statistics, Principal Component Analysis (PCA), and Ward's minimum variance clusters were used.

Results— For both topographies, the pH was slightly acid, OM, phosphorus, potassium, sodium and boron low. In the high topography, a higher content of sulfur, iron, and zinc was recorded, and in the low topography, a higher concentration of calcium, magnesium, CIC, and manganese was recorded. PCA led to a reduction of the initial dimensions from 14 to 4, which accumulated the total explained variance of the extraction of the 4 components with 71.63%.

Conclusions— The concentrations of nutrients in the soils cultivated with rice in the La Mojana subregion were identified, which are a guide in the fertilization plans according to the topographic conditions of the plots.

Keywords— Agroecosystem; rice; available nutrients; dryland; sustainability; ground; topography

I. Introducción

Wetlands are complex systems that have physical, chemical and biological characteristics associated with a water regime, either temporarily or permanently, due to these characteristics, they present a high degree of productivity and are considered ecosystems of great importance for the conservation of many plant and animal species, and very fragile habitat [1]. In the colombian Caribbean is the Momposina depression, one of the most important wetland complexes in the country. Within the Momposina depression is the subregion of La Mojana, which acts as a regulator of the dynamics in the buffering of the Magdalena, Cauca and San Jorge rivers, a condition that benefits the ecosystem in its natural richness in flora, fauna and environment, generating a balance ecological for the Caribbean coast and the country.

La Mojana comprises eleven municipalities in four departments: Antioquia (Nechí); Bolívar (Magangué, Achí and San Jacinto del Cauca); Córdoba (Ayapel) and Sucre (San Marcos, Guaranda, Majagual, Sucre, Caimito and San Benito Abad), which add up to an approximate extension of 513 464 hectares [2]. Due to the agroecological conditions that exist, rice cultivation becomes the main line of the economy along with livestock. According to the IV National Rice Census of 2016, 71 315 hectares were planted in La Mojana of the 90 751 hectares of the humid Caribbean, the most important municipality in rice area is Majagual in Sucre with 19 479 hectares, which represents 21.4% of the planted area in the region [3].

Among the most important factors for the development of rice cultivation under the mechanized rainfed system, the chemical properties of the soils stand out, which have an important effect on the sustainability and competitiveness of the rice company. Therefore, the objective of this study was to carry out the chemical characterization of the soils of Majagual (Sucre, Colombia), to distinguish the chemical variables that influence the development and production of the crop.

II. Revisión de Literatura

Rice is one of the most important crops for human consumption due to its caloric intake (30%-80%). In 2019, the cultivated area of rice was approximately 162.1 million hectares. For that same year, China positioned itself as the main producer of rice worldwide, with an approximate production of 209.6 million tons, followed by India with 177.65 tons [4].

In Latin America and the Caribbean, rice is key in food security policies. In Colombia, rice is grown under very diverse agroecological conditions and management systems. Management is given under a scheme of chemical fertilization, soil decompaction, water retention and availability, which are determining factors in crop productivity [5].

In the last 10 years, the planting area in Colombia was approximately 476 thousand hectares, of which 47% is in the Llanos Zone and 25% in the Central Zone, with a mean production of 2.5 million tons. While for 2019, the total area planted nationwide was 540 thousand hectares, with an approximate production of 2.5 million tons of dry paddy rice [5].

Despite the figures, UT researchers point out that the competitiveness indicators for rice production in Colombia show its non-participation in the world rice market and its fragile position in the national market [6]. In this sense, Colombian rice farmers must improve their competitiveness and economic efficiency by reducing costs and increasing technical efficiency and yields. Additionally, it is necessary to improve the entire production process, especially soil suitability, sustainable water management, use of certified seed, minimum required fertilization, integrated pest management. The soil is a fundamental component in agricultural production systems and especially in rice cultivation, however, inadequate management practices can lead to a degradation of its physical, chemical, and biological properties, causing a decrease in the productivity of the plants lands [7], [8].

The rice-growing areas of the humid Caribbean include the departments of Antioquia, Bolívar, Córdoba, Chocó and Sucre, where 90 751 hectares are planted annually, contributing 15.89% of the national total [3]. Majagual is a municipality in northern Colombia which belongs to the La Mojana subregion, within the Momposina depression, in the department of Sucre [9]. It is a region of great agricultural and livestock abundance, dominated by a landscape of alluvial and flood plains, where the continuous accumulation of fluvial sediments from the Cauca and San Jorge rivers that characterize the formation of soils in depressions with poor drainage characteristics [10].

In this municipality, around 33,724 ha (38.5% of the total area of the municipality) have soils with optimal suitability (A1) favorable for the growth and development of mechanized rainfed rice cultivation. On the other hand, 56.9% of the territorial area of the municipality (49 998 ha) exhibits moderate suitability or unsuitable soils (A2), either due to texture or acidity conditions and exchangeable aluminum content [11].

In this region it is possible to find areas of high and low topography with contrasting soil characteristics that affect crop productivity. Soils located in plots with high topography are characterized by having light textures where infiltration tends to be faster, resulting in more aerated soils; while soils located in low areas have higher clay and silt contents, with moderate to slow infiltration, that is, poorly drained and, therefore, less aerated [12].

In flooded soils, the redox potential decreases [13], [14], [15], [16], [17], which is an indicator of the low level of oxygen present [18], this affects microbiological and chemical processes that produce important changes in the physical and chemical characteristics of soils, as well as the availability of nutrients for plants [19], [20], [21], [17].

At the microbiological level, both in well-aerated tall plots and low plots with poor drainage, the presence of nitrogen-fixing bacteria such as *Azotobacter* sp., *Azospirillium* sp. and phosphorus-solubilizing bacteria, however, the highest concentration of (CFU)/g has been found in plots with low topography [22], [12]. These types of diazotrophic bacteria have been considered of agricultural importance for producing regulators of growth such as auxins, cytokinins and gibberellins, which favor the development of the plant, root growth, resistance to osmotic stress due to increased chlorophyll and increased phosphorus (P) in the tissue due to its action in the dissolution of phosphates and soil minerals [23], [24], [25], [26].

On the other hand, in plots with low topography there is a preference for certain weeds that are representative of the area, such as lambe lambe (*Leersia hexandra* Swarts), canutillo (*Hymenachne amplexicaulis* Rudge), bijao bocachica (*Thalia geniculata* L.), among others, while that in plots with high topography, species such as Argentine grass (*Cynodon dactylon* L.), bicho (*Senna obtusifolia* L.), etc. [12].

Due to the geographical characteristics of the area and the importance it has for being a strong municipality in the agricultural sector, mainly in the cultivation of mechanized rainfed rice; A chemical characterization of the soils of the municipality of Majagual, Sucre, was carried out with the aim of carrying out a better management and productive use, contributing with possible nutrition recommendations in the study area and, in addition, giving a conservationist management.

III. Methodology

A. *Description of the study area*

Majagual is a municipality in northern Colombia, in the department of Sucre (subregion of La Mojana). It has an extension of 876 km² and limits to the north with Sucre-Sucre, to the south with Guaranda-Sucre, to the east with Achi-Bolívar, to the west with San Benito Abad-Sucre and Ayapel-Córdoba. It is located at an altitude of 25 meters above sea level, between the coordinates 8° 33" north latitude and 74° western longitude. It has an mean temperature of 28° C, with a relief dominated entirely by lowlands, swampy and floodable, in which the water supply of the San Jorge River and the Cauca system exerts a notable influence [27].

B. *Research Type*

A descriptive field investigation was carried out in which 16 farms cultivated with rice under the mechanized rainfed management system were selected. Within each farm, two plots located in areas with high topography and low topography were selected.

C. *Soil sampling*

Thirty-two soil samples were taken in rice plots considering the topography (high and low), distributed in a representative manner throughout the study area following the methodology proposed by the IGAC [28]. Table 1 lists the geographical location of the farms and the high and low plots sampled.

Table 1.
Identification, location, and topographical characteristics of the plots (high and low) of the farms in the study area.

#	Plots topography	Farm	Plots	Latitude	Length
1	High	Villa Rochy	Los Campanos	08°32´312´´	74°35´577´´
2	Low	Villa Rochy	La Bendy	08°32´315´´	74°35´333´´
3	High	El Engordadero	Las Casas 1	08°36´959´´	74°39´158´´
4	High	El Engordadero	El Cristo	08°36´992´´	74°38´244´´
5	Low	El Engordadero	La Viuda	08°36´406´´	74°40´459´´
6	High	El Rosario	Frente la casa	08°36´391´´	74°40´470´´
7	High	Campanos de Huira	El Corral	08°30´134´´	74°36´091´´
8	Low	Campanos de Huira	Bajo	08°30´398´´	74°36´158´´
9	Low	Maracaibo	Los Campanos	08°28´360´´	74°49´116´´
10	High	Maracaibo	Los Uveros	08°27´956´´	74°48´910´´
11	High	Maracaibo	Los Robles	08°28´470´´	74°49´018´´
12	Low	Santa Elena	Las 17	08°32´838´´	74°34´443´´
13	Low	Santa Elena	Los Campanos	08°32´774´´	74°34´620´´
14	High	Santa Elena	La Casa - Alto	08°25´884´´	74°40´673´´
15	High	Santa Elena	Minga - Bajo	08°25´866´´	74°40´695´´
16	Low	La Carolina	La Paja	08°32´789´´	74°34´720´´
17	High	Wilber	La Casa	08°26´131´´	74°41´678´´
18	Low	Wilber	El Guácimo	08°26´023´´	74°41´578´´
19	Low	Wilber	Marcel	08°25´072´´	74°42´200´´
20	Low	El Platanal	Campanos Verdes	08°33´644´´	74°35´836´´
21	Low	El Platanal	Guillo Uriel	08°33´692´´	74°35´815´´
22	High	El Platanal	El Arenal	08°33´024´´	74°35´589´´
23	Low	Asi es la vida	Enrique Mejía	08°26´326´´	74°41´212´´
24	Low	San José	Las 17	08°33´081´´	74°39´420´´
25	High	San José	Las 15	08°33´141´´	74°39´473´´
26	Low	El Salvador	Las 17	08°30´054´´	74°36´088´´
27	High	La Florida	La Muela	08°34´760´´	74°38´601´´
28	Low	Nueva Esperanza	Nueva Esperanza	08°36´938´´	74°41´106´´
29	Low	Villa Raquel	Las Treinta	08°33´209´´	74°38´798´´
30	High	El Manantial	Manantial 2	08°28´033´´	74°48´094´´
31	High	El Manantial	Manantial 1	08°27´919´´	74°48´149´´
32	Low	Las Claras	Los Robles	08°26´152´´	74°41´990´´

Fuente: Autores.

D. *Soil chemical analysis*

The samples were taken to the soil and water laboratory of the UCO and analyzed by the chemical methods used by the laboratory recommended by the IGAC [29]. The chemical analyzes performed were: pH in a soil: water suspension (1:1) by the potentiometric method; organic matter (MO%) following the wet digestion methodology of Walkley and Black; phosphorus (P) by the Bray-Kurtz II electrometric method expressed in $mg.kg^{-1}$; Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K) cations and the cation exchange capacity (CEC) were determined by extraction with 1N ammonium acetate at pH 7 (1N NH4OAc) and spectrophotometric determination of atomic absorption. The data was expressed in meq/100 g of soil. The microelements iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn), boron (B), sulfur (S) and phosphate were extracted with a double acid solution and determined by atomic absorption spectrophotometry. In the same way, the Ca/Mg ratios were established; (Ca + Mg)/K and Mg/K. Data were expressed in $mg.kg^{-1}$ of soil.

E. *Statistical analysis*

Descriptive statistics were performed on the data, using the soil chemical analysis interpretation table [30]. Principal component analysis and Ward's minimum variance hierarchical grouping analysis were carried out to evaluate the chemical properties of the soils of Majagual-Sucre (Colombia) and to identify the groups based on the behavior of the evaluated variables.

Principal component analysis was performed considering the matrix of bivariate correlations generated by n numerical variables to obtain n components or orthogonal factors that allow a better interpretation of the relationship between the variables. This analysis was performed with fourteen variables (pH, MO, S, P, Ca, Mg, K, Na, CIC, Cu, Fe, Zn, Mn and B). The SAS statistical software version 9.4 was used for data processing [31].

IV. Results

Table 2 shows the results obtained from the soil analyzes carried out in the 32 plots of the 16 farms. In general terms, the means recorded in the soils of the municipality of Majagual according to the interpretation values of soil fertility analysis [32], were: slightly acidic pH, low organic matter, high sulfur (S), low phosphorus (P), calcium (Ca^{+2}) very high, magnesium (Mg^{+2}) high, potassium (K^{+}) medium, sodium (Na^{+}) low, Cation Exchange Capacity (CEC) medium, copper (Cu) high, iron (Fe) and manganese (Mn) very high, zinc (Zn) medium and boron (B) low.

Table 2.
Results of the chemical properties of the rice soils of 32 farms in Majagual (Sucre, Colombia).

#	Farm	pH	MO	S	P	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	CIC	Cu	Fe	Zn	Mn	B
		(1:1)	%	(mg/kg)		(meq/100 g of soil)					(mg/kg)				
1	Villa Rochy	6.08	1.72	17	13.1	11	11	0.23	0.33	22.6	0.4	149.4	0.4	123.1	0.16
2	Villa Rochy	7.17	1.03	25.1	12.8	11	10	0.1	0.5	21.6	0.4	37.6	0.4	127.5	0.17
3	El Engordadero	6.75	1.36	31.6	8.9	6	4.2	0.08	1.09	11.3	5.6	491.9	2.4	81.6	0.31
4	El Engordadero	5.77	1.36	14.3	5.7	7	5	0.09	0.35	12.4	8.4	271.9	3.6	57.6	0.18
5	El Engordadero	5,94	1.72	16.8	7.3	9.5	5.8	0.13	0.24	15.7	9.2	160	4	110.4	0.36
6	El Rosario	6.17	1.37	85.4	7.8	8	5	0.1	0.2	13.3	6.8	175.8	3.2	79.1	0.29
7	Campanos de Huira	5.59	1.65	21	11.1	9	6.7	0.47	0.22	16.3	8.8	204	3.6	156	0.14
8	Campanos de Huira	4.91	1.98	58	5.7	10	9.2	0.23	0.54	20.7	13.2	287.8	4	88.7	0.13
9	Maracaibo	7.83	1.25	8	3	8.25	10.9	0.06	0.39	19.7	2	66	2.4	145.2	0.19
10	Maracaibo	7.35	2.05	11	5.4	5.4	6.1	0.12	0.3	12	4.4	193.6	4.8	74.8	0.21
11	Maracaibo	6.75	2.03	11.4	6.1	5.47	5.17	0.09	0.37	11.1	10.8	929.7	3.6	44	0.18
12	Santa Elena	5.94	1.36	35.2	17.4	9	4.2	0.15	0.17	13.5	11.2	153.9	4	119.9	0.21
13	Santa Elena	5.18	2.75	80	20.8	9	4.2	0.18	0.26	13.9	19.2	233.2	7.6	105.6	0.2
14	Santa Elena	5.71	1.2	32.7	33.7	2	3.3	0.31	0.11	5.7	2	48	2	28	0.26
15	Santa Elena	5.56	1.38	22.9	6.5	5	5.8	0.05	0.15	11	4	96	2	44	0.21
16	La Carolina	5.99	2.48	84.5	37.1	12.5	3.5	0.46	0.5	17	12	378.4	7.2	154	0.21
17	Wilber	5.41	1.76	1.3	3.8	9.5	7	0.1	0.22	17.3	3.6	113.6	2	48	0.17
18	Wilber	6.06	0.64	1.3	3.8	8.5	10.5	0.09	0.26	19.4	2	77.6	2.4	44.8	0.19
19	Wilber	6.17	1.44	1.3	6.9	10	9.5	0.08	0.33	19.9	4	73.2	3.2	92	0.21
20	El Platanal	7.23	0.96	16.3	6.9	13.5	13	0.13	0.63	27.3	2.4	31.6	2.8	104.4	0.16
21	El Platanal	6.59	2.24	11.3	6.9	12.5	10	0.17	0.72	23.4	5.6	116	3.6	132.4	0.18
22	El Platanal	6.29	1.28	1.3	22.5	11.5	7.5	0.1	0.26	19.4	6	98.4	3.2	76	0.19
23	Así es la vida	6.98	1.03	6.3	3.8	9	14.5	0.09	1.41	25	3.6	124.8	2.4	112.4	0.17
24	San José	6.57	0.69	26.6	3.8	14.5	18	0.22	0.85	33.6	2.8	42.8	3.2	139.6	0.19
25	San José	6.36	0.86	1.33	16	10.5	10	0.09	0.28	20.9	5.2	122.8	2.8	83.6	0.21

#	Farm	pH	MO	S	P	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	CIC	Cu	Fe	Zn	Mn	B
		(1:1)	%	(mg/kg)		(meq/100 g of soil)					(mg/kg)				
26	El Salvador	5.66	2.57	16.3	19.9	12	12	0.5	0.28	24.8	8	299.2	5.6	139.2	0.2
27	La Florida	5.47	2.08	37.2	6.9	11	6.5	0.29	0.24	18.4	5.2	100.8	2.8	61.2	0.16
28	Nueva Esperanza	6.08	1.28	21.5	9.5	13	9.5	0.15	0.41	23.1	5.6	78	3.6	92.8	0.3
29	Villa Raquel	5.78	2.57	16.3	17.5	22	3	0.2	0.28	25.5	7.2	118	4	160.8	0.27
30	El Manantial	6.12	2.03	12.7	4.1	11.5	10.5	0.12	0.74	22.9	4.8	333.4	1.2	31.6	0.19
31	El Manantial	5.6	1.86	13.1	10.3	10.5	9.5	0.13	0.35	20.5	5.6	404	2	48.4	0.23
32	Las Claras	5.76	0.96	6.3	2.6	14	11	0.13	0.22	25.3	4	60.8	3.6	56	0.18

Source: Authors.

It can be seen in Table 3, the general mean for all the 32 plots of soil analyzed in the municipality of Majagual, Sucre. The soils presented a slightly acid reaction with mean pH values of 6.2 and a coefficient of variation of 11%. The organic matter presented mean values of 1.6% with a coefficient of variation of 37.5%. This percentage is considered low when compared to the data reported for the interpretation of soil analysis at the national level [32]. pH and CEC are responsible for nutrient mobility and availability to plants. Soils with low pH and reduced microbial activity show an increase in the solubility and mobility of metals, facilitating the contamination of groundwater and which can also become toxic for the crop. Choosing soils with the parameters mentioned above can help reduce adverse environmental impacts through agricultural production and positively influence biodiversity and the delivery of goods and services provided by the soil. Organic matter is also a source of energy for biological activities and provides better nutrient availability, bulk density, and Cation Exchange Capacity (CEC), which by themselves are important factors for high resilience and performance [33].

Table 3.
Descriptive statistics of the rice soils composition in the municipality of Majagual (Sucre, Colombia).

Values	pH	MO	S	P	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	CIC	Cu	Fe	Zn	Mn	B
	(1:1)	%	(mg/kg)		(meq/100 g de suelo)					(mg/kg)				
Minimum	4.9	0.6	1.3	2.6	2.0	3.0	0.1	0.1	5.7	0.4	31.6	0.4	28.0	0.1
Maximum	7.8	2.8	85.4	47.1	22.0	18.0	0.5	1.4	33.6	19.2	929.7	7.6	160.8	0.4
Mean	6.2	1.6	23.3	10.9	10.1	8.2	0.2	0.4	18.9	6.1	189.8	3.3	92.6	0.2
SD	0.7	0.6	23.2	8.5	3.6	3.6	0.1	0.3	5.9	4.0	178.3	1.6	39.5	0.1
CV	11.3	37.5	99.6	78.0	35.6	43.9	50.0	75.0	31.2	65.6	93.9	48.5	42.7	50.0

SD: Standard deviation; CV: Coefficient of variation.
Source: Authors.

The sulfur concentration showed a mean of 23.3 mg/kg and a coefficient of variation of 99.6%, being an adequate level for the good development of the crop, although it is important to relate it to the iron content that was found on mean in excessive levels and affect its availability [30].

Phosphorus, with an mean of 10.9 mg/kg and a coefficient of variation of 78.0%, registered low levels according to the standard interpretation values of soil analysis, results that coincide with those reported in soils of the Valle del Sinú with 75% of sites analyzed with content in the soil (< 20 $mg.kg^{-1}$) [34], and also, it should be taken into account that possibly some amount must be precipitated forming iron phosphate due to the iron levels that were presented. in excess.

On mean, calcium registered values of 10.1 meq/100 g of soil, with a coefficient of variation of 35.6, and magnesium with values of 8.2 meq/100 g of soil, with a coefficient of variation of 43.9%; being high levels; normal Ca^{2+} nutrition may be disturbed Mg^{2+} exceeds calcium [35].

Less dispersion was observed in the potassium concentration with levels of 0.2 meq/100 g of soil with a coefficient of variation of 50.0 %. The sodium concentration was low, with values having an antagonistic relationship with minerals such as phosphorus, potassium, magnesium, nitrates (NO), calcium, zinc, and manganese means at 0.4 meq/100 g of soil and a coefficient of variation of 75.0%; being suitable for the relationship with other minerals and for the development of plants and for the absorption of elements such as potassium and phosphorus [36].

The Cation Exchange Capacity (CEC) on mean registered ideal levels, which means that the soil has a capacity to release positive ions, the most important cations in relation to the growth of rice plants are calcium, magnesium, potassium, ammonium (NH), sodium, and hydrogen (H^+) [37]. For copper, a high mean level was presented with a value of 6.1 mg/kg with a coefficient of variation of 65.6% and it has an antagonistic relationship with the phosphorus and zinc.

Regarding iron, it was observed that there is great variability, with a mean of 189.8 mg/kg with a coefficient of variation of 93.9%. A management strategy for excessive iron content would be acidity conditions, the availability of irrigation for water to circulate; they should not be flooded soils because a toxicity problem is generated since the solubility level and the favorable contents of the other minerals increase; and thus avoid affecting the development of plants [30], [37]. In the study area where the crops are planted in a rainfed system, iron is an element that can affect the development of the crop in conditions of water stress, due to its low availability.

Zinc was found on mean at 3.3 mg/kg with a coefficient of variation of 48.5%, with mean levels according to the standard values of the interpretation of soil analysis, which are adequate to meet the requirements for the crop; however, as noted above, it can be affected by excessive iron content. Manganese with an mean of 92.6 mg/kg and a coefficient of variation of 42.7%, which are excessive levels, but may be regulated by iron and copper and by low organic matter content, which implies that it does not cause toxicity in the crop and boron was found on mean with low levels of 0.2 mg/kg with a coefficient of variation of 50.0%, but for crop requirements and the characteristics of acidity and the type of soil that are clay loam favor its availability for the development of the crop.

In the interpretation of ionic relations of the results obtained in the soil analyzes of the 32 rice plots of Majagual, it is observed in Table 4, that the Ca/Mg relation was found on mean at a low level, with values of 1.2 where the ideal, according to the standard values of interpretation of ionic relations of soils, is between 3-6; this can cause calcium deficit even though it was found at high levels. This element is affected by this relationship and hence its low availability for cultivation; being an important element for cell reproduction, tissue resistance, hormone synthesis, respiration regulator, improves the quality of the harvest, in the protection against the attack of diseases and, at least in part, of the mechanisms of adaptation and plant response to changes in pH, light, temperature and others that may take place in the medium [38], [39].

Table 4.
Interpretation levels of ionic relations of the soil analysis of the results of the chemical properties in the rice soils of 32 farms in Majagual (Sucre, Colombia).

Values	Ca/Mg	Ca/K	Ca+Mg/K	Mg/K	Ca/B	Fe/Mn	P/Zn
Minimum	0.7	20.0	32.0	30.0	20.0	1.1	6.5
Maximum	1.2	44.0	58.0	36.0	55.0	5.8	4.9
Mean	1.2	51.0	51.7	41.5	51.0	2.2	3.5

SD: Standard Deviation; CV: Coefficient of Variation.
Source: Authors.

The Ca/K ratio mean was of 51, being an excessive level, compared to the ideal levels found between 15 to 30; with these ranges the assimilation of potassium is affected. In the Ca+Mg/K ratio, the mean values observed are 51.7, being high compared to the ideal levels, which are between 20 and 40; this relationship affects the availability of potassium. In the Mg/K ratio, it was found on mean with levels of 41.5; high compared to the ideal levels of this ratio (8 to 10), and it happens as in the previous case, affecting the assimilation of potassium.

It can be seen in Table 4 that the Ca/B ratio mean levels of 51, this ratio is very low compared to the ideal reference levels of this ratio which is 2000; element that is affected for its availability is calcium. In the Fe/Mn ratio, on mean, it registered a value of 2.2; low levels compared to the ideals which range between 5.0 and 10.0; this relationship affects the assimilation of iron.

The P/Zn ratio, according to Table 4, presented mean levels of 3.5, which are low compared to the ideal levels of 10; wherein said relationship considerably influences the assimilation of phosphorus.

A. *Characteristics of the nutritional content in the plots with low and high topography of Majagual - Sucre*

It can be seen in Table 5, that the pH, OM, K, Mn and B do not show variation in the contents for the high and low topography scenarios, mostly showing a slightly acid reaction; organic matter was found at low levels, according to the ranges of values for the interpretation of the analysis, as well as K; for Mn it registered high levels and for B with medium to low values.

On plots with low topography, Ca, Mg, Na and CIC show higher levels when they were compared with high plots topography, it was recorded for Ca and Mg with mean values of 12.5 which are high compared to the ideal levels are 5.0 - 10 for Ca and 2.5 - 3.0 for Mg. In the case of Na, it presented mean values of 24.3, which are high compared to the standard levels, and the mean CIC in the low plots presented higher ranges compared to the plots with high topography, giving it very favorable conditions for the availability of the elements.

In the high topography plots, S, P, Cu, Fe and Zn shows higher levels compared to low topography plots, while the S showed values of 28.0 which are considered high. Phosphorus presented values of 12.9, being higher in the high topography, although in general terms, for both conditions it was found to be deficient; the Cu showed high levels (7.3 mg/kg) in the plots with high topography compared to the standards values of 2.0 mg/kg - 3.0 mg/kg; the Fe presented values of 244.1 in high topography plots and the Zn presented mean values of 3.6 within normal parameters (3.0 - 4.0).

Table 5.
Descriptive statistics of the chemical composition of rice soils in conditions of high plots and low plots in the municipality of Majagual (Sucre, Colombia).

Lower Plots	pH	MO	S	P	Ca	Mg	K	Na	CIC	Cu	Fe	Zn	Mn	B
	(1:1)	%	(mg/kg)		(meq/100 g de suelo)					(mg/kg)				
Minimum	4.9	0.7	1.3	3.0	8.3	3	0.06	0.3	19.7	0.4	31.6	0.4	31.6	0.1
Maximum	7.8	2.6	58.0	19.9	22.0	22.0	0.5	1.4	33.6	13.2	333.4	5.6	160.8	0.3
Mean	6.4	1.6	19.6	9.1	12.5	12.5	0.2	0.6	24.3	5.2	146.1	2.8	113.5	0.2
SD	0.8	0.7	14.5	5.7	3.6	3.6	0.1	0.3	3.8	3.6	107.7	1.5	34.4	0.03
CV	12.5	43.8	74.0	62.6	28.8	28.8	50.0	50.0	15.6	69.2	73.7	53.6	30.3	15.0
High Plots	pH	MO	S	P	Ca	Mg	K	Na	CIC	Cu	Fe	Zn	Mn	B
	(1:1)	%	(mg/kg)		(meq/100 g de suelo)					(mg/kg)				
Minimum	5.2	0.6	1.3	2.6	2.0	3.3	0.05	0.1	5.7	2.0	48.0	2.0	28.0	0.1
Maximum	7.4	2.8	85.4	37.1	14.0	11.0	0.5	1.1	25.3	19.2	929.7	7.6	156.0	0.4
Mean	6.0	1.5	28.0	12.9	3.7	6.4	0.2	0.3	15.8	7.3	244.1	3.6	79.5	0.2
SD	0.5	0.5	27.0	9.7	3.0	2.4	0.2	0.2	4.8	4.0	205.5	1.5	36.0	0.06
CV	8.3	33.3	96.4	75.2	81.1	37.5	100.0	66.7	30.4	54.8	84.2	41.7	45.3	30.0

SD: Standard deviation; CV: Coefficient of variation.
Source: Authors.

It was observed that of 91 bivariate correlation values of Pearson, ten were significant ($P \leq 0.05$), presenting six with a positive association and four with a negative association. In general terms, the positive values of the correlations ranged from low values (0.0096) to high values (0.8151), while the negative values were low (–0.0091 to –0.4915). The CIC/Mg ratio presented the highest positive association, while Mg/Cu had the highest negative association. The value of the determinant of the correlation matrix was 0.009, which confirmed the existence of a linear relationship between variables. In the sedimentation graph, a notable change in the slope of the trend line was observed from the third component, to then continue a declining pattern in the fourth component. In this way, the analysis suggested the extraction of four components (Fig. 1).

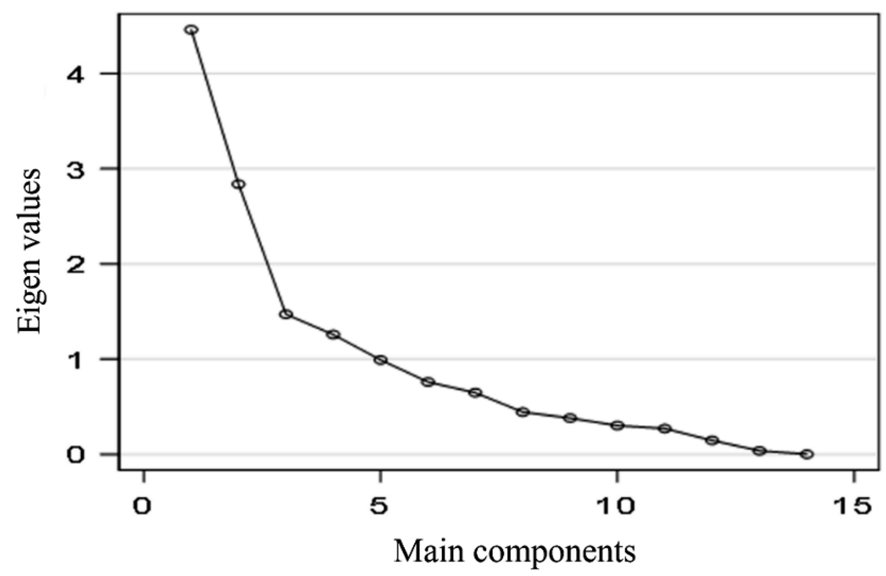

Fig. 1. Sedimentation of eigenvalues.
Source: Authors.

The PCA led to a reduction of the initial dimensions from 14 to 4, which accumulated the total variance explained from the extraction of four components of 71.63%, where the first component contributed 31.87%, the second 20.27%, the third 10.51% and the fourth component 8.98%. The descriptive statistics are shown in Table 6.

- *First component*: It was dominated by copper (0.39), made up of the variables zinc, organic matter, and sulfur, in such a way that they presented positive correlations indicating that an increase in zinc and organic matter involves an increase in copper and on the other hand an increase of copper causes a decrease in magnesium.
- *Second component*: Calcium (0.48), made up by manganese, cation exchange capacity, potassium and magnesium who showed positive correlations indicating that an increase in manganese, cation exchange capacity, potassium and magnesium involve an increase in calcium.
- *Third component*: Iron (0.57) in this component an important participation of the sodium variable was also found, in such a way that the analysis suggests an increase in iron and sodium favors the pH and generates a decrease in phosphorus.
- *Fourth component*: Boron (0.62), made up by pH and phosphorus; where it is observed that, with an increase in boron, there is an increase in pH and phosphorus and a decrease in iron.

Table 6.
Eigenvector analysis of the correlation matrix.

Chemical variables		Components			
		1	2	3	4
pH	pH	–0.266051	–0.012779	0.339938	0.455248
MO	MO	0.335999	0.167310	0.164849	–0.192110
S	S	0.323385	0.082270	0.072634	0.171922
P	P	0.296261	0.101398	–0.256957	0.297043
Ca	Ca	–0.067491	0.475445	–0.124579	0.000004
Mg	Mg	–0.362532	0.264243	0.078422	–0.168186
K	K	0.241783	0.323643	–0.178237	–0.097450
Na	Na	–0.193624	0.157255	0.565007	0.146656
CIC	CIC	–0.262090	0.462390	–0.004459	–0.108795
Cu	Cu	0.390811	0.087670	0.248485	–0.137892
Fe	Fe	0.197972	–0.135394	0.571258	–0.208915
Zn	Zn	0.343902	0.219572	0.146027	0.057163
Mn	Mn	0.039800	0.466676	0.053030	0.348919
B	B	0.107567	–0.153713	–0.032500	0.615835

Source: Authors.

In the conglomerate analysis of the chemical properties of the soils of Majagual (Sucre, Colombia), the grouping of 4 main conglomerates was evidenced.

- In group 1, they are identified by a neutral pH, low in OM, phosphorous, potassium and boron; average zinc content; ideal iron content and high calcium, magnesium, CIC, copper and manganese content.
- In group 2, they are identified by a slightly acidic to neutral pH, with low content of OM, phosphorus, potassium and boron; medium content of CEC, calcium and zinc and high content of copper, sulfur, magnesium, iron and manganese.
- In group 3, they are identified by a strongly acidic to moderately acidic pH, with a low content of OM, phosphorus and boron; medium to high content of CEC and calcium; and high contents of iron, magnesium, copper and manganese.
- In group 4, they are identified by a moderately acidic pH, with a low boron content; average OM and phosphorus content; ideal content of potassium and CEC and with a high content of calcium, magnesium, copper, iron, zinc and manganese (Fig. 2).

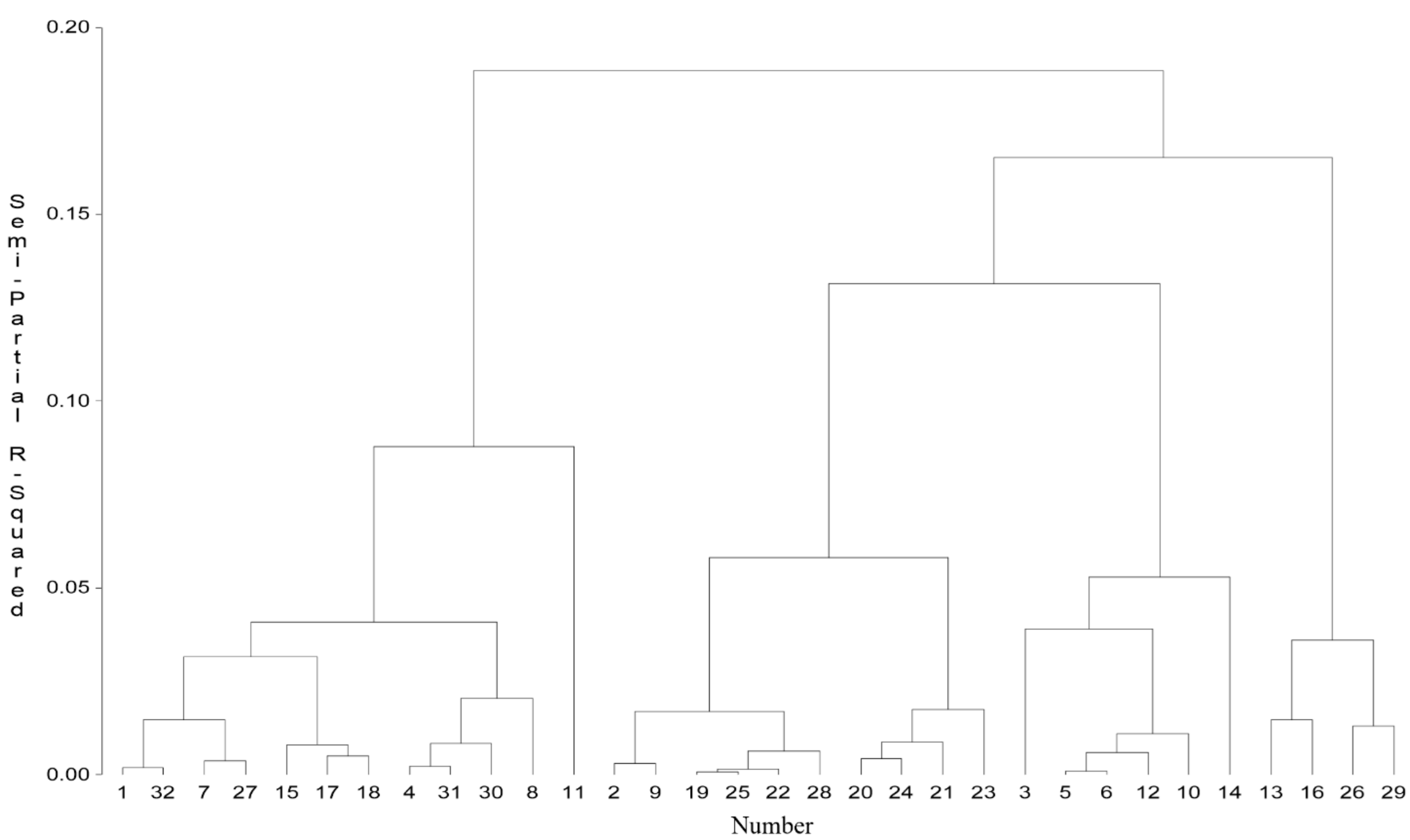

Fig. 2. Dendrogram of the rice soils of 32 farms in Majagual, Sucre.

Source: Authors.

V. Discussion

According to the results obtained for each of the components that make up the soil analysis of the 32 plots monitored, it was observed that in the case of soil pH, averages of 6.2 were found. This value may be due to the frequency and intensity of the rains and the texture of the soil that favors the leaching of cations and the predominance of acidifying elements. It should be noted that this range in which it occurs is ideal for the maximum availability of nutrients required for rice cultivation [30], [40], [41].

In the case of organic matter, although it registered low values, according to the standard interpretation of soil analysis, it is important to indicate that it does not represent an immediate source of nutrients for plants, but rather makes the soil obtain a series of properties favorable for the development of crops, making them loose, with greater moisture retention capacity, raising the concentration of nutrients and maintaining a better balanced soil chemistry, since it increases negatively charged colloids (greater cation exchange capacity) and those with a positive charge (greater anion exchange capacity), which results in a greater storage capacity for cationic nutrients (ammonium, calcium, magnesium, potassium, iron, zinc, copper, manganese) and anionics (phosphate, sulfate, borate, molybdate) and as a source of energy for the microbial population of the soil, giving ideal conditions for mixing with origin and inorganic fertilizers or an important synergy that favors the development of the crop and increases the yields and quality of the rice grain [42], [43], [44]. To favor and increase the content of organic matter in rice fields, the incorporation of chaff is recommended with the aim of recycling nutrients for greater availability, soil fertility and reduction of inorganic fertilization, which leads to decrease production costs in rice cultivation [45], in addition to the practice of nutrient recycling it is possible to increase yields in rice cultivation between 1.0 to 1.4 tons/hectare and also helps to conserve resources nature and the environment [46].

High sulfur contents were found in both topographies, a condition that coincides with investigations carried out in the Sinu Valley [34], which indicate that high values of sulfur (S) in the soil with values greater than 15 mg kg^{-1} and the are related to areas susceptible to flooding (swampy areas), associated with areas with accumulations of iron sulfide or pyrite (FeS2), whose mineralization provides S content, which influences the soil pH (oxide processes - reduction of organic matter) [47].

Phosphorus in both topography conditions was found at low levels, being lower in low plots, due to the condition of finding more moisture content favoring its leaching [30], in addition, its availability is affected in acid and dry soils [42]. These phosphorus contents are influenced by the iron that was found in excessive form, and possibly some amount must be precipitated forming iron phosphate, affecting the absorption and availability for plants; that is why it is recommended to carry out applications of phosphorus, to compensate for said deficit; information that coincides with researchers of the UM [48], where they mention that in conditions of acidity the iron mineral can precipitate phosphorus and not be assimilable for adsorption by plants, hence the need to carry out the application in higher contents of this mineral. It is also worth highlighting the importance of phosphorus for the proper development of the plants, favoring greater root formation, tillering potential, strengthening the stems, and thus avoiding the overturning of the rice plants and finally a quality and weight of the rice grains, favorable conditions for yield potential.

Potassium levels in the area are low to medium, being an adequate content for the requirements of rice cultivation, despite the conditions of acidity and humidity, study that coincides with UNAL studies [30], where it indicates that these levels are adequate both for the requirements of the crop that are between 0.2 meq/100 g to 0.4 meq/100 g of soil; although an excess of rains can affect the levels of this mineral and therefore the need is created to carry out applications of higher contents of this element to compensate for said deficit.

The calcium (Ca) - potassium (K) ratio registered an excessive level, compared to the ideal levels that are between 15 - 30; with these ranges the assimilation of potassium (K) is affected, in addition to the fact that this element was found at low to medium levels, for this reason it is necessary to carry out fertilizations of this mineral to avoid its deficiency, which is basic for cell reproduction , fertilization, photosynthesis, protein and sugar synthesis, carbohydrate transport, respiration regulator, water regulator, basic in enzyme activation and protection against diseases [38], [39].

The same situation occurs with the calcium + magnesium/potassium ratio, the values observed on average were high compared to the ideal levels that are between 20 - 40; this relationship affects the availability of potassium (K) and as mentioned above it is essential for the good development of the crop, therefore it is advisable to carry out fertilizations of this mineral. It is important to know and determine the conditions of the Ca/Mg, Ca/K, Mg/K, Ca/B, Fe/Mn and P/Zn ionic ratios in order to carry out the appropriate corrective measures to avoid deficiencies of minerals such as calcium, potassium and phosphorus that are basic for the good development of the crop.

The CIC registered values from medium to high, with the low topography being the one that presented the highest values, a condition that favors greater availability of nutrients and better development of the rice crop; results that coincide with research where they refer to the

CIC as a vault where the soil stores the nutrients necessary for plant life. Nutrients such as potassium, magnesium, calcium, nitrogen, find there a place to be stored and dissolved in the soil water and thus be absorbed by plants. Technically, the CEC of the soil refers to the number of cation exchange sites it may have. The more exchange sites, the greater the cation storage capacity and the greater its availability to plants [49].

Regarding high iron content, research PPI, PPIC and IRRI indicates that the critical concentration of Fe in the soil solution for toxicity to occur varies widely [50]. Values ranging from 10 mg Fe/L to 1000 mg Fe/L have been reported. This implies that the toxicity is not only related to the concentration of Fe in the soil solution. Differences between critical concentrations in soil solution are caused by differences in the potential of rice roots to resist the effects of Fe toxicity, which in turn depends on the growth and physiological state of the crop and variety (oxidation capacity of the roots). No critical levels have been established for Fe content in the soil, however, soils with pH Fe/L (in calcareous soils low in organic matter) up to > 1000 mg Fe/L (in acid soils). A high concentration of Fe^{2+} in the soil can retard the absorption of K and P. Under conditions of strong reduction, the production of H_2S and FeS can contribute to the decrease in the oxidation power of the roots. The oxidation of Fe^{2+} to Fe^{3+} due to the release of O_2 by the roots acidifies the rhizosphere (important for P uptake) and promotes the formation of the brownish layer on the roots. In the case of Fe, it has an antagonistic relationship with minerals such as P, K, Mg, NO, Ca, Zn and Mn.

In the main components analysis, four components were identified, the first component was dominated by copper (0.39); the second for calcium (0.48); the third for iron (0.57) and the fourth for boron (0.62). And in the conglomerate analysis of the chemical properties of the soils of Majagual (Sucre, Colombia), the grouping of four main conglomerates was evidenced that, from the chemical point of view of the soil, there are conditions for the development of rice cultivation in the soils of Majagual region, however, there are environments that favor their relationship, movement and availability for a good development of the crop. All these conditions that were related allow to identify the different managements to take advantage of the chemical contents that the soils of Majagual have for the planting of rice.

For mechanized upland rice planting system conditions, it is important to know the growth and development of the plant, its interaction with climatic factors, such as temperatures, relative humidity, solar radiation, wind and especially rainfall, because they influence on soil moisture and nutrient solution for absorption [51].

V. Conclusions

The chemical characterization of the soils of the municipality of Majagual - Sucre showed slightly acidic pH, with average values of Cation Exchange Capacity and zinc, and with low values of organic matter, phosphorus, potassium, sodium and boron and high values of sulfur, calcium, magnesium, copper, iron and manganese.

The comparisons obtained in the averages of the chemical analyses, for the plots with high topography, recorded higher contents of sulfur, phosphorus, copper, iron and zinc, compared to the plots with low topography.

The low topography registered the highest average contents of calcium, magnesium, sodium, cation exchange capacity and manganese, when compared to the plots with high topography.

Organic Matter (OM) registers a deficit for both topographic conditions in the soil; however, plots with low topography, because they have a higher Cation Exchange Capacity (CEC) and better humidity conditions, allow nutrients to be more available for rice cultivation.

Iron becomes an important element due to the high content it registered, because it has an antagonistic relationship with minerals such as phosphorus, potassium, magnesium, nitrates (NO), calcium, zinc, and manganese, fundamental for the growth, development and production of rice cultivation.

The values of the chemical characterization of the soils of the municipality of Majagual - Sucre, become a guide to the fertility of the soils, in the fertilization plans, the crops that are planted and especially as a reference for the topographical conditions of the rice soils for the La Mojana subregion.

The chemical characterization of soils for areas under agricultural exploitation is required because it provides professionals in the area with a guide to design productive projects with adequate management of the necessary nutrients, soil conservation and environmental protection.

In order to determine the characteristics that are described in agricultural production in an integral way, it is important to include, in addition to the chemical characterization, the physical and biological properties, where the indicators that influence the productive agroecosystems in Colombia can be obtained.

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