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Chemical and textural characterization of soil used for livestock production

Caracterización química y textural de suelos utilizados en la producción ganadera

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ABSTRACT

Extensive livestock farming practices can alter the physicochemical properties of soil, reducing its fertility and forage biomass productivity. This information is limited, making it difficult to formulate sustainable management strategies. The objective of this study was to characterize the chemical properties and texture of soils used for livestock production in four municipalities of Putumayo, Colombia. A total of 234 soil samples were collected from livestock systems in Orito, Puerto Asís, Valle del Guamuez, and Villagarzón. The following chemical characteristics were evaluated: pH, electrical conductivity, organic matter, nitrogen, phosphorus, sulfur, calcium, magnesium, potassium, aluminum, iron, manganese, zinc, boron, and carbon; ionic ratios and base saturation: Ca/Mg, Mg/K, (Ca+ Mg)/K, CEC; granulometry: sand, clay, silt, and textural classification. The data were analyzed using descriptive statistics. A test of homogeneity of variance and comparison between municipalities was performed using Welch's ANOVA. Spearman's correlation was used to determine the relationship between variables. Differences between municipalities were identified in pH, phosphorus, calcium, magnesium, potassium, and organic carbon. Orito had the lowest pH value (4.20), the highest aluminum concentration (1.05 cmol/kg), and the lowest phosphorus content (3.36 mg/kg). Valle del Guamuez had the highest levels of phosphorus (9.60 mg/kg) and copper (0.53 mg/kg). The texture showed a predominance of sand in Orito (41.97%) and a higher silt content in Villagarzón and Puerto Asís (>32%). These results demonstrate soil variability between municipalities, highlighting the need to implement differentiated practices to improve soil fertility and the sustainability of livestock systems.

Key words: grassland soil; macronutrients; micronutrients; organic matter; soil acidity; soil texture

RESUMEN

Las prácticas ganaderas extensivas pueden alterar las propiedades fisicoquímicas del suelo, reduciendo su fertilidad y productividad de biomasa forrajera. Esta información es limitada, dificultando la formulación de estrategias de manejo sostenible. El objetivo de esta investigación fue caracterizar las propiedades químicas y la textura de suelos dedicados a la producción ganadera en Putumayo, Colombia. Se recolectaron 234 muestras de suelo en sistemas ganaderos en Orito, Puerto Asís, Valle del Guamuez y Villagarzón. Se evaluaron las características químicas: pH, conductividad eléctrica, materia orgánica, nitrógeno, fósforo, azufre, calcio, magnesio, potasio, aluminio, hierro, manganeso, zinc, boro y carbono; relaciones iónicas y saturación de bases: Ca/Mg, Mg/K, (Ca+ Mg) /K, CIC; granulometría: arena, arcilla, limo y clasificación textural. Los datos fueron analizados mediante estadística descriptiva. Se realizó una prueba de homogeneidad de varianza y comparación entre municipios mediante ANOVA de Welch. La correlación de Spearman se empleó para determinar la relación entre las variables. Se identificaron diferencias entre municipios en pH, fósforo, calcio, magnesio, potasio y carbono orgánico. Orito presentó los valores más bajos de pH (4,20), mayor concentración de aluminio (1,05 cmol/kg) y menor contenido de fósforo (3,36 mg/kg). Valle del Guamuez registró mayores niveles de fósforo (9,60 mg/kg) y cobre (0,53 mg/kg). La textura mostró predominio de arena en Orito (41,97 %) y mayor contenido de limo en Villagarzón y Puerto Asís (>32 %). Los resultados evidencian variabilidad edáfica entre municipios, lo que resalta la necesidad de implementar prácticas diferenciadas para mejorar la fertilidad del suelo y la sostenibilidad de los sistemas ganaderos.

Palabras clave: acidez del suelo; macronutrientes; materia orgánica; micronutrientes; suelo de pradera; textura del suelo

INTRODUCTION

The importance of soil lies in its role as a provider of goods and services essential to humans, which can be classified by the type of benefit they provide: provisioning, regulating, and cultural services (Tellez *et al*., 2023). These services include food and fiber production, regulation of the hydrological cycle, carbon storage, and support for soil biodiversity. These functions are essential for the sustainability of productive systems and the balance of terrestrial ecosystems (Panda, 2025).

Soil is an important resource that performs environmental functions such as providing nutrients to plants, storing organic matter and nutrients, and hosting organisms that transform organic matter (Silva & Correa, 2009). These functions largely determine the productivity and stability of agroecosystems; therefore, their proper management is key to ensuring the sustainability of agricultural activities (Montenegro-Gómez *et al*., 2022). According to Arteaga *et al*. (2016), land use in Colombia is distributed as follows: 62.5% for forestry purposes, 19% for agroforestry, 9.1% for agriculture, and 9% for livestock, which highlights the importance of comprehensive soil resource management in the country's rural development.

According to FAO (2020), cattle production is carried out by 1.3 billion producers, contributing on average 45% of the global agricultural GDP. However, this economic activity is blamed for biodiversity loss, including the loss of flora and fauna, due to ecosystem deterioration, disruption of biological cycles, and the physical and chemical degradation of the soil (Tovar *et al*., 2016). Farming practices and trampling caused by overgrazing reduce vegetation cover, compromise porosity, and hinder water infiltration, promoting surface runoff and leading to erosion, salinity, and nutrient loss (Siavosh *et al*., 2000; Martínez-Aguilar *et al*., 2020). Consequently, soil degradation is one of the main limiting factors for the sustainability of livestock systems (Carranza-Patiño *et al*., 2024).

In Colombia, more than 77% of soils used for livestock farming show erosion and compaction, resulting in losses of about 25 tons per hectare. This necessitates ongoing characterization to determine soil properties and monitor changes in soil fertility associated with livestock farming. Characterizing the chemical and physical properties of soil is a fundamental tool for assessing its fertility, identifying production constraints, and formulating management strategies that improve the efficiency of livestock systems (Cadena-Torres *et al*., 2021).

In this regard, variables such as pH, cation exchange capacity, organic matter content, macronutrient and micronutrient levels, and soil texture provide key information about soil fertility and its capacity to sustain productive processes (Rodríguez Colorado *et al*., 2022). Integrating these parameters enables more accurate diagnoses that inform decision-making on fertilization practices, pasture management, the implementation of silvopastoral systems, and soil conservation strategies.

The Putumayo Department, located in southwestern Colombia, has remarkable agroecological diversity, making it a strategic region for developing livestock production systems. The region is characterized by high rainfall and generally acidic soils with limited natural fertility, conditions that require appropriate management strategies to ensure the sustainability of production systems. Despite these limitations, livestock farming is one of the main rural economic activities in the department, playing an important role in generating income and ensuring food security for local communities (Flórez Delgado *et al*., 2024).

Characterizing soils in livestock areas is a fundamental step in designing sustainable management plans, as the soil's physicochemical properties determine not only its fertility but also its response to conservation practices, amendments, and efficient resource use (Álvarez *et al*., 2023). In this context, this research aims to compare the physicochemical quality of soils across four municipalities representative of livestock activity in Putumayo to identify patterns and significant differences and to guide specific agronomic recommendations.

MATERIALS AND METHODS

Study Area and Characterization of the Livestock System

The study was conducted in the municipalities of Puerto Asís, Villagarzón, Orito, and Valle del Guamuez in the Putumayo Department, Colombia, as part of the project "Strengthening the Livestock Sector through the Implementation of Sustainable Practices in the Department of Putumayo" (BPIN: 2015000100086), funded by the General Royalties System. The study covered 234 livestock farms owned by small and medium-sized producers engaged in dual-purpose farming with traditional management practices.

The characterization of the livestock system in the municipalities of Puerto Asís, Villagarzón, Orito, and Valle del Guamuez shows a predominance of the dual-purpose cattle farming model, geared toward the simultaneous production of milk and meat. This system is mainly developed on medium-sized farms, with areas ranging from 31 to 53 hectares and predominantly flat topography that facilitates the establishment of pastures for grazing.

In terms of production, the cattle inventory is mainly composed of females used for breeding and milk production, averaging 11 to 13 animals per farm, while males are mainly used for fattening and commercialization. Milk production varies among municipalities, with average values ranging from 4.4 to 6.6 liters of milk per cow per day, and Orito shows the highest production levels. From a breed perspective, Bos indicus animals predominate, especially the Gyr breed and its crosses with Holstein, Brown Swiss, and Creole breeds, which are adapted to the climatic conditions of the Amazon region.

Pasture management is based mainly on rotational grazing systems, adopted by about 94% of producers, with an average of 9 to 12 paddocks per farm, which improves forage availability throughout the year. The predominant forage species are Brachiaria brizantha, Brachiaria humidicola, and Panamanian grass, which are well adapted to humid tropical soils. The soils have high acidity (pH < 5.5), low base saturation, and exchangeable aluminum, characteristics that limit the soil's natural fertility and forage productivity.

In general, loamy-clay and clay soil textures with good drainage predominate, which conditions agronomic management strategies to improve pasture productivity.

Finally, livestock farming in these municipalities remains traditional, with low adoption of technologies, limited use of production records, and limited pasture fertilization, highlighting the need to strengthen innovation processes and sustainable management of the livestock production system in the region. Table 1 presents the main indicators of the livestock system in the municipalities studied.

Table 1. *Main production indicators for the livestock system*

Indicator	Valle del Guamuez	Orito	Puerto Asís	Villagarzón
Average area of the property (ha)	31.06	32.82	53.24	39.25
Average altitude (m above sea level)	361	474	254	394
Average temperature (°C)	26.9	28.0	28.0	24.9
Predominant production system	Dual purpose	Dual purpose	Dual purpose	Dual purpose
Females per property	11.47	6.41	13.57	9.81
Males per property	1.76	2.49	2.39	2.02
Milk production (L/cow/day)	4.44	6.57	4.89	6.22
Average number of pastures	9.03	10.79	10.08	12.06
Pasture rest days (winter)	37	46.79	49.40	43.04
Predominant soil type	Loamy	Clay	Loamy	Loamy
Soil condition	High acidity	High acidity	High acidity	High acidity
Predominant forages	*Brachiaria* spp.,	*Brachiaria* spp.	*Brachiaria* spp.	*Brachiaria* spp.

Soil Sampling and Laboratory Analysis

Soil samples were collected from an area of 468 hectares (2 ha per farm). A composite soil sample was collected from each farm, consisting of 15 subsamples taken at a depth of 30 cm using a grid pattern. For each cattle farm, chemical characteristics, ionic ratios, base saturation, and textural classification were determined at the Soil Agro-environmental Laboratory located in La Unión, Valle (Table 2).

Table 2. *Chemical parameters, ionic ratios, base saturation, and textural classification of the soils evaluated in the cattle ranches.*

Parameter	Determination method
Chemical properties	
pH	Electrometric
Organic matter	Walkley Black
Total nitrogen	Kjeldahl
Phosphorous	Method Bray II
Sulfur	Turbidimetry
Calcium	
Magnesium	Extraction with 1N ammonium acetate at pH 7 and quantification by atomic absorption spectrometry
Potassium	
Aluminum	
Iron	DTPA extraction
Manganese	DTPA extraction
Copper	Atomic absorption
Zinc	Atomic absorption
Boron	Azomethine
Organic carbon	Walkley Black
Ionic ratios and base saturation	
Calcium / Magnesium Magnesium / Potassium (Calcium + Magnesium) / Potassium Cation exchange capacity	
Granulometry and textural classification	
Sand	
Clay	Bouyoucos
Silt	

Selection of Sampling Units

Within each property, relatively homogeneous units were identified based on vegetation cover, slope, drainage, and management, excluding areas directly affected by specific practices such as pens, watering holes, salt licks, livestock trails, and areas with manure accumulation. Figure 1 shows the sampling sites for each municipality.

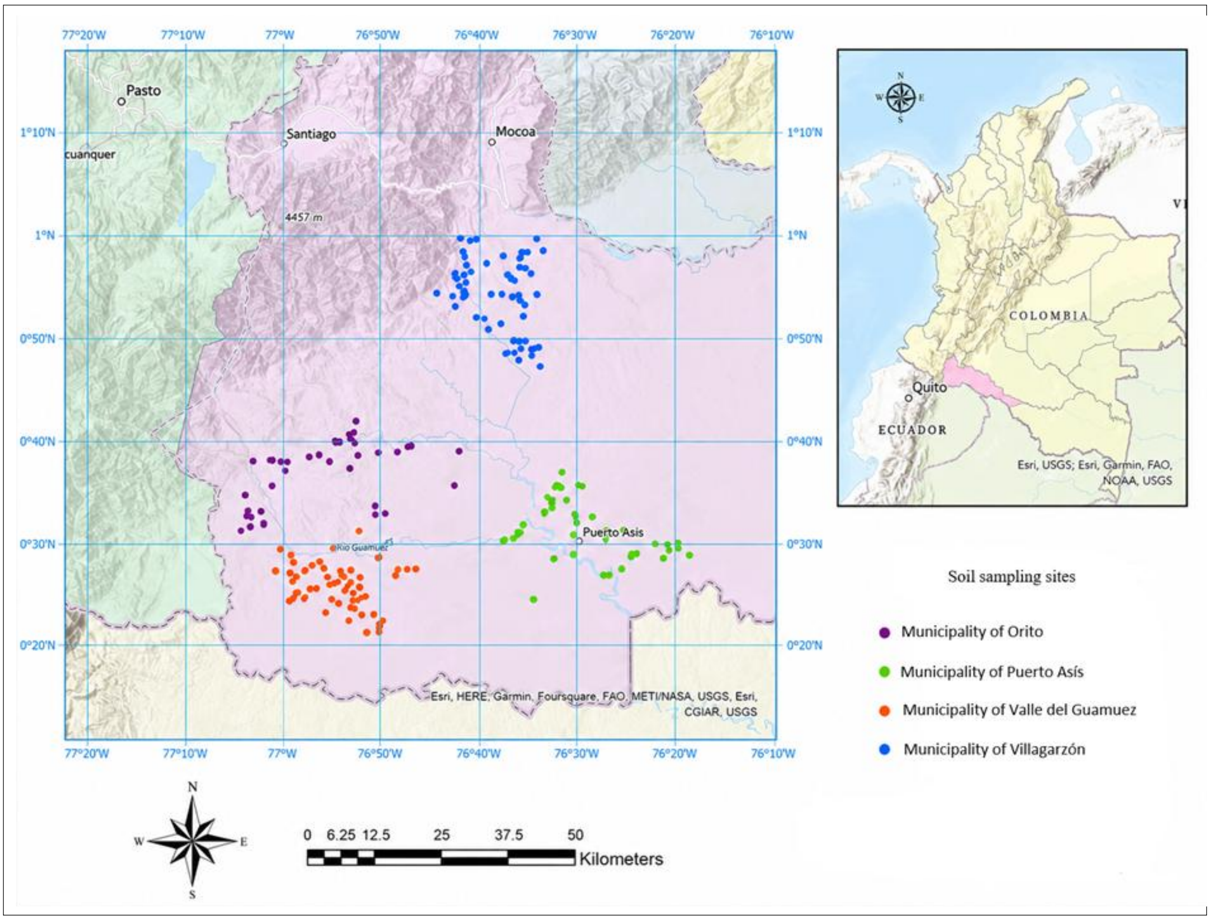

Figure 1. *Sampling sites*

Statistical Analysis

The data were analyzed using descriptive statistics for each municipality. Levene's test was performed to assess the homogeneity of variances for each study variable. To compare municipalities, one-way analysis of variance was applied with Tukey's test for soil parameters that met the assumptions of normality and homogeneity, and Welch's test for parameters with unequal variances, in both cases with an error probability of $p < 0.05$. Spearman's correlation was used to assess relationships among soil chemical variables. Statistical analyses were conducted using SPSS v. 20.

RESULTS

Significant differences in acidity levels, available nutrients, and cation exchange capacity indicate that edaphic conditions are heterogeneous across municipalities, directly affecting the yield and composition of established forage species. Table 3 presents the analysis of variance for the four municipalities with respect to the chemical and textural parameters of the soil used in livestock production.

Table 3. *Analysis of variance for the chemical and textural parameters of the soil used for livestock production*

Municipality Parameter	Unit	Orito		Villagarzón		Puerto Asís		Valle del Guamuez		Sig.
		Mean	S.T.	Mean	S.T.	Mean	S.T.	Mean	S.T.	
pH	--	4.20^{a}	0.077	4.66^{b}	0.058	4.80^{b}	0.106	4.91^{b}	0.073	0.000
Organic matter	%	5.11^{a}	0.128	4.10^{a}	0.124	3.99^{a}	0.106	4.79^{a}	0.095	0.157
Total nitrogen	%	08.42^{a}	8.139	0.22^{b}	0.006	0.22^{b}	0.005	0.26^{a}	0.005	0.000
Phosphorous	Ppm	3.36^{a}	0.609	6.27^{ab}	0.999	5.22^{ab}	1.272	9.60^{b}	1.563	0.007
Sulfur	Ppm	2.04^{a}	0.289	4.25^{a}	0.180	3.97^{a}	0.281	29.90^{a}	25.86	0.509
Calcium	Meq/100g	1.05^{a}	0.188	2.27^{b}	0.190	2.18^{b}	0.167	1.92^{b}	0.132	0.000
Magnesium	Meq/100g	0.41^{a}	0.051	1.32^{b}	0.117	1.37^{b}	0.112	0.92^{c}	0.067	0.000
Potassium	Meq/100g	0.16^{a}	0.014	0.48^{b}	0.029	0.32^{ab}	0.030	0.26^{a}	0.027	0.001
Aluminum	Meq/100g	1.05^{a}	0.082	0.60^{b}	0.041	0.59^{b}	0.075	0.46^{b}	0.041	0.000
Iron	Ppm	47.76^{a}	6.913	49.22^{a}	2.391	36.36^{a}	2.146	44.70ª	3.674	0.092
Manganese	Ppm	2.97^{a}	0.478	2.91^{a}	0.260	3.91^{a}	0.510	3.49ª	0.594	0.451
Copper	Ppm	0.19^{a}	0.035	0.39^{b}	0.043	0.40^{b}	0.034	0.53^{b}	0.053	0.000
Zinc	Ppm	0.73^{a}	0.101	0.85^{a}	0.219	0.59^{a}	0.072	1.71ª	0.956	0.523
Boron	Ppm	0.18^{a}	0.748	0.29^{a}	0.015	0.34^{a}	0.016	0.31ª	0.013	0.197
Organic carbon	%	2.97^{a}	0.074	2.38^{b}	0.072	2.32^{b}	0.062	2.78a	0.055	0.000
Calcium/Magnesium	--	2.58^{a}	0.236	2.06^{a}	0.131	1.80^{a}	0.125	3.57a	0.798	0.050
Magnesium/Potassium	--	3.04^{a}	0.558	4.66^{ab}	0.494	5.89b	0.707	5.01^{ab}	0.509	0.018
(Calcium + Magnesium)/Potassium	--	10.46^{a}	1.916	12.03^{a}	1.100	1.88^{a}	1.607	16.63ª	1.949	0.049
Cation Exchange capacity	--	4.15^{a}	2.147	4.50^{a}	0.369	5.07^{a}	0.961	3.51ª	0.177	0.641
Sand	%	41.97^{a}	1.833	35.69^{b}	1.396	33.65^{b}	1.188	37.61^{ab}	1.290	0.003
Clay	%	31.13^{a}	0.827	31.43^{a}	0.778	32.85^{a}	0.545	31.12ª	0.682	0.311
Silt	%	26.88^{a}	1.176	32.95^{b}	0.749	33.49^{b}	0.830	31.26^{b}	0.907	0.000

Soil acidity (pH) and aluminum

The average pH in Orito (4.20) was significantly lower than in the other municipalities, which had similar values (between 4.66 and 4.91), indicating higher acidity. This acidity coincided with a significantly higher exchangeable aluminum content in Orito (1.05 cmolc/kg), suggesting potential root toxicity in that municipality. In contrast, the other three municipalities had lower aluminum levels (between 0.46 and 0.60 cmolc/kg), consistent with their relatively less acidic pH.

Organic matter, total nitrogen, and carbon

Organic carbon (OC) showed significant differences: Orito and Valle del Guamuez showed higher values (2.97% and 2.78%, respectively), while Villagarzón and Puerto Asís had lower values (around 2.3%) (Table 2).

Macronutrients: phosphorus, sulfur, calcium, magnesium, and potassium

Valle del Guamuez had the highest P content (9.60 mg/kg), while Orito had the lowest (3.36 mg/kg) (Table 2). This pattern may reflect limited availability of this nutrient in more acidic soils. For calcium and magnesium, Orito recorded significantly lower values, consistent with its low cation exchange capacity (CEC) and higher acidity. Potassium showed intermediate differences: Villagarzón had the highest value (0.48 cmolc/kg), significantly higher than that recorded in Orito (0.16 cmolc/kg) (Table 2), reflecting better soil fertility.

Micronutrients: iron, manganese, copper, zinc, and boron

The only micronutrient that showed significant differences was copper: Orito had a very low value (0.19 mg/kg) compared with the other municipalities, especially Valle del Guamuez, which had the highest value (0.53 mg/kg). Iron, manganese, zinc, and boron did not show statistically significant differences among municipalities, although numerical variations were observed, such as the higher zinc content in Valle del Guamuez (1.71 mg/kg) compared with that in Puerto Asís (0.59 mg/kg) (Table 2).

Cation Ratios and Nutrient Balance

These ratios, which help evaluate nutrient balance, showed differences across some comparisons (Table 2). Puerto Asís had a high Mg/K ratio (5.89), which may reflect a relative excess of magnesium over potassium, while Valle del Guamuez had the highest Ca+Mg/K ratio (16.63), which may indicate imbalances in the relative availability of these essential nutrients.

Soil texture

There were significant differences in the proportion of sand and silt (Table 2). Orito had the highest proportion of sand (41.97%), which may be associated with lower nutrient and water retention. In contrast, Villagarzón and Puerto Asís showed higher silt content (more than 32%), which gives them better structure and retention capacity. The clay fraction did not show significant differences.

Relationships among Soil Chemical Variables

Table 4 presents the correlations between the chemical variables of the soil for livestock use in the four municipalities.

The results reveal key relationships that contribute to understanding soil fertility status. It is worth noting the strong negative correlation between pH and aluminum ($r = -0.973$; $p < 0.01$), indicating that as soil acidity increases, aluminum toxicity also increases, thereby limiting the root development of forage species. Likewise, organic matter, total nitrogen, and carbon show perfect correlations ($r = 1.000$), reflecting their close interdependence as indicators of soil quality. On the other hand, phosphorus is positively correlated with iron and manganese, while sulfur is positively correlated with calcium and magnesium, demonstrating the interaction between macronutrients in overall soil fertility. Calcium and magnesium, with a high correlation ($r = 0.780$; $p < 0.01$), show joint behavior, while potassium is moderately associated with both cations, suggesting that its availability depends on an adequate cationic balance. As for micronutrients, copper showed positive correlations with calcium and sulfur, while zinc showed a direct relationship with aluminum, which could limit its availability in acidic soils.

Table 4. *Spearman's correlation between soil chemistry variables for livestock use*

	pH	EC	OM	TN	P	S	Ca	Mg	K	Al	Fe	Mn	Cu	Zn		B	OC
pH	Correlation coefficient	1.000	-0.219**	-0.191**	-0.189**	0.032	0.586**	0.652**	-0.973**	-0.106	-0.973**	-0.106	-0.192**	0.382**	-0.409**	0.071	-0.191**
	Sig. (bilateral)	.	0.001	0.003	0.004	0.627	0.000	0.000	0.000	0.105	0.000	0.105	0.003	0.000	0.000	0.282	0.003
EC	Correlation coefficient	-0.219**	1.000	0.076	0.075	0.263**	0.034	0.061	0.200**	0.298**	0.200**	0.298**	0.174**	0.137*	0.190**	0.099	0.076
	Sig. (bilateral)	0.001	.	0.246	0.253	0.000	0.602	0.350	0.002	0.000	0.002	0.000	0.008	0.036	0.004	0.130	0.247
OM	Correlation coefficient	-0.191**	0.076	1.000	1.000**	0.032	-0.302**	-0.319**	0.352**	-0.140	0.177**	0.114	-0.013	-0.173**	0.092	0.053	1.000**
	Sig. (bilateral)	0.003	0.246	.	0.000	0.313	0.000	0.000	0.000	0.016	0.003	0.041	0.421	0.004	0.080	0.212	0.000
TN	Correlation coefficient	-0.189**	0.075	1.000**	1.000	0.031	-0.301**	-0.318**	0.176**	0.115	0.176**	0.115	-0.013	-0.172**	0.092	0.052	1.000**
	Sig. (bilateral)	0.004	0.253	0.000	.	0.636	0.000	0.000	0.007	0.080	0.007	0.080	0.841	0.008	0.160	0.425	0.000
P	Correlation coefficient	0.032	0.263**	0.032	0.031	1.000	-0.156*	-0.025	-0.022	0.337**	-0.022	0.337**	0.339**	0.113	0.124	0.105	0.032
	Sig. (bilateral)	0.627	0.000	0.628	0.636	.	0.017	0.706	0.738	0.000	0.738	0.000	0.000	0.086	0.059	0.108	0.622
S	Correlation coefficient	0.586**	0.034	-0.302**	-0.301**	-0.156*	1.000	0.607**	-0.588**	-0.073	-0.588**	-0.073	-0.147*	0.449**	-0.347**	-0.041	-0.301**
	Sig. (bilateral)	0.000	0.602	0.000	0.000	0.017	.	0.000	0.000	0.264	0.000	0.264	0.024	0.000	0.000	0.534	0.000
Ca	Correlation coefficient	0.652**	0.061	-0.319**	-0.318**	-0.025	0.607**	1.000	-0.644**	-0.103	-0.644**	-0.103	-0.082	0.391**	-0.273**	0.158*	-0.318**
	Sig. (bilateral)	0.000	0.350	0.000	0.000	0.706	0.000	.	0.000	0.116	0.000	0.116	0.214	0.000	0.000	0.016	0.000
Mg	Correlation coefficient	0.526**	0.064	-0.352**	-0.352**	-0.096	0.563**	0.780**	-0.530**	-0.057	-0.530**	-0.057	-0.022	0.387**	-0.209**	0.204**	-0.352**
	Sig. (bilateral)	0.000	0.333	0.000	0.000	0.144	0.000	0.000	0.000	0.385	0.000	0.385	0.741	0.000	0.001	0.000	0.000
K	Correlation coefficient	0.181**	0.233**	-0.139*	-0.139*	0.039	0.296**	0.408**	-0.178**	0.216**	-0.178**	0.216**	0.176**	0.267**	0.209**	0.158*	-0.140*
	Sig. (bilateral)	0.006	0.000	0.033	0.034	0.558	0.000	0.000	0.006	0.001	0.006	0.001	0.007	0.000	0.001	0.016	0.032
Al	Correlation coefficient	-0.973**	0.200**	0.177**	0.176**	-0.022	-0.588**	-0.644**	1.000	0.111	1.000	0.111	0.168*	-0.384**	0.405**	-0.075	0.178**
	Sig. (bilateral)	0.000	0.002	0.007	0.007	0.738	0.000	0.000	.	0.089	.	0.089	0.010	0.000	0.000	0.255	0.006
Fe	Correlation coefficient	-0.106	0.298**	0.114	0.115	0.337**	-0.073	-0.103	0.111	1.000	0.111	1.000	0.548**	0.238**	0.339**	0.147*	0.114
	Sig. (bilateral)	0.105	0.000	0.081	0.080	0.000	0.264	0.116	0.089	.	0.089	.	0.000	0.000	0.000	0.025	0.082
Mn	Correlation coefficient	-0.192**	0.174**	-0.013	-0.013	0.339**	-0.147*	-0.082	0.168*	0.548**	0.168*	0.548**	1.000	0.206**	0.412**	0.247**	-0.014
	Sig. (bilateral)	0.003	0.008	0.840	0.841	0.000	0.024	0.214	0.010	0.000	0.010	0.000	.	0.001	0.000	0.000	0.830
Cu	Correlation coefficient	0.382**	0.137*	-0.173**	-0.172**	0.113	0.449**	0.391**	-0.384**	0.238**	-0.384**	0.238**	0.206**	1.000	-0.039	0.204**	-0.173**
	Sig. (bilateral)	0.000	0.036	0.008	0.008	0.086	0.000	0.000	0.000	0.000	0.000	0.000	0.001	.	0.554	0.002	0.008
Zn	Correlation coefficient	-0.409**	0.190**	0.092	0.092	0.124	-0.347**	-0.273**	0.405**	0.339**	0.405**	0.339**	0.412**	-0.039	1.000	0.119	0.092
	Sig. (bilateral)	0.000	0.004	0.160	0.160	0.059	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.554	.	0.069	0.161
B	Correlation coefficient	0.071	0.099	0.053	0.052	0.105	-0.041	0.158*	-0.075	0.147*	-0.075	0.147*	0.247**	0.204**	0.119	1.000	0.052
	Sig. (bilateral)	0.282	0.130	0.423	0.425	0.108	0.534	0.016	0.255	0.025	0.255	0.025	0.000	0.002	0.069	.	0.425
OC	Correlation coefficient	-0.191**	0.076	1.000**	1.000**	0.032	-0.301**	-0.318**	0.178**	0.114	0.178**	0.114	-0.014	-0.173**	0.092	0.052	1.000
	Sig. (bilateral)	0.003	0.247	0.000	0.000	0.622	0.000	0.000	0.006	0.082	0.006	0.082	0.830	0.008	0.161	0.425	.

Note. EC: electrical conductivity; OM: organic matter; TN: total nitrogen; P: phosphorus; S: sulfur; Ca: calcium; Mg: magnesium; k: potassium; Al: aluminum; Fe: iron; Mn: manganese; Cu: copper; Zn: zinc; B: boron; OC: organic carbon

DISCUSSION

The evaluated soils are used for producing forages for cattle feeding; therefore, chemical fertility parameters are determinants of pasture productivity and the nutritional quality of the feed offered to cattle (Leyva *et al*., 2018). The observed acidic pH, particularly in Orito, is characteristic of highly weathered humid tropical soils, where Oxisols and Ultisols predominate, with low base saturation and high exchangeable aluminum. This condition restricts the development of many forage species, particularly grasses, by interfering with the absorption of nutrients such as phosphorus, calcium, and magnesium. In addition, the high concentration of exchangeable aluminum in Orito (1.05 cmolc/kg) can be toxic to roots, reducing the depth and efficiency of the root system (Rosas Patiño *et al*., 2025). This limits the ability of plants to explore the soil profile and compromises drought tolerance and biomass production. Livestock production generates conditions that favor soil acidification, especially when there is overgrazing and high animal stocking (Niu *et al*., 2025). The decomposition of excreta (ammonium-rich urine) and the leaching of basic cations promote a decrease in pH. In tropical livestock soils such as those of Putumayo, this leads to increased solubility of aluminum, which can reach concentrations toxic to roots (Orsag, 2010). This is the case in Orito, where a very low pH (4.20) and the highest value of exchangeable aluminum (1.05 cmolc/kg) were recorded, negatively affecting the root development of forage plants. In contrast, the other municipalities, with slightly higher pH, show lower levels of aluminum, which represents less restrictive conditions for pasture establishment (Rofner *et al*., 2025). Similar results were reported by Herrera *et al*. (2023) in the northern subregion of Antioquia (Colombia) on pastures with pH values ranging from 5.0 to 6.0.

The behavior of organic matter, total nitrogen, and carbon may be linked to the accumulation of organic residues or to differences in grazing management (Izquierdo & Arévalo, 2021). Organic matter (OM), total nitrogen (N), and organic carbon (OC) are key indicators of soil quality and its capacity to sustain productive systems. In poorly managed livestock systems, compaction and overgrazing limit root growth and reduce the return of plant residues to the soil, thereby decreasing OM and OC content (Santander Quiñones *et al*., 2021). Villagarzón and Puerto Asís show low OC levels (about 2.3%), which can affect moisture and nutrient retention and soil biological activity (Sánchez-Gómez *et al*., 2025). These OC levels are lower than those suggested by Montaño *et al*. (2018), who stated that the appropriate level for this parameter should be 5%. These values reflect a progressive deterioration of soil under intensive grazing conditions without biomass replenishment. Several studies in tropical livestock systems have shown that grassland degradation reduces the return of biomass to the soil and accelerates the mineralization of organic matter, leading to significant carbon losses and a decline in soil fertility (Conant *et al*., 2017). The close correlation observed among organic matter, nitrogen, and carbon is consistent with their common origin in the soil organic fraction and their participation in interdependent biogeochemical cycles.

The low availability of phosphorus in Orito (3.36 mg/kg) and Puerto Asís (5.22 mg/kg) represents a critical limiting factor for forage production, since this nutrient is essential for root development and the formation of reproductive structures (Apráez & Achicanoy, 2015). These say values are lower than those reported by Gueçaimburu *et al*. (2019), who found an average of 9.14 mg/kg in the Pampas region of Argentina; they also argue that levels of this element decrease with soil compaction, a phenomenon caused by extensive grazing. Potassium deficiency in Orito and Valle del Guamuez can also affect disease resistance and water use efficiency. In contrast, Villagarzón shows higher levels of calcium, magnesium, and potassium, nutrients that favor a higher foliar growth rate and better forage quality (Ferro *et al*., 2020).

Macronutrients are fundamental to forage growth and the nutritional value of cattle feed (Amangandi Sinchipa *et al*., 2023a). Phosphorus (P), essential for root development, showed very low values in Orito (3.36 mg/kg) and higher values in Valle del Guamuez (9.60 mg/kg). This difference may be due to both acidic conditions and management practices. Slightly higher levels were reported by Giannini *et al*. (2022), with an average of 12.5 mg/kg in the Arroyo Pergamino watershed region of Argentina.

Sulfur (S), important for protein synthesis, showed no significant differences, although its extremely high value in Valle del Guamuez (29.90 mg/kg) may indicate a particular condition. These values fall within the range reported by Lisowska *et al*. (2022), which spans 2 to 29 mg/kg. The researchers used fertilizers based on residual elemental sulfur and organic materials. Calcium (Ca) and magnesium (Mg) values were lower in Orito, affecting plant cell structure and forage quality (Amangandi Sinchipa *et al*., 2023b). Potassium (K), necessary for water use efficiency and stress resistance, was also low in Orito (0.16 cmolc/kg) and higher in Villagarzón (0.48 cmolc/kg), indicating better fertility conditions in the latter. However, these values are below the average of 1.26 mmol/kg reported by Orcellet *et al*. (2025) in the Pampas and Mesopotamia regions of Argentina.

The relative copper deficiency in Orito may reduce the digestibility and nutritional value of the forage, as copper participates in enzymatic processes and protein synthesis (Gómez *et al.*, 2019). Although other micronutrients such as zinc and manganese did not show significant differences, the observed variations could influence the mineral composition of the pasture, indirectly affecting animal health and the need for supplementation (Bernal & Forero, 2014). Micronutrients, although required in smaller amounts, are vital for plant metabolic processes. In acidic or leached soils, these elements can be in unavailable forms. In this analysis, only copper (Cu) showed significant differences, with very low values in Orito (0.19 mg/kg) and higher values in Valle del Guamuez (0.53 mg/kg). These values differ from those reported in three municipalities in the Magdalena Medio region, Colombia, where the average was 5.53 mg/kg (Hernández-Arroyave & Jiménez-Arango, 2018). This may affect digestibility and enzyme synthesis in forage. Zinc (Zn) showed a similar trend, with higher values in Valle del Guamuez. Iron (Fe) and manganese (Mn), although not significantly different, also play important roles in photosynthesis and plant enzymology (Rai *et al*., 2021). Boron (B) did not show relevant differences, but its balance remains important for plant health. The variations observed in micronutrients such as copper and zinc may be related to differences in parent material, degree of weathering, and leaching processes. Although required in small amounts, these elements are essential for enzymatic, photosynthetic, and metabolic processes in plants (Alloway, 2008). In heavily leached tropical soils, micronutrient availability may be reduced or present in non-assimilable forms, which affects the nutritional quality of forage and, consequently, animal productivity.

The relationships among calcium, magnesium, and potassium are key indicators of soil chemical balance. Imbalances in these ratios can lead to antagonisms in root nutrient uptake, affecting plant growth and forage quality (Marschner, 2012). For example, a relative excess of magnesium can limit potassium uptake, while a low Ca/Mg ratio can impair soil structure and root aeration. In livestock systems with limited fertilization, these imbalances tend to become more pronounced due to the continuous removal of nutrients by pastures without adequate replenishment. The Ca/Mg and Mg/K ratios are important for avoiding antagonisms in the absorption of nutrients by the roots of forage plants (Xie et al., 2021). A relative excess of magnesium, as observed in Puerto Asís (Mg/K = 5.89), can limit potassium uptake and reduce vegetative development (Puenayan & Benavides, 2025). Likewise, unbalanced ratios, such as the very high (Ca + Mg)/K value observed in

Valle del Guamuez, can alter soil structure and reduce the efficiency of applied fertilizers. These ratios reflect the balance among essential cations in the soil and are fundamental to avoiding antagonisms in nutrient absorption (Kome *et al*., 2019). In Puerto Asís, a high Mg/K ratio (5.89) was observed, indicating possible interference with potassium absorption due to the relative excess of magnesium. In turn, Valle del Guamuez presented the highest (Ca + Mg)/K ratio (16.63), which could reflect a disproportion that affects the optimal development of pastures. These imbalances are common in livestock systems in which fertilization is not adjusted according to soil analysis and can result in forages with low nutritional efficiency. The (Ca + Mg)/K ratio observed in Valle del Guamuez was higher than that reported by Diovisalvi *et al*. (2021), who obtained an average of 8 when quantifying this relationship by evaluating different levels of soybean productivity.

Observed textural differences directly influence water and nutrient dynamics. Soils with higher sand content have lower water-holding capacity and are more susceptible to leaching, reducing their potential fertility. In contrast, soils with higher proportions of silt and clay tend to retain nutrients more effectively, although they may be more susceptible to compaction under intensive grazing (Weil & Brady, 2016). Soil texture influences water and nutrient retention, as well as root system aeration (Labrador, 2008). Orito, with sandier soils (42%), likely experiences higher nutrient leaching and lower water retention, which is unfavorable for the establishment of long-lasting pastures. On the other hand, Villagarzón and Puerto Asís, with higher proportions of silt, provide more stable conditions for forage production, although they may require adequate drainage management to avoid compaction (Hajji-Hedfi *et al*., 2025). These results differ from those reported by Rodríguez Colorado et al. (2022), who reported silt loam soil texture on 28% of livestock farms in Norte de Santander, Colombia. In livestock farming systems, constant trampling, especially on wet soils, favors compaction and reduces porosity. Overgrazing also exposes the soil to erosion, promoting the loss of fine fractions (silt and clay) and increasing the proportion of sand (López Hernández *et al*., 2020). This phenomenon is reflected in Orito, where the sandy fraction was the highest (41.97%), reducing moisture and nutrient retention capacity. In contrast, Villagarzón and Puerto Asís have higher proportions of silt (more than 32%), which can improve soil structure but also requires management to avoid waterlogging and surface compaction (Hetz *et al*., 2025).

pH shows a strong negative correlation with aluminum (r = -0.973, $p < 0.01$), indicating that as the soil becomes more acidic, the concentration of exchangeable aluminum increases, a characteristic of Amazonian soils, as reported by Rosas Patiño *et al*. (2025). This is an expected relationship in tropical soils, but in poorly managed livestock systems with high stocking rates, excess urine, and no liming, this effect is aggravated (Estupiñán *et al*., 2009). Aluminum, in high concentrations, becomes toxic to roots, preventing root development of forage species. Livestock-induced acidification can therefore reduce pasture productivity if corrective measures are not taken (Mora Marín *et al*., 2017).

Organic matter, total nitrogen, and carbon show perfect correlations with each other (r = 1.000), which is expected given that they are interrelated components of soil organic matter. They also show negative correlations with calcium (r = -0.318**), magnesium (r = -0.352**), and sulfur (r ≈ -0.301**), suggesting that soils with higher OM content may be more prone to nutrient leaching. Intensive livestock practices, by compacting the soil and reducing the return of plant residues, decrease the stable accumulation of organic matter and carbon (Medina, 2016). In addition, in areas of high manure deposition without redistribution, localized accumulations may occur, distorting the overall chemical balance of the soil (Rayne & Aula, 2020; Bienes Allas, 2005).

Phosphorus (P) shows positive correlations with iron (r = 0.337**) and manganese (r = 0.339**), suggesting that these micronutrients co-occur under similar chemical conditions. However, phosphorus shows a negative correlation with sulfur (r = -0.156*) and is not significantly associated with pH or OM, which may indicate fixation into forms unavailable in acidic soils. Sulfur shows positive correlations with calcium (r = 0.607**) and magnesium (r = 0.563**), indicating that overall soil fertility tends to be interrelated. Extensive cattle ranching without nutrient replenishment tends to reduce these essential elements through leaching or continuous extraction by forages (Nieto *et al*., 2025). Calcium and magnesium are highly correlated (r = 0.780**), suggesting a common origin or their joint presence in amendments. Loss of these elements by leaching or lack of liming practices is common in soils managed without diagnosis. Potassium (K), although more mobile, correlates moderately with calcium (r = 0.408**) and magnesium (r = 0.436**), suggesting that soils with better cation structure tend to retain more potassium. Animal trampling and overgrazing may reduce the soil's capacity to retain these cations, affecting forage productivity (Mamani Paredes *et al*., 2024).

Although not explicitly presented in the matrix, cation ratios can be inferred from the strong correlations among the individual elements. Calcium and magnesium (r = 0.780**) tend to be in equilibrium under conditions of good base fertility. While an unbalanced Mg/K ratio (such as the high Mg/K value observed in Puerto Asis) can hinder potassium uptake. These imbalances arise from inadequate use of amendments, fertilization without soil analysis, or leaching caused by grazing on light and poorly drained soils (Álvarez-Sánchez *et al*., 2014). The maintenance of cation balance is key for efficient plant nutrition and to avoid problems in forage quality (Muñoz *et al*., 2016).

CONCLUSIONS

The results suggest that Orito has the most acidic and least fertile soils from a chemical perspective, with high aluminum concentrations and low levels of calcium, magnesium, potassium, and phosphorus. Valle del Guamuez showed better chemical fertility, especially in phosphorus, copper, and carbon. Villagarzón and Puerto Asís were in intermediate positions characterized by soils with moderate acidity, average organic matter levels, and intermediate nutrient availability, with no extreme chemical limitations. These findings support the need for differentiated soil management in each municipality, considering liming practices, balanced fertilization, and organic matter conservation.

Correlations among soil parameters reveal key relationships that reflect soil fertility and the impact of livestock practices in Putumayo's productive systems. The strong negative association between pH and aluminum stands out, confirming the risk of toxicity in acidic soils. The close relationship among organic matter, nitrogen, and carbon reaffirms their link to soil quality, while correlations among cations (Ca, Mg, K) reveal imbalances that can affect nutrient uptake. Interactions between micronutrients and macronutrients also suggest that soil fertility results from multiple interdependent factors, influenced by grazing management and the absence of corrective practices. It is recommended that liming be managed and practices that increase soil organic matter be adopted to improve cation exchange capacity and fertility in livestock systems in Putumayo.

AUTHOR CONTRIBUTIONS

Conceptualization: D.F.F.D and D.R.C.L.; Methodology: D.K.F.G. and D.R.C.L.; Research: D.F.F.D. and D.K.F.G.; Validation: D.R.C.L. and D.K.F.G.; Writing: preparation of the original draft: D.F.F.D. and D.R.C.L.; Writing: review and editing: D.F.F.F. and D.K.F.G.; Funding Acquisition: D.F.F.D. and D.R.C.L.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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