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Physicochemical variability of Andisols in Colombian monogenetic volcanic fields under diverse management systems

Variabilidad físico-química de Andisoles en campos volcánicos monogenéticos colombianos bajo distintos sistemas de manejo

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ABSTRACT

Andisols are highly productive soils formed by the progressive weathering of volcanic products. Two volcanic areas of Colombia were evaluated to compare soil characteristics and the influence of volcanic products on regional soil components. Fifty-four sites were sampled in the Tapias-Guacaica (TGMVF) and Guamuez-Sibundoy (GSMVF) monogenetic volcanic fields, and different production systems were assessed using soil physicochemical parameters. The results indicate that the soils of the TGMVF have a neutral pH, good cation exchange capacity, structural stability, macroporosity, and adequate drainage of water and nutrients, with low retention capacity. In contrast, the soils of the GSMVF exhibit high levels of organic matter, carbon, nitrogen, and phosphorus, as well as microporosity, mesoporosity, and efficient mobility and fixation of water and nutrients. Based on these parameters, the analysis of variance identified two and three distinct groups for the TGMVF and GSMVF, respectively. The behavior of the physicochemical variables, mainly total porosity (Pr), bulk density (ρa), particle density (ρr), cation exchange capacity (CEC), and structural stability (SS), may be affected by external factors such as compaction and internal factors such as soil wetting and drying cycles, especially in the pasture system of both volcanic fields. In general, the physicochemical variation of the soils has been influenced by factors such as geological time, soil management, vegetation, topography, and parent material. These results establish the basis for promoting appropriate agricultural practices in the fields.

Keywords: agropastoral systems; crops; organic matter; soil quality; volcanic ash; volcanic parent material

RESUMEN

Los Andisoles son suelos altamente productivos generados a partir del intemperismo progresivo de productos volcánicos. Se evaluaron dos zonas volcánicas de Colombia para comparar las características del suelo y la influencia de los productos volcánicos en los componentes edáficos de la región. Se muestrearon 54 sitios de los campos volcánicos monogenéticos Tapias-Guacaica (TGMVF) y Guamuez-Sibundoy (GSMVF), de los cuales se tomaron distintos sistemas productivos para evaluar parámetros fisicoquímicos del suelo. Los resultados indican que los suelos del TGMVF presentan un pH neutro, buena capacidad de intercambio catiónico, estabilidad estructural, macroporosidad y drenaje adecuado de agua y nutrientes, pero dificultad en la retención. En contraste, los suelos del GSMVF exhiben niveles elevados de materia orgánica, carbono, nitrógeno, fósforo, microporosidad, mesoporosidad, y movilidad y fijación eficientes de agua y nutrientes. Con base en estos parámetros, el análisis de varianza mostró dos y tres grupos distintivos para el TGMVF y el GSMVF, respectivamente. El comportamiento de las variables fisicoquímicas, principalmente porosidad total (Pr), densidad aparente (ρa), densidad real (ρr), capacidad de intercambio catiónico (CEC) y estabilidad estructural (SS), puede verse afectado por fuerzas externas como la compactación y fuerzas internas como los ciclos de humedecimiento y secado del suelo, especialmente en el sistema de potrero de ambos campos volcánicos. En general, la variación fisicoquímica de los suelos ha sido influenciada por factores como el tiempo geológico, el manejo del suelo, la vegetación, la topografía y el material parental. Estos resultados establecen la base para promover prácticas agrícolas adecuadas en los campos.

Palabras clave: calidad de suelos; cenizas volcánicas; cultivos; materia orgánica; material parental volcánico; sistemas agropastorales

INTRODUCTION

Soils formed from the progressive weathering of volcanoclastic deposits and lava flows from volcanic eruptions have been classified as Andisols (Dahlgren *et al*., 2004; Soil Survey Staff, 1999; Wilson *et al*., 2017). These soils have physical and chemical characteristics rarely found in soils derived from other materials (Delmelle *et al*., 2015; Nanzyo, 2002). These soils are characterized by several distinct properties. Their bulk density tends to be less than 0.8 $g.cm^{-3,}$ while their permeability and porosity tend to be high (greater than 1.3 × 10-5 cm/s and 60 vol %, respectively). These characteristics are related to the presence of allophane minerals, which contribute to the development of porous soil structures, thereby favoring water movement. Likewise, volcanic soils exhibit high organic matter content, high water-holding capacity, and high total porosity (Anggriawan *et al*., 2023). The soils also exhibit a characteristic stable microaggregate assembly structure, characterized by elevated water and nutrient fixation capacity due to the presence of organic material and colloidal fracturing dominated by alumina-humus or allophane/imogolite complexes (Echeverri Tafur *et al*., 2014).

Additionally, they have a high cation and anion exchange capacity, elevated phosphorus retention, and significant aluminum and iron contents. In southern Colombia, particularly in Cauca and Nariño, and in some Melanudands of the Gran Caldas region, mean pH values of 4.3 in epipedons and 5.3 in endopedons have been reported (Instituto Geográfico Agustín Codazzi, 2015). As a result of the characteristics described above, Andisols contribute significantly to agricultural and forestry production (Lobos Ortega *et al*., 2021; Takahashi & Dahlgren, 2016; Valle & Carrasco, 2018).

The Andes are home to a great diversity of soils (Kristensen & Lützen, 2013); the factors that influence their formation are climate, geology, and topography (Sánchez & Rubiano, 2015). In general, the soils of the Andes are classified into four groups: Andisols, Inceptisols, Ultisols, and Oxisols (Buol *et al*., 2011). Of these soils, Andisols cover around 4.5% of the surface area (approximately 5.2 million hectares) of the mountain range (Sánchez & Rubiano, 2015). In Colombia, located in the northern Andes, Andisols are distributed across mountainous landscapes, foothills, alluvial plains, and occasionally fluviomarine areas (Avila Pedraza, 2025).

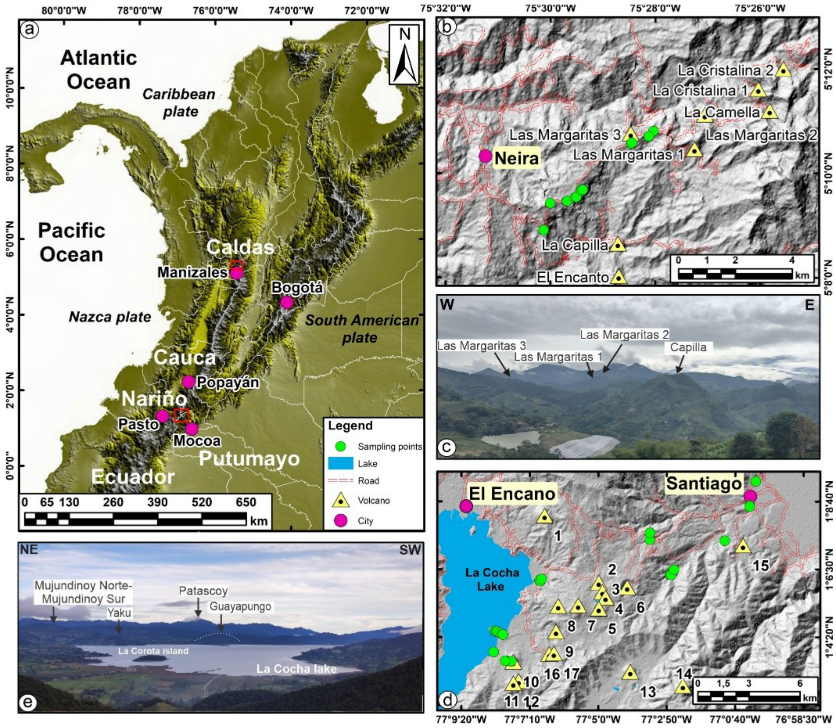
However, the intensive management of these soils has resulted in the degradation of their physical and chemical properties, which has generated negative impacts that significantly reduce their quality and productive capacity (Delmelle *et al*., 2015; Jaurixje *et al*., 2013; Takahashi & Shoji, 2001; *Torres et al*., 2006).

Based on the above, the purpose of this study was to evaluate the physicochemical variability of Andisol soils in the Tapias-Guacaica (TGMVF) and Guamuez-Sibundoy (GSMVF) monogenetic volcanic fields under different management systems, in order to understand the anthropogenic impact on land use.

MATERIALS AND METHODS

Location

In this study, Andisol soils were sampled from the center and southwest regions of the Central Cordillera of the Colombian Andes (Figure 1a) (Instituto Geográfico Agustín Codazzi, 2015; IUSS Working Group WRB, 2006; Jaurixje *et al*., 2013). Specifically, the Andisols analyzed in this work are associated with two volcanic zones of the country: the Tapias-Guacaica Monogenetic Volcanic Field (TGMVF; Vargas-Arcila *et al*., 2023) and the Guamuez-Sibundoy Monogenetic Volcanic Field (GSMVF) (CVMGS; Murillo-Orobio *et al*., 2024).



Note. (a) Northern continental margin of the Andes mountain range; (b) Illustration of the Tapias-Guacaica Monogenetic Volcanic Field; (c) Panoramic photograph of the Tapias-Guacaica Monogenetic Volcanic Field; (d) Illustration of the Guamuez-Sibundoy Monogenetic Volcanic Field; and (e) Panoramic photograph of the Guamuez-Sibundoy Monogenetic Volcanic Field.

Figure 1. *Location map of the study areas.*

The TGMVF is located between the city of Manizales and the town of Neira, in the department of Caldas (Figure 1b and c). The climate is characterized by temperatures ranging from 17 to 22 °C, precipitation ranging from 2000 tp 2200 mm/year, relative humidity ranging from 75 to 90%, and an average altitude ranging from 1000 to 4200 m a.s.l. (Arias-Díaz *et al*., 2023). On the other hand, the GSMVF is located in the Upper Amazon Basin, between Lake La Cocha in the department of Nariño and the Sibundoy Valley in the department of Putumayo (towns of Santiago, Colón, Sibundoy, and San Francisco) (Figure 1d and e). The climate is characterized by an average temperature of 11.6 °C, annual precipitation between 1562 and 1852 mm/year, relative humidity between 83 and 87%, and an average altitude between 2000 and 3400 m a.s.l. (Mendoza Sabogal *et al*., 2014).

This study describes the physical and chemical properties of Andisols in two different regions of Colombia, where volcanic products have influenced the soils for thousands of years. Furthermore, it discusses the impact of major components on nutrient distribution. This study provides information that could enable communities located in the vicinity of the study areas to make well-informed decisions about appropriate conservation practices for this natural resource.

Materials

Physicochemical properties of Andisol soils

Physicochemical properties were evaluated in a total of 54 sampled lots (Table 1). Of these, 20 were collected in the TGMVF and 34 in the GSMVF. The samples were collected from a variety of habitats, including secondary forests, pine plantations (*Pinus sylvestris*), Andean blackberry crops (*Rubus glaucus*), and paddocks.

Table 1. *Physicochemical properties evaluated and method of determination*

Physicochemical variables	Method of determination	Unit
Bulk density (ρa)	Cylinder of known volume	$g.cm^{-3}$
True density (ρr)	Pycnometer	$g.cm^{-3}$
Total porosity (Pr)	$1-(\frac{\rho a}{\rho r})*100$	%
Gravimetric humidity (GH)	105 °C stove	%
Volumetric humidity (VH)	$(\frac{\rho a}{\rho ag})*GH$	%
Hydraulic conductivity (CH)	Constant head permeameter	cm/hour
Structural stability (SS)	dry sieving	DPM-mm
Microporosity (MiPr)	$MiPr = GH * \left(\frac{4D^2H}{\pi*100}\right); MiPr = \left(\frac{MiPr}{50}\right) Pr$ MiPr = Microporosity (%) *GH* = Gravimetric humidity (%) *D* = ring diameter (cm) *H* = ring height (cm) π = 3.1416	%
Macroporosity (MaPr)	$MaPr = Pr - MiPr; MaPr = \left(\frac{MaPr}{50}\right) Pr$	%
Mesoporosity (MePr)	$MePr = Pr - MaPr\ ; MaPr = \left(\frac{MePr}{50}\right) Pr$	%
Color in wet soil	Munsell Table	-
Texture	To the touch	-
pH	Active acidity/pH in soils GA-R-46, version 06, 2021-10-25.	Units of pH
Electrical conductivity (EC)	NTC 5596:2008 Method B.	dS/m
Organic Carbon (C)	Determination of organic carbon in soil GA-R-119 version 4, 2021-10-25.	g/100g
Organic Matter (OM)	Calculation according to NTC 5403 Walkey & Black.	g/100g
Total nitrogen (TN)	$N_{total} = \frac{OM*5}{100}$ Calculation	%
Disposable nitrogen (DN)	$N_{Disposable} = \frac{N_{total}*2}{100}$ N Calculation	%
Disposable phosphorus (P)	Available phosphorus in soils GA-R-48, 07, 2021-10-25 version.	mg/kg
Disposable sulfur (S)	Calcium monobasic phosphate	mg/kg
Cation Exchange Capacity (CEC)	$Ca^{2+} + Mg^{2+} + K^{+} + Al^{3+}$ Calculation	cmol(+)/kg
Disposable boron (B)	Calcium monobasic phosphate	mg/kg
Acidity (Al+H; A)	KCl	cmol(+)/kg
Interchangeable aluminum (Al)	KCl	cmol(+)/kg
Disposable calcium (Ca)	Interchangeable bases on GA-R-50 version 9, 2021-10-25 floors.	cmol(+)/kg
Disposable magnesium (Mg)	Interchangeable bases on GA-R-50 version 9, 2021-10-25 floors.	cmol(+)/kg
Disposable potassium (K)	Interchangeable bases on GA-R -50 version 9, 2021-10-25 floors.	cmol(+)/kg
Disposable Olsen iron (Fe)	NTC 5526:2007 Method D.	mg/kg
Disposable Olsen copper (Cu)	NTC 5526:2007 Method D.	mg/kg
Disposable Olsen manganese (Mn)	NTC 5526:2007 Method D.	mg/kg
Disposable Olsen zinc (Zn)	NTC 5526:2007 Method D.	mg/kg
Ca-Mg ratio	Ca/Mg Calculation	-
Mg-K ratio	Mg/K Calculation	-
K-Mg ratio	K/Mg Calculation	-
Ca-K ratio	Ca/ K Calculation	-
Ratio (Ca+Mg)/K	(Ca+Mg)/K Calculation	-

Physical properties of Andisol soils

For the sampling process, a soil pit with dimensions of 30 × 30 × 40 cm was created. Furthermore, two beveled rings of known volume (4.8 cm in diameter, 2.5 cm in height, and 2 mm in thickness) were used to collect samples at depths of 0-20 and 20-40 cm. These samples were taken to determine bulk density (ρa), hydraulic conductivity (HC), gravimetric moisture (GM), and volumetric moisture (VM). At these same depths, one 500 g sample was taken to determine the particle density (ρr), structural stability, pore distribution, texture, and soil color. Additionally, 1 kg of soil was collected to determine structural stability (SS).

Chemical properties of Andisol soils

Ten sampling points were established for each of the 54 lots evaluated. These ten points were randomly distributed to cover the largest possible area. Soil samples were then collected from each of these points in a "V" shape to cover the majority of the soil profile. The 10 sampled portions were mixed, and a representative 1 kg sample was collected. These representative samples were labeled and sent to the soil laboratory of the Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA), where the chemical variables of the evaluated soils were determined.

Statistical analysis

A general linear mixed model (MLGyM) was fitted to analyze the field variables, with the fixed factors comprising a volcanic field of origin (locality), system, and their interaction. The residual variance was modeled to include different variances according to the heteroscedasticity observed in the fixed effects, while the residual correlation for successive observations from a monogenetic volcanic field or the same system was modeled using a compound symmetry model. The Akaike (AIC) and Bayesian (BIC) criteria were used to select the variance and residual correlation structures. The mixed model fitting was performed using the lme function of the nlme package of R, through the interface implemented in InfoStat (Di Rienzo *et al*., 2020).

The analysis of the interactions was conducted through a comparison of means for the combinations of the levels of all evaluated factors, using the Di Rienzo, Guzmán, and Casanoves DGC methodology (Di Rienzo *et al*., 2020), at a significance level of 5%. Similarly, a cluster analysis was performed using Ward's method and Euclidean distance to examine the relationships between the groups of variables evaluated in relation to the production systems under study. All these statistical analyses were performed using InfoStat, version 2019 (Di Rienzo *et al*., 2020).

Principal Component Analysis (PCA) was used to investigate the correlation between the soil physicochemical variables and the production systems in the two study areas. The analysis was performed using the "FactoMineR" package (Husson *et al*., 2020) and the "factoextra" package (Kassambara, 2017). In addition, the Monte Carlo test with all permutations was employed to evaluate the overall effect of sampling sites on the analyzed physicochemical variables using the "Ade4" package (Dray & Dufour, 2007). All analyses were performed using R version 4.2.0 (R Core Team, 2024) and RStudio version 1.3.1 (Posit Team, 2024).

RESULTS

Physicochemical properties of Andisol soils

Highly significant variations were observed in the different physicochemical variables of Andisol soils in the two monogenetic volcanic fields (Table 2). Additionally, considerable differences were observed in the interactions for more than 20% of the variables evaluated. In 56% of the cases, there was a very significant effect of the field of origin of the samples (location), while in 44% of the cases, there were differences related to the evaluated management systems.

Table 2. *Analysis of variance of fixed effects related to the physicochemical properties of soils from the Tapias-Guacaica and Guamuez-Sibundoy Monogenetic Volcanic Fields and five management systems in central and southwestern Colombia.*

Variable	L	S	Lx S
ρa	<0.0001***	0.5432ns	0.0785*
ρr	0.0001***	0.9360ns	0.9954ns
Pr	0.0002***	0.2720ns	0.0425*
MiPr	0.6703ns	0.0484*	0.0051*
MaPr	0.6703ns	0.0484*	0.0051*
MePr	0.6703ns	0.0484*	0.0051*
SS	0.4251ns	0.6782ns	0.0080*
GH	<0.0001***	0.0287*	0.0688*
VH	<0.0001***	0.1011ns	0.1245ns
HC	0.0679*	0.4410ns	0.2463ns
pH	<0.0001***	0.494ns	0.6947ns
EC	0.2214ns	0.0059*	0.2553ns
C	0.0004***	0.1034ns	0.9646ns
OM	0.0004***	0.1034ns	0.9786ns
TN	0.0004***	01034ns	0.9786ns
DN	0.0004***	0.1034ns	0.9786ns
P	0.7391ns	<0.0001***	0.7999ns
S	0.772ns	0.5979ns	0.9849ns
CEC	<0.0001***	0.41ns	0.7612ns
B	0.2461ns	0.1797ns	0.5336ns
A	0.002***	0.4534ns	0.9265ns
Al	0.5034ns	0.5034ns	0.6616ns
Ca	<0.0001***	0.542ns	0.677ns
Mg	0.8157ns	0.0251*	0.158ns
K	0.4507ns	0.0186*	0.9115ns
Fe	0.0003***	0.0214*	0.1051ns
Cu	0.0008***	0.0003***	0.1241ns
Mn	0.0011***	0.0479*	0.1254ns
Zn	0.4529ns	0.0001***	0.8184ns
Ca-Mg	<0.0001***	0.8178ns	0.4424ns
Mg-K	0.3275ns	0.0335*	0.1079ns
K-Mg	0.2686ns	0.0004***	0.187ns
Ca-K	0.3639ns	<0.0001***	0.5845ns
(Ca+Mg)/K	<0.0001***	0.3223ns	0.5411ns

Note. $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). Not significant (ns): Location (L), representing the values of each field as a whole. System (S) and their interaction (LxS).

Regarding the mean values of the physical variables (Table 3), no significant differences were observed among the evaluated systems of the TGMVF. In contrast, in the GSMVF, the MiPr, MaPr, and MePr variables showed significant differences in the secondary forest system, constituting 30% of the physical variables, while the GH variable showed significant differences in the pasture system, representing 10% (Table 3). However, the average values of the physical variables indicate that in the TGMVF, the pasture system exhibits the highest mean values for ρa, MiPr, MePr, and HC, while the secondary forest system presents the highest values for Pr and SS. Conversely, the pine crop exhibits the highest mean values for ρr, GH, and VH. In the GSMVF, the pasture system had the highest mean values for Pr, SS, GH, and VH, whereas the secondary forest showed significant results in MiPr, MePr, and HC. The pasture system had the highest values for ρr and MaPr, whereas the blackberry crops had the highest values for ρa and SS (Table 3).

Similarly, significant variations were observed in the chemical variables of the monogenetic volcanic field systems, particularly in electrical conductivity (EC). In the TGMVF, the pine plantation exhibited a significantly lower EC (0.44 ± 0.07) than the secondary forest and pasture systems. Furthermore, in the GSMVF system, the cutting pasture showed a significantly higher EC value (1.98 ± 0.99) than the other land uses evaluated.

The pine plantation system in the TGMVF exhibited high significance in EC, while the other systems and chemical variables evaluated were not significant (Table 3). For the GSMVF, the secondary forest, paddock, and blackberry crop systems showed significant differences in approximately 41.6% of the variables evaluated, including EC, P, CEC, Ca, Mg, Fe, Cu, Zn, and the Ca:Mg and K:Mg ratios (Table 3). It is important to note that, for Mg, the secondary forest and cutting pasture systems showed significant differences compared with the paddock and blackberry cultivation systems, although they did not show significant differences between them. Likewise, for Fe, the paddock and cutting pasture systems were significantly different from the secondary forest and blackberry cultivation treatments but did not show significant differences from each other. Regarding the physical variables, no significant differences were observed in the TGMVF, whereas in the GSMVF, the secondary forest and paddock systems showed significant differences of 40% in the variables MiPr, MaPr, MePr, and GH. The physical property of MaPr showed a significant difference in the cutting pasture, paddock, and blackberry cultivation systems compared to the secondary forest system, but no significant differences were observed among the first three systems mentioned.

The highest mean values of the chemical variables in the soils evaluated in the TGMVF were found in the paddock system, with higher values for C, OM, TN, DN, P, B, A, Al, Zn, and the Ca:K and (Ca+Mg)/K ratios (Table 3). In the secondary forest system, pH, EC, S, CEC, Ca, K, and the Ca:Mg and K:Mg ratios had higher values, while the pine plantation had higher values for Fe, Cu, Mn, and the Mg:K ratio. In the TGMVF, the pine plantation had the lowest pH value, followed by the paddock systems. On the other hand, in the GSMVF, the highest mean values were found in the cutting pasture system for variables such as pH, EC, C, OM, TN, DN, P, S, CEC, Ca, Mg, K, Fe, Cu, Zn, and the Ca:Mn, Ca:K, and (Ca+Mg)/K ratios. However, the secondary forest system exhibited higher values for B, Mn, and the Mg:K ratio. In addition, the paddock system had the highest Al content. Similarly, the blackberry crops had the highest value for the K:Mg ratio. Finally, in the GSMVF, the systems with the lowest pH values, and therefore the most acidic, were the paddock system, followed by the blackberry crops (Table 3).

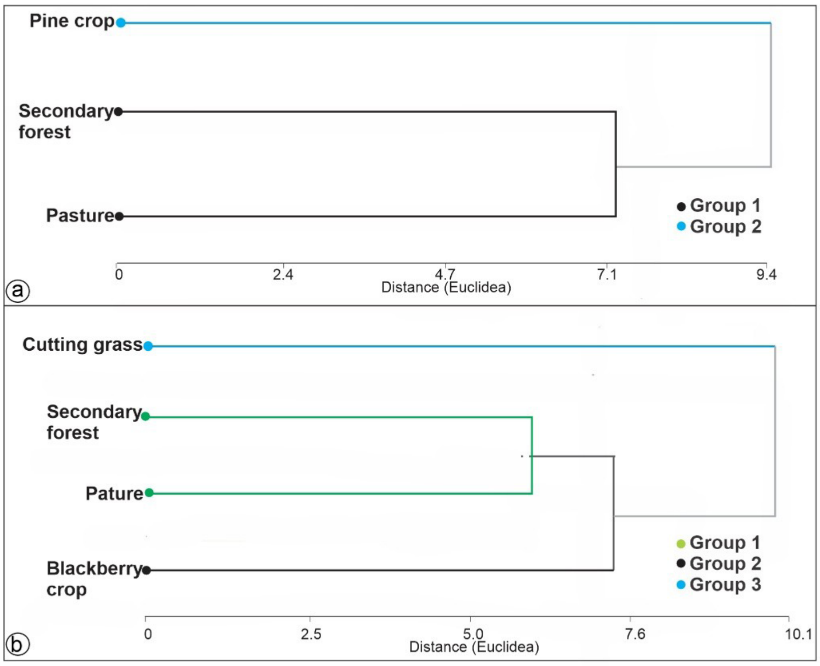
Table 3. *Mean values ± standard deviation for the physical and chemical properties of Andisol soils studied in the Tapias-Guacaica and Guamuez-Sibundoy Monogenetic Volcanic Fields according to their significance for each management system evaluated.*

Variable	TGMVF			GSMVF			
	Secondary forest	Pine plantation	Pasture	Secondary forest	Paddock	Cutting pasture	Andean Blackberry plantation
ρa	0.79±0.10	0.87±0.09	0.89±0.07	0.57±0.07	0.38±0.07	0.42±0.12	0.60±0.12
ρr	2.29±0.16	2.37±0.15	2.24±0.12	1.87±0.11	1.82±0.11	1.93±0.19	1.81±0.19
Pr	65.47±3.20	63.13±2.92	60.67±2.39	69.67±3.02	78.67±3.02	78.13±5.45	66.20±5.45
MiPr	17.94±0.64	18.80±0.59	19.93±0.48	20.25±0.58b	18.48±0.58a	18.10±1.05a	16.39±1.05a
MaPr	14.13±1.28	12.39±1.17	10.14±7.03	9.50±1.16a	13.04±1.16b	13.81±2.09b	17.21±2.09b
MePr	17.94±0.64	18.80±0.59	19.93±0.48	20.25±0.28b	18.480±0.58a	18.10±1.05a	16.39±1.05a
SS	1.94±0.69	1.47±0.63	0.31±0.51	0.66±0.19	1.07±0.19	0.45±0.35	0.90±0.35
GH	81.72±21.63	89.20±19.75	82.16±16.12	185.84±41.04a	340.90±41.04b	233.50±73.99a	120.57±73.99a
VH	62.46±7.03	70.07±6.42	60.72±5.24	81.06±5.58	99.22±5.58	94.54±10.07	72.44±10.07
HC	0.07±0.12	0.22±0.11	0.26±0.09	0.39±0.07	0.37±0.07	0.32±0.13	0.12±0.13
pH	7.24±0.47	5.80±0.43	6.88±0.35	5.22±0.19	5.08±0.19	5.26±0.33	5.17±0.33
EC	0.72±0.08b	0.44±0.07a	0.65±0.06b	0.68±0.22a	1.11±0.22a	1.98±0.99b	0.76±0.39a
C	4.04±0.31	3.70±0.29	4.34±0.23	9.48±1.46	9.64±1.46	11.20±2.63	7.30±2.63
OM	6.97±0.55	6.38±0.50	7.41±0.41	16.32±2.51	16.63±2.51	19.31±4.53	12.31±4.53
TN	0.35±0.03	0.32±0.02	0.37±0.02	0.82±0.13	0.83±0.13	0.97±0.23	0.62±0.23
DN	7.0E-04±5.5E-05	6.4E-04±5.0E-05	7.4E-04±4.1E-05	1.6E-03±2.5E-04	1.7E-03±2.5E-04	1.9E-03±4.5E-04	1.2E-03±4.5E-04
P	10.67±3.18	14.95±2.90	16.17±2.37	13.37±4.09a	16.70±4.09a	71.10±7.38b	24.92±7.38a
S	13.34±1.27	10.03±1.16	12.97±0.94	12.40±3.56	11.90±3.56	20.45±6.42	10.75±6.42
CEC	32.42±7.92	10.26±7.23	27.46±5.91	8.97±1.58a	6.43±1.58a	18.19±2.86b	4.94±2.86a
B	0.18±0.02	0.15±0.03	0.22±0.03	0.35±0.07	0.23±0.07	0.25±0.13	0.07±0.13
A	0.00±0.04	0.00±0.04	0.07±0.03	2.25±0.74	2.46±0.74	2.42±1.33	1.43±1.33
Al	0.00±0.03	0.00±0.03	0.05±0.02	1.44±0.58	1.99±0.58	1.84±1.05	1.05±1.05
Ca	30.86±7.88	8.96±7.20	25.84±5.88	4.41±1.41a	2.64±1.41a	13.68±2.54b	2.18±2.54a
Mg	1.07±0.17	1.00±0.16	1.12±0.13	1.44±0.18b	0.94±0.18a	1.57±0.32b	0.43±0.32a
K	0.44±0.06	0.24±0.06	0.35±0.05	0.49±0.07	0.42±0.07	0.73±0.13	0.33±0.13
Fe	118.06±36.69	186.21±33.50	124.22±27.35	248.33±70.67a	490.54±70.67b	568.37±127.41b	220.93±127.41a
Cu	1.77±0.37	2.14±0.34	1.56±0.28	2.53±0.43a	3.74±0.43a	5.89±0.77b	3.45±0.77a
Mn	1.94±0.54	3.39±0.50	1.96±0.41	26.69±4.77	12.06±4.77	9.93±8.60	8.26±8.60
Zn	3.78±1.01	4.22±0.92	4.88±0.75	5.10±1.24a	5.61±1.24a	15.74±2.24b	4.73±2.24a
Ca-Mg	29.07±7.74	9.32±7.06	23.71±5.77	3.02±0.60a	3.23±0.60a	7.67±1.09b	5.25±1.09a
Mg-K	2.79±0.70	4.24±0.64	3.57±0.52	3.26±0.36	2.47±0.36	2.35±0.65	1.34±0.65
K-Mg	0.41±0.06	0.26±0.05	0.34±0.04	0.38±0.06a	0.48±0.06a	0.52±0.10a	0.81±0.10b
Ca-K	66.82±21.27	41.63±19.42	74.82±15.86	10.91±2.93	7.72±2.93	21.62±5.28	7.45±5.28
(Ca+Mg)/K	69.61±21.55	45.87±19.67	78.39±16.06	14.17±3.19	10.19±3.19	23.97±5.76	8.79±5.76

Note. Means within each column sharing the same letter are not significantly different according to the DGC test ($p < 0.05$), whereas means without a letter indicate no significant differences.

Relationship between soil characteristic variables and soil covers

The CA was carried out using Ward's method and Euclidean distance for the physicochemical variables of the evaluated soils. The results showed the formation of two groups in the TGMVF and three groups in the GSMVF. The first group in the TGMVF was represented by the secondary forest and paddock production systems, which presented the best soil quality values for the evaluated variables. The second group, which corresponds to the pine plantation production system, presented lower quality in terms of the composition of the soil physicochemical properties (Figure 2a). The first group in the GSMVF was represented by the blackberry crop system, followed by the second group corresponding to the secondary forest and paddock production systems, which presented the best quality values for the evaluated variables. The third group was the cut paddock system, which presented the best quality in terms of the composition of the soil physicochemical properties (Table 3; Figure 2b).

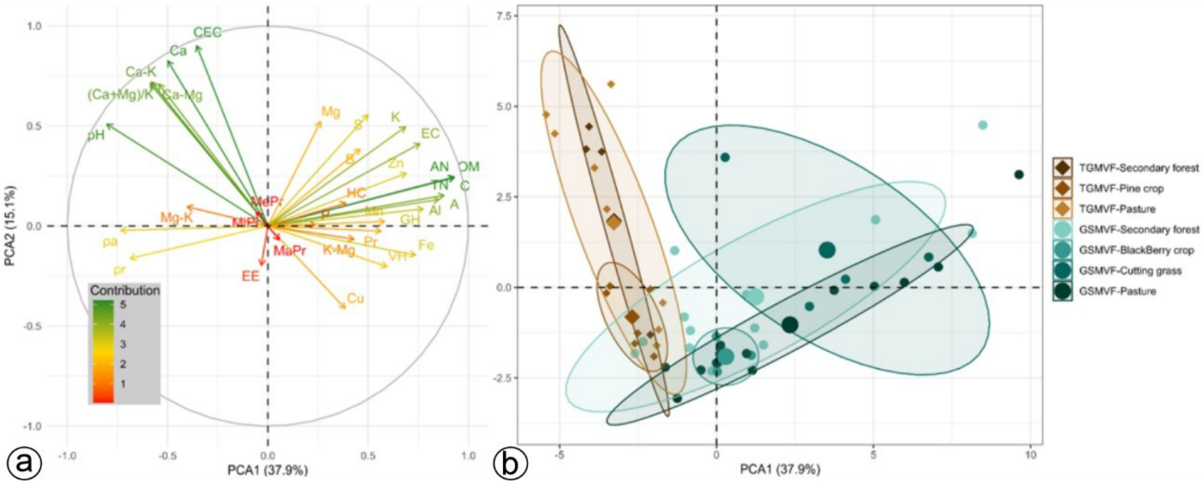


Note. (a) Tapias-Guacaica Monogenetic Volcanic Field; (b) Guamuez-Sibundoy Monogenetic Volcanic Field.

Figure 2. *Cluster analysis using Ward's method and Euclidean distance for the physicochemical variables of the production systems*

In addition, the relationship between the soil physicochemical variables and the systems evaluated in the two monogenetic volcanic fields (TGMVF and GSMVF) is presented using PCA. The first two PCA components account for 53% of the variance, with the soil physicochemical variables clustered into two groups according to the evaluated locations ($p < 0.0001$; 37.9% of the variance explained). The first principal component (PC1) has an eigenvalue greater than one, explaining 37.9% of the variance. When analyzing the coefficients of the vectors associated with the first two components, it was found that the variables of greatest importance, in order, were C, OM, TN, ρa, and VH.

According to Figure 3, the first principal component (PC1) with a contribution of 37.9%, separated the ρa, ρr, SS, CEC, Ca, and pH variables and the Mg-K, Ca-K, (Ca+Mg)/K, and Ca-Mg ratios toward the negative end of that component, associated with the paddock, secondary forest, and pine crop production systems of the TGMVF. In contrast, the Pr, GH, VH, S, K, Mn, Zn, P, EC, DN, C, OM, Al, TN, A, Fe, Cu, and CH variables were associated with the positive end of the component, correlated with the cutting pasture and the paddock production systems in the GSMVF. In contrast, the second component (PC2), with a contribution of 15.1%, separated the secondary forest variables MiPr, MePr, Mg, and B of the GSMVF toward the positive end of this component. Meanwhile, the MaPr variable and the K-Mg ratio, associated with the blackberry crop systems of the GSMVF, were separated toward the negative end of this component.



Note. (a) correlation circle of the soil physicochemical variables; the color of the vectors indicates the contribution of the variables to the PCs; (b) sampling sites. Significance was determined by the Monte Carlo test with all disturbances.

Figure 3. Projection of soil physicochemical properties and observations on the PC1/PC2 ordination plane of the Principal Component Analysis (PCA), grouped according to the production systems of the Tapias-Guacaica and Guamuez-Sibundoy Monogenetic Volcanic Fields.

DISCUSSION

Physical properties

The highest OM content in the GSMVF (16.32%) was associated with the cutting pasture system, whereas the TGMVF presented a lower OM content (6.97%). This difference may be related to lower temperatures in high-altitude environments, which can favor organic matter accumulation by reducing decomposition rates (Hoyos-Sanclemente *et al*., 2025). However, this difference should not be attributed exclusively to climate, since vegetation, land use, and soil management can also influence organic matter accumulation (Alavi-Murillo *et al*., 2022). Structural stability in both volcanic fields is similar; however, the TGMVF soils exhibit slightly better structural stability due to less soil disturbance or a higher presence of stable aggregates (Fernández De Andrade, 2014; Lobo & Pulido, 2006). Nevertheless, for the other physical properties, the GSMVF soils present significant advantages in several aspects, such as lower ρa and ρr, higher porosity, and better water-holding capacity. The lower bulk and particle density indicate a looser and more aerated soil structure, which is beneficial for water infiltration and retention (Cruz *et al*., 2004; Kientz *et al*., 2000). However, this same structure may be more susceptible to compaction under intensive agricultural practices or heavy machinery, reducing porosity and affecting soil aeration (Kientz *et al*., 2000; Yin *et al*., 2021). The higher total porosity and macroporosity in GSMVF favor better water and air dynamics in the soil, but may also increase susceptibility to erosion on slopes or under intense rainfall (Volverás-Mambuscay *et al*., 2020). Higher gravimetric and volumetric moisture levels in GSMVF are indicative of better water-holding capacity, crucial for agriculture in volcanic areas. However, these soils may be prone to saturation and waterlogging under high rainfall conditions, which could negatively affect plant growth (Arias *et al*., 2010; Rica Radulovich, 2009). Higher hydraulic conductivity in GSMVF suggests better soil permeability, facilitating water movement through the soil profile, but may also imply a higher risk of nutrient and contaminant leaching, especially in soils with lower cation exchange capacity (Nissen *et al*., 2006; Sandoval *et al*., 2007). These physical characteristics must be properly managed to maintain soil productivity (Volverás-Mambuscay *et al*., 2020).

Chemical properties

Association of soil chemistry with parent material

Soil formation occurs as a progressive process involving the erosion of parent material over time and the interaction of this process with different local environmental factors (Gallego *et al*., 2023; Shoji *et al*., 1993). The classification of Andisol soils is dependent upon the characteristics of their parent material within 12 established soil orders (Bockheim *et al*., 2014; Soil Survey Staff, 2010). Thus, Andisols are formed from volcanic parent material, regardless of composition (Delmelle *et al*., 2015). Due to the extent of dispersion, most volcanic soils develop from volcaniclastic deposits of intermediate to acidic composition (Ayris & Delmelle, 2012; Delmelle *et al*., 2015; Dörner *et al*., 2012; Nanzyo *et al*., 1993). In Colombia, approximately 80% of soils present acidic conditions, and at least 50% have problems with aluminum toxicity, associated with low pH, low base saturation, and intense leaching, conditions that may limit root growth and functioning (Cuervo-Alzate & Osorio, 2020; Instituto Geográfico Agustín Codazzi, 2015). This is exemplified by the Andisol soils evaluated in this study.

The geological characterization conducted in the field indicates that the Andisol soils analyzed in the TGMVF were formed from the degradation of pyroclastic fall deposits associated with the eruptive activity of Cerro Bravo and Nevado del Ruiz (cf. Picón *et al*., 2024). In contrast, the soils at the GSMVF were formed from the degradation of both pyroclastic fall deposits of unknown origin (cf. Medina-Castellanos *et al*., 2017). The deposits of both regions are composed of pumice fragments, volcanic lithics, and free crystals of plagioclase, amphibole, and biotite. The weathering of these pyroclastic fragments has resulted in a reduction of elements such as Si, Fe, Mg, Ca, K, P, and Al, which has led to an enrichment of the resulting soil (e.g. Brantley & Chen, 2018; Bray *et al*., 2015; Medina-Castellanos *et al*., 2017; Rasmussen *et al*., 2011; Schott *et al*., 1981; White, 2002), as evidenced by the results of this study.

Acidification

Weathering of a fall deposit contributes to soil acidification in the long term (months or years), possibly affecting soil pH due to the oxidation of S compounds (elemental S) present in the fall deposits that form sulfuric acid (cf. Ayris & Delmelle, 2012; Cronin *et al*., 1998). Thus, considering the lithology of the parent material, especially the presence of glass (amorphous aluminosilicate), the Andisol soils analyzed here indicate that, regardless of the management system, the TGMVF soils are in the neutral to moderately acidic range (pH 5.80 ± 0.43 to 7.24 ± 0.47), whereas the GSMVF soils are strongly acidic (pH 5.08 ± 0.19 to 5.26 ± 0.33). According to the Instituto Geográfico Agustín Codazzi (2015), these acidic conditions are commonly associated with high rainfall and intense leaching in Colombian soils, which can result in low base saturation.

Contrast of chemical variables

A comparative analysis of the chemical variables obtained in the soils of the study zones under similar management systems, such as secondary forest and paddock, indicates that the Andisol soils from the TGMVF have lower contents of OM, C, TN, P, B, Al, Fe, Cu, Mn, and Zn than the GSMVF soils (Table 5).

The geographic region where the TGMVF is located is characterized by precipitation ranging from 2000 to 2200 mm per year and relative humidity between 75 and 90% (Arias-Díaz *et al*., 2023). In contrast, the GSMVF region experiences precipitation ranging from 1000 to 2500 mm per year and relative humidity between 83 and 87% (Medina-Castellanos *et al*., 2017; Mendoza Sabogal *et al*., 2014). Therefore, both areas are characterized by a rainy and humid climate, mountainous topography, and slopes ranging from moderate to very steep (Arias-Díaz *et al*., 2023; Medina-Castellanos *et al*., 2017). Climate, topography, and environmental variables control the relative degree of weathering and soil development and do not differ significantly between these two areas (e.g., Bockheim *et al*., 2005; Delmelle *et al*., 2015; Eger *et al*., 2021; Sisay *et al*., 2024). In mountainous environments, topography influences soil development through water movement, drainage, and erosion. In Colombia, differences in soil properties have been reported among Andisols from mountainous regions, reflecting variations in environmental and topographic conditions (Instituto Geográfico Agustín Codazzi, 2015). For instance, although these factors may contribute to the genesis of the Andisol soils analyzed here, they do not appear to be the primary elements controlling their characteristics.

An additional element that defines soil characteristics is time. Studies conducted in Andisol soils have shown that chrono-sequential analysis can be used to understand soil development over time (Gallardo *et al*., 2012; Huggett, 1998; Walker *et al*., 2010; Wardle *et al*., 2004). Under different ages of formation but with similar climatic, topographic, and vegetation conditions, a positive relationship has been established between C accumulation and the abundance of poorly crystalline and non-crystalline minerals (Delmelle *et al*., 2015; Harden, 1982). Also, an increase in C, TN, and P in Andisol soils from 300 to 20,000 years BP and a reduction in these properties from 150,000 years BP onward have been demonstrated (cf. Crews *et al*., 1995). Considering that TGMVF soils are influenced by volcanic inputs associated with the volcanic activity of the Central Cordillera (ca. 2000 ka BP), GSMVF soils have developed mainly on deposits that originated ca. 15,000 ka BP (cf. Murillo-Orobio *et al*., 2024; Picón *et al*., 2024).

Variations in chemical properties between the two monogenetic volcanic fields may also be due to soil management and predominant vegetation. In the TGMVF, the near-neutral pH and low OM and C concentrations in the secondary forest and cutting pasture systems may reflect a higher rate of decomposition and mineralization due to soil moisture conditions in a temperate climate and/or different management practices (Broquen *et al*., 2005; Julca-Otiniano *et al.*, 2006; Sandoval Aparicio *et al*., 2022). In contrast, the GSMVF, with systems such as secondary forest, paddock, and blackberry crops, exhibited the highest levels of acidic soils, which could be related to greater decomposition of OM and leaching of basic cations caused by relatively higher rainfall (Kientz *et al*., 2000; Marín *et al*., 2017). The high EC observed in some crops, especially Andean blackberry, could indicate an accumulation of salts, possibly derived from excessive fertilization practices (Cortés *et al*., 2013). The higher C and OM levels in the GSMVF suggest a higher accumulation of plant residues and a lower mineralization rate, which may be associated with a denser vegetation cover, climatic conditions (cold climate with an average temperature of 11.6 °C), or management practices (Cortés *et al*., 2013). This high OM content may also indicate a risk of slow decomposition under waterlogged conditions, affecting nutrient availability (Alavi-Murillo *et al*., 2022). High TN and DN levels suggest that, in systems such as blackberry crops, there may be more intensive fertilization (Gutiérrez *et al*., 2017), while in the secondary forest, higher biological activity could also indicate a risk of nitrate leaching in soils with low retention capacity (Julca-Otiniano *et al*., 2006).

Impact of major components on nutrient distribution

In Andisols soils, nutrient mobility, gas exchange, microbial activity, water retention and transport, and root growth are mainly facilitated by the soil pore system (Bartoli *et al*., 2007; Dörner *et al*., 2012; Nanzyo *et al*., 1993; Nimmo, 2005). It is not uncommon for Andisols soils to retain more than 30% of plant-available water because they generally have high Pr, which allows them to retain a large amount of water under different stress conditions (Furuhata & Hayashi, 1980; Meza-Pérez & Geissert-Kientz, 2006; Saigusa *et al*., 1987). The development of weathering processes (alteration of geological material over time) results in an increase in porosity (Nanzyo, 2002). These processes contribute to the development of a highly stable porous structure, which is caused by an increase in noncrystalline materials derived from pumice fragments and free crystals and in the OM content of the soil, forming porous aggregates (Dörner *et al*., 2012; Parfitt & Hemni, 1980). Thus, it is expected that the Andisol soils of the TGMVF, which are younger than those of the GSMVF, will exhibit a lower percentage of Pr due to their lower OM and C accumulation. In addition, it has been demonstrated that weathering processes cause young soils to be associated with MaPr, while older soils are associated with MePr and MiPr (Furuhata & Hayashi, 1980; Nanzyo, 2002; Nanzyo *et al*., 1993). Consequently, the soils of the TGMVF present macropores that can facilitate the gravitational accommodation of air, water, and nutrients. However, these soils also present issues with the retention and mobility of these essential materials. In contrast, the moderately old soils of the GSMVF are more suitable for retaining and distributing water and nutrients available to plants, balancing aeration, and maintaining soil moisture in times of drought (cf. Hillel, 2003). On the other hand, in Andisol soils, Mg, N, and B can be strongly retained in the micropores, especially in the presence of OM and allophane (Galindo *et al*., 2022). This can lead to a sustained but slow availability of these nutrients in the soils of volcanic fields, especially in the GSMVF (cf. Amezquita, 1999). The high CEC of Andisols allows good retention of these nutrients (Malagón Castro, 2023). Therefore, the secondary forest system tends to enhance soil MiPr and MePr due to OM accumulation (Christensen, 1996; Graham *et al*., 2002), improving the retention and availability of nutrients such as Mg, N, and B. Regarding the GSMVF Andean blackberry cropping system, intensive agriculture can reduce MePr and increase MaPr (Volverás-Mambuscay *et al*., 2016), which may lead to the dominance of runoff (or leaching of nutrients such as K) (Hofstede *et al*., 2023; Triana *et al*., 2009).

A favorable relationship between Andisol soils and the production system requires high Pr and low ρa (Clunes *et al*., 2021; Dörner *et al*., 2010; Nanzyo, 2002). Therefore, moderate to high ρa represents a drawback for soils associated with TGMVF systems, as it results in a limited development of a porous soil structure. This, in turn, negatively affects the distribution of nutrients from the soil to the roots of the plants cultivated in each system (Shoji *et al*., 1993). The behavior of the physicochemical variables, mainly Pr, ρa, ρr, CEC, and SS, can be affected by external forces such as animal trampling and internal forces such as soil wetting and drying cycles (Dörner *et al*., 2012; Reszkowska *et al*., 2011), especially in the paddock system of both volcanic fields. Furthermore, the probable intensive agricultural practices associated with blackberry cultivation in the

GSMVF affect the percentage of MePr in the soil, resulting in low nutrient availability for this system (Ceballos & Hernández, 2010).

CONCLUSIONS

The moderate to strongly acidic pH of these soils is likely related to their parent material or, in the case of Andean blackberry crops, to the type of soil management practices. Likewise, the content of Fe, Mg, Ca, K, P, and Al may be attributed to the parent material, predominantly as a result of the weathering of free crystals. Significant statistical differences were observed in the 24 chemical and 12 physical variables evaluated. In more than 20% of the evaluated variables, highly significant differences were present in the interactions between location and system. Furthermore, in 56% of the variables, a very significant effect of the field of origin was evident, and a significant effect was observed for 44% of the variables across the systems of both volcanic fields. Finally, the physicochemical variations observed may be mainly due to factors such as geological time, the management of each system, and vegetation. These factors may be influenced by common aspects observed in the two monogenetic volcanic fields, such as the temperate to cold climate, mountainous topography, and parent material.

AUTHOR CONTRIBUTIONS

Conceptualization, A.d.S.G.-A.; Data curation, E.M.-M. and R.J.A.-E.; Formal analysis, E.M.-M. and R.J.A.-E.; Funding acquisition, H.M.; Investigation, all authors.; Methodology, A.d.S.G.-A., R.J.A.-E., G.B.-C., M.A.B.-B. and B.R.G.-G.; Project administration, A.d.S.G.-A., R.J.A.-E. and H.M.; Resources, A.d.S.G.-A. and H.M.; Software, E.M.-M. and R.J.A.-E.; Supervision, A.d.S.G.-A. and H.M.; Validation, A.d.S.G.-A., R.J.A.-E., G.B.-C., M.A.B.-B. and B.R.G.-G.; Visualization, A.d.S.G.-A., R.J.A.-E., G.B.-C., M.A.B.-B., B.R.G.-G., E.M.-M. and H.M.; Writing – original draft, all authors; Writing – review & editing, all authors.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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